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Improving surface water flood mapping: estimating local drainage rates

Project code SC120020/R

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

The ‘Risk of Flooding from Surface Water’ dataset is published by the Environment Agency and shows areas susceptible to surface water flooding. The mapping is used by Lead Local Flood Authorities (LLFAs) and other (flood) Risk Management Authorities to identify which communities are vulnerable to flooding and the likely extent of any impact that might occur in severe weather.

Urban drainage systems (property drainage, highways drainage and public sewers) are highly effective at removing storm water and preventing flooding. Most of the time when it rains, these systems safely remove storm water – protecting property and infrastructure. In heavy rainfall, these systems become overwhelmed and the resulting surplus storm water can cause flooding. This is what is represented in the Risk of Flooding from Surface Water, which is produced using:

- local risk mapping (produced by LLFAs) where it exists and can be used
- mapping produced by the Environment Agency that covers all of England and is called the ‘updated Flood Map for Surface Water’ (uFMfSW)

The mapping in uFMfSW is national in coverage and so the modelling underlying it required simplification – especially as to how the conveyance capacity of urban drainage systems was represented. One simplification was that the modelling generally assumed a default urban drainage capacity (modelled as a ‘drainage rate’ of 12mm per hour) in built-up areas. Feedback from users of the maps was that a more locally appropriate modelled drainage rate would improve mapping robustness, increasing its value. It was also recognised that no advice was provided to guide users in selecting more appropriate drainage rates for local re-creation or re-interpretation of the Environment Agency’s surface water flood maps.

This report describes the outputs of an Environment Agency project to examine new methods and to provide guidance on assigning locally accurate drainage capacity values or ‘drainage rates’. The project was undertaken by staff from JBA and CH2M (now Jacobs) as two separate projects in 2014 to 2015. Some drainage hydraulic modelling simulations were completed by RPS using hydraulic sewer models supplied by water utilities. The results from all the studies are combined into this single report.

Two independent approaches were investigated as a means of estimating drainage rates for an area. The first was an empirical method based on observed relationships between catchment characteristics and drainage rate. The second was a statistical method based on revisiting the original statistical model used to develop the national default drainage capacity value.

The results from the empirical method were inconclusive. No simple explanatory factors were detected to help define ‘true’ drainage rates. This is in part due to the limited sample size of only 6 catchments. It is also the case that a single drainage rate, averaged over a catchment, is the result of multiple factors acting together. It is considered unlikely that it would be possible to identify reliable catchment descriptors based on this method.

A statistical method for estimating local drainage rates by using local information about drainage level of service, critical duration rainfall, percentage run-off, and rainfall depth, duration and frequency (DDF) was also tested. This method adapts the Monte Carlo approach used to derive the national default 12mm per hour drainage rate value.

A number of test catchments highlighted some of the difficulties associated with defining local ranges of the parameters. For example, this method does not take into account that the critical duration grids produced in the original uFMfSW are based on, and not independent of, the 12mm per hour standard drainage rate assumption. Similarly, it is difficult to define the level of service of a sewer system as this is not independent of the duration of the storm event. A commonly used approach, which overcomes some of these issues, is to define the sewer capacity losses by defining the rainfall exceedance probability event that corresponds to the capacity of the sewer system. This sewer capacity hydrograph can be defined for different duration events.

The effect of locally defining the DDF parameters was found to be modest – but not insignificant – in the test catchments (a change of 2mm per hour). A national methodology could incorporate the use of local DDF parameters in defining the sewer capacity. Local DDF parameters are readily available, but it should be noted that the DDF parameters are not independent of each other and should therefore be sampled as sets in the Monte Carlo analysis. However, the method assumes that sewers are designed to a capacity based on local rainfall characteristics – a questionable assumption, in particular, for older sewer systems.

In some cases, the resulting change in drainage rate concurs with the direction of change revealed in the empirical method. This provides a degree of confidence that it is usable as a basis for estimating drainage rate and/or examining the sensitivity of drainage rate to catchment characteristics. A larger number of sites would need to be tested to increase confidence in this conclusion. The method is most reliably applied where there is specific local knowledge of the sewer system level of service, critical storm duration and percentage run-off.

Overall, the range of sewer capacities calculated using locally defined parameters confirmed the robustness and general applicability of the default 12mm per hour rate as a national estimate of the sewer capacity.

This report also presents advice on how to represent the impact of revising drainage rates through flood mapping. As remodelling is expensive and the appropriate resources may not be available to LLFAs, a rainfall proxy method has been developed and tested. The proxy method was developed to give a quick insight into the sensitivity of small (5km × 5km) areas to the drainage rate parameter.

Several test catchments demonstrated that, in practice, there is some variation in the suitability of the proxy method. This is illustrated in the results of several case studies, which highlighted the importance of sense checking the results of the proxy analysis. It is important to be aware of the limitations of the proxy method so as not to over interpret the results. One of the case studies (Greater Manchester) was remodelled using the local range of drainage rates calculated using the statistical method. The flood maps for each drainage rate were compared, allowing areas that are sensitive to a change in drainage capacity to be distinguished. This provides evidence to base investment decisions on.

Both methods provide insights into the sensitivity of an area to the drainage rate parameter. The drainage rate parameter does not necessarily need to be calculated using the statistical method. It is possible, for example, to assess the sensitivity to the drainage rate by comparing the standard lower (6mm per hour) and standard higher (18mm per hour) rates to the default 12mm per hour rate using the proxy method or remodelling.

Remodelling is only recommended where larger areas are of interest, more detailed results are required or where no suitable rainfall proxies are available. The most robust representation of drainage rate is always through using detailed hydraulic modelling of underground drainage networks. The proxy method is recommended for gaining a quick insight into the sensitivity of a given area to the drainage rate parameter. It is easiest to apply on one 5km × 5km uFMfSW modelling tile at a time and is therefore better suited to examining changes in drainage rate across smaller areas.

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1 Introduction

1.1 Background

Surface water flooding results from run-off generated from rainfall falling on land and being routed according to topography. The Environment Agency's updated Flood Map for Surface Water (uFMfSW) is published as the 'Risk of Flooding from Surface Water' to show areas at risk from surface water flooding. The Risk of Flooding from Surface Water dataset is Open Data and is accessible to the public online.[1]

Urban drainage systems include property drainage, highways drainage and public sewers. They are highly effective at removing storm water and preventing flooding. Most of the time when it rains, these systems safely remove storm water protecting property and infrastructure. In heavy rainfall, these systems become overwhelmed and the resulting surplus storm water can cause flooding. It is this surplus storm water that is represented in the uFMfSW. Detailed investigations into the local causes and reduction of surface water flood risks may lead to the development of a Surface Water Management Plan.

Lead Local Flood Authorities (LLFAs) have access to the detailed mapping and modelling information (9 modelled flood scenarios) created for the uFMfSW which underpins the data available online. The information is used by LLFAs and other (flood) Risk Management Authorities (RMAs) to determine:

- which communities are vulnerable to flooding
- the likely extent of any impact that might occur in severe weather

The surface water flooding maps are used in conjunction with maps showing flooding from rivers and the sea.

The wide range of uses of the model data and maps include:

- testing sensitivity to climate change
- testing the effectiveness of some flood risk management measures (for example, reducing the extent of impermeable areas)

The mapping's national coverage meant that the underlying modelling required simplification, especially about how the conveyance capacity of urban drainage systems was represented. Full details behind the direct rainfall modelling method and its parameterisation are given in Appendix A.

As a simplifying measure, the modelling underlying uFMfSW generally assumed a default urban drainage capacity (or 'drainage rate') in built-up areas. The default drainage rate was 12mm per hour, although some local variants were applied at the request of LLFAs. Users of the maps suggested that a more locally appropriate modelled drainage rate would improve the robustness of the mapping and increase its value. In addition, no advice had been provided to guide users in selecting more appropriate drainage rates for local re-creation or re-interpretation of the Environment Agency's Risk of Flooding from Surface Water maps.

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[1] https://flood-warning-information.service.gov.uk/long-term-flood-risk/map

1.2 Purpose of this report

This report describes the outputs of a joint Defra and Environment Agency research and development project to examine new methods and to provide guidance on assigning locally accurate drainage rates. The project was undertaken by staff from JBA and CH2M (now Jacobs) in 2014 to 2015 as separate projects. Some drainage hydraulic modelling simulations were completed by RPS using hydraulic sewer models supplied by water utilities. The results from all the studies are combined into this single report.

Two independent approaches were investigated as a means of estimating drainage rates for an area. The first was an empirical method based on observed relationships between catchment characteristics and drainage rate. The second was a statistical method based on revisiting the original statistical model used to develop the national default drainage capacity value.

For some of these tests, Depth Duration Frequency (DDF) data was extracted from the FEH CD-ROM which is referenced throughout the report. After the project completed, the FEH CD-ROM was superseded by the FEH Web Service[2]. This can be accessed online and the data must be used with an appropriate licence from CEH (https://fehweb.ceh.ac.uk/Home/Terms).

The DDF data used in this project is from FEH99, which corresponds to the data used in the uFMfSW. The FEH99 DDF data presented in the case studies and Appendix spreadsheet tools are for illustration purposes only. Users need to access the DDF data direct from the FEH Web Service for their own use. Please note the FEH99 DDF data has been superseded by the FEH13 DDF model, which is more appropriate to use for any new local surface water modelling.

1.3 Structure of this report

Sections 2 and 3 describe the methods, results and conclusions of the empirical and statistical approaches respectively.

Section 4 examines the tested methods for illustrating flood mapping sensitivity to different drainage rates by using a rainfall proxy method that avoids costly re-simulation of direct rainfall models.

Section 5 provides succinct guidance for LLFAs and others wishing to apply different drainage rates to surface water flood maps.

Appendix A offers a detailed background into the workings of direct rainfall flood modelling and mapping as applied in Environment Agency surface water flood mapping products.

Appendix B contains information on the basis for adjusting input parameters to the drainage capacity equation.

Appendix C presents information on the Monte Carlo analysis spreadsheet tool used to prepare new drainage capacity values by changing input parameters.

Appendix D describes a rainfall calculator spreadsheet tool developed to generate design rainfall profiles using the DDF model from the Flood Estimation Handbook (FEH).

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[2] FEH Web Service (https://fehweb.ceh.ac.uk)

The 2 spreadsheet tools are available to download separately from the project web page on the Environment Agency's FCERM Research and Development website.

Also available to download is a separate user guide which explains how to:

- estimate a new drainage rate to better accommodate local characteristics in surface flood water maps
- apply the rainfall proxy method

2 Empirical approach

2.1 Introduction

The default ‘drainage rate’ parameter (12mm per hour) used in the model underlying the uFMfSW is a simplifying proxy, averaged over an area, for a range of physical characteristics which control:

- how much storm water is removed by urban drainage systems
- how much storm water remains on the surface

The physical characteristics can be separated into above ground and below ground types.

Above ground characteristics that can have an impact on drainage rates include:

- the pattern of directly plumbed connections such as roof downspouts and overland flow to gullies
- the number, location and design of road gullies and other storm water inlets
- road gradient (this affects the efficiency of gullies)

Below ground characteristics that can have an impact on drainage rates include:

- hydraulic influence of backwater or drowned outfalls such as backwater effects occurring at high tides
- the gradient, diameter and condition of sewers, resulting in conveyance capacity
- the serviceability of sewers, based on accumulated debris, defects and permanent or seasonal groundwater infiltration
- the presence and operation of pumping stations, combined sewer overflows and online flow controls such as penstocks
- the effect of storage (including retention systems) and conveyance in piped networks
- the pattern and function of foul, storm and combined sewers (all of which will receive run-off)
- the location of any pinch points in the storm network as these can cause backwater effects

2.2 Method

It is assumed that detailed hydraulic models of urban areas, including underground piped networks, will generate a more robust flood map than simplified direct rainfall methods as applied in the uFMfSW.

Flood outlines from repeated simulations of direct rainfall models using different drainage rates were compared with flood outlines from detailed hydraulic models. This comparison was used to:

- identify any catchment characteristics that could be used as indicators of drainage rate
- determine a rationale for selecting a different drainage rate to the default 12mm per hour

Direct rainfall and detailed hydraulic models were prepared for the following locations:

- Market Harborough – a market town in Leicestershire
- Ellenbrook – a district of Ipswich, Suffolk
- Stirchley – a district south of south of Birmingham city centre
- Liverpool – three areas in central Liverpool

The detailed hydraulic models were used to prepare flood outlines for 1 in 30 and 1 in 100 year return period rainfall events at 1, 3 and 6 hour duration.

The direct rainfall models were used to prepare flood outlines for the same events with a low (6mm per hour), medium (12mm per hour) (the default) and high (18mm per hour) drainage rate parameter setting. Flood outlines were compared by visual inspection and examination of flood areas and volumes.

To identify the 'true' drainage rate, direct rainfall model flood outlines using the 3 drainage rates were matched with the outlines from the detailed hydraulic model to establish the most suitable drainage rate for that location. In effect, the drainage rate parameter is used to calibrate the direct rainfall model against the results of a detailed hydraulic model. Explanations for the drainage rate were then sought by looking at catchment characteristics such as:

- building density
- impervious area
- sewer diameter
- sewer gradient

It was hoped that simple rules could be developed that would link drainage rate to an easily measurable catchment characteristic.

2.3 Results

The mapping outputs for Market Harborough, Ellenbrook and Stirchley are shown in Figures 2.1, 2.2 and 2.3 respectively. Figure 2.4 shows the location of 3 further areas examined in Liverpool.

Figure 2.1 Comparison of flood extents for Market Harborough, southern area, 1 in 30 storm event

Figure 2.2 Comparison of flood extents for Ellenbrook, southern area, 1 in 100 storm event

Figure 2.3 Comparison of flood extents for Stirchley, northern area, 1 in 100 storm event

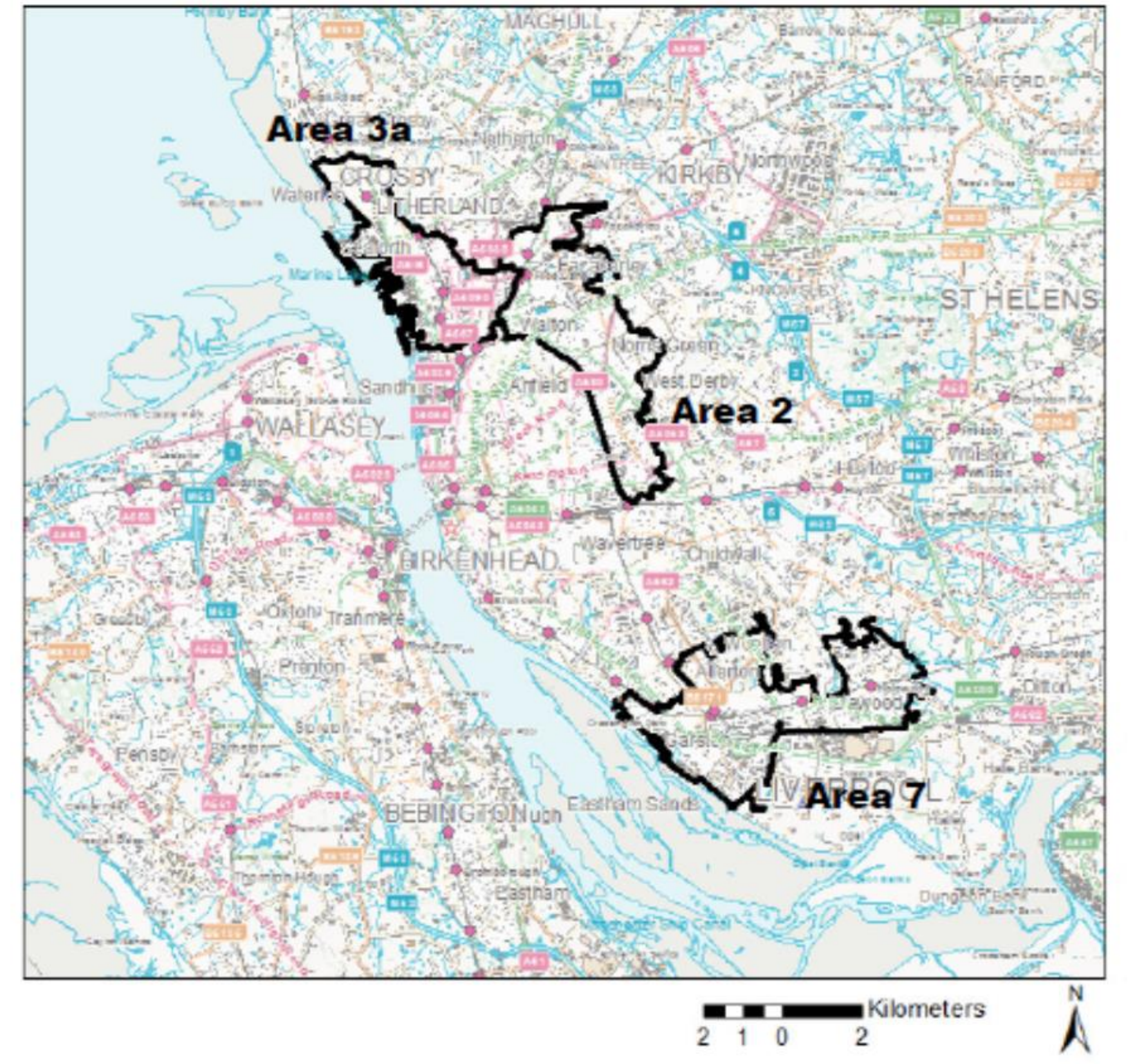

Figure 2.4 Sites investigated in Liverpool

Estimates of a ‘best fit’ or ‘true’ drainage rate for each location were made by visually comparing flood outlines from different modelling approaches and analysing comparisons of flooded area and volume. The ‘best fit’ or ‘true’ drainage rate is the drainage rate that, when applied to a direct rainfall flood model, results in a flood outline most similar to the flood outline generated with a detailed hydraulic model. Table 2.1 summarises these results.

Table 2.1 ‘Best fit’ or ‘true’ direct rainfall drainage rate

Location	Direct rainfall drainage rate (mm per hour)
Market Harborough	18
Ellenbrook	18
Stirchley	6
Liverpool (Area 2)	9
Liverpool (Area 3a)	6
Liverpool (Area 7)	12

Models, mapping data and model results were analysed to see whether any underlying explanation for the true drainage rate could be developed. This was achieved by plotting the true drainage rate against a range of catchment descriptors and examining any visible trends. The catchment descriptors examined were:

- building density (building per km^2)
- percentage impervious area
- median sewer diameter
- sewer density (km of sewer per km^2 catchment area)
- manhole density
- sewer gradient
- frequency distribution of sewer diameters

The relationships between the drainage rate and catchment descriptors are illustrated in Tables 2.2 and 2.3, and Figures 2.5 to 2.11.

Table 2.2 Watershed properties of the 6 study areas

Area	**Drainage rate (mm per hour)**	**Type of model**	**Area (km^2)**	**Building density (buildings per km^2)**	**Impervious area (%)**
Market Harborough	18	Combined	0.56	2,950	40
Ellenbrook	18	Storm	1.19	4,850	34
Stirchley (Ripple Road)	6	Combined	2.25	3,480	35
Liverpool (Area 2)	9	Combined	13.7	2,870	45
Liverpool (Area 3a)	6	Combined	10.3	2,380	46
Liverpool (Area A7)	12	Combined	16.1	1,460	30

Table 2.3 Sewer network properties of the 6 study areas

Area	Drainage rate (mm per hour)	Median pipe diameter (mm)	Pipe density (km per km^2)	Manhole density (number per km^2)	Pipe gradient (%)
Market Harborough	18	150	28.8	940	2.15
Ellenbrook	18	225	9.2	190	2.76
Stirchley (Ripple Road)	6	225	18.9	330	2.27
Liverpool (Area 2)	9	225	17.7	480	1.80
Liverpool (Area 3a)	6	225	15.5	410	1.27
Liverpool (Area A7)	12	225	9.0	220	1.53

