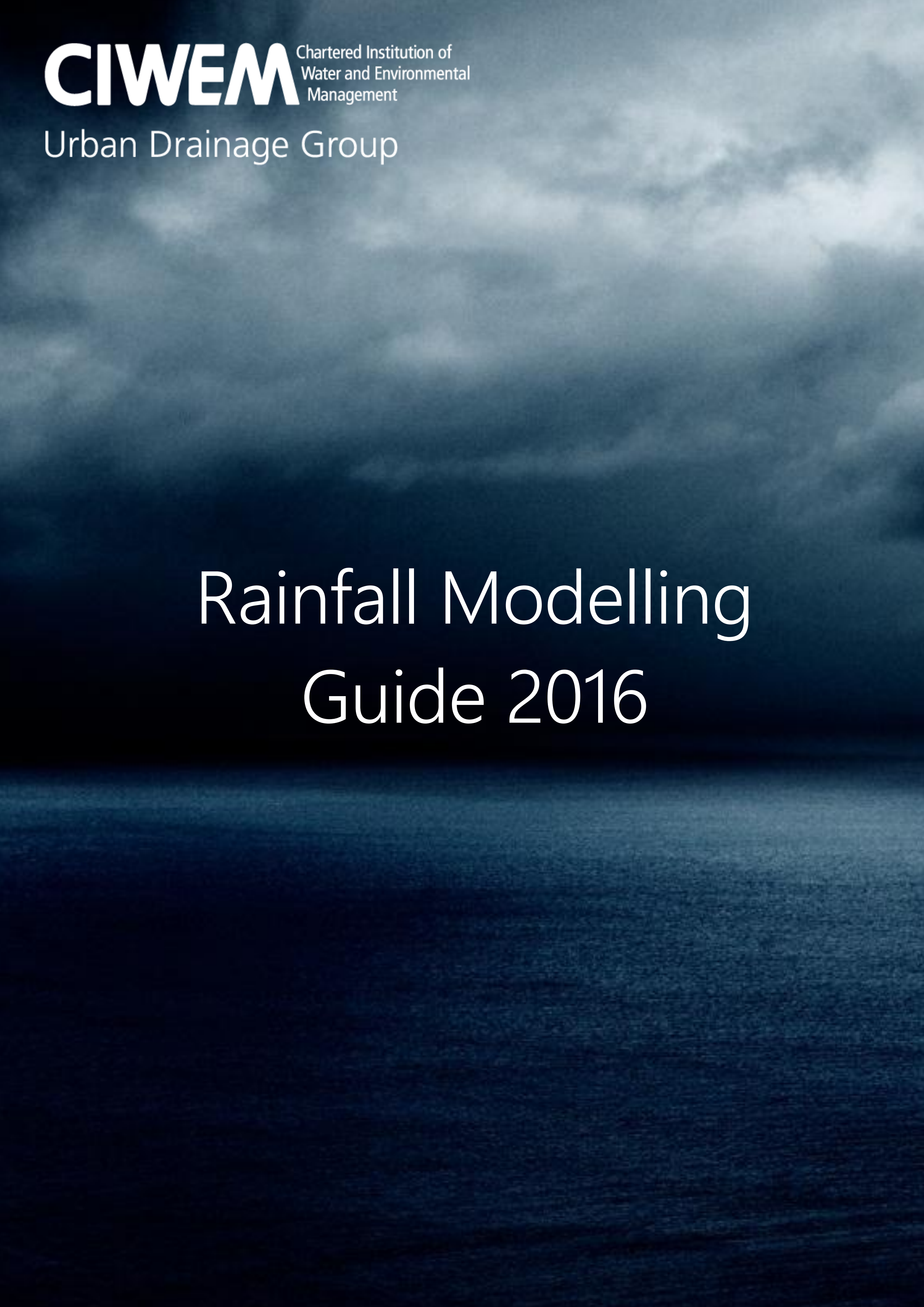

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Technical enquiries

All technical enquiries and suggestions relating to this publication should be addressed to the Urban Drainage Group mailbox: UDG@CIWEM.org. CIWEM welcomes any comments on this document.

This publication has been checked by the editor members of the CIWEM UDG Committee for major errors. However, this publication does not necessarily represent the views of the CIWEM UDG Committee. It is issued for guidance in good faith but without accepting responsibility for its content.

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Cover image: A lone yacht in a storm by Douglas Kurn, courtesy of Atkins CIWEM Environmental Photographer of the Year Competition

Image courtesy of Susdrain

Contents

1. INTRODUCTION

Rainfall is an important element in the hydraulic modelling of Urban Drainage Systems, as it directly contributes to runoff. Hence any inaccuracies caused by poor measurement or inappropriate use of rainfall data will have a direct consequence on the outputs from the hydraulic modelling process.

It is the intention of this good practice guide to provide to the Urban Drainage practitioner a summary of current good practice in the UK industry. This will of course be a snapshot of the current available methods and processes.

The guide has been split into three main sections, being:

- Modelling of rainfall for model verification
- Modelling of rainfall in design – design storms and long-time series
- Modelling climate change effects.

Although included in a separate section, the effect of climate change is an integral aspect of the use of rainfall in design.

The guide is specifically written to cover the rainfall aspects of hydraulic modelling, and associated parameters such as antecedent conditions and evapotranspiration. It is not intended to cover any other aspect of the hydraulic modelling process.

The main emphasis of the guide is related to the requirements for the modelling of wastewater and storm water networks, rather than the modelling of large watercourses.

1.1 Rainfall Data Sources

Rainfall data is generally collected by the use of raingauges or by the use of weather radar.

1.1.1 Raingauges

Raingauges measure the temporal variation in rainfall at specific locations where the raingauge is sited. Although there are a number of different types of measurement device available, including tipping bucket gauges, piezoelectric sensor plate drop counters, weighing gauges and weather stations, it is the tipping bucket variety that are most commonly utilised. This is due to their generally low cost and reliability. There are a number of daily measuring raingauges also available.

A typical tipping bucket raingauge is constructed from a plastic cylinder with a funnel at the top that routes rainfall on to two buckets that rotate over a central pivot. The volume of the buckets is generally sized to correspond to a rainfall depth of 0.2mm over the plan area of the funnel. There are two buckets so that as one fills and tips, the second one takes its position and continues to collect rainfall and vice-versa. Data is recorded electronically for the time of each tip, which allows the temporal variance in intensity to be calculated.

The tip data is then converted to an average intensity expressed in units of mm/hr within any time period that the data is required. This is generally a 2 minute period for short-term flow surveys, and can be up to 15 minutes for long term data.

It is possible to reduce both the timestep and bucket volume to increase the precision of the data, but two minute timestep data with a 0.2mm volume is considered to provide sufficiently accurate data for urban drainage purposes, given the error in the actual measurements, within flow monitor data and within the hydraulic models themselves. If the timing of each tip is collected, the rainfall intensity can be re-calculated for any timestep required. In a number of cases data can be collected in real time by the use of telemetry.

In the UK, the Met Office and partner organisations, including the Environment Agency (EA), Natural Resources Wales and the Scottish Environment Protection Agency (SEPA) have a network of around 1000 quality controlled tipping bucket raingauges.

Raingauges have the great advantage of providing a direct measurement of rainfall close to the ground. However, raingauge measurements can contain errors arising from a variety of sources. Systematic errors common to all