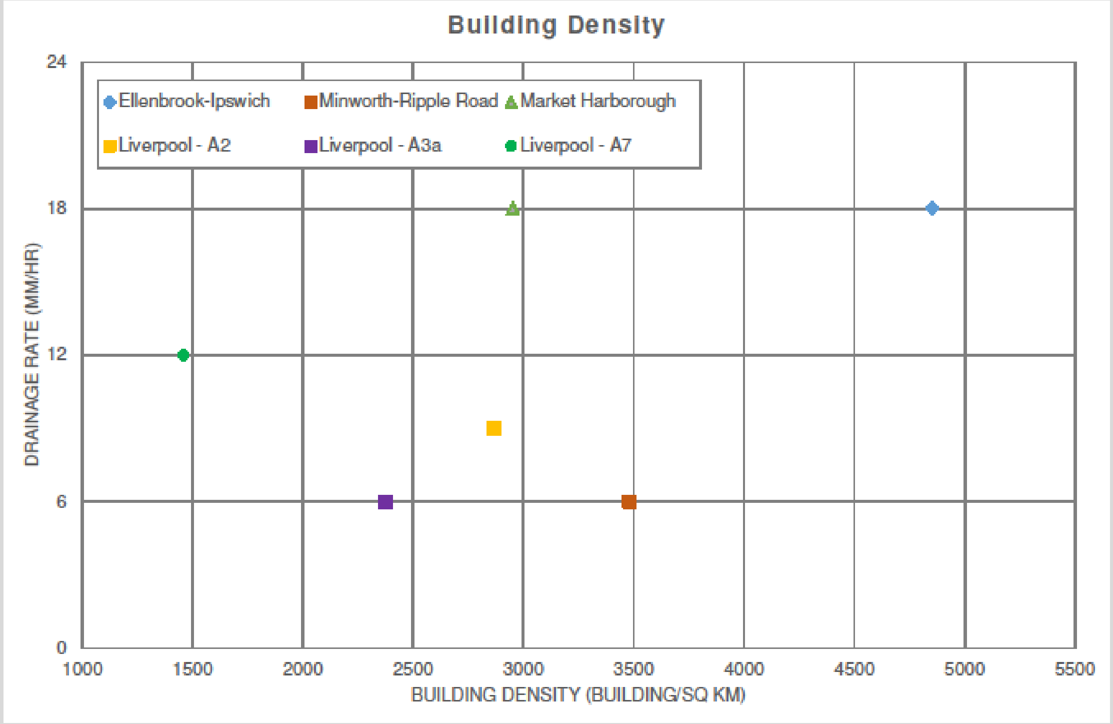

Figure 2.5 Comparison of building density for the 6 study areas

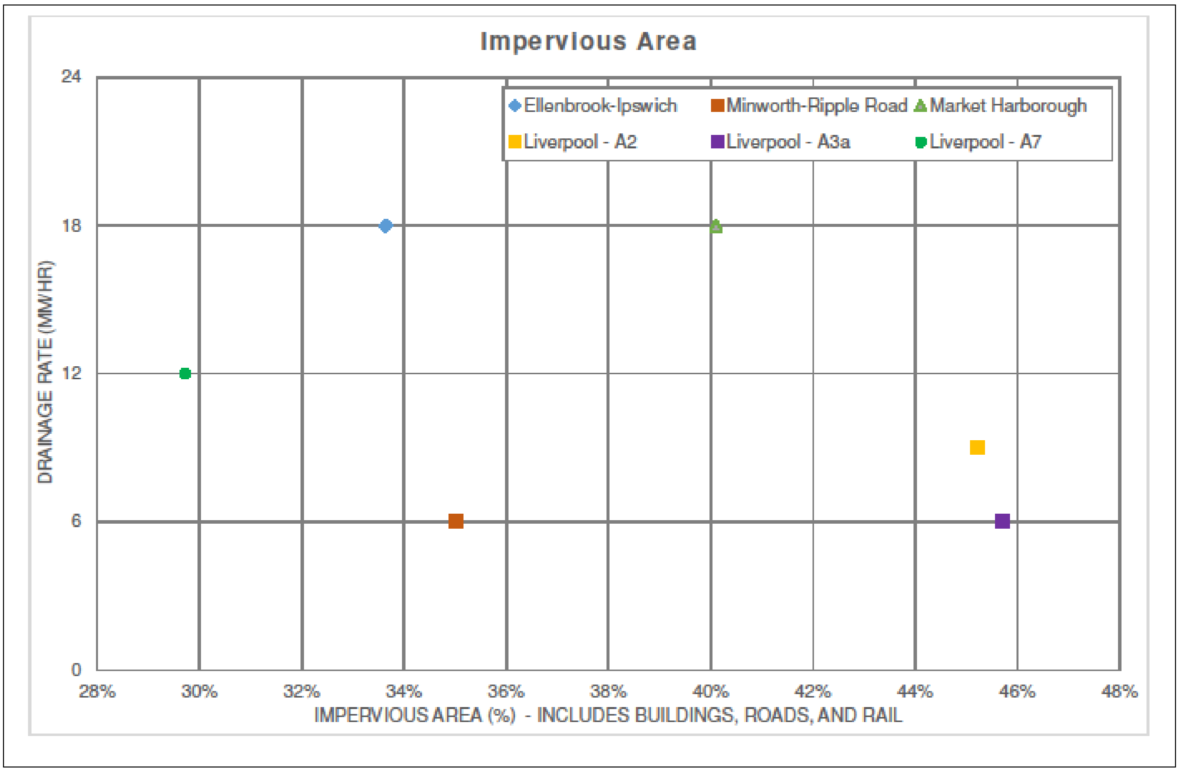

Figure 2.6 Comparison of impervious area for the 6 study areas

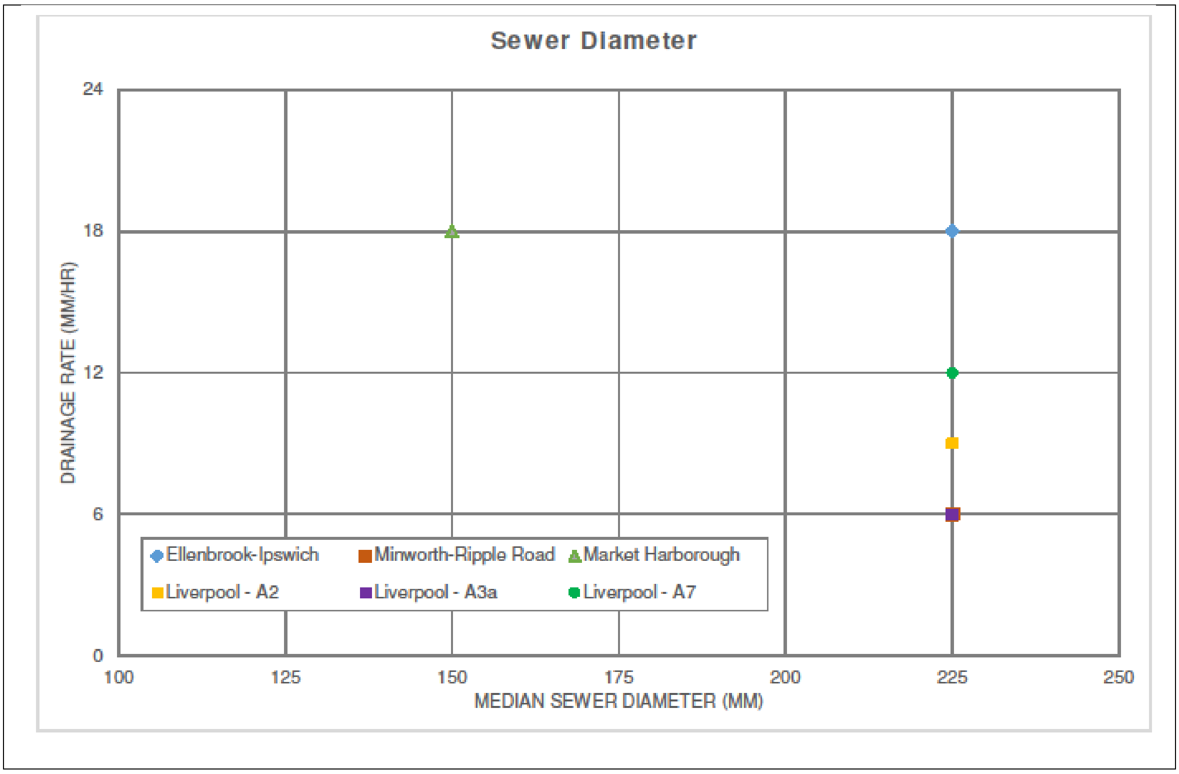

Figure 2.7 Comparison of median pipe size for the 6 study areas

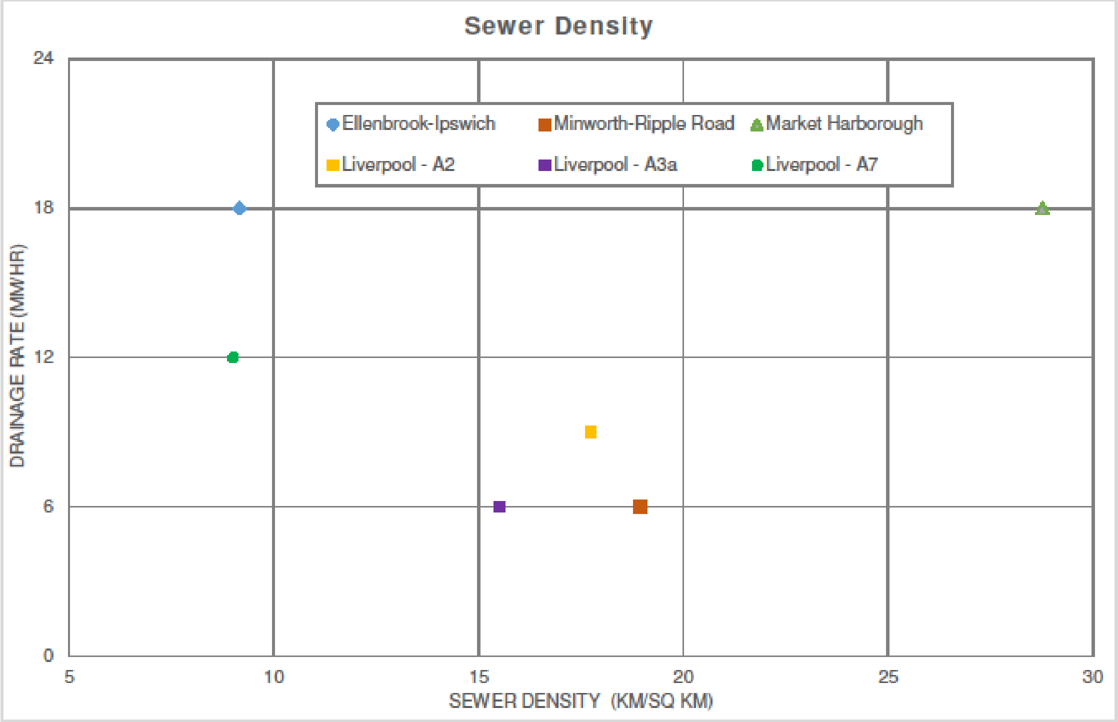

Figure 2.8 Comparison of pipe density for the 6 study areas

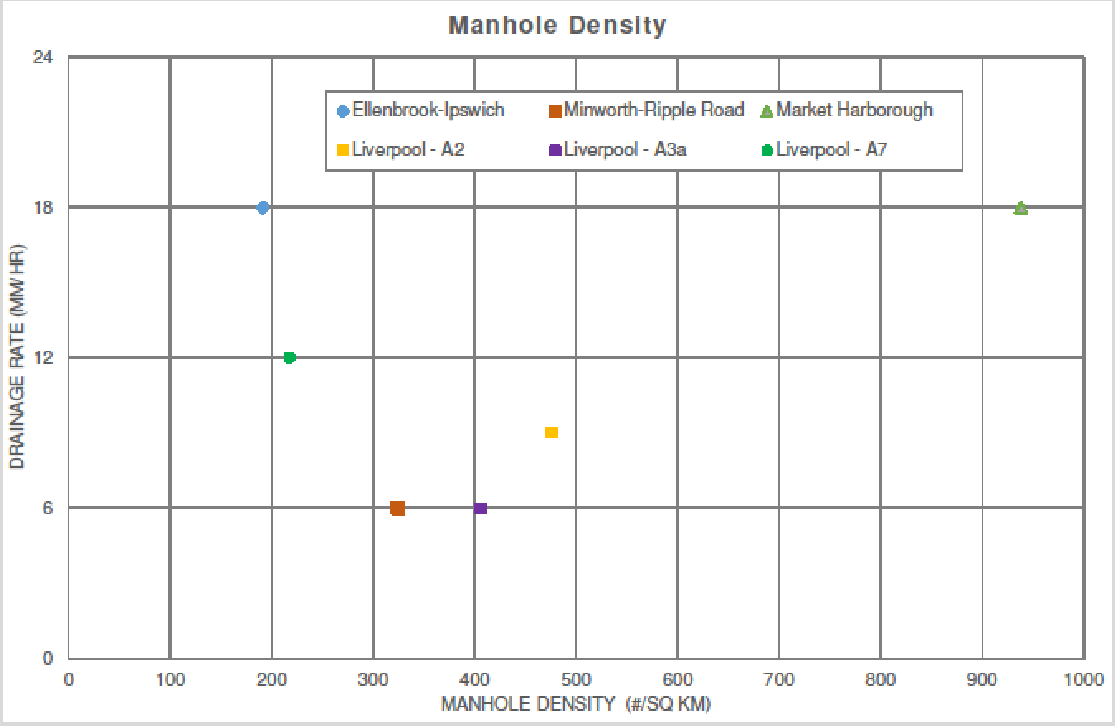

Figure 2.9 Comparison of manhole density for the 6 study areas

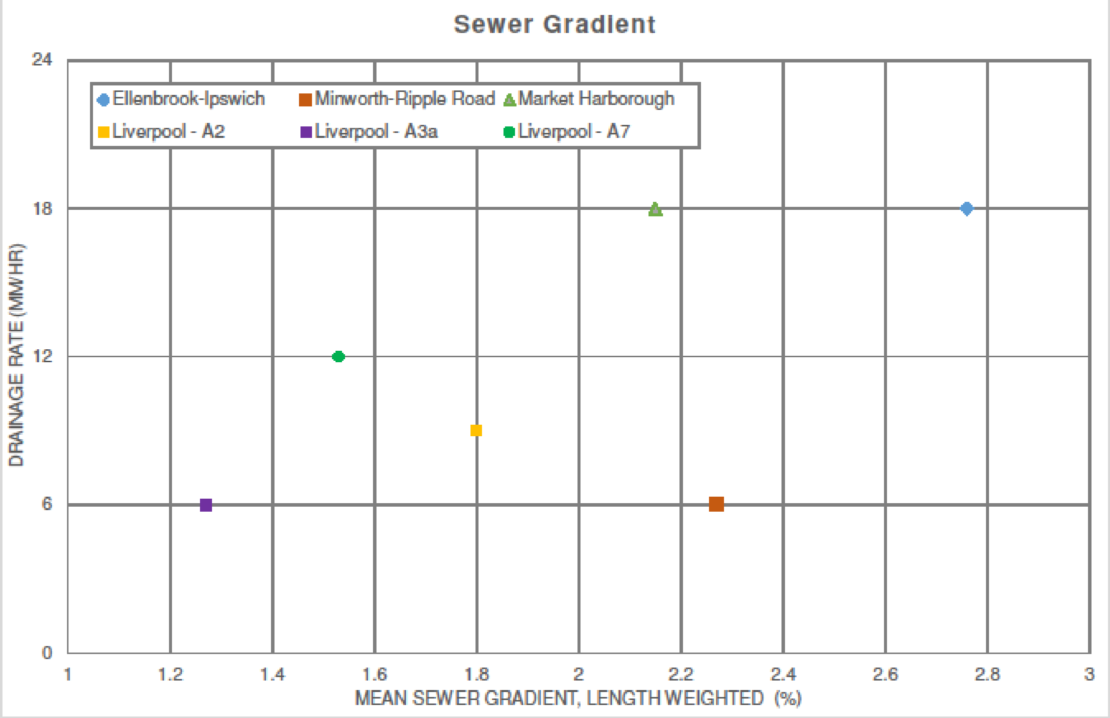

Figure 2.10 Comparison of sewer gradient for the 6 study areas

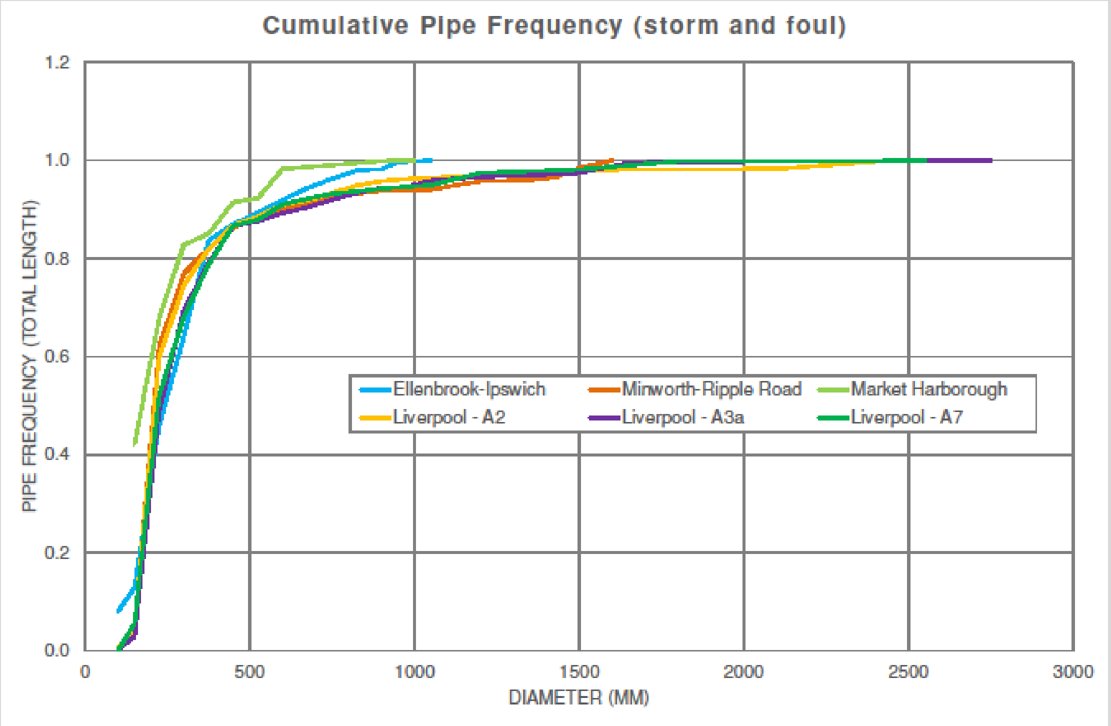

Figure 2.11 Cumulative pipe size distributions for the 6 study areas

2.4 Conclusions

The results of this analysis were inconclusive. No simple explanatory factors were detected to help to define ‘true’ drainage rates.

This is partly due to a limited sample size of only 6 catchments. The availability of detailed hydraulic model results was a limiting factor here. It was also beyond the resources of this project to prepare a greater number of case study locations to establish a ‘true’ drainage rate through calibration against direct rainfall model results.

It is also the case that a single drainage rate, averaged over a catchment, is the result of multiple factors acting together. In the light of this experimental experience, it is considered unlikely that it would be possible to identify reliable catchment descriptors based on this method.

3 Statistical approach

3.1 Method

The national estimate of the drainage rate (12mm per hour) used in the uFMfSW is obtained using a drainage system capacity equation. This equation uses the percentage run-off, critical storm duration, level of service of the drainage system, and the depth, duration and frequency parameters of typical rainfall events. The full approach is described in Horritt et al (2009), and further described in Appendix A.

A single estimate is made by carrying out a statistical analysis of nationally defined ranges of the parameters of the equation. This method, which uses a modified form of the Rational Method, is described in full in Appendix B.

The default 12mm per hour rate was calculated by:

- defining a national range of the parameters of the drainage system capacity equation (Table 3.1)
- using a Monte Carlo technique (repeated random sampling) to arrive at a central estimate (the modal value of the frequency distribution) of the most likely drainage rate nationally

Table 3.1 Parameters used for the national estimate of drainage system capacity

Parameter		National range
Percentage run-off (PR)		30–80%
Critical storm duration (T_{CRIT})		0.5–2 hours
Level of service of drainage system (LoS)		5–30 years (mode of 10 years)
Depth, duration and frequency (DDF) rainfall parameters	C	-0.026 ± 0.0034
	D1	0.38 ± 0.039
	E	0.30 ± 0.011
	F	2.4 ± 0.063

The estimate of drainage rate can be refined by making estimates of locally specific ranges of the parameters of the drainage system capacity equation (PR, T_{CRIT}, LoS and DDF). This allows local knowledge of the parameters and knowledge of mitigation measures to be used. For example, if measures have been taken in an area to reduce PR such as the extensive use of green roofs or permeable paving, it may be possible to reduce the range of PR. This locally refined range can then be used within the statistical analysis of the drainage system capacity equation to obtain a revised local estimate of the drainage system capacity.

Appendix B provides guidance on methods to estimate local values of PR, T_{CRIT}, LoS and DDF parameters.

A spreadsheet tool was developed to generate new drainage rate estimates from varying input parameter ranges. The tool is described in Appendix C.

For the test catchments (some in common with those examined for the empirical approach), local evidence was used to improve on parameter estimation and to derive a revised drainage rate.

Incorporating local knowledge was tested in 3 of the catchments:

- Stirchley – local knowledge of rainfall characteristics
- Market Harborough – local knowledge of rainfall characteristics and T_{CRIT}
- Greater Manchester – local knowledge of rainfall characteristics, PR and T_{CRIT}

One of the catchments (Ellenbrook) was used the method to test a possible future scenario – 'what if' scenario for sewer maintenance.

3.2 Results

3.2.1 Stirchley

In Stirchley, drainage capacity was estimated by revising only the rainfall DDF parameters using the exact values for this location rather than the default full range (Table **3**.2). It was not possible to draw conclusions about the LoS in the district, in part because of recent investment to upgrade capacity in some locations.

Table 3**.2** **Local estimates of parameters for the drainage system capacity equation: Stirchley**

Parameter	Estimate type	Value
LoS (years)	National range	
minimum		5
mode		10
maximum		30
T_{CRIT} (hours)	National range	
minimum		0.5
maximum		2
PR (%)	National range	
minimum		30
maximum		80
DDF parameters	Local exact value	
C		0.027
D1		0.348
E		0.306
F		2.412

This method reduced the modal value for drainage capacity from 12.0mm per hour to 10.5mm per hour (Figure 3.1). This result is consistent with the empirical approach for the same location in as far as the default value is considered too high. However, it is not surprising that altering the rainfall parameter alone has only a modest impact on assumed drainage capacity.

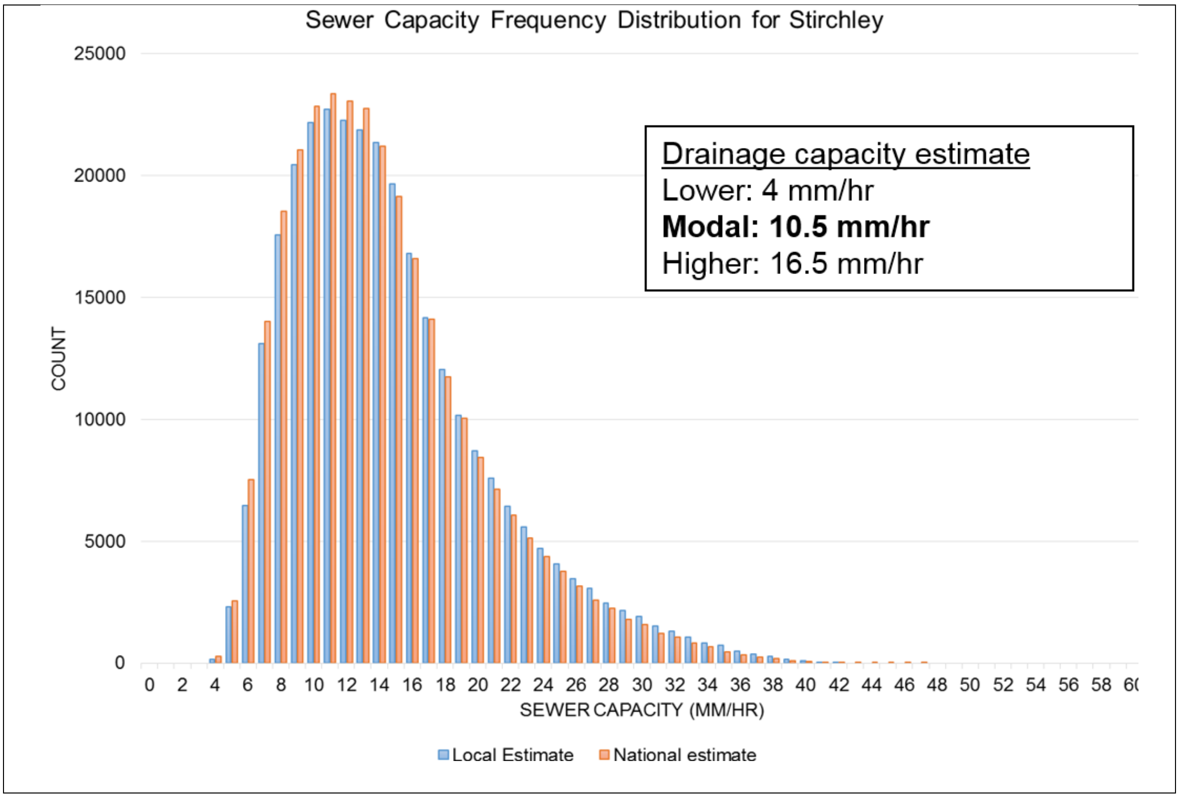

Figure 3.1 Drainage system capacity frequency distribution for Stirchley

3.2.2 Market Harborough

Analysis of local mapping and terrain revealed the town to be more steeply sloping than average. Data from a pre-prepared uFMfSW critical duration grid for a 1 in 1,000 year event revealed that the one hour duration grid was critical in 83% of the area. The range of T_{CRIT} was therefore changed from the default of 0.5–2.0 hours to a revised estimate of 0.5–1.0 hours. DDF estimates for the exact location were extracted from the FEH CD-ROM[3]. Table 3.3 presents the new drainage capacity equation parameters that were then applied.

Table 3.3 Local estimates of parameters for the drainage system capacity equation: Market Harborough

Parameter	Estimate type	Value
LoS (years)	National range	
minimum		5
mode		10
maximum		30
T_{CRIT} (hours)	Local range	

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[3] Now superseded by the FEH Web Service (https://fehweb.ceh.ac.uk)

Parameter	Estimate type	Value
minimum		0.5
maximum		1
PR (%)	National range	
minimum		30
maximum		80
DDF parameters	Local exact value	
C		-0.024
D1		0.331
E		0.304
F		2.572

Figure 3.2 shows the resulting frequency distribution of drainage rate generated by altering the input ranges as described. The modal drainage rate shifts from the national average of 12mm per hour to a locally specific 18mm per hour. This result concurs with the conclusion of the empirical approach for the same location.

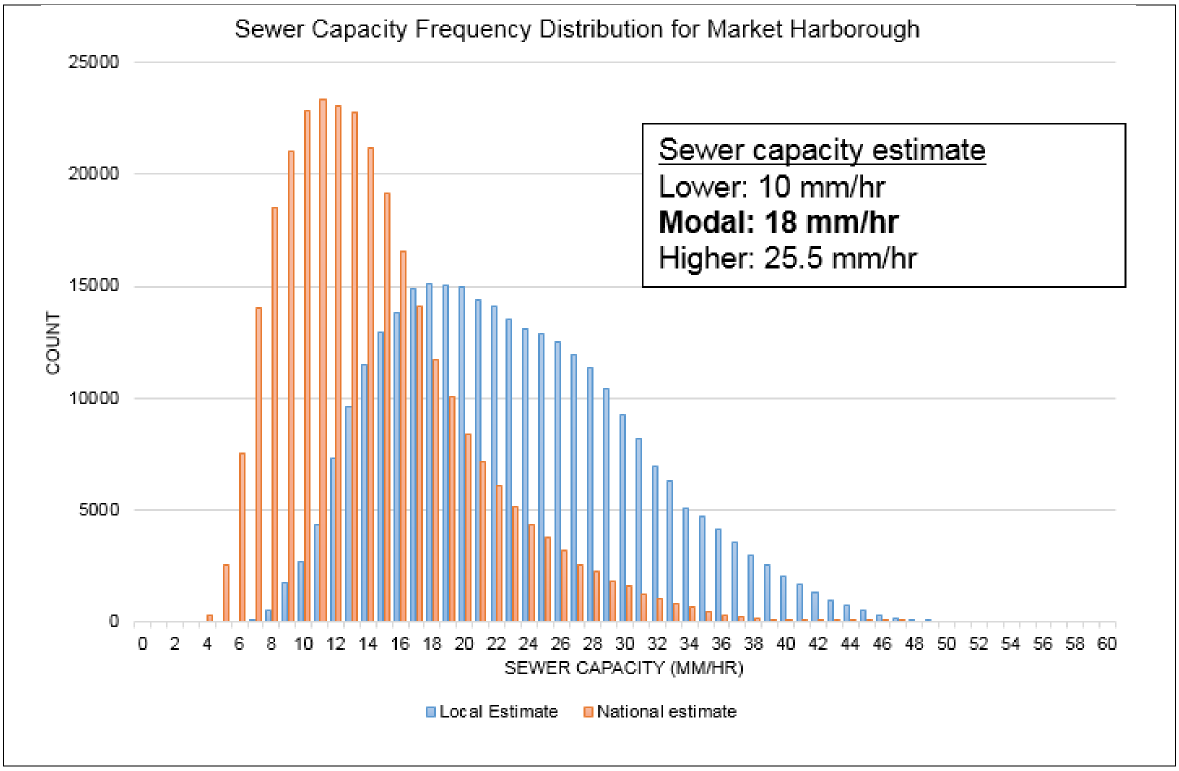


Figure 3.2 Drainage system capacity frequency distribution for Market Harborough

3.2.3 Greater Manchester

The whole of Greater Manchester was considered, an area of 1,277km^2.

The parameters were locally refined based on information extracted from previous surface water flooding analysis completed by the Association of Greater Manchester Authorities (AGMA). Table 3.4 illustrates the local parameter estimates T_{CRIT} (1 hour) and PR (60–85%) as well as the rainfall DDF parameters, which were revised using the exact values for the centre of this location rather than the default full range.

Table 3.4 Local estimates of parameters provided by AGMA for use in the drainage system capacity equation: Greater Manchester

Parameter	Estimate type	Value
LoS (years)	National range	
minimum		5
mode		10
maximum		30
T_{CRIT} (hours)	Local exact value	
minimum		1
maximum		1
PR (%)	Local range	
minimum		60
maximum		85
DDF parameters	Local range	
C D1 E F		Sampled as sets from centroids of model tiles from across Greater Manchester

The modal value for drainage capacity increased from 12mm per hour to 16mm per hour (Figure 3.3). The mode and higher estimate (21mm per hour) compares favourably with an estimate made by AGMA which was included in uFMfSW model simulations. The estimate used 2 values of either 0mm per hour or 18mm per hour for zones mapped as shown in Figure 3.4.

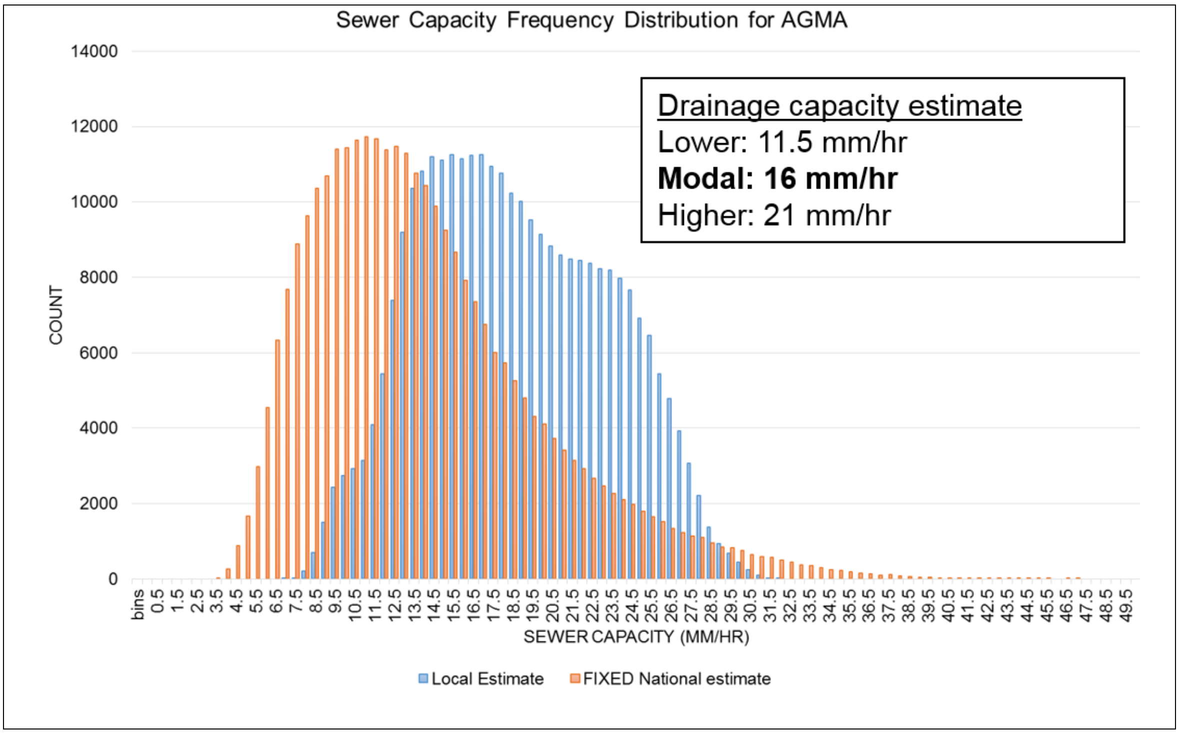
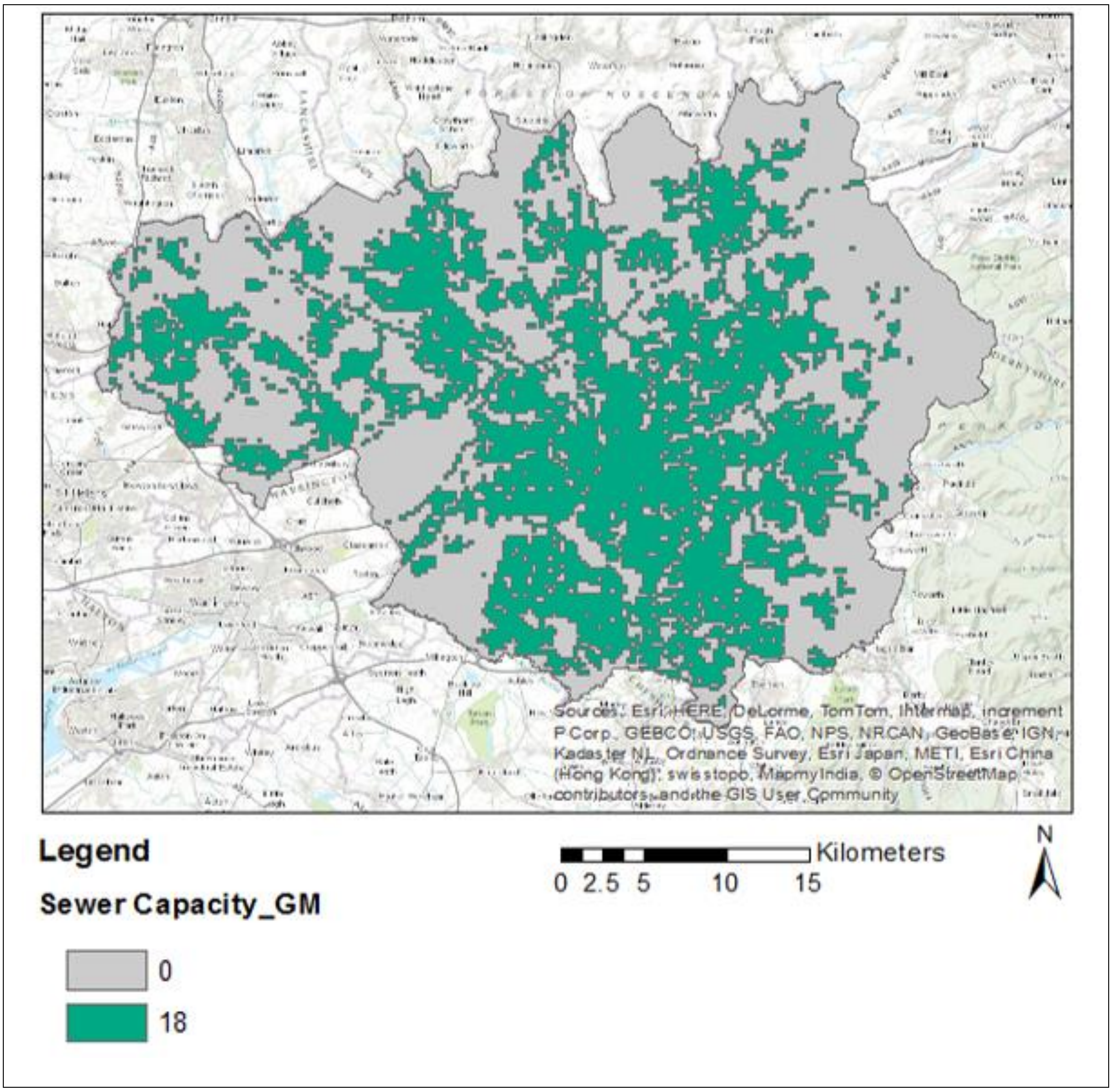


Figure 3.3 Drainage system capacity frequency distribution for Greater Manchester



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3.4 Drainage system capacities provided by AGMA for Greater Manchester (mm per hour)

3.2.4 Ellenbrook

Ellenbrook, a district of Ipswich, was identified as an area at high risk of flooding (Ipswich Surface Water management Plan, Ipswich Borough Council 2012). Maintenance and upgrading the drainage system is one way in which the drainage system capacity in Ellenbrook could be improved. The net effect of this improvement work was investigated using the LoS parameter within the drainage system capacity equation. Although detailed information on the LoS of the existing drainage system was not available, the effect of narrowing the range of the estimate of LoS on the flood map in Ellenbrook was explored.

To investigate the effect of improving the level of service of the drainage system in Ellenbrook, the range of the input parameter LoS was narrowed by increasing the lower bound of its range. In the national estimate of drainage system capacity, the LoS is assumed to be a triangular distribution of between 5 and 30 years, with a mode of 10 years. Changing the distribution of LoS to a local range of 10 to 30 years, with a mode of 20 years, was calculated to determine the effect on the drainage system capacity

(Table 3.5). This increased LoS could be achieved by maintenance activities such as removing blockages and regular jetting.

Table 3.5 Local estimates of parameters for Ellenbrook

Parameter	Estimate type	Value
LoS (years)		
minimum	Local range	10
mode	Local range	20
maximum	National range	30
T_{CRIT} (hours)	National range	
minimum		0.5
maximum		2
PR (%)	National range	
minimum		30
maximum		80
DDF parameters	Exact local values	
C		
D1		
E		
F		

The drainage system capacity estimate for Ellenbrook increases from the national estimate of 12mm per hour to 14mm per hour (Figure 3.5) by:

- increasing the minimum LoS of the drainage system from 5 to 10 years
- using local DDF parameters

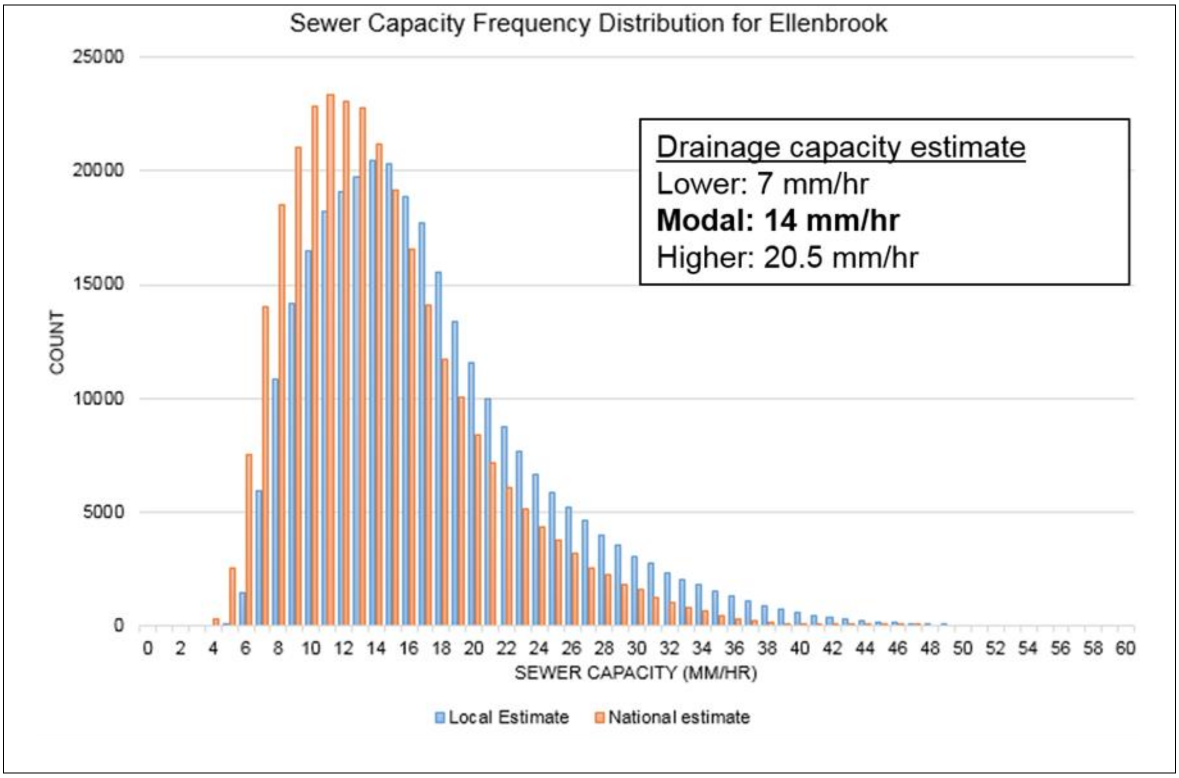


Figure 3.5 Drainage system capacity frequency distribution for Ellenbrook

3.3 Conclusions

The method used local information about drainage LoS, T_{CRIT}, PR, and rainfall DDF to estimate drainage rates.

The method adapts the Monte -Carlo approach used to derive the national default 12mm per hour drainage rate value.

The test catchments highlighted some of the difficulties associated with defining local ranges of the parameters. For example, the method does not take into account that the critical duration grids produced in the original uFMfSW are based on, and not independent of, the 12mm per hour standard drainage rate assumption. Similarly, it is difficult to define the LoS of a sewer system as it is not independent of the duration of the storm event. A commonly used approach which overcomes some of these issues is to define the sewer capacity losses by defining the rainfall exceedance probability event that corresponds to the capacity of the sewer system. This sewer capacity hydrograph can be defined for different duration events.

The effect of locally defining the DDF parameters was found to be modest, but not insignificant, in the test catchments (a change of 2mm per hour). A national methodology could incorporate the use of local DDF parameters in defining the sewer capacity. Although local DDF parameters are readily available, the DDF parameters are not independent of each other and should therefore be sampled as sets in the Monte Carlo analysis. However, the method assumes that sewers are designed to a capacity based on local rainfall characteristics – a questionable assumption, in particular, for older sewer systems.

In some cases, the resulting change in drainage rate concurs with the direction of change revealed in the empirical method. This provides a degree of confidence that it is usable as a basis for estimating drainage rate and/or for examining the sensitivity of drainage rate to catchment characteristics.

A larger number of sites would need to be tested to increase confidence in this conclusion. The method is most reliably applied where there is specific local knowledge of the sewer system LoS, T_{CRIT} and PR.

The range of sewer capacities calculated using locally defined parameters confirms the robustness and general applicability of the default 12mm per hour rate as a national estimate of the sewer capacity.

4 Representing the effect of new drainage rates

4.1 Introduction

Section 2 and 3 demonstrate how a revised drainage rate can be estimated. This section presents advice on how to represent the impact of revising drainage rates through flood mapping. Two methods are possible:

- rainfall proxy method
- remodelling

As remodelling is expensive and the appropriate resources may not be available to LLFAs, a rainfall proxy method has been developed and is recommended. Remodelling is recommended only where:

- larger areas are of interest (for example, where the area spans several 5km × 5km uFMfSW modelling tiles)
- more detailed results are required
- where no suitable rainfall proxies are available

All the data required for remodelling was supplied to each LLFA on a hard disk drive in November 2014. The uFMfSW method statement (Environment Agency 2013a) describes the modelling approach used in detail.

The proxy method is recommended to gain a quick insight into the sensitivity of a given area to the drainage rate parameter. It is easiest to apply on one 5km × 5km uFMfSW modelling tile at a time and is therefore better suited to examining changes in drainage rate across smaller areas.

4.2 Rainfall proxy method

The rainfall proxy method was developed to avoid remodelling and builds on work undertaken by the Natural Hazards Partnership to develop a Hazard Impact Model for Surface Water Flooding (CEH Wallingford, 2015). The method reuses existing uFMfSW mapping for each of the 9 underlying rainfall scenarios to help understand the effect of applying a local estimate of drainage system capacity.

In the uFMfSW, the drainage rates are applied using the direct rainfall approach, as described in Appendix A. The PR and drainage system capacity are removed from the rainfall profile before it is applied to the model area.

Because the direct rainfall is approach is used, it can be assumed that the total volume of rainfall applied to the model is a key factor in determining the flood depths and outlines, regardless of the shape of the rainfall hydrograph. This means that flood maps for 2 storms of different durations and intensities, but with the same total rainfall volume, should have similar flood depths and outlines.

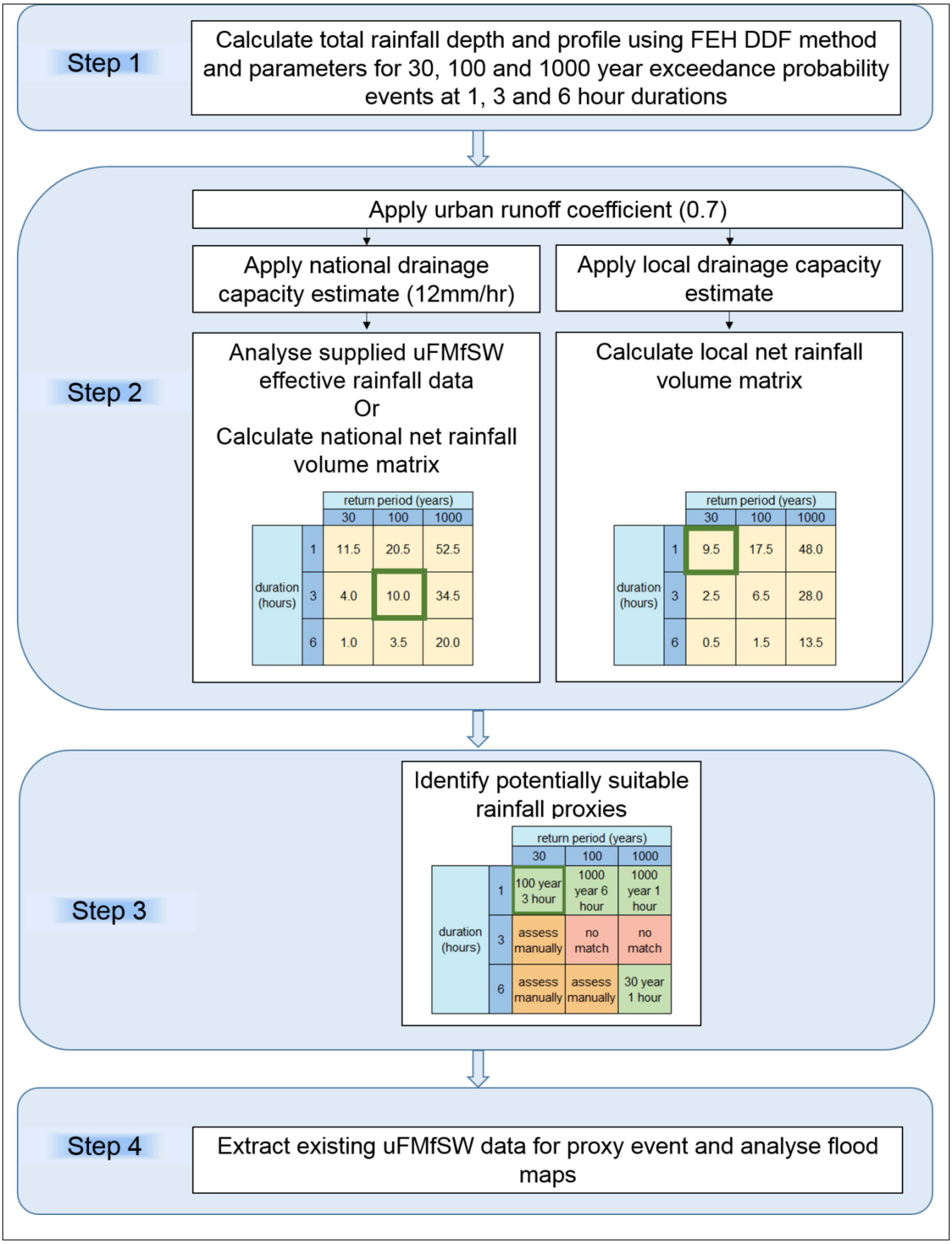
Flood mapping associated with 1, 3 and 6 hour duration storms for the 1 in 30, 1 in 100 and 1 in 1,000 rainfall probabilities is available to LLFAs on a 5km × 5km grid square basis. The rainfall proxy method identifies whether any of the existing uFMfSW flood maps can be reused to represent different local drainage system capacity assumptions.

As summarised in the flowchart shown in Figure 4.1, the net rainfall volume is calculated for the 9 existing uFMfSW flood maps and compared with the net rainfall of the events with local drainage system capacities. If an existing uFMfSW flood map has a similar net rainfall as one of the events with local drainage system capacity, then it can be used as a proxy for the event with local drainage system capacity.

In the example used in Figure 4.1, the uFMfSW flood map for the 100 year exceedance probability 3 hour duration event is used as a proxy for the 30 year exceedance probability 1 hour event. The sensitivity of the method to the threshold used to define net rainfall volumes is discussed in Section 4.2.1.

A spreadsheet-based tool was developed to help calculate the total rainfall profiles for the 1,000, 100 and 30 year exceedance probability events at 1, 3 and 6 hour durations. Instructions for this tool are given in Appendix D. The spreadsheet used the FEH99 DDF data (as this underpins the uFMfSW flood maps) to calculate the total rainfall profile for a given model tile. This data, and more up to date FEH13 DDF data can be accessed from the FEH Web Service.

The separate user guide that accompanies this report provides further guidance on how to apply the rainfall proxy method (SC120020/1 Improving surface water mapping: estimating local drainage rates user guidance PowerPoint presentation)



		return period (years)		
duration (hours)		30	100	1000
	1	11.5	20.5	52.5
	3	4.0	10.0	34.5
	6	1.0	3.5	20.0

		return period (years)		
duration (hours)		30	100	1000
	1	9.5	17.5	48.0
	3	2.5	6.5	28.0
	6	0.5	1.5	13.5

		return period (years)		
duration (hours)		30	100	1000
	1	100 year 3 hour	1000 year 6 hour	1000 year 1 hour
	3	assess manually	no match	no match
	6	assess manually	assess manually	30 year 1 hour

Figure 4.1 Process flowchart to identify potentially suitable rainfall proxies

4.2.1 Identifying proxies

A method was developed to decide which maps can be reused as proxies. Whether total net rainfall volumes are similar enough to be used as proxies depends on:

- the difference between them
- the sensitivity of the model area to the rainfall volume

A quantitative method was developed to identify which rainfall volumes can be classed as similar using a threshold value. The percentage difference between the rainfall volumes is used to quantify the difference between the volumes.

Three case study sites (Market Harborough, Stirchley and Ellenbrook) were used to assess the sensitivity of the method to the use of different percentage thresholds. The threshold is varied from 5% to 30% in 5% increments for the case study sites.

The net rainfall volume in the case study sites varied from <0.5mm per hour to 69.5mm per hour. Figure 4.2 shows the limits of the rainfall volumes that are classed as ‘similar’ for the different thresholds. At small rainfall volumes, a very large threshold would be required to obtain any proxies. It is therefore recommended that for rainfall volumes <5mm per hour, suitable proxies are identified using judgement by manually comparing the rainfall volumes.

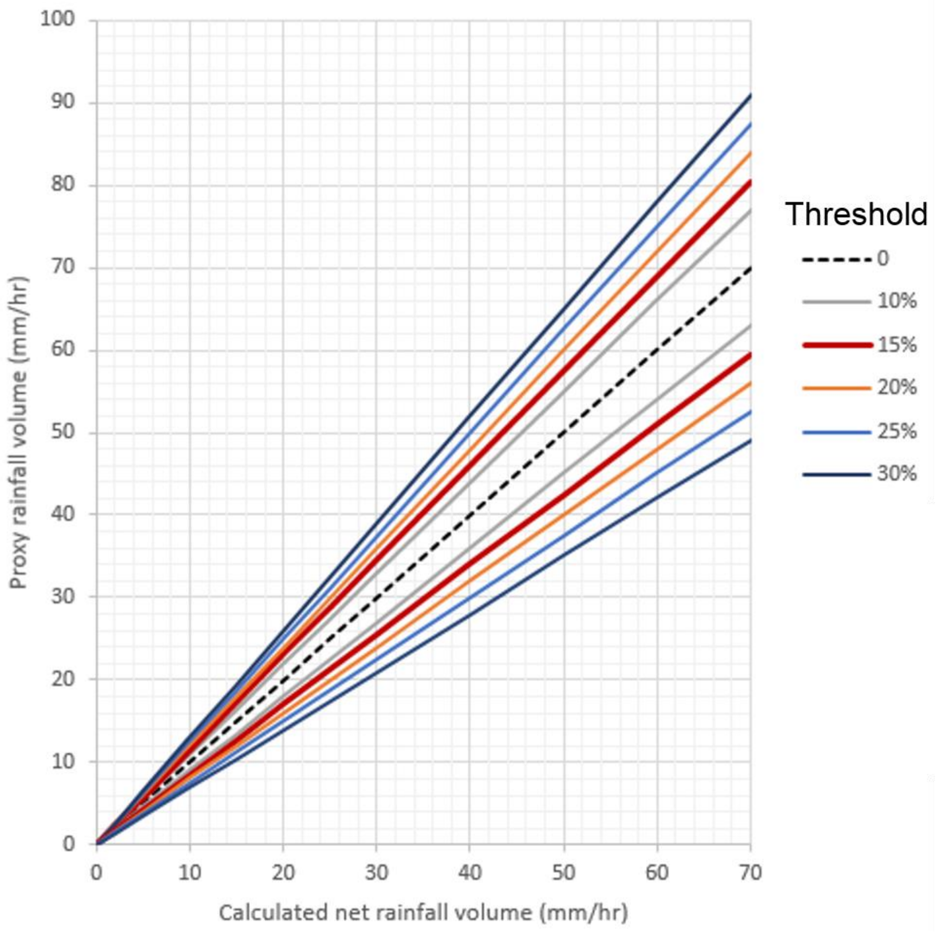


Figure 4.2 Sensitivity of rainfall volumes to threshold percentage difference between the net rainfall and the proposed proxy

The steps in Figure 4.1 were followed to calculate the net rainfall volume matrices for the 3 case study sites. Proxy analysis was carried out to identify rainfall volumes that could be classed as similar. To test the sensitivity of the method to the percentage threshold, the threshold was varied between 5% and 30% in 5% increments. The number of proxies identified at each threshold is shown for each case study site in Figures 4.3 to 4.5. Where the rainfall volume is <5mm per hour, the method identified that a proxy should be chosen manually.

The threshold at which proxies are identified for all of the rainfall volumes that are >5mm per hour was 30% for Market Harborough and 15% for both Stirchley and

Ellenbrook. The 15% and 30% lines in Figure 4.2 show the range of rainfall volumes that are classed as similar at those thresholds. After studying Figure 4.2 and the results of the sensitivity analysis, the threshold of 15% was chosen for identifying proxies.

In the case studies, the biggest absolute difference in rainfall volume that the chosen threshold of 15% could result in is a net rainfall volume of 70mm per hour being represented by a rainfall proxy of 60 or 80mm per hour. The lowest net rainfall volume, 5mm per hour (as this is the threshold for manual assessment), could be represented by a 4mm or 6mm per hour proxy.

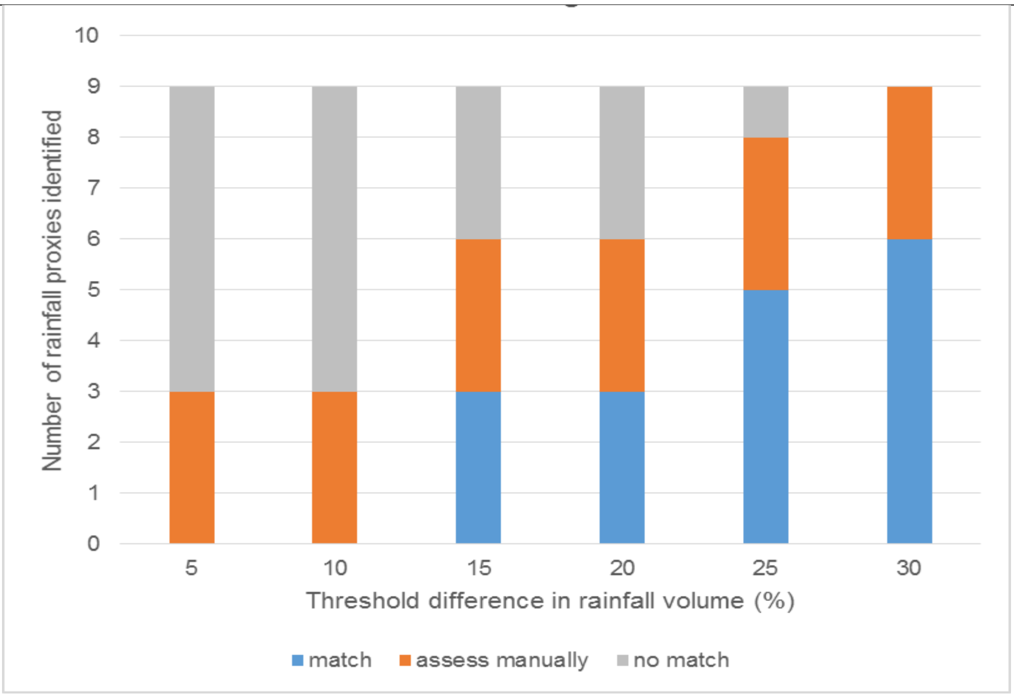


Figure 4.3 Threshold sensitivity analysis for Market Harborough

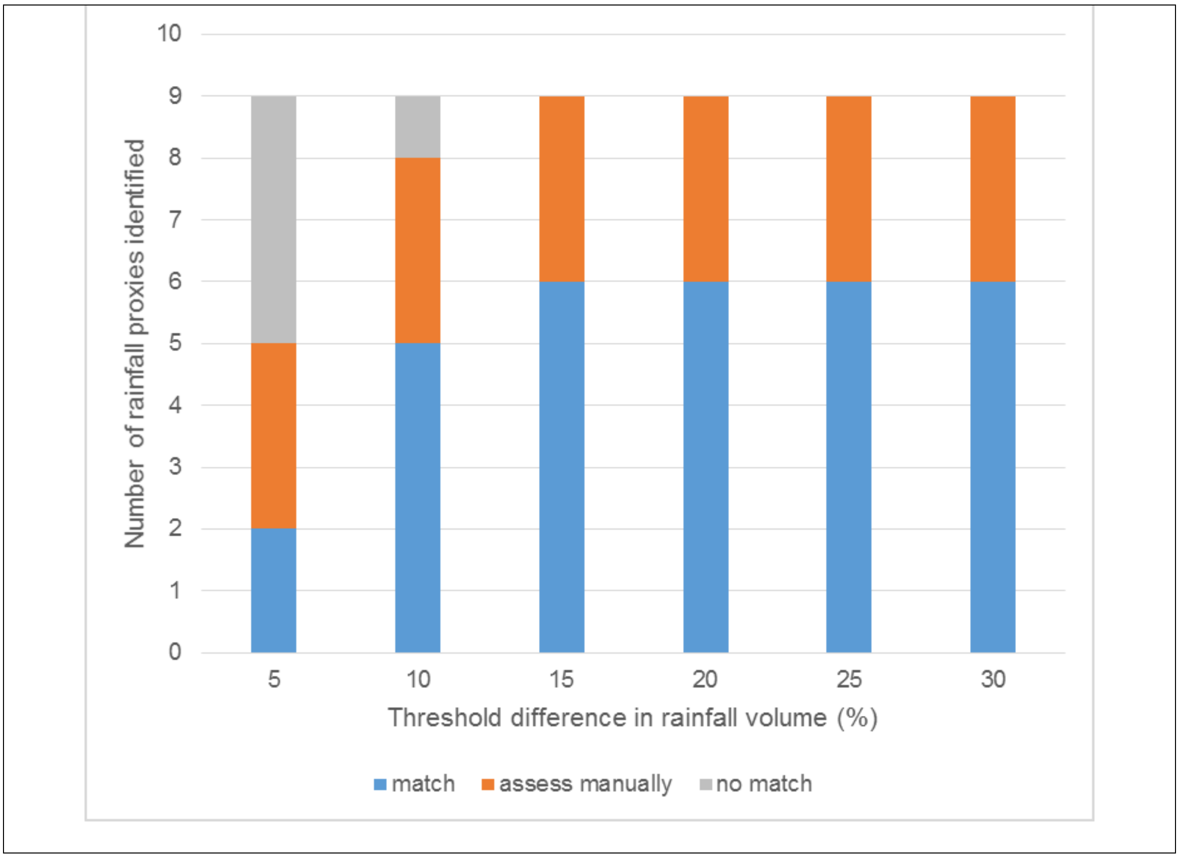


Figure 4.4 Threshold sensitivity analysis for Stirchley

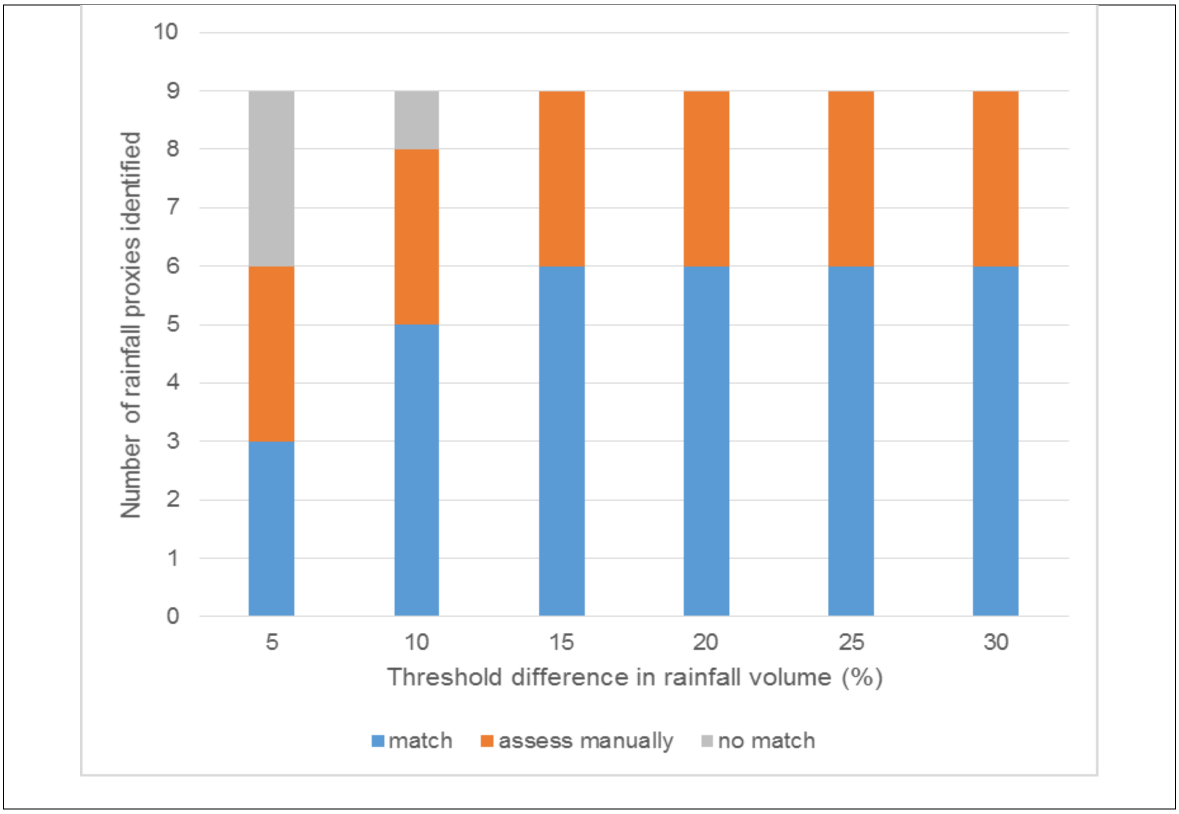


Figure 4.5 Threshold sensitivity analysis for Ellenbrook

4.3 Case studies

Local drainage system capacities were estimated for the case study sites at Market Harborough, Stirchley, Ellenbrook and Greater Manchester based on local information on the parameters of the drainage system capacity equation (Table 4.1).

The rainfall proxy method was used for the case study sites at Market Harborough, Stirchley and Ellenbrook, which all have small areas (<5km^2). Greater Manchester, with a model area of over 1,000km^2, was remodelled using the local drainage system capacities.

Perhaps unsurprisingly, the sensitivity of each model to a change in the drainage system capacity is different in each case (Table 4.1).

Table 4.1 Local estimates of drainage system capacity for the case study sites

Location	Drainage system capacity estimate (mm per hour)		
	Lower (-1 SD)	Mode	Upper (+1 SD)
National estimate	6	12	20
Market Harborough	10	18	25.5
Stirchley	4	10.5	16.5
Ellenbrook	7	14	20.5
Greater Manchester	11.5	16	21

Notes: SD = standard deviation

4.3.1 Case study site 1: Market Harborough

This site has an assumed drainage rate of 18mm per hour. Emergency services may benefit from a locally refined flood depth map for surface water to plan their response to this type of flooding. For emergency planning, a ‘credible worst case’ is typically assumed and therefore the 1,000 year event was used to determine the effect of using the local drainage system capacity. This process followed the steps shown in Figure 4.1.

Step 1: Calculate total rainfall profiles

The total rainfall profiles were calculated for the 1, 3 and 6 hour duration, 1,000, 100 and 30 year exceedance probability storms using the rainfall calculator spreadsheet (see Appendix D). The spreadsheet uses the FEH method and descriptors to calculate the total rainfall profile for a given model tile.

Step 2: Calculate net rainfall profiles and total volume of net rainfall

Net rainfall profiles from the existing uFMfSW were calculated by applying the run-off coefficient of 0.7 and the default national drainage system capacity of 12mm per hour to the total rainfall profiles. The net rainfall profiles using the local estimate of drainage system capacity were calculated by applying the run-off coefficient of 0.7 and the local estimate of drainage system capacity of 18mm per hour to the total rainfall profile (Figure 4.6).

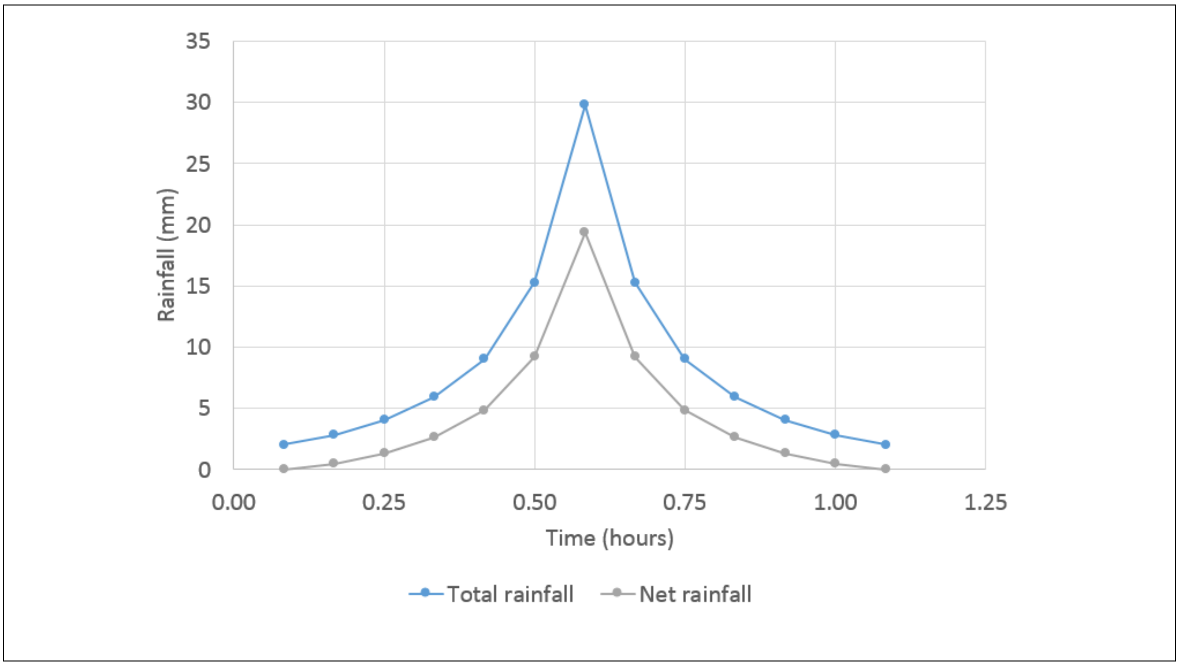
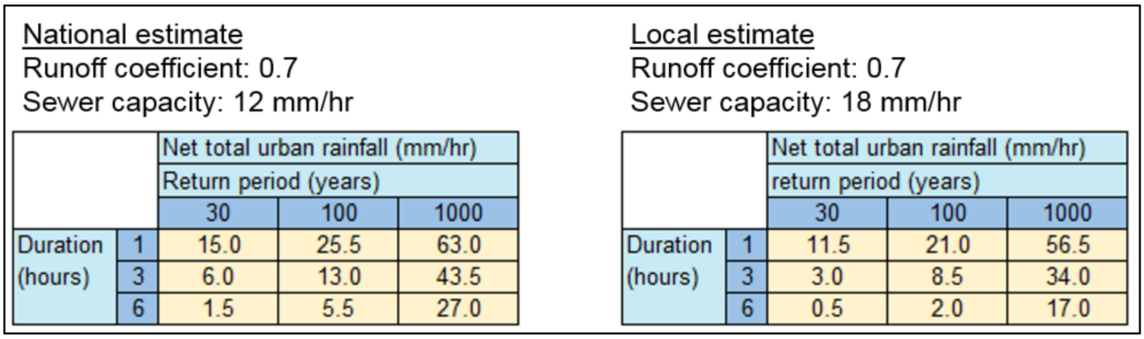


Figure 4.6 Total and net rainfall profile for Market Harborough using local drainage system capacity of 18mm per hour (1,000 year event, 1 hour summer profile)

The total volume of the net rainfall was calculated for the 9 exceedance probabilities and event durations, and compiled in net rainfall matrices for the national and local estimate (Figure 4.7).

The 1,000 year exceedance probability event is arguably of most interest for emergency planning. The total net rainfall volumes using the local drainage system capacity for the 1,000 year event are 56.5mm per hour, 34.0mm per hour and 17.0mm per hour for the 1, 3 and 6 hour events respectively (Figure 4.7, right panel).



National estimate
Runoff coefficient: 0.7
Sewer capacity: 12 mm/hr

		Net total urban rainfall (mm/hr)		
		Return period (years)		
		30	100	1000
Duration (hours)	1	15.0	25.5	63.0
	3	6.0	13.0	43.5
	6	1.5	5.5	27.0

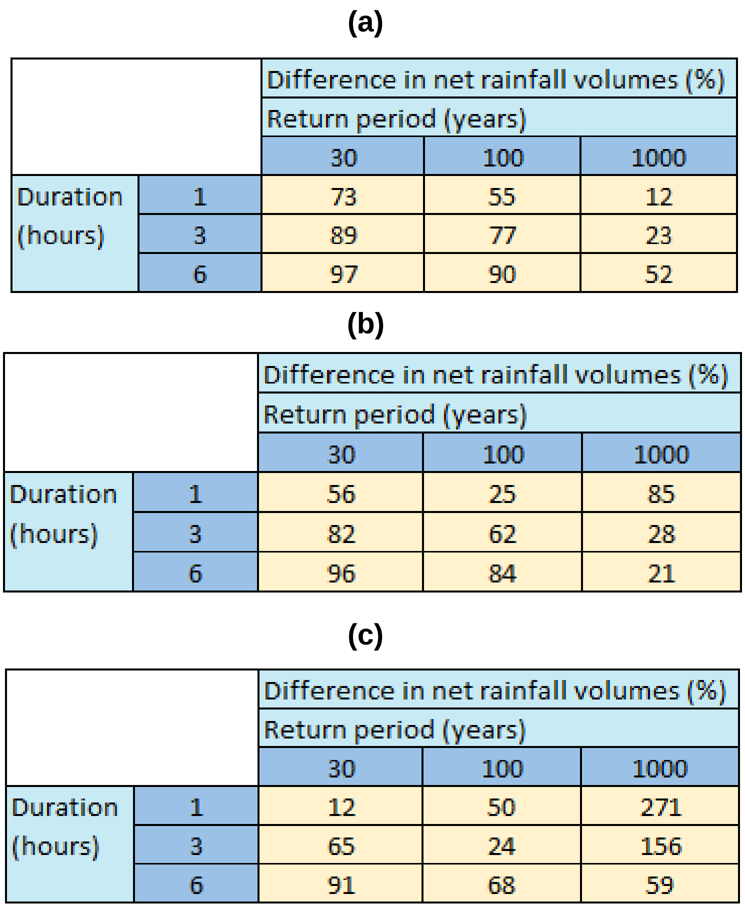
Local estimate
Runoff coefficient: 0.7
Sewer capacity: 18 mm/hr

		Net total urban rainfall (mm/hr)		
		return period (years)		
		30	100	1000
Duration (hours)	1	11.5	21.0	56.5
	3	3.0	8.5	34.0
	6	0.5	2.0	17.0

Figure 4.7 National and local total net rainfall volume matrices for Market Harborough

Step 3: Identify suitable rainfall proxies

The percentage difference between each local net rainfall volume and the 9 existing uFMfSW net rainfall volumes was calculated (Figure 4.8).



(a)

		Difference in net rainfall volumes (%)		
		Return period (years)		
		30	100	1000
Duration (hours)	1	73	55	12
	3	89	77	23
	6	97	90	52

(b)

		Difference in net rainfall volumes (%)		
		Return period (years)		
		30	100	1000
Duration (hours)	1	56	25	85
	3	82	62	28
	6	96	84	21

(c)

		Difference in net rainfall volumes (%)		
		Return period (years)		
		30	100	1000
Duration (hours)	1	12	50	271
	3	65	24	156
	6	91	68	59

Figure 4.8 Percentage difference in net rainfall volume between the existing uFMfSW net rainfall volume and the net rainfall volume obtained using the local estimate of drainage system capacity of (a) 56.5mm per hour for the 1,000 year, 1 hour event; (b) 34.0mm per hour for the 1,000 year, 3 hour event; and (c) 17.0mm per hour for the 1,000 year, 6 hour event

Based on the analysis set out in Section 4.2.1, a threshold of 15% difference between the net rainfall volumes was used to identify existing mapping that could be used as proxies for the 1,000 year events with local drainage rates. Two events (both with a 12% difference) can potentially be used as proxies: 1,000 year, 1 hour event (Figure 4.8a) and 30 year, 1 hour event (Figure 4.8c). The results of the proxy analysis are summarised in Table 4.2.

Table 4.2 Existing uFMfSW maps identified as potential proxies for local estimate of drainage system capacity of 18 mm/hour in Market Harborough

Local estimate event		Existing uFMfSW event identified as proxy		Percentage difference between net rainfall volumes (%)
Event	Net rainfall volume (mm per hour)[1]	Event	Net rainfall volume (mm per hour)	
1,000 year, 1 hour	56.5	1,000 year, 1 hour	63.0	12
1,000 year, 3 hour	34.0	None	–	–
1,000 year, 6 hour	17.0	30 year, 1 hour	15.0	12

Notes: [1] From Figure 4.7

Step 4: Produce and analyse flood maps using existing uFMfSW data

In the uFMfSW the 1,000 year, 6 hour event has a total rainfall volume of 27mm per hour. When the local drainage rate of 18mm per hour is applied, the total rainfall volume reduces to 17mm per hour. This local estimate can be represented by data from the uFMfSW for the 30 year, 1 hour event because it has a similar total rainfall volume (Figure 4.8c).

Hence the flood depth map for the 1,000 year, 6 hour event can be compared to the flood depth map for the 30 year, 1 hour event as a proxy for the 1,000 year, 6 hour event using local drainage rates (Figure 4.9). It can be seen that the local drainage rate has a significant impact on the flood outline and depth.

Because of the nature of the direct rainfall method, the flood maps for longer duration events are more sensitive to the drainage rates. Figure 4.9 shows the flood depth maps for the 6 hour event; the differences in the flood depth maps for the national and local estimate would be reduced for shorter event durations.

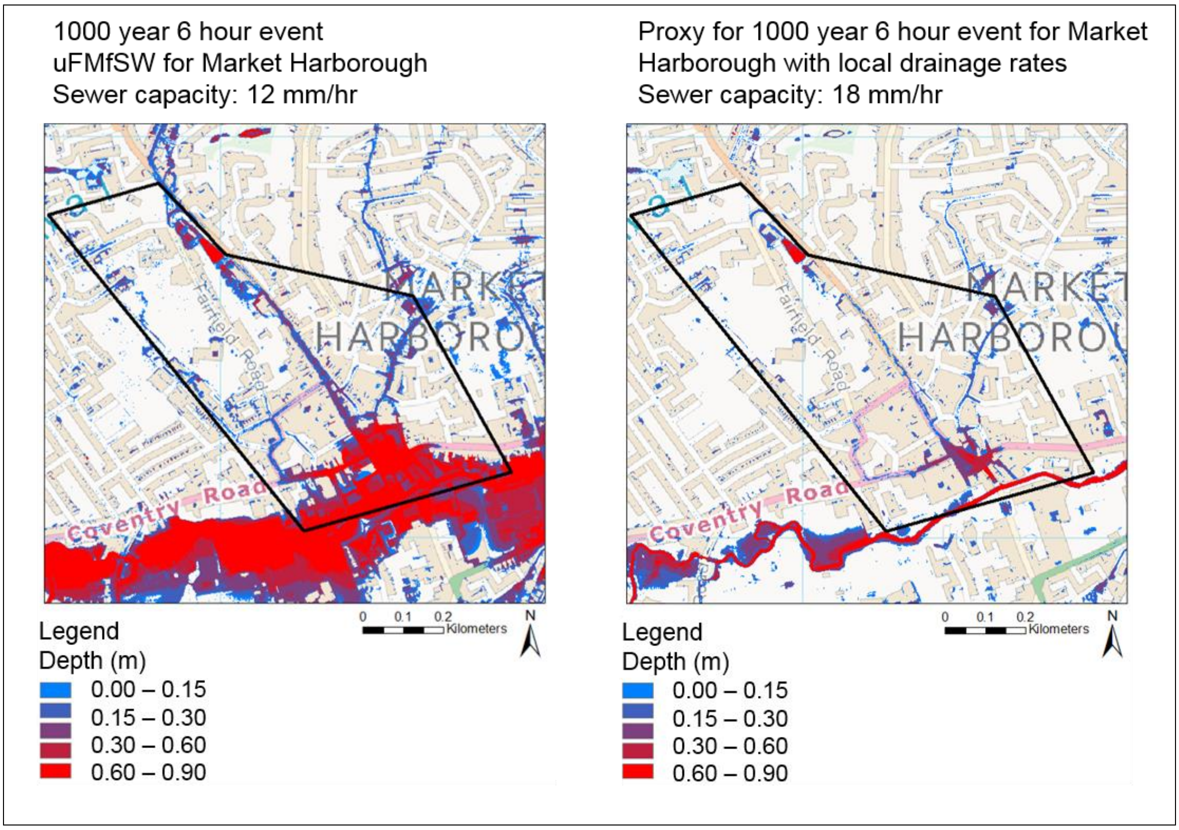


Figure 4.9 Comparison of flood depth maps for the 1,000 year, 6 hour event for Market Harborough using national and local drainage rates

The proxy analysis indicates that the use of a local drainage rate makes a significant difference to the extent of flooding in Market Harborough (Figure 4.10).

The analysis should be validated (for example using local knowledge, flood records or through remodelling of known events) before being used for local plans and decision-making. At the time of writing, the full range of scenarios (30, 100, 1,000 return periods and 1, 3 and 6 hour durations) would need to be produced and supplied to the Enviornment Agency to use the amended mapped outputs to update the Risk of Flooding from Surface Water.

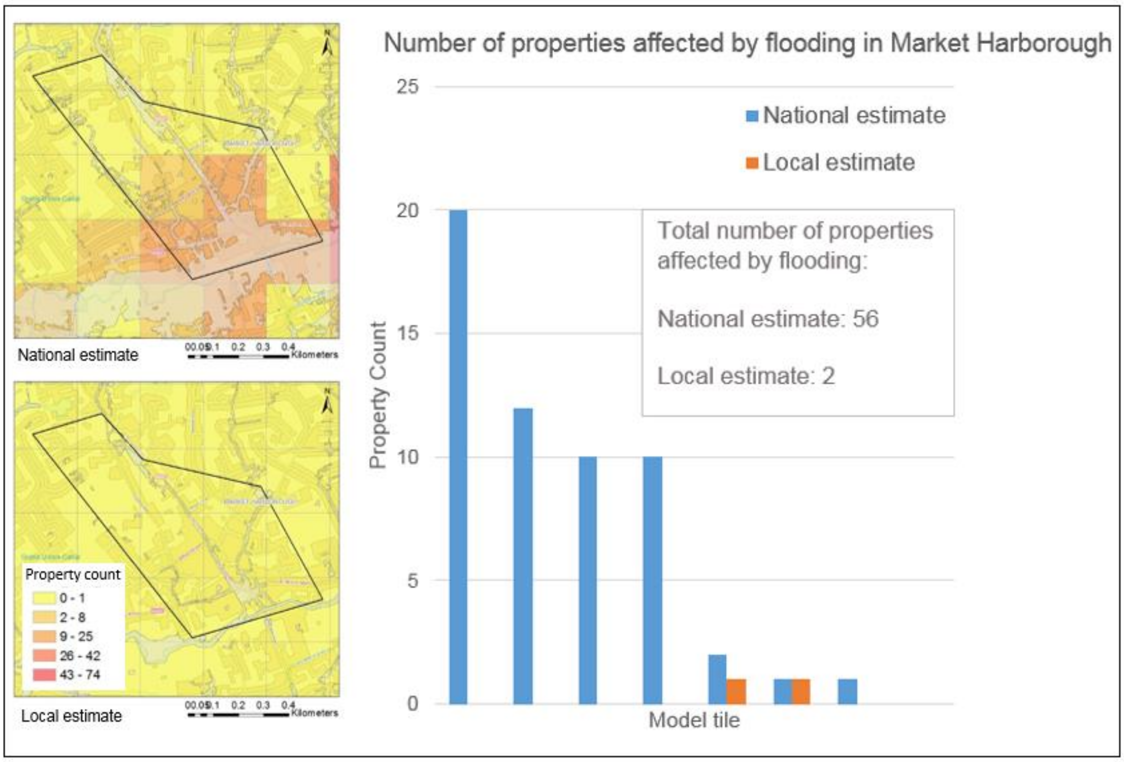


Figure 4.10 Number of properties affected by flooding in Market Harborough for the 1,000 year, 6 hour event using national and local drainage rates

4.3.2 Case study site 2: Ellenbrook

The drainage system capacity calculated for Ellenbrook using local DDF parameters and an LoS of 10–30 years is 14mm per hour. This is a small increase from the national estimate of 12mm per hour. The impact of this on the flood depth maps was explored using the rainfall proxy method.

As the case study concerns the LoS of the sewer system, the 30 year exceedance probability events are arguably of most interest. The process set out in Figure 4.1 was followed to identify whether any of the existing uFMfSW data could be reused as proxies.

Step 1: Calculate total rainfall profiles

The total rainfall profiles were calculated for the 1, 3 and 6 hour duration, 1,000, 100 and 30 year exceedance probability storms using the rainfall calculator spreadsheet (see Appendix D). The spreadsheet uses the FEH method and descriptors to calculate the total rainfall profile for a model tile.

Step 2: Calculate net rainfall profiles and total volume of net rainfall

Net rainfall profiles from the existing uFMfSW were calculated by applying the run-off coefficient of 0.7 and the national drainage system capacity of 12mm per hour to the total rainfall profiles. The net rainfall profiles using the local estimate of drainage system capacity were calculated by applying the run-off coefficient of 0.7 and the local estimate of drainage system capacity of 14mm per hour to the total rainfall profile (Figure 4.11).

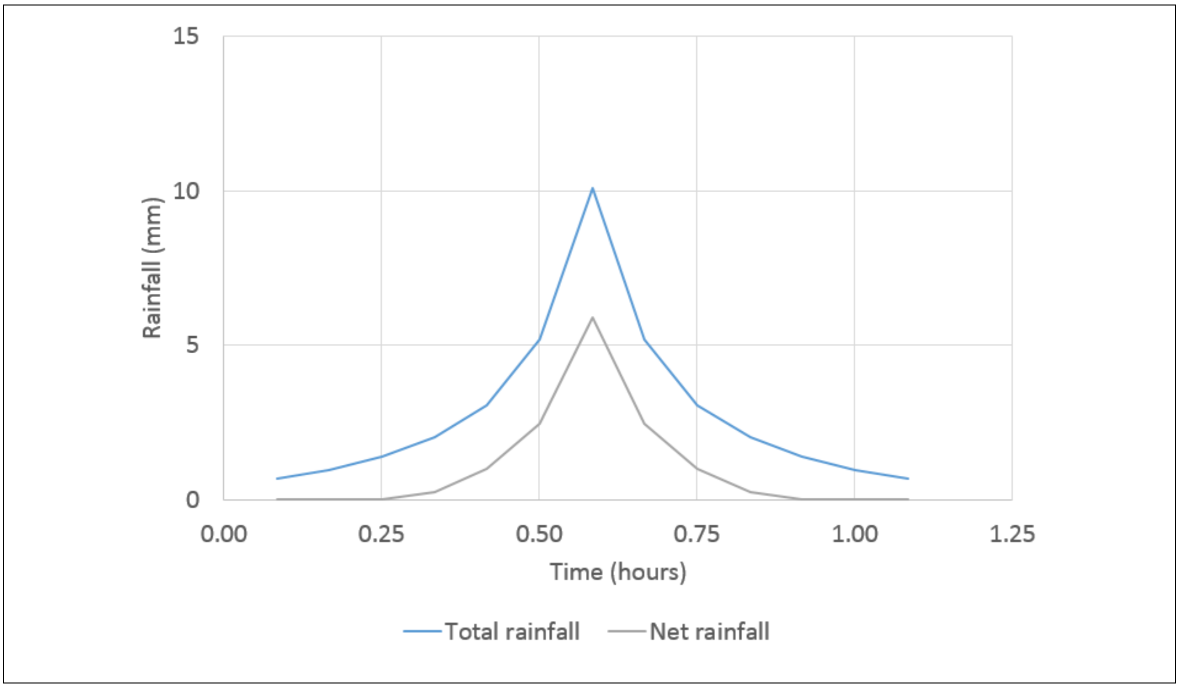
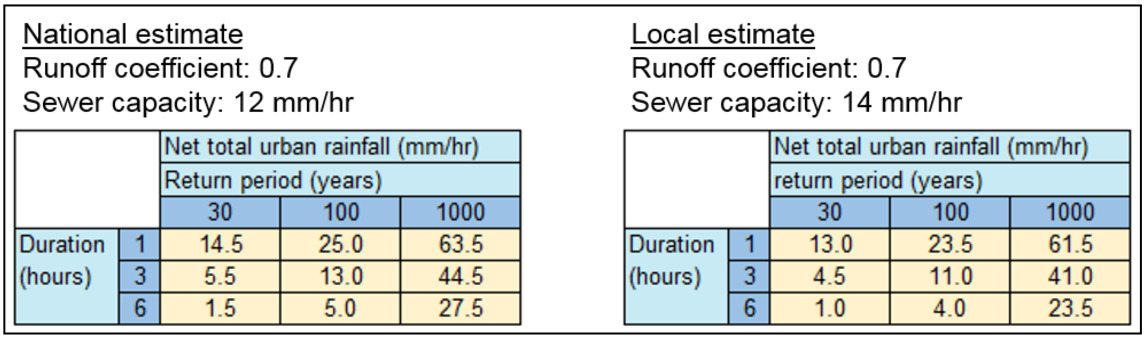


Figure 4.11 Total and net rainfall profile for the 30 year, 1 hour event using local drainage system capacity of 14mm per hour

The total volume of the net rainfall was calculated for the 9 exceedance probabilities and event durations, and compiled in net rainfall matrices (Figure 4.12).

The 30 year exceedance probability event is of most interest for the assessment of modelling improvements to the sewer system. The total net rainfall volumes for the 30 year event with local drainage rates are 13.0mm per hour, 4.5mm per hour and 1.0mm per hour for the 1, 3 and 6 hour events respectively (Figure 4.12, right panel).



National estimate
Runoff coefficient: 0.7
Sewer capacity: 12 mm/hr

		Net total urban rainfall (mm/hr)		
		Return period (years)		
		30	100	1000
Duration (hours)	1	14.5	25.0	63.5
	3	5.5	13.0	44.5
	6	1.5	5.0	27.5

Local estimate
Runoff coefficient: 0.7
Sewer capacity: 14 mm/hr

		Net total urban rainfall (mm/hr)		
		return period (years)		
		30	100	1000
Duration (hours)	1	13.0	23.5	61.5
	3	4.5	11.0	41.0
	6	1.0	4.0	23.5

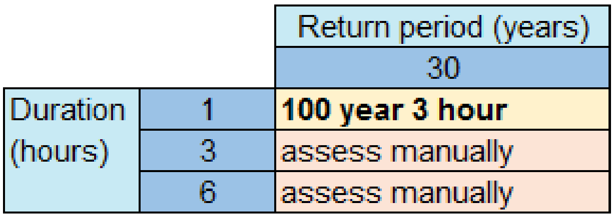
Figure 4.12 National and local total net rainfall volume matrices for Ellenbrook

Step 3: Identify suitable rainfall proxies

The same process was used as for the Market Harborough case study site (see Section 4.3.1) to identify which existing uFMfSW maps could be used as proxies. Net rainfall volumes within 15% of the local net rainfall volumes were identified as appropriate for use as potential proxies. At volumes <5mm per hour, proxies should be identified manually as the 15% threshold would not lead to any matches.

The rainfall calculator spreadsheet (see Appendix D) was used to identify the proxies. Figure 4.13 shows the results of the proxy analysis for the 30 year exceedance probability event. The 100 year, 3 hour uFMfSW map was identified as a proxy for the 30 year, 1 hour event with the local drainage rate. As the 3 and 6 hour duration events have net rainfall volumes <5mm per hour, suitable proxies were identified manually.

Table 4.3 summarises the results of the proxy analysis. It shows that the existing data for the 100 year, 3 hour event can be used as a proxy for the 30 year, 1 hour event with local drainage rates; both have a total net rainfall volume of 13.0 mm/hour.



		Return period (years)
		30
Duration (hours)	1	**100 year 3 hour**
	3	assess manually
	6	assess manually

Figure 4.13 **Output from rainfall calculator spreadsheet tool identifying potential proxy rainfall events for Ellenbrook**

Table 4.3 **Existing uFMfSW maps identified as potential proxies for local estimate of drainage system capacity of 14mm per hour at Ellenbrook**

Local estimate event		Existing uFMfSW event identified as proxy		Percentage difference between net rainfall volumes (%)
Event	Net rainfall volume (mm per hour)[1]	Event	Net rainfall volume (mm per hour)	
30 year, 1 hour	13.0	100 year, 3 hour	13.0	0
30 year, 3 hour	4.5	100 year, 6 hour	5.0	11
30 year, 6 hour	1.0	30 year, 6 hour	1.5	33

Notes: [1] From Figure 4.12

Step 4: Produce and analyse flood maps using existing uFMfSW data

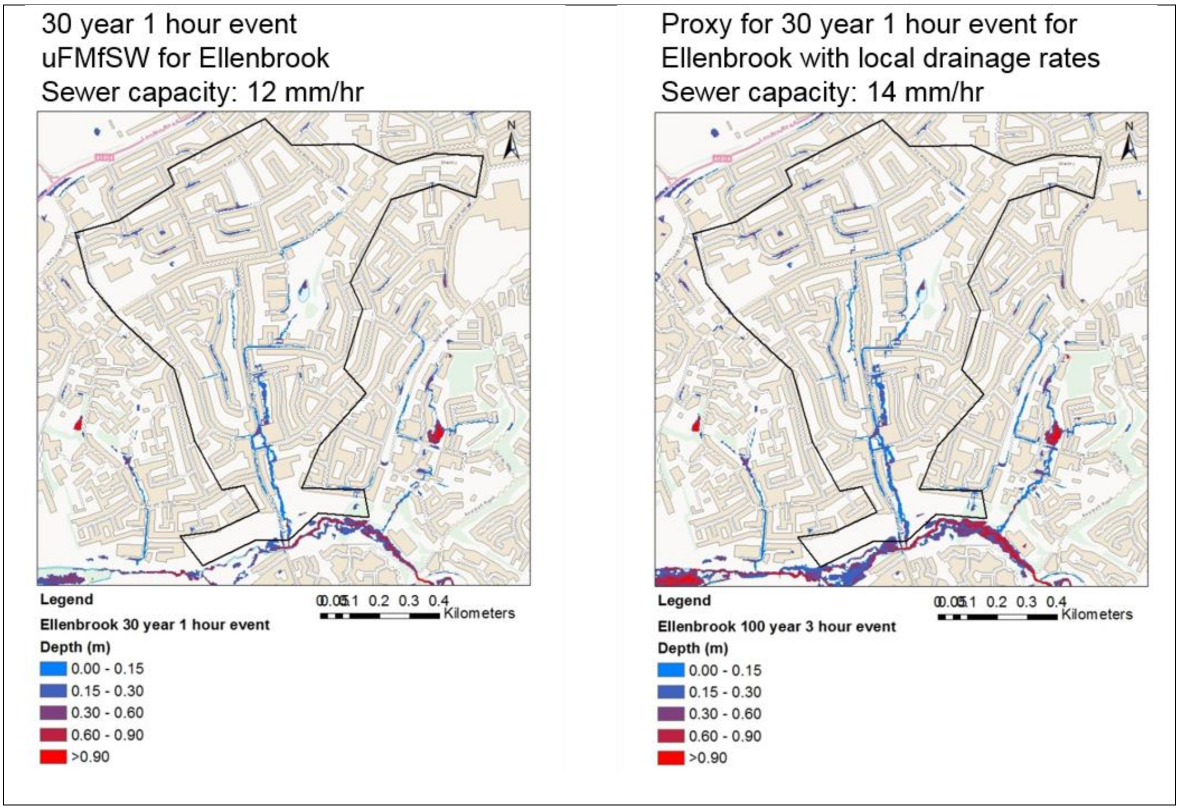
The flood depth maps for the 30 year, 1 hour event with local and national drainage rates are compared in Figure 4.14. Increases in the flood depths and outline are seen when the local drainage rates are used.

It is recommended that new developments are designed to keep out water at flood depths up to 0.3m (Defra 2012). When the local drainage rate is used for the Ellenbrook case study site, the number of cells with a flood depth >0.3m increases by 68% (Figure 4.15). The flood maps for the 30 year, 3 hour event and the proxy for the 30 year, 3 hour event show a similar trend.

The results in Figure 4.14 and 4.15 are unexpected, as the increased drainage system capacity is expected to lead to a decrease in flood depths. However, the assumption that flood depth maps with the same total volume of net rainfall can be used as proxies may not be true for this location. It is possible that other factors, such as the duration or intensity of the rainfall, govern the flood patterns in Ellenbrook.

This case study highlights the importance of sense checking the outputs to avoid incorrect interpretation of the results.

In Ellenbrook, the drainage system capacity estimate was increased from the national estimate of 12mm per hour to a local estimate of 14mm per hour. Contrary to expectations, the flood depth maps show an increase in flooding for the higher drainage system capacity. This is thought to be due to the rainfall proxy method not being appropriate in Ellenbrook as factors other than the total net rainfall volume are significant for controlling flood outlines and depths in the area. In this case, remodelling flood extents with revised drainage rates is recommended in this case as the proxy method is insufficiently robust.



30 year 1 hour event
uFMfSW for Ellenbrook
Sewer capacity: 12 mm/hr

Proxy for 30 year 1 hour event for
Ellenbrook with local drainage rates
Sewer capacity: 14 mm/hr

Figure 4.14 Comparison of flood hazard maps for the 30 year, 1 hour event for Ellenbrook using national and local drainage rates

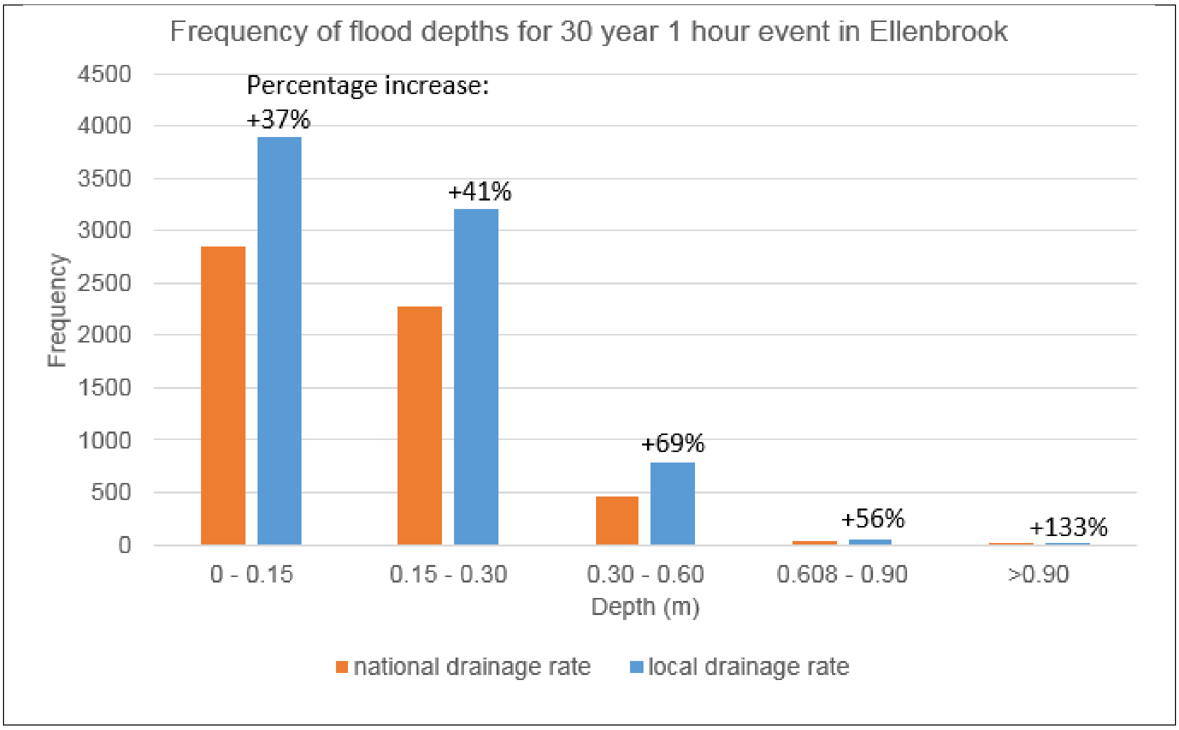


Figure 4.15 Comparison of flood depths for the 30 year, 1 hour event in Ellenbrook using the national and local drainage rates

4.3.3 Case study site 3: Stirchley (Ripple Road)

Birmingham City Council was one of around the 10% of LLFAs that responded to the request to provide bespoke drainage rates for the uFMfSW. Local drainage system capacities of 9mm, 12 and 20mm per hour were assigned in Stirchley as shown in Figure 4.16.

Monte Carlo analysis of the drainage system capacity equation was carried out to obtain a drainage system capacity for Stirchley using local DDF parameters. The drainage system capacity obtained was 10.5mm per hour, slightly lower than the national value of 12mm per hour. As the drainage system capacity applied to Stirchley is not uniform in the uFMfSW, it is not practical to use the rainfall proxy method. Remodelling would be necessary to examine the effect of using the local drainage system capacity estimate, but since local drainage system capacities had been supplied by the LLFA for Stirchley, it was possible to validate the calculated local rate.

Assuming that the drainage system capacities given in Figure 4.16 are an improvement on the national estimate of drainage system capacity, it can be seen that the local drainage system capacity of 10.5mm per hour obtained using the Monte Carlo analysis would lead to improved representation of flooding over a central strip of the model area (around Ripple Road) compared with the national estimate of 12mm per hour.

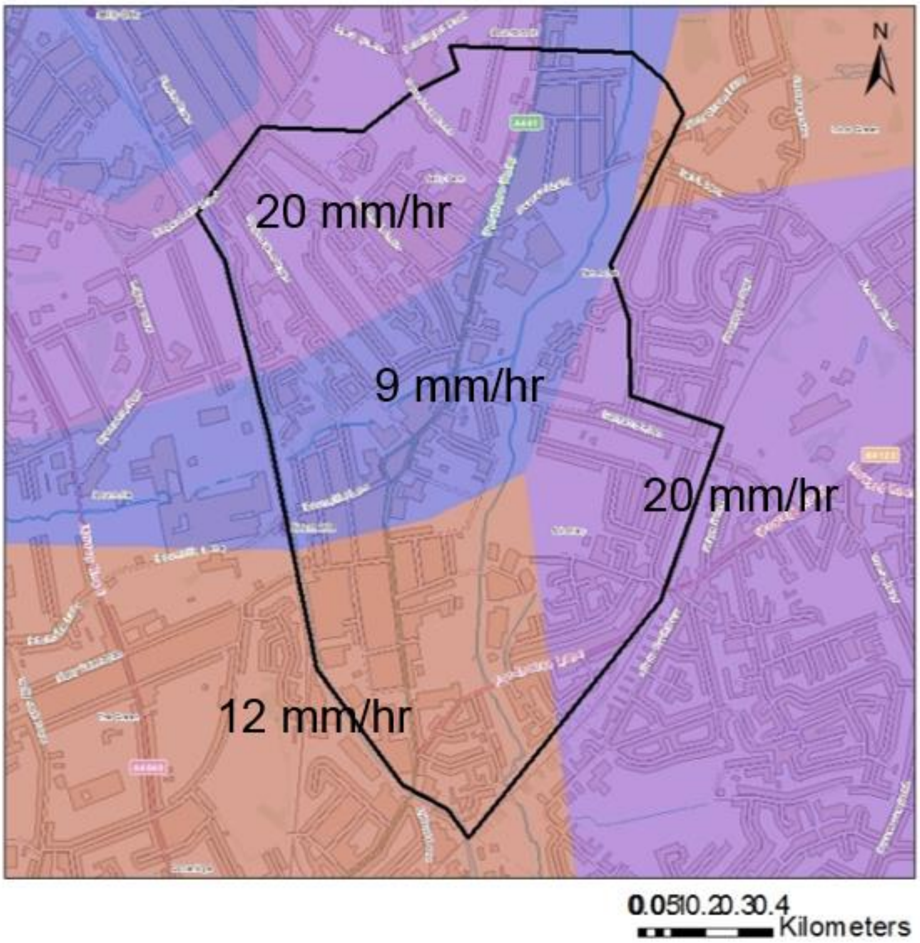


Figure 4.16 Drainage system capacities used in uFMfSW for Stirchley

Notes: As identified in LLFA feedback process.
The case study area is approximately centred on Ripple Road.

For the rest of the model area, however, the local drainage system capacity of 10.5mm per hour would lead to an overestimation of flooding. In this case, remodelling with the calculated local drainage system capacity would not be of any value. The complexity of the drainage rates means that obtaining a local estimate by locally refining one of the parameters of the drainage system capacity equation does not always lead to a better representation of flooding. Even in a small model area, a blanket drainage system capacity may not apply.

4.3.4 Case study site 4: Greater Manchester

In the process of creating the uFMfSW, LLFAs were given the opportunity to modify the default drainage rate applied across their administrative area.

The information provided by AGMA on PR rates and drainage system capacities for Greater Manchester was incorporated in the uFMfSW. As the drainage rates for Greater Manchester were carefully calculated, the uFMfSW can be used to validate the flood maps produced using the drainage system capacities from the Monte Carlo analysis.

Greater Manchester has a model area of 1,277km^2 and consists of over 80 5km × 5km model tiles. It was not therefore possible to show the flood maps for the whole of Greater Manchester and so a reduced area was chosen to demonstrate the results and analysis carried out for Greater Manchester. This area was selected primarily because of the availability of validation data. Within the demonstration area, 2 smaller test areas were chosen (Figure 4.17) to show the flood maps in more detail.

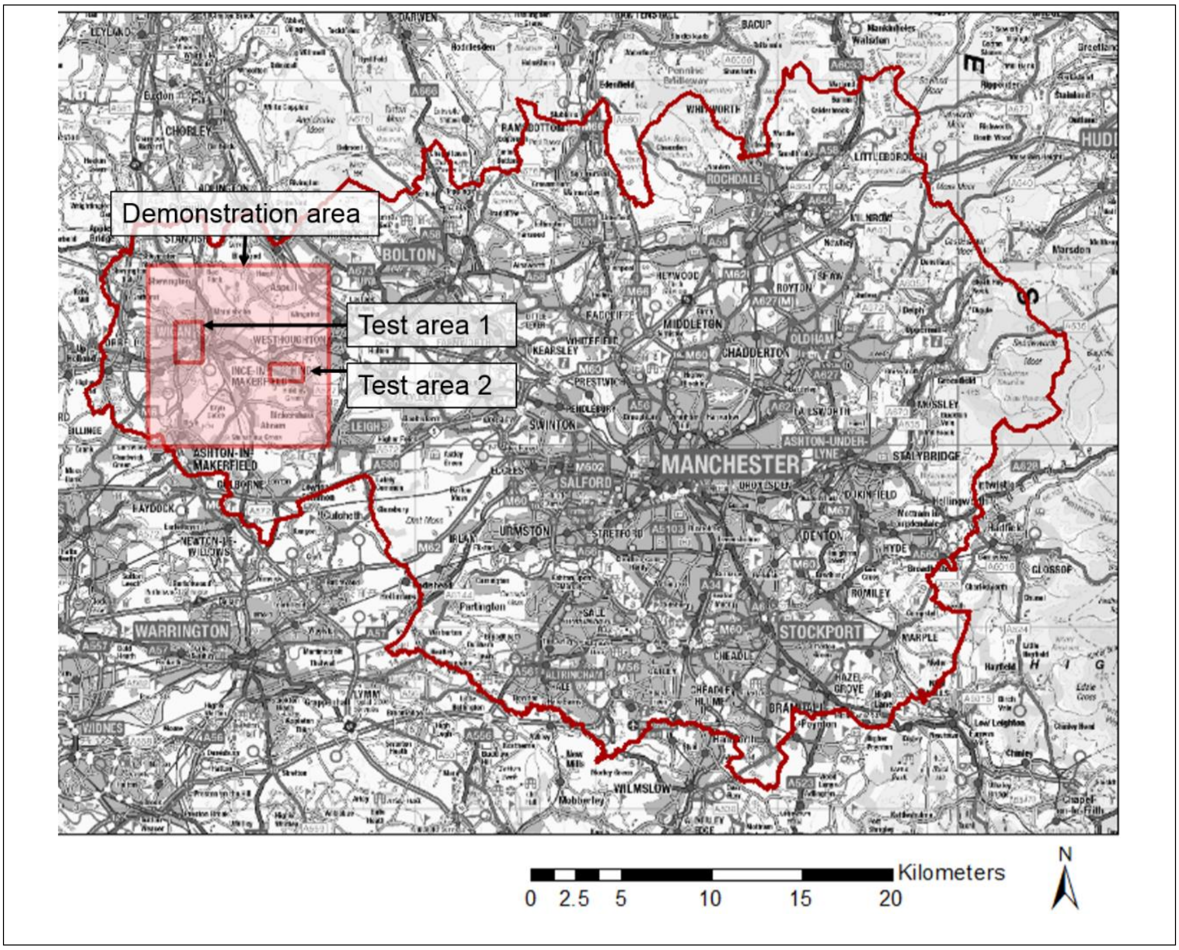


Figure 4.17 Greater Manchester showing the 2 test areas within the chosen demonstration area

Three drainage system capacity estimates (modal, lower and upper) were made in the Monte Carlo analysis. The lower and upper estimates are a standard deviation above and below the modal estimate of the drainage system capacity. For Greater Manchester, the drainage system capacity obtained using the Monte Carlo analysis is 16mm per hour; the upper estimate is 21mm per hour and the lower estimate is 11.5mm per hour.

Flood depth maps were calculated for Greater Manchester using the modal, upper and lower estimate of drainage system capacity. The new drainage system capacities were applied where the drainage system capacity used in the uFMfSW is 18mm per hour.

Analysis of wet cells in each flood depth map was performed to determine:

- where all 3 maps agreed (score of 3 out of 3)
- where 2 of the maps agreed (score of 2 out of 3)
- where only one map calculated a cell as being wet (score of 1 out of 3)

Four different thresholds (0.15, 0.3, 0.6 and 0.9m) were used to classify cells as ‘wet’ or ‘dry’. Figure 4.18 shows an example of the maps at the 4 different thresholds used to define a cell as ‘wet’ or ‘dry’. As expected, more cells are classified as ‘wet’ at lower depth thresholds.

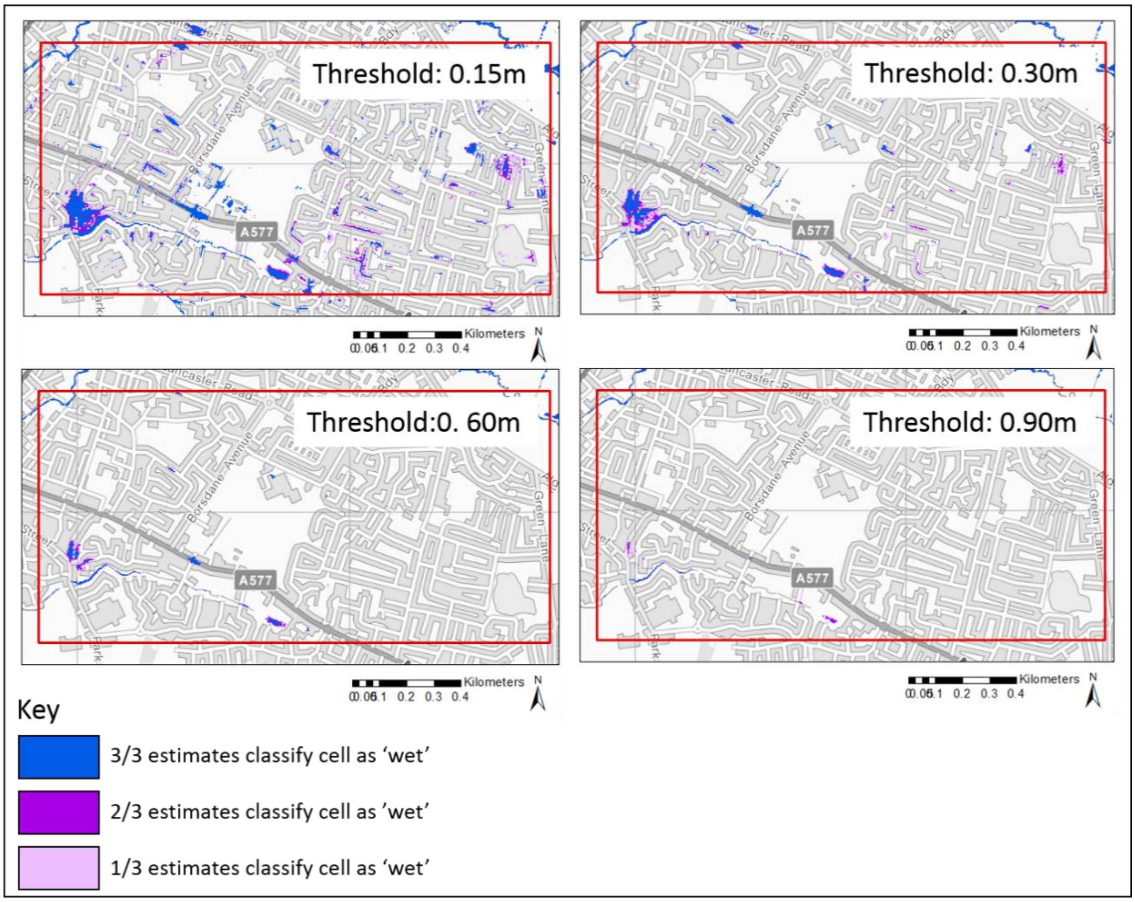


Figure 4.18 Sensitivity analysis of different depth thresholds to define cells as wet demonstrated in test area 2

Cells where 3 out of 3 maps predicted flooding were not sensitive to the estimate of the drainage system capacity, with the flood maps predicting flooding whether the lower, modal or upper estimate of the drainage system capacity was used. Where either 2 out of or 1 out of 3 of the maps predicted flooding, there was sensitivity in the model to the drainage system capacity.

Figure 4.19 shows the number of cells with each score at the different depth thresholds for the entire demonstration area. As expected, the number of wet cells decreases as the depth threshold increases.

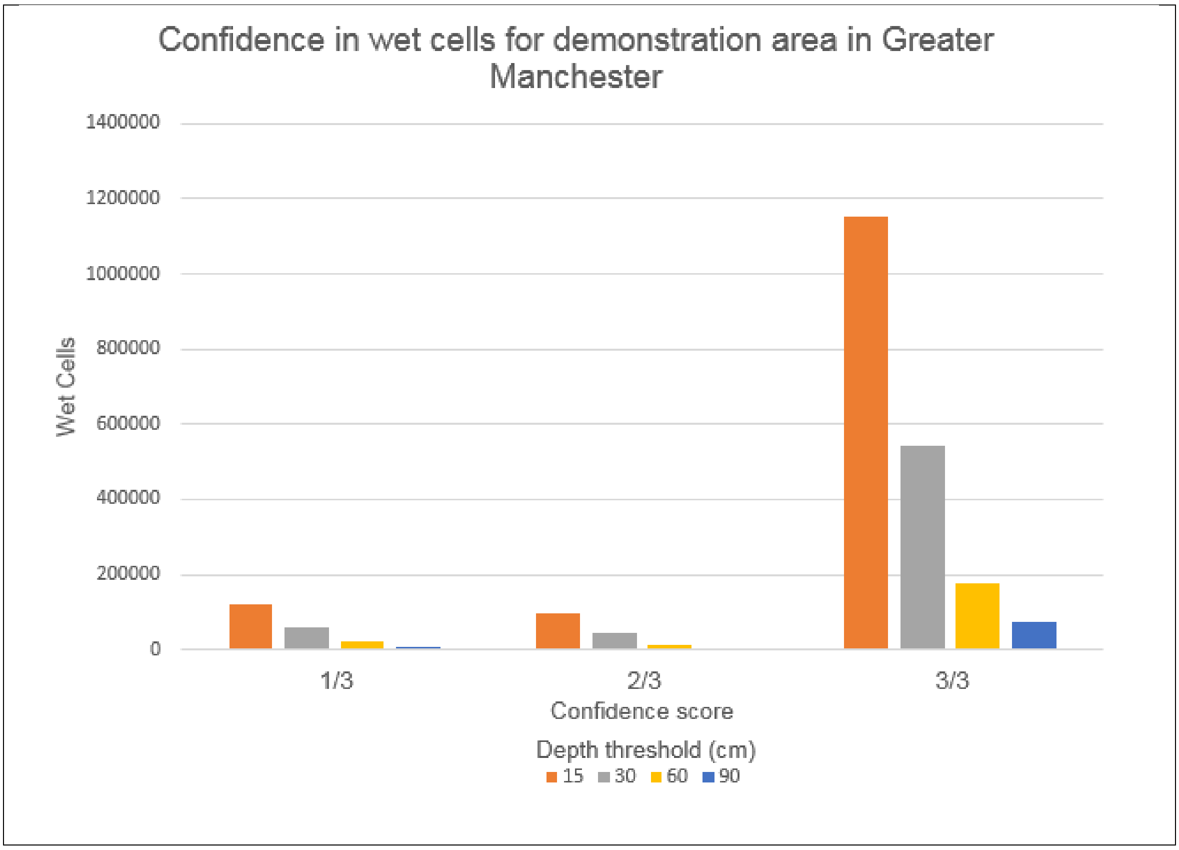


Figure 4.19 Number of wet cells for the demonstration area in Greater Manchester where 3, 2 or 1 of the drainage system capacity estimates led to prediction of a cell being wet

However, it is more informative to investigate the number of wet cells with each score as a proportion of the total wet area. The proportion of wet cells with each score is almost constant for the different depth thresholds (Table 4.4). This implies that there is no difference in the level of sensitivity to the drainage system capacity at different depths of flooding.

Table 4.4 Proportion of wet cells at each confidence score for the 4 different depth thresholds (%)

Confidence score	Proportion of wet cells (%)				
	15 cm threshold	30 cm threshold	60 cm threshold	90 cm threshold	Mean
1	9	9	10	9	9.3
2	7	7	6	6	6.5
3	84	84	83	85	84

The mean proportion of wet cells with a score of 3 out of 3 is 84% for all the thresholds (Table 4.4). This means that, in over 4 out of 5 of all wet cells, the lower, modal and higher estimate of the drainage system capacity have resulted in the prediction that flooding will occur. This implies that, in Greater Manchester, there is little sensitivity to drainage system capacity with different results being produced in only 16% of wet cells (that is, 16% of the cells in the demonstration area are sensitive to whether the lower, modal or upper estimate of the drainage system capacity is used).

Without considering any limitations of the flood maps beyond the sensitivity to the drainage rates, it can be concluded that flooding will occur in cells where 3 out of 3 flood maps have predicted flooding. Where 2 out of 3 or 1 out of 3 maps have predicted flooding, flooding might occur depending on whether the lower, modal or upper estimate of the drainage system capacity is closest to representing the true drainage system capacity.

For example, Figure 4.20 shows maps for test areas 1 and 2 within the demonstration area with depth thresholds of 0.3m and 0.15m respectively; 0.3m is the depth of flooding at which water is thought to enter properties.

By studying test area 1, the following can be concluded in terms of the model outputs from the 3 different drainage system capacity estimates.

- The hypermarket west of the river **will flood** to at least a depth of 0.3m.
- Wigan and Leigh College **may flood** to a depth of 0.3m or above.
- Some properties on Frog Lane **will flood** to 0.3m or beyond, but the extent of flooding is **uncertain.**

Similarly, inspection of test area 2 in Figure 4.20 shows the following.

- The area containing Hindley nursery, residential properties and the A577 (providing access to the fire station) **will flood** to a depth of at least 0.15m.
- Streets surrounding properties in the east of the test area **will flood** to a depth of at least 0.15m, but the number of properties affected is **uncertain**.
- Streets surrounding properties in the west of the test area **will flood** to a depth of 0.15m or above.
- The 3 schools in the area **will** all be affected by a small amount of flooding.

These statements can help to identify priority areas in emergency planning.

The maps can also be interpreted in terms of sensitivity to the drainage rate. For example, the hypermarket shown in test area 1 in Figure 4.20 is predicted to flood whether the lower, modal or higher estimate of the drainage system capacity is applied. Investing in moderately improving the drainage system capacity in this area will therefore not prevent the hypermarket from flooding. Wigan and Leigh College, on the other hand, is predicted to flood in 2 out of the 3 drainage system capacity scenarios, and flood more extensively in 1 of the 3 scenarios. This indicates sensitivity to the drainage system capacity, indicating that moderately increasing the drainage system capacity to prevent flooding of the College could be an option. Further detailed modelling would be essential to investigate this option.

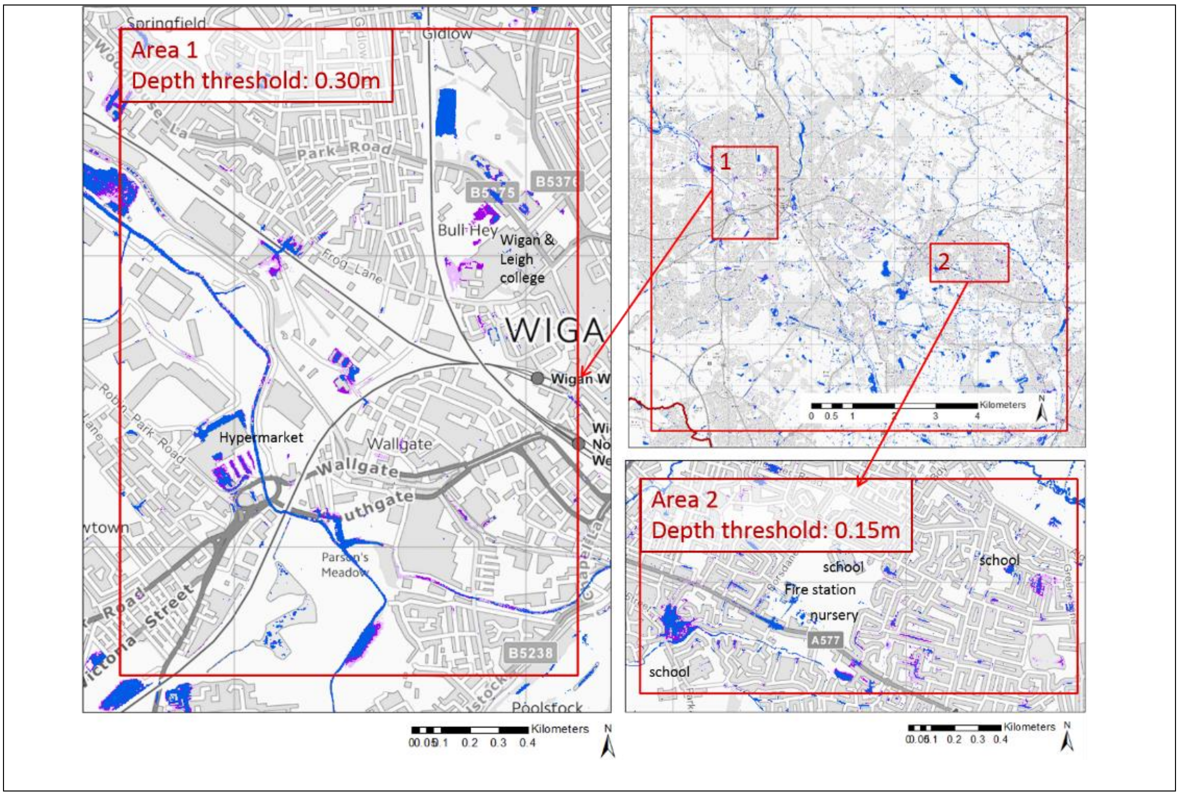


Figure 4.20 Test areas within the demonstration area showing where 3 out of 3, 2 out of 3 and 1 out of 3 maps predict cells to be wet at a depth threshold of 0.30m for test area 1 and 0.15m for test area 2

The Greater Manchester area was remodelled, replicating the uFMfSW methodology, with local drainage system capacities derived using Monte Carlo analysis of the drainage system capacity equation with local input parameters.

The sensitivity of the model to the drainage system capacity estimates was mapped. There was least sensitivity where all 3 drainage system capacity estimates resulted in ‘wet’ cells; this was the case in over 4 out of 5 of all wet cells. The model was sensitive to the drainage system capacity in the remaining 16% of wet cells (these areas can be identified on the maps). Knowing which areas are more sensitive to the drainage system capacity can help to identify areas in which it might be possible to reduce surface water flooding by increasing the drainage system capacity.

4.3.5 Conclusions

This project has confirmed that 12mm per hour remains a robust general estimate for drainage rates many situations. To assess how sensitive a location may be to this drainage rate used in the national uFMfSW model, two methods have been presented as potential alternatives to detailed modelling.

The alternative statistical method to remodelling developed in this project gives a quick insight into the sensitivity of small (5km × 5km) areas to the drainage rate parameter. This is important as remodelling is expensive and the appropriate resources may not be available to LLFAs. Remodelling is still recommended for larger areas of interest or where more detailed results are required.

The case studies demonstrated that, in practice, there is some variation in the results produced by the proxy method. The case studies at Market Harborough and Ellenbrook illustrate this point. At Market Harborough, using the locally calculated drainage rate (which was higher than the national rate) had a significant impact on the flood outline, greatly reducing the number of properties in the area at risk of flooding. At Ellenbrook, however and contrary to expectations, the proxy method showed an increase in flooding for a higher drainage rate. It is likely that factors other than the net rainfall profile are significant in controlling flood outlines and depths in this area.

The Stirchley case study demonstrated that, although the alternative statistical method refines the drainage rate locally, it does not reflect the variation of the drainage rate across the catchment (already established at this location).

The Greater Manchester area was remodelled using the local range of drainage rates calculated using the statistical method. The flood maps for each drainage rate were compared with each other in order to identify areas that were sensitive (or not) to a change in drainage capacity. This indicated the level of confidence around flood risk and the merits of further investigating drainage improvements. Such information provides evidence useful in making investment decisions.

Although neither the empirical or statistical methods investigated are reliable for refining the local drainage rate, both methods provide an insight into the sensitivity of an area to the drainage rate parameter.

Further insight into the sensitivity of an area can be achieved by comparing the standard lower (6mm per hour) and standard higher (18mm per hour) rates to the default 12mm per hour rate using the proxy method or remodelling.

The proxy method is recommended for examining changes in drainage rate across smaller areas (5km × 5km uFMfSW modelling tile). However, it is important to be aware of the limitations of this method; it may not work for all locations but could be a useful starting point where resources for remodelling are limited. All results should be validated or checked against local records and flooding knowledge.

Remodelling remains the most reliable way of assessing flood risk from surface water, especially for larger areas.

4.4 Recommendations for further work

This research has highlighted the limitations of using the uFMfSW method to accurately represent the role that urban drainage systems play in protecting areas from flooding.

The project importantly demonstrated that applying different drainage rates within the uFMfSW method is useful for assessing the sensitivity of flood depths and extents to the generalised capacity of urban drainage. However, it cannot easily be linked to actual drainage capacity.

This research has provided some guidance for LLFAs on how to gain an insight into the sensitivity of drainage rates on the results of national generalised surface water flood maps, which can help indicate where more detailed risk analysis should be targeted. However, it does not provide a mechanism to understand the true impact of drainage capacity on surface water flood risk locally.

Further work is required to support LLFAs to better understand the mechanisms causing surface water flooding locally and the suitability of different modelling/risk assessment approaches to represent these for planning purposes in the development of business cases and for feasibility design.

This could help to target modelling resources and to implement a risk-based, proportional approach to modelling using national flood maps to inform locally focused studies where factors like drainage capacity require more detailed analysis. This could be in the form of guidance or best practice in using surface water or urban drainage models and maps to represent the most important elements of the drainage system such as:

- the capacity of road gullies, highways drains and storm and combined sewers
- their impact on surface water flooding

5 Guidance

This guidance is intended for LLFAs (or other users) considering the sensitivity of uFMfSW mapping to assumptions of ‘drainage rate’ – the key modelled parameter representing the capacity of urban drainage systems.

The most common reason for considering a revision to the default ‘drainage rate’ is to improve the accuracy of mapping when the default 12mm per hour value is considered inappropriate. This project has, however, confirmed that 12mm per hour remains a robust general estimate for many situations.

This guidance supports users in assigning a revised rate for their location (using a statistical method) and a quick way to re-purpose existing mapping (proxy method) to view flood mapping equivalent to that prepared using the revised drainage rate. The approach allows for a rapid assessment of the extent to which the revised drainage rate increases or decreases mapped flood extents.

Figure 5.1 presents a recommended procedure for users to follow, with cross-references to the relevant part of this report for further information.

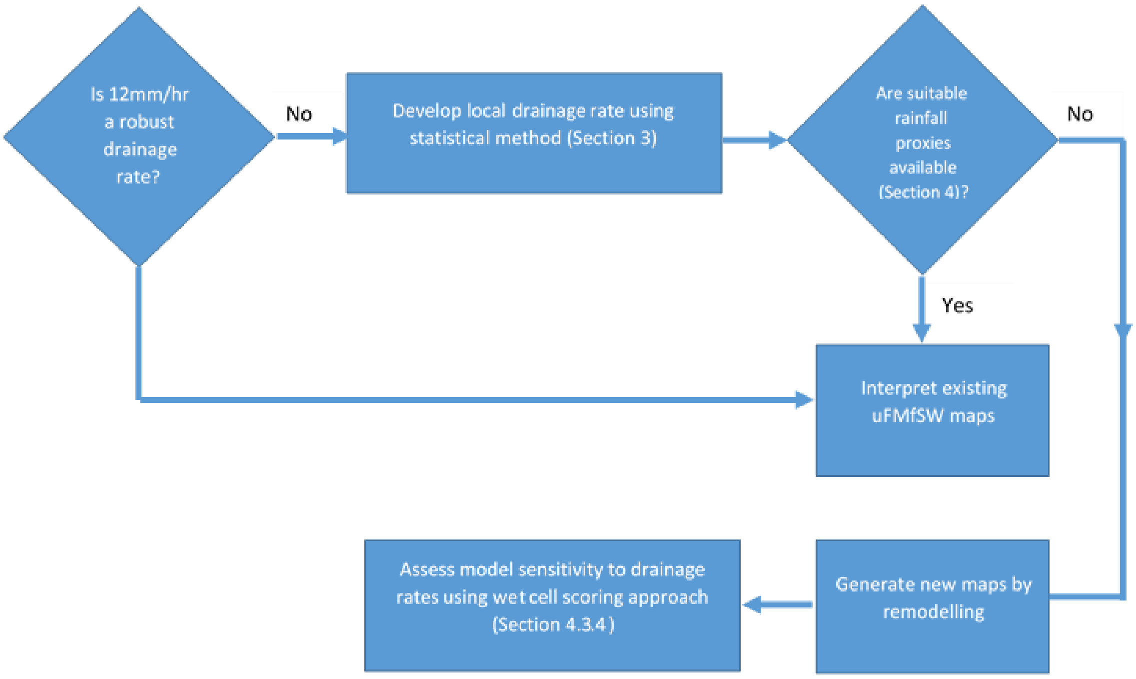


Figure 5.1 Flowchart showing overview of suggested process to improve mapping using local knowledge and reuse of uFMfSW data

The separate user guide that accompanies this report provides further guidance on how to estimate a new drainage rate (SC120020/1 Improving surface water mapping: estimating local drainage rates user guidance PowerPoint presentation). Figure 5.2 also illustrates, in more detail, the process for preparing a new drainage rate using the recommended statistical method.

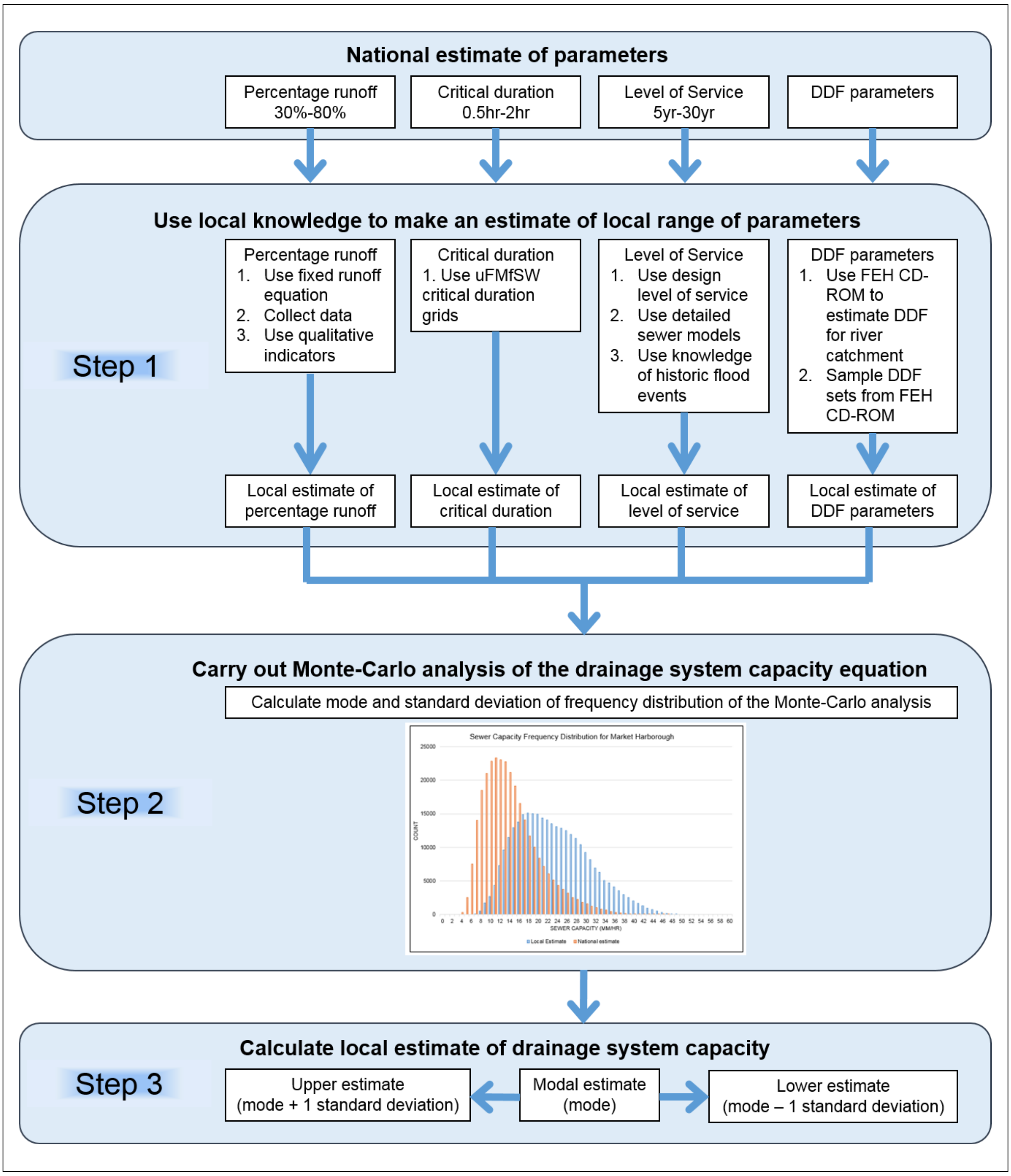


Figure 5.2 Flowchart for obtaining a local estimate of the drainage system capacity using the statistical method

Notes: The FEH CD-ROM used in this project was superseded by the FEH Web Service (https://fehweb.ceh.ac.uk) in November 2015.

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List of abbreviations

AGMA	Association of Greater Manchester Authorities
DDF	depth, duration and frequency
FEH	Flood Estimation Handbook
LLFAs	Lead Local Flood Authorities
LoS	level of service
PIMP	percentage impermeable area
PR	percentage run-off
REH	Revitalised Flood Hydrograph
RMAs	Risk Management Authorities
SOIL	water holding capacity of the soil
T_{CRIT}	critical storm duration
UCWI	urban catchment wetness index
uFMfSW	updated Flood Map for Surface Water

Appendix A: Flood Map for Surface Water technical details

A.1 Representation of rainfall and drainage losses within national scale models

Direct rainfall models applied at the national scale typically use simplified representations of infiltration and drainage processes, with parameters taken from datasets with national coverage, for example, land cover mapping and Flood Estimation Handbook (FEH) catchment descriptors. As such, these proxy representations have been very simple by necessity, particularly when compared with techniques used in detailed urban drainage modelling.

In the first generation Areas Susceptible to Surface Water Flooding (AStSWF) mapping, no allowance for subsurface drainage or infiltration capacity was made and 100% run-off from a 1 in 200, 6 hour duration storm was assumed in all areas. This assumption led to an overestimation of flooding in many areas and highlighted the need to adjust the rainfall inputs to account for these processes in any future modelling.

For the second generation Flood Map for Surface Water (FMfSW), 2 adjustments were made to the initial rainfall inputs to calculate more representative (or ‘net’) rainfall–run-off depths over rural and urban areas (Horritt et al. 2009).

- In rural areas, a uniform percentage run-off (PR) coefficient of 39% was applied. This figure was based on an analysis of FEH catchment descriptor data available for 5 test sites and is dependent on soil type, rainfall depth and a catchment wetness index representing antecedent conditions.
- In urban areas, a PR coefficient of 70% was applied (after Akan and Houghtalen 2003) and then 12mm per hour was removed to represent the effects of urban drainage infrastructure.

This drainage rate of 12mm per hour was derived from an assumed level of service (LoS) (for example, a well-built and maintained sewer will carry a 1 in 30 probability storm), run-off coefficient, critical storm duration (T_{CRIT}) and the depth, duration and frequency (DDF) parameters. These parameters and their associated uncertainties are combined in a Monte Carlo analysis, using the Rational Method to estimate drainage system capacities in mm per hour. This results in a range of capacities ranging from 7mm per hour to 25mm per hour (10th and 90th percentile values respectively); the median value of 12mm per hour was used as a nationally representative figure.

For the third generation mapping, the updated Flood Map for Surface Water (uFMfSW), the same 70% PR and 12mm per hour default drainage rate combination was retained as the default parameter in urban areas.

Efforts were made at the time to improve on this representation using sewer models and data collated to support Ofwat’s Future Impacts on Sewer Systems in England and Wales study (Mott MacDonald 2011), but the analysis proved inconclusive. Although simulations had been carried out in 100 sewer catchments, these were only for the 1 in 10 probability storm. This proved to be insufficient to identify which catchments or subcatchments were consistently at or exceeding sewer capacity in order to draw further conclusions.

Lead Local Flood Authorities (LLFAs) were given the option to provide alternative information on drainage rates and infiltration/run-off rates via a data request issued by the Environment Agency in summer 2012 (Environment Agency 2012). Approximately 10% of LLFAs provided information on drainage rates, critical storm durations and infiltration/run-off rates in response to this data request. Following basic sense checks, these data were processed into suitable formats for incorporating within the rainfall hydrology calculations and hydraulic modelling. Where data could not be used as supplied, inconsistencies were resolved via one-to-one discussions. In general, there was low confidence that alternative drainage rates were evidence-based.

In rural areas and the green portions within urban areas, run-off volumes for the uFMfSW were determined using the losses model from the Revitalised Flood Hydrograph (ReFH) rainfall–run-off method (Kjeldsen et al. 2005) parametrised using 1km resolution Hydrology of Soil Types mapping (Boorman et al. 1995).

A full description and justification for the chosen methods is provided in the uFMfSW national scale surface water flood mapping methodology report (Environment Agency 2013a). A summary figure that explains how the various adjustments are applied spatially within the uFMfSW direct rainfall models is provided in Figure A.1. The same methods are applied to each of the 9 rainfall scenarios used to produce the uFMfSW (that is, 1, 3 and 6 hour duration storms for the 1 in 30, 1 in 100 and 1 in 1,000 return period rainfall probabilities). Initial (or total) rainfall depths for each scenario were derived using a FEH DDF model constructed for each 5km × 5km modelling tile using parameters from the FEH CD-ROM (used at the time of uFMfSW, but superseded by the FEH Web Service, 2015).

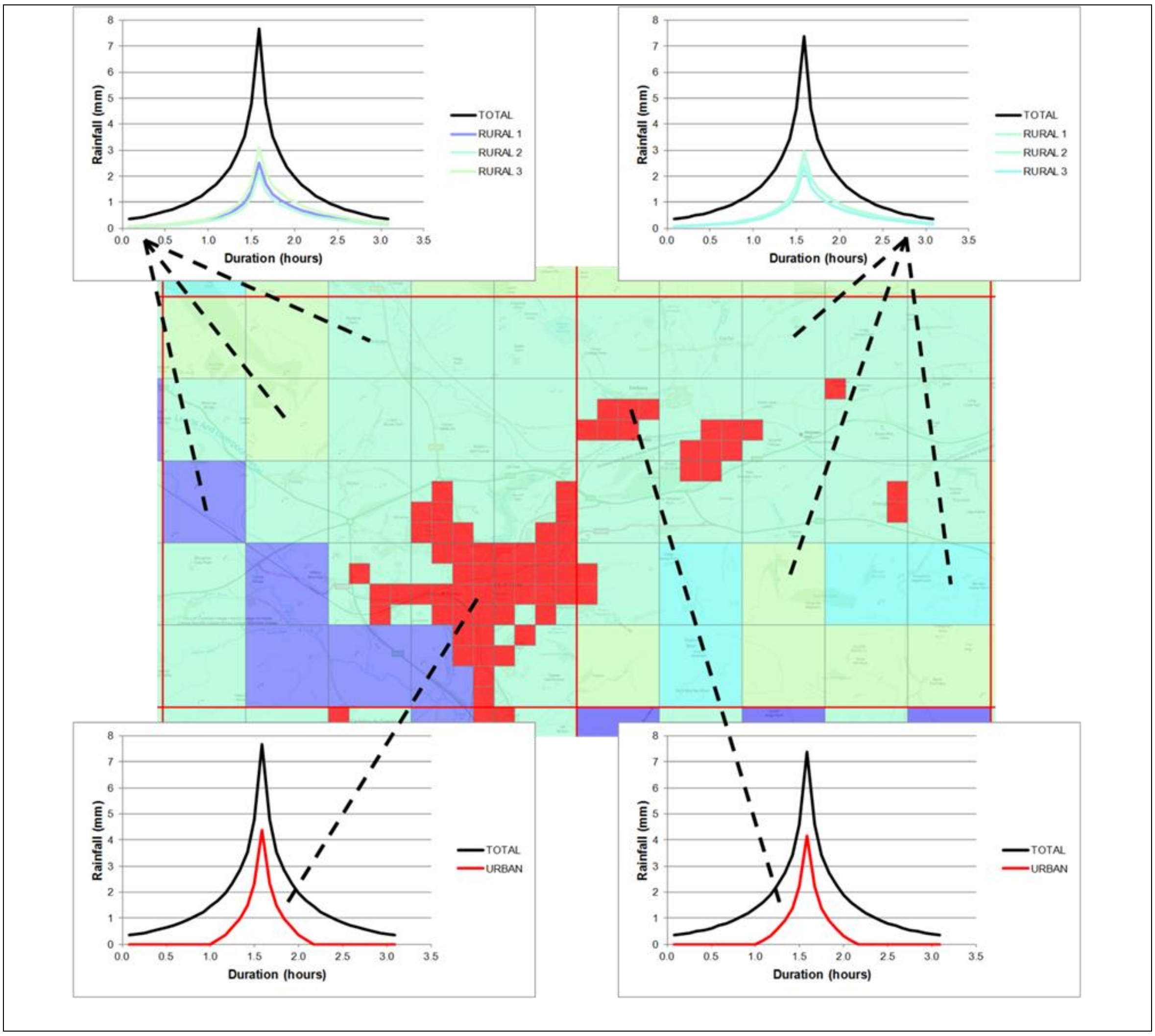

Figure A.1 Example application of different net rainfall hyetographs according to urban–rural classification for 2 adjacent 5km × 5km modelling tiles

A.2 Derivation of default 12mm per hour drainage rate

Obtaining a national estimate of manmade drainage capacity is challenging due to the complex and varied nature of the drainage infrastructure found in urban areas. However, a national estimate of 12mm per hour for drainage system capacity was derived by Horritt et al. (2009) used a modified version of the Rational Method:

$$Rate = PR.T_{CRIT}^{(Cy+D1-1)}.e^{Ey+F}Rate = PR.T_{CRIT}^{(Cy+D1-1)}.e^{Ey+F} \qquad \text{(A.1)}$$

$$y = -ln\left(-ln(1-\frac{1}{LoS})\right)y = -ln\left(-ln(1-\frac{1}{LoS})\right) \qquad \text{(A.2)}$$

Equations A.1 and A.2 take into account the percentage run-off (PR), critical storm duration (T_{CRIT}), level of service of the drainage system (LoS) and the DDF parameters that describe the rainfall (C, D1, E and F).

A range and distribution of each parameter were estimated across England and Wales. The PR range is based on 5 pilot sites:

- Bradford
- Kensington and Chelsea
- Torquay
- North Brent
- Swindon

PR was calculated for each site based on the percentage impermeable area (PIMP) using the Wallingford procedure (Equation A.3):

$$PR = 0.828\,PIMP + 25.0\,SOIL + 0.078\,ICWI - 20.7 \qquad \text{(A.3)}$$

where SOIL is the water holding capacity of the soil (that is, it describes permeable areas) and UCWI is the urban catchment wetness index. A range of 30–80% run-off, with a uniform distribution was obtained for the pilot sites.

Limited information is available on the LoS of sewers in England and Wales. Estimates for catchments in Surrey (15 years), Sussex (5–30 years) and Lincoln (20 years) were taken from Defra (2008). These data, combined with experience of sewer modelling, led to a broad LoS estimate of 5–30 years, with a triangular distribution and a modal value of 10 years towards the lower end of the range.

T_{CRIT} was estimated for the same 5 pilot catchments used to estimate PR. Two approaches were applied and compared:

- an equation for time-to-peak from using the IH124 method (Marshall and Bayliss 1994)
- the time-to-peak from the ReFH model

The 2 approaches used Flood Studies Report (FSR) (NERC 1975) and FEH catchment descriptors respectively.

Time-to-peak is thought to be representative of critical duration as it is applied to small catchments. Estimates ranging from approximately 15 minutes to 2 hours were obtained using the 2 methods. However, both methods should be treated with caution as they are based on data for gauged catchments, most of which are >3.5km^2 and are influenced by the hydraulics of the channels they are based on.

Critical durations of 30 minutes to 10 hours are reported for some of the 5 pilot studies in the Integrated Urban Drainage pilot catchments listed above (Defra 2008). These are thought to be longer than the range obtained from the time-to-peak equations because they are from detailed models that have a better representation of underground storage. The models may use flood volume, rather than area to identify the critical duration, which would also bias the estimates towards longer durations. For these reasons, a pragmatic decision was taken to vary the critical storm duration between 0.5 and 2 hours.

To obtain a measure of the variation in DDF parameter values across England and Wales, DDF parameters were obtained for 9 sites (Table A.1), chosen for their geographical spread and mix of coastal and inland locations. The mean and standard deviation for the 9 sites of each DDF parameter were taken as representative of the distribution of the DDF parameters for urban areas across England and Wales. However, it should be noted that because the DDF parameters are not independent of each other, sampling them independently from the derived ranges may not be representative of their joint distributions.

The parameter ranges derived using the methods described above are summarised in Table A.2. These parameter ranges were applied within a Monte Carlo analysis of equations A.1 and A.2. A total of 1,000 random samples were generated across the parameter ranges and a drainage system capacity was calculated for each sample, resulting in a frequency distribution of estimated capacities. The modal value of this distribution, 12mm per hour, was chosen as the national estimate of drainage system capacity to be used within the FMfSW.

Table A.1 DDF parameter values for 9 selected sites in England and Wales

Site	C	D1	E	F
Westminster	-0.025	0.368	0.290	2.454
Penzance	-0.031	0.45	0.284	2.379
Aberystwyth	-0.031	0.394	0.299	2.258
Newcastle	-0.022	0.414	0.275	2.34
Manchester	-0.027	0.328	0.303	2.456
Skegness	-0.021	0.357	0.307	2.437
Birmingham	-0.027	0.358	0.308	2.423
Derby	-0.026	0.333	0.301	2.387
Burnley	-0.025	0.384	0.304	2.399
Mean/standard deviation	-0.026 ± 0.0034	0.38 ± 0.039	0.30 ± 0.011	2.4 ± 0.063

Table A.2 Summary of parameters used for national estimate of sewer capacity

Parameter		National range
Percentage run-off (PR)		30–80%
Critical storm duration (T_{CRIT})		0.5–2 hours
Level of service of drainage system (LoS)		5–30 years (mode of 10 years)
Depth, duration, frequency (DDF) rainfall parameters	C	-0.026 ± 0.0034
	D1	0.38 ± 0.039
	E	0.30 ± 0.011
	F	2.4 ± 0.063

Appendix B: Statistical approach parameter estimation

B.1 Percentage run-off

The percentage run-off (PR) describes the fraction of the rainfall volume that is not infiltrated, intercepted, lost (for example, through evapotranspiration) or stored (for example, as depression storage) when it lands. It depends on many factors such as storm intensity and the permeability, roughness and slope of the surface on which the rainfall lands. Antecedent conditions make a significant difference as the PR will be greater if the depression storage is already full. Furthermore, the PR is not constant during an event but increases as the catchment ‘wets up’.

Various methods are available for calculating the PR.

The Wallingford procedure, developed for the design of urban drainage systems, incorporates several methods for the estimation of PR.

The method used to obtain the national range of PR described in Appendix A is the ‘old run-off equation’ or ‘fixed UK run-off model’ (Equation B.1). This uses the percentage impermeable area (PIMP), the water holding capacity of the soil (SOIL) and urban catchment wetness index (UCWI) to calculate a constant value of percentage run-off (PR).

$$PR = 0.828\ PIMP + 25.0\ SOIL + 0.078\ ICWI - 20.7 \tag{B.1}$$

The old run-off equation gives a fixed value of run-off throughout the rainfall event; this does not account for the increase in PR as the catchment wets up. The relationship was derived from large catchments for the purpose of sewer modelling and hence its applicability to small catchments and validity at events greater than the 30 year annual probability event is uncertain.

The method was superseded by the revised model – the new UK run-off model, which deals with impermeable areas by splitting them into 2 fractions. One fraction represents direct connection to the drainage system and has a run-off coefficient of 1; the other fraction is treated as if it were permeable, taking into account a dynamic wetness index. The fraction is determined by surface type (for example, paved surface: 0.6) and is calibrated by the user (Shaw et. al. 2011). However, a lack of guidance as to what value to choose for one of the parameters used in the method, the antecedent precipitation index (NAPI), has made application of the method difficult in practice.

Both the ReFH and FEH methods provide methods for calculating PR. However, the assumption of a PR coefficient is implicit within these methods; a standard PR is calculated, which is modified for urban areas by applying a factor of 0.7.

Another method for calculating the percentage was developed more recently, that is, the ‘UKWIR percentage run-off equation’. This has the following advantages.

- It allows the paved component of the run-off to be treated separately to the pervious run-off.
- It accounts for different surface types with different run-off characteristics.
- It allows the difference in run-off in winter and summer to be taken account of.

- It takes the change in run-off during an event into account.

The UKWIR equation uses a large number of parameters – a level of complexity which makes it a more appropriate method for detailed sewer modelling.

Taking into account the level of detail and data requirements of the various methods to estimate PR, the following methods are recommended for deriving local parameter estimates:

- Use the fixed UK run-off model (Equation 3.1) to obtain a local estimate of PR using local values of PIMP, SOIL and UCWI. A range of values can be used for PIMP and UCWI to overcome difficulties in their estimation.
- Collect data to calculate the local PR. For example, compare water levels of features such as ponds before and after a rainfall event with the measured rainfall, or carry out temporary sewer monitoring.
- Use qualitative descriptors to increase or decrease the PR. Factors identified in the development of the UKWIR run-off model which increase or decrease the percentage run-off include (UKWIR 2014):
    - steeper catchment (median value slope >2° after Environment Agency 2013b)
    - large proportion of roofs
    - low proportion of small permeable areas such as grass verges and flower beds
    - wet antecedent conditions
    - long critical event duration

  Carry out sensitivity analysis of the drainage system capacity equation to choose a local range.

B.2 Critical duration

The critical duration is the storm duration that causes the greatest depth of surface water flooding. The critical duration is affected by many factors such as:

- the size and steepness of the upstream catchment
- the density of the drainage network
- and antecedent wetness conditions

The methods available to calculate the critical duration (or the time-to-peak) that can be taken as representative of the critical duration for small catchments are described in Appendix A. However, the validity of these methods for surface water flooding of small areas is uncertain as they are based on gauged flows for large catchments.

Alternatively, sewer modelling methods, such as the Wallingford procedure, may provide more appropriate estimates.

Rather than calculating a critical duration it is possible to reuse existing uFMfSW data. Raster data exist which show whether the 1 hour, 3 hour or 6 hour duration storm caused the greatest depth of flooding for each pixel. It is therefore recommended that the distribution of critical storm durations from these raster data for the model area should be used to inform a local estimate of the range of T_{CRIT}. The distribution can be sampled directly in the Monte Carlo analysis, or the modal value can be used to adapt the national range of T_{CRIT}.

In low-lying areas, it is possible that the critical duration may be longer than 6 hours, which is the longest duration modelled in the uFMfSW. Here it may be possible to use the results of detailed modelling studies, local knowledge or knowledge of the history of flooding to estimate a local range of critical duration. However, it may be difficult to obtain an estimate of critical duration even where durations of historical flood events are known as it is difficult to separate the effects of surface water and fluvial flooding. Where it is known that the critical duration is likely to be higher than 6 hours but it is difficult to define a likely range, a sensitivity analysis can be carried out to give an indication of the effect of the critical duration on the drainage system capacity.

Similarly, the critical duration grids will not indicate whether critical duration is shorter than 1 hour, or whether the critical duration lies between the values of 1, 3 and 6 hours. Sensitivity analysis is recommended to assess the sensitivity of the model to the critical duration.

B.3 Level of service

The level of service (LoS) is the design exceedance probability rainfall event that can be contained within the drainage system without causing surface water flooding. As discussed in Appendix A, it is very difficult to obtain an estimate of the LoS of drainage systems.

A record of the LoS that the drainage system was designed to may exist, but even where this is known, the system may not necessarily be operating at the design LoS. Maintenance issues such as blockages may reduce the capacity of the drainage system and result in the drainage system operating below the original design standard.

Furthermore, options for estimating the LoS of the drainage system are limited to the use of local knowledge of flood events or data from detailed sewer models.

Methods for making a local estimate of the level of service are as follows.

- Use the known design LoS, making allowances for degradation of the system over time. Sewers that were designed to the requirements of ‘Sewers for Adoption’ (Water Research Centre 2006) will have an LoS of 30 years.
- Use level of service from detailed sewer modelling studies if available.
- Use local knowledge or knowledge of historic flood events to make an estimate of the extremeness of events which have and have not been contained by the drainage system. It can be difficult to separate fluvial and surface water flooding where this occurs in the floodplain.

Where a good estimate of the LoS of the drainage system is available, the option to bypass the drainage system capacity equation should be considered and to instead assume that the rainfall depth of the LoS exceedance probability event is equivalent to the drainage system capacity.

B.4 Depth–duration–frequency parameters

The DDF parameters describe the shape of the frequency distribution of rainfall in an area. They are available from the FEH Web Service[4] (or the FEH CD-ROM if a copy is

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[4] https://fehweb.ceh.ac.uk

available) on a 1km × 1 km grid. A local estimate of the DDF parameters can be made by obtaining the DDF parameters for the model area.

If the model area only spans one 1km tile, then the value for this tile can be used.

If more than one 1km sample tile is spanned, then the fact that the DDF parameters are not independent and cannot therefore be sampled independently should be taken into account. The simplest way to overcome this problem is to use a single, representative estimate of the DDF parameters for a model area. Where there is little variation in the DDF parameters, the DDF values at the centroid of the model area can be used.

If the model area approximates to a river catchment, and access to the FEH Web Service or the FEH CD-ROM is available, it can be used to obtain an estimate of the average DDF parameters for a larger area.

If the area of interest does not approximate to a river catchment and is too large to be represented by the DDF descriptors at the centroid of the area, then the DDF parameters can be sampled as sets at given point locations within the area of interest. A list of the DDF parameter sets for each 1km grid square within the urban model area can then be randomly sampled in the Monte Carlo analysis of the drainage system capacity equation.

B.5 Sensitivity

Table B.1 lists the sensitivity of the drainage rate equation to the ranges used in each input parameter. For example, drainage rate can vary 10mm per hour between a minimum PR of 30 and a maximum PR of 80.

Table B.1 Change in drainage system capacity estimate when parameter is varied over national range

Parameter	Estimated range (from national range estimate)	Change in drainage system capacity estimate (mm/hour)
Percentage run-off	30–80%	10
Critical duration	0.5–2 hours	11
Level of service	5–30 years	6
DDF parameters	9 representative sites for England and Wales (see Table A.1)	2

B.6 Summary

A summary of the available methods and sources of data for obtaining local estimates of the drainage system capacity equation parameters is given in Table B.2.

Table B.2 Methods and sources of data for obtaining local estimates of the drainage system capacity equation parameters

Parameter	**Method/information for making estimate of local parameter range**		
Percentage run-off	Fixed UK run-off model equation	Level and rainfall data	Qualitative factors such as steepness
Critical storm duration	Reuse existing data from uFMfSW	Sewer design equations such as the Wallingford procedure	Local knowledge
Level of service of drainage system	Known design level of service	Detailed modelling studies	Local knowledge
Depth, duration and frequency rainfall parameters	DDF parameters at centroid of catchment	FEH Web Service to obtain average DDF parameters	Sample sets of DDF parameters for model area

Appendix C: Monte Carlo analysis spreadsheet guidance

File name: SC120020/1 Appendix C_SewerCapacity-MC Analysis Tool (v0.2-March 2015).xls

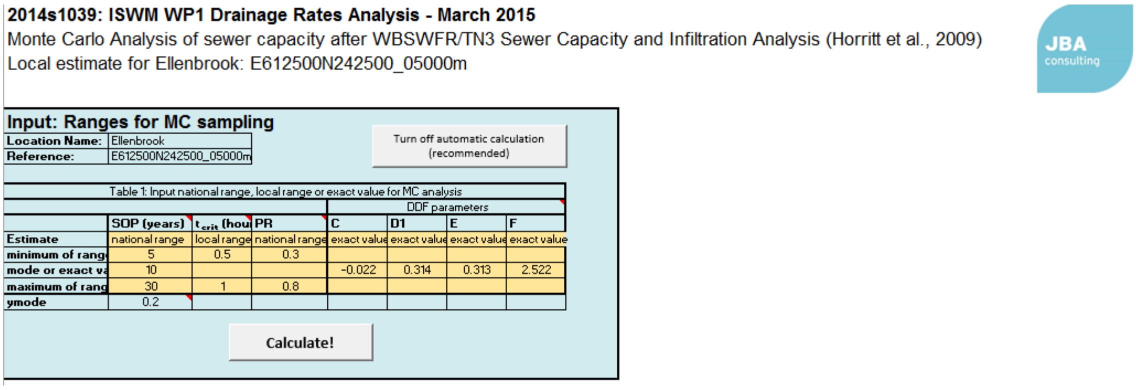
SC120020/1 is an example Monte-Carlo calculator spreadsheet tool. This can be used to plot a frequency distribution of the calculated drainage system capacities. The modal result is the locally calculated drainage system capacity.

The spreadsheet is used to undertake Monte Carlo analysis of the sewer capacity equation. It consists of 3 boxes: input, calculations and output. The user enters the range or exact values of level of service, critical duration, percentage run-off and the DDF parameters (Figure C.1).

It is recommended that the automatic calculation function is turned off using the button provided because the numerous samples make the spreadsheet slow if a re-calculation is performed during editing. Once the user has finished entering the input information, the 'Calculate!' button is used to perform the calculation to generate the output.

A total of 300,200 random samples are generated for each given range of the parameters of the sewer capacity equation; the first of these can be seen in Figure C.2. The random samples of LoS are generated from a triangular distribution, the T_{CRIT} and PR are sampled from uniform distributions and the DDF parameters are generated from normal distributions of the samples as per the original analysis by Horritt et al. (2009). The sewer capacity is calculated for each randomly sampled set of variables.

The range of sewer capacities is then divided into 1 mm bins and the frequency of occurrence of the sewer capacity within the bins is calculated to obtain the frequency distribution shown in Figure C.3. The mode and standard deviation are calculated from the frequency distribution. The upper and lower values are the mode plus and minus one standard deviation respectively. The frequency distribution plot allows the difference to be seen between the distribution for the local and national estimates of the sewer capacity equation.



2014s1039: ISWM WP1 Drainage Rates Analysis - March 2015
Monte Carlo Analysis of sewer capacity after WBSWFR/TN3 Sewer Capacity and Infiltration Analysis (Horritt et al., 2009)
Local estimate for Ellenbrook: E612500N242500_05000m

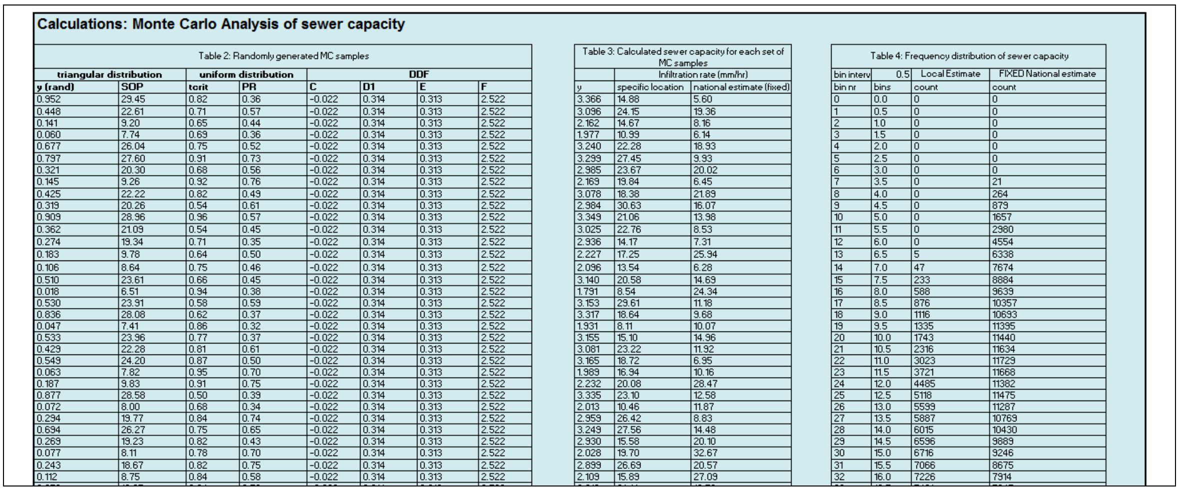
Input: Ranges for MC sampling

Location Name: Ellenbrook
Reference: E612500N242500_05000m

Table 1: Input national range, local range or exact value for MC analysis

				DDF parameters			
	SOP (years)	**t_{crit} (hou**	**PR**	**C**	**D1**	**E**	**F**
Estimate	national range	local range	national range	exact value	exact value	exact value	exact value
minimum of rang	5	0.5	0.3				
mode or exact va	10			-0.022	0.314	0.313	2.522
maximum of rang	30	1	0.8				
ymode	0.2						

Figure C.1 Example of Monte Carlo analysis spreadsheet input box



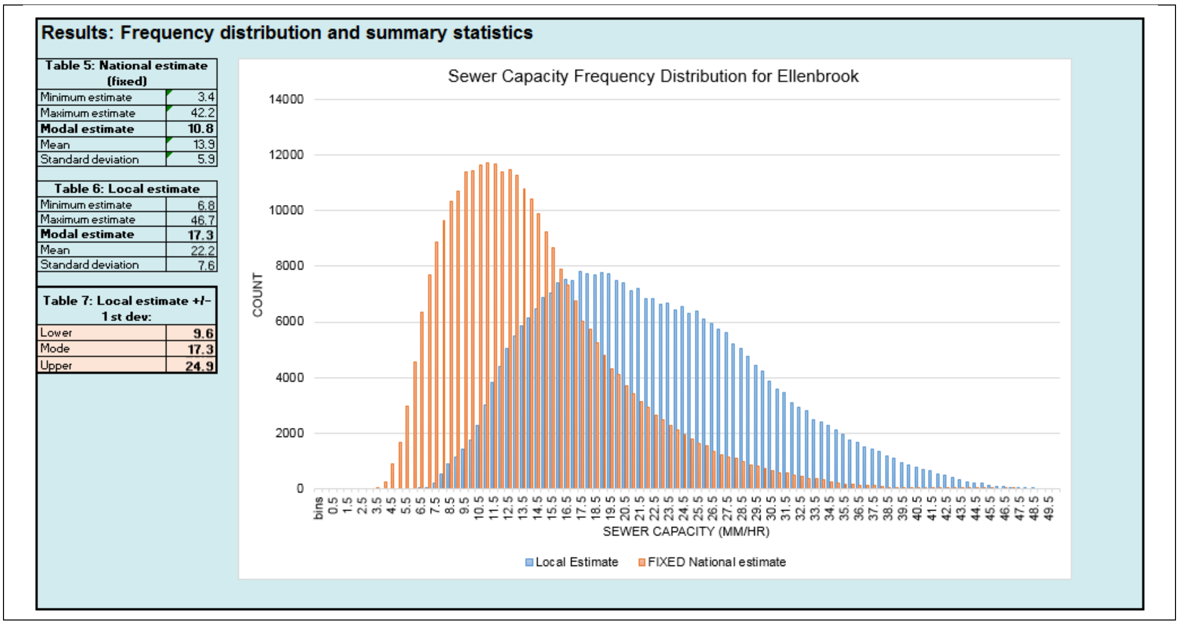
Calculations: Monte Carlo Analysis of sewer capacity

Table 2: Randomly generated MC samples							
triangular distribution		**uniform distribution**		**DDF**			
y (rand)	**SOP**	**tcrit**	**PR**	**C**	**D1**	**E**	**F**
0.952	29.45	0.82	0.36	-0.022	0.314	0.313	2.522
0.448	22.61	0.71	0.57	-0.022	0.314	0.313	2.522
0.141	9.20	0.65	0.44	-0.022	0.314	0.313	2.522
0.060	7.74	0.69	0.36	-0.022	0.314	0.313	2.522
0.677	26.04	0.75	0.52	-0.022	0.314	0.313	2.522
0.797	27.60	0.91	0.73	-0.022	0.314	0.313	2.522
0.321	20.30	0.68	0.56	-0.022	0.314	0.313	2.522
0.145	9.26	0.92	0.76	-0.022	0.314	0.313	2.522
0.425	22.22	0.82	0.49	-0.022	0.314	0.313	2.522
0.319	20.26	0.54	0.61	-0.022	0.314	0.313	2.522
0.909	28.96	0.96	0.57	-0.022	0.314	0.313	2.522
0.362	21.09	0.54	0.45	-0.022	0.314	0.313	2.522
0.274	19.34	0.71	0.35	-0.022	0.314	0.313	2.522
0.183	9.78	0.64	0.50	-0.022	0.314	0.313	2.522
0.106	8.64	0.75	0.46	-0.022	0.314	0.313	2.522
0.510	23.61	0.66	0.45	-0.022	0.314	0.313	2.522
0.018	6.51	0.94	0.38	-0.022	0.314	0.313	2.522
0.530	23.91	0.58	0.59	-0.022	0.314	0.313	2.522
0.836	28.08	0.62	0.37	-0.022	0.314	0.313	2.522
0.047	7.41	0.86	0.32	-0.022	0.314	0.313	2.522
0.533	23.96	0.77	0.37	-0.022	0.314	0.313	2.522
0.429	22.28	0.81	0.61	-0.022	0.314	0.313	2.522
0.549	24.20	0.87	0.50	-0.022	0.314	0.313	2.522
0.063	7.82	0.95	0.70	-0.022	0.314	0.313	2.522
0.187	9.83	0.91	0.75	-0.022	0.314	0.313	2.522
0.877	28.58	0.50	0.39	-0.022	0.314	0.313	2.522
0.072	8.00	0.68	0.34	-0.022	0.314	0.313	2.522
0.294	19.77	0.84	0.74	-0.022	0.314	0.313	2.522
0.694	26.27	0.75	0.65	-0.022	0.314	0.313	2.522
0.269	19.23	0.82	0.43	-0.022	0.314	0.313	2.522
0.077	8.11	0.78	0.70	-0.022	0.314	0.313	2.522
0.243	18.67	0.82	0.75	-0.022	0.314	0.313	2.522
0.112	8.75	0.84	0.58	-0.022	0.314	0.313	2.522

Table 3: Calculated sewer capacity for each set of MC samples		
	Infiltration rate (mm/hr)	
y	specific location	national estimate (fixed)
3.366	14.88	5.60
3.096	24.15	19.36
2.162	14.67	8.16
1.977	10.99	6.14
3.240	22.28	18.93
3.299	27.45	9.93
2.985	23.67	20.02
2.169	19.84	6.45
3.078	18.38	21.89
2.984	30.63	16.07
3.349	21.06	13.98
3.025	22.76	8.53
2.936	14.17	7.31
2.227	17.25	25.94
2.096	13.54	6.28
3.140	20.58	14.69
1.791	8.54	24.34
3.153	29.61	11.18
3.317	18.64	9.68
1.931	8.11	10.07
3.155	15.10	14.96
3.081	23.22	11.92
3.165	18.72	6.95
1.989	16.94	10.16
2.232	20.08	28.47
3.335	23.10	12.58
2.013	10.46	11.87
2.959	26.42	8.83
3.249	27.56	14.48
2.930	15.58	20.10
2.028	19.70	32.67
2.899	26.69	20.57
2.109	15.89	27.09

Table 4: Frequency distribution of sewer capacity			
bin interv	0.5	Local Estimate	FIXED National estimate
bin nr	bins	count	count
0	0.0	0	0
1	0.5	0	0
2	1.0	0	0
3	1.5	0	0
4	2.0	0	0
5	2.5	0	0
6	3.0	0	0
7	3.5	0	21
8	4.0	0	264
9	4.5	0	879
10	5.0	0	1657
11	5.5	0	2980
12	6.0	0	4554
13	6.5	5	6338
14	7.0	47	7674
15	7.5	233	8884
16	8.0	588	9639
17	8.5	876	10357
18	9.0	1116	10693
19	9.5	1335	11395
20	10.0	1743	11440
21	10.5	2316	11634
22	11.0	3023	11729
23	11.5	3721	11668
24	12.0	4485	11382
25	12.5	5118	11475
26	13.0	5599	11287
27	13.5	5887	10769
28	14.0	6015	10430
29	14.5	6596	9889
30	15.0	6716	9246
31	15.5	7066	8675
32	16.0	7226	7914

Figure C.2 Example of Monte Carlo analysis spreadsheet calculations box



Results: Frequency distribution and summary statistics

Table 5: National estimate (fixed)	
Minimum estimate	3.4
Maximum estimate	42.2
Modal estimate	**10.8**
Mean	13.9
Standard deviation	5.9

Table 6: Local estimate	
Minimum estimate	6.8
Maximum estimate	46.7
Modal estimate	**17.3**
Mean	22.2
Standard deviation	7.6

Table 7: Local estimate +/- 1 st dev:	
Lower	**9.6**
Mode	**17.3**
Upper	**24.9**

Figure C.3 Example of Monte Carlo analysis spreadsheet output box

Appendix D: Rainfall calculator spreadsheet guidance

File name: SC120020/2 Appendix D_Effective Rainfall Matrix Calculator (v0.3 March 2015).xls

SC120020/2 is an example spreadsheet that can be used to produce net summer rainfall profiles for the 3.3 percent, 1 percent and 0.1 percent annual exceedance probability events with 1, 3, and 6 hour durations for the national and local estimates of the drainage system capacity. The user can use an alternative software package.

Required inputs:

- *The drainage system capacity used in the national Risk of Flooding from Surface Water modelling. This was 12mm/hr unless a different drainage rate was indicated by LLFA at the time. This was changed to 6mm/hr in places identified as having a low drainage rate and 18mm/hr in areas identified as having high drainage rates*
- *The local drainage system capacity as calculated the in the Statistical Method*
- *The FEH DDF parameters for the centroid of the model tile. The DDF parameters are accessed via the FEH Web Service*

To create the DDF parameters in the uFMfSW, England and Wales was divided into 5km x 5km "tiles" that provided the basis for rainfall estimation and subsequent hydraulic modelling. For each tile, a model of rainfall depth-duration-frequency (DDF) was constructed using parameters available from the FEH (Flood Estimation Handbook) CD-ROM at the tile centroid, and the techniques outlined in Volume 2 of the FEH (Faulkner 1999). Each DDF curve was then used to calculate a tile-specific total rainfall depth for a storm of given duration and probability.

The FEH CD-ROM has since been replaced with the FEH Web Service and DDF parameters have been updated. However, to compare local drainage rates against the uFMfSW results, and test the sensitivity to change, the DDF input to uFMfSW will be needed (FEH99 DDF, available from FEH Web Service).

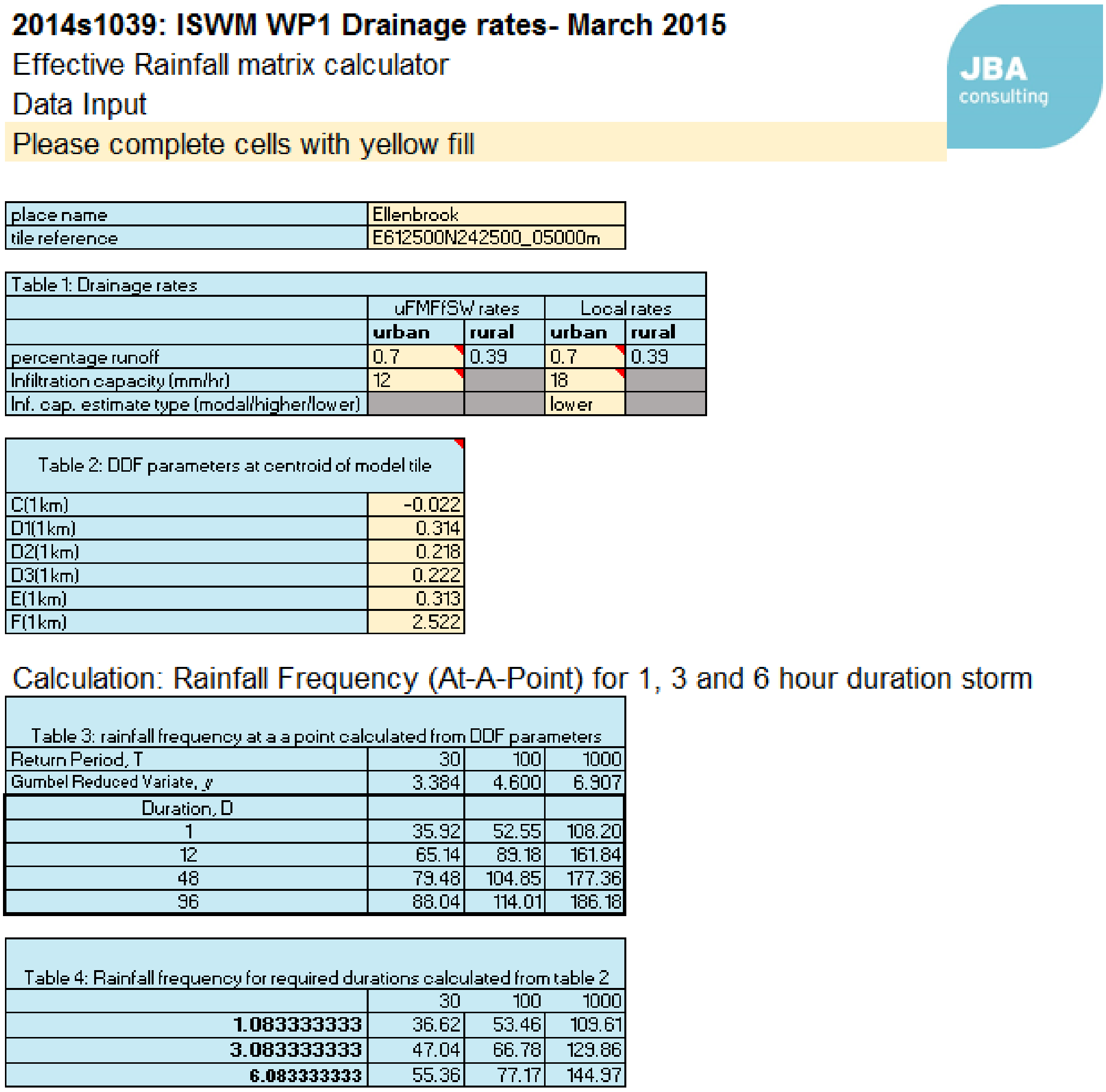
The rainfall calculator spreadsheet uses the FEH99 DDF parameters to calculate design rainfall profiles.

Enter the national drainage rates in the ‘uFMfSW rates’ cells in Table 1 of the spreadsheet (Figure D.1). This value is most likely to be 12mm per hour but could be 6mm per hour or 20mm per hour where areas were identified as having low or high drainage rates respectively when the uFMfSW was created. The local drainage rates are entered in the ‘local rates’ cells in Table 1. The infiltration capacity is the local value calculated using the Monte Carlo analysis spreadsheet (see Appendix C).

Enter the DDF parameters for the centroid of the model tile in Table 2 of the input box (Figure D.2). These must be accessed from the FEH Web Service. If the model area spans more than one tile and approximates a river catchment, calculate average DDF parameters for the model area. The cells that users need to fill in are highlighted with yellow fill.

The summer profile is calculated for the 30, 100 and 1,000 year exceedance probability events with 1, 3 and 6 hour durations. The net rainfall is calculated for the national and local drainage rates entered in the input box; the calculations for the 30 year event with national drainage rates are shown in Figure D.2c.

The output box (Figure D.**3**) shows the rainfall matrices, which contain the total net rainfall volume for each of the 9 modelled events using the national drainage rates and the local drainage rates. The proxy analysis described in Section 4.2.1 is applied by pressing the ‘Proxy analysis’ button to identify whether any of the existing uFMfSW maps can be reused as proxies for the local drainage rate scenarios. Different thresholds can be set for the percentage difference between the rainfall volumes and for the value beneath which manual assessment should be carried out (see sensitivity analysis in Section 4.2.1). The existing uFMfSW rainfall events that are identified by the spreadsheet tool as potential proxies are given in the output matrix (Figure D.**3**).



2014s1039: ISWM WP1 Drainage rates- March 2015

Effective Rainfall matrix calculator

Data Input

Please complete cells with yellow fill

place name	Ellenbrook
tile reference	E612500N242500_05000m

Table 1: Drainage rates				
	uFMFfSW rates		Local rates	
	urban	**rural**	**urban**	**rural**
percentage runoff	0.7	0.39	0.7	0.39
Infiltration capacity (mm/hr)	12		18	
Inf. cap. estimate type (modal/higher/lower)			lower	

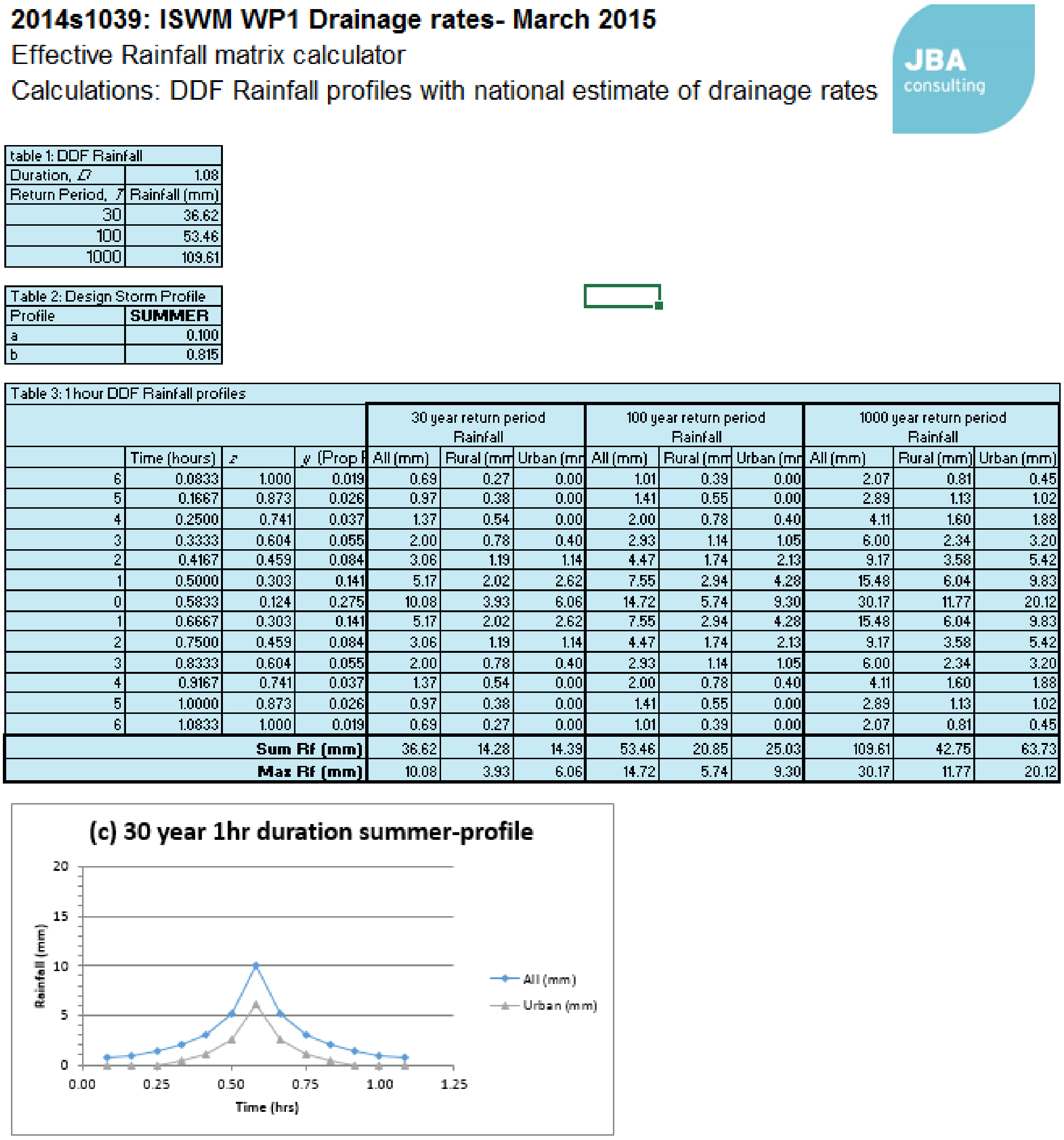
Table 2: DDF parameters at centroid of model tile	
C(1km)	-0.022
D1(1km)	0.314
D2(1km)	0.218
D3(1km)	0.222
E(1km)	0.313
F(1km)	2.522

Calculation: Rainfall Frequency (At-A-Point) for 1, 3 and 6 hour duration storm

Table 3: rainfall frequency at a a point calculated from DDF parameters			
Return Period, T	30	100	1000
Gumbel Reduced Variate, *y*	3.384	4.600	6.907
Duration, D			
1	35.92	52.55	108.20
12	65.14	89.18	161.84
48	79.48	104.85	177.36
96	88.04	114.01	186.18

Table 4: Rainfall frequency for required durations calculated from table 2			
	30	100	1000
1.083333333	36.62	53.46	109.61
3.083333333	47.04	66.78	129.86
6.083333333	55.36	77.17	144.97

Figure D.1 Example of rainfall calculator spreadsheet input box



2014s1039: ISWM WP1 Drainage rates- March 2015

Effective Rainfall matrix calculator

Calculations: DDF Rainfall profiles with national estimate of drainage rates

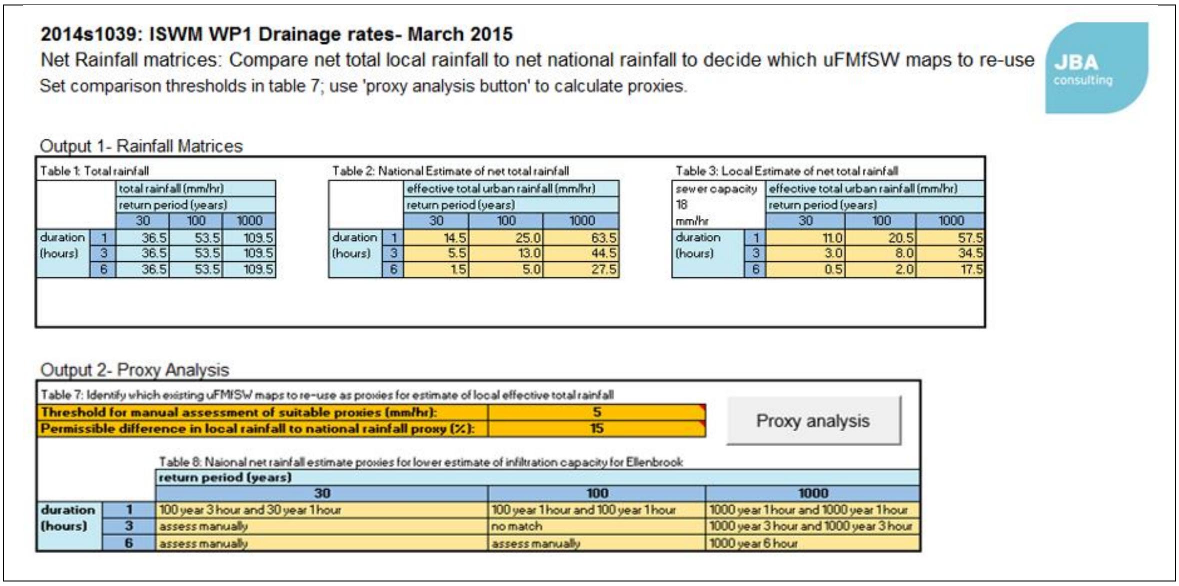
table 1: DDF Rainfall	
Duration, *D*	1.08
Return Period, *T*	Rainfall (mm)
30	36.62
100	53.46
1000	109.61

Table 2: Design Storm Profile	
Profile	**SUMMER**
a	0.100
b	0.815

Table 3: 1 hour DDF Rainfall profiles

				30 year return period Rainfall			100 year return period Rainfall			1000 year return period Rainfall		
	Time (hours)	*z*	*y* (Prop R	All (mm)	Rural (mm	Urban (mm	All (mm)	Rural (mm	Urban (mm	All (mm)	Rural (mm)	Urban (mm)
6	0.0833	1.000	0.019	0.69	0.27	0.00	1.01	0.39	0.00	2.07	0.81	0.45
5	0.1667	0.873	0.026	0.97	0.38	0.00	1.41	0.55	0.00	2.89	1.13	1.02
4	0.2500	0.741	0.037	1.37	0.54	0.00	2.00	0.78	0.40	4.11	1.60	1.88
3	0.3333	0.604	0.055	2.00	0.78	0.40	2.93	1.14	1.05	6.00	2.34	3.20
2	0.4167	0.459	0.084	3.06	1.19	1.14	4.47	1.74	2.13	9.17	3.58	5.42
1	0.5000	0.303	0.141	5.17	2.02	2.62	7.55	2.94	4.28	15.48	6.04	9.83
0	0.5833	0.124	0.275	10.08	3.93	6.06	14.72	5.74	9.30	30.17	11.77	20.12
1	0.6667	0.303	0.141	5.17	2.02	2.62	7.55	2.94	4.28	15.48	6.04	9.83
2	0.7500	0.459	0.084	3.06	1.19	1.14	4.47	1.74	2.13	9.17	3.58	5.42
3	0.8333	0.604	0.055	2.00	0.78	0.40	2.93	1.14	1.05	6.00	2.34	3.20
4	0.9167	0.741	0.037	1.37	0.54	0.00	2.00	0.78	0.40	4.11	1.60	1.88
5	1.0000	0.873	0.026	0.97	0.38	0.00	1.41	0.55	0.00	2.89	1.13	1.02
6	1.0833	1.000	0.019	0.69	0.27	0.00	1.01	0.39	0.00	2.07	0.81	0.45
			Sum Rf (mm)	36.62	14.28	14.39	53.46	20.85	25.03	109.61	42.75	63.73
			Max Rf (mm)	10.08	3.93	6.06	14.72	5.74	9.30	30.17	11.77	20.12

Figure D.2 Example of rainfall calculator spreadsheet calculations box



2014s1039: ISWM WP1 Drainage rates- March 2015

Net Rainfall matrices: Compare net total local rainfall to net national rainfall to decide which uFMfSW maps to re-use

Set comparison thresholds in table 7; use 'proxy analysis button' to calculate proxies.

Output 1- Rainfall Matrices

Table 1: Total rainfall

		total rainfall (mm/hr)		
		return period (years)		
		30	100	1000
duration (hours)	1	36.5	53.5	109.5
	3	36.5	53.5	109.5
	6	36.5	53.5	109.5

Table 2: National Estimate of net total rainfall

		effective total urban rainfall (mm/hr)		
		return period (years)		
		30	100	1000
duration (hours)	1	14.5	25.0	63.5
	3	5.5	13.0	44.5
	6	1.5	5.0	27.5

Table 3: Local Estimate of net total rainfall

sewer capacity 18 mm/hr		effective total urban rainfall (mm/hr)		
		return period (years)		
		30	100	1000
duration (hours)	1	11.0	20.5	57.5
	3	3.0	8.0	34.5
	6	0.5	2.0	17.5

Output 2- Proxy Analysis

Table 7: Identify which existing uFMfSW maps to re-use as proxies for estimate of local effective total rainfall

Threshold for manual assessment of suitable proxies (mm/hr):	5
Permissible difference in local rainfall to national rainfall proxy (%):	15

Table 8: Naional net rainfall estimate proxies for lower estimate of infiltration capacity for Ellenbrook

		return period (years)		
		30	**100**	**1000**
duration (hours)	**1**	100 year 3 hour and 30 year 1 hour	100 year 1 hour and 100 year 1 hour	1000 year 1 hour and 1000 year 1 hour
	3	assess manually	no match	1000 year 3 hour and 1000 year 3 hour
	6	assess manually	assess manually	1000 year 6 hour

Figure D.3 Example of rainfall calculator spreadsheet output box

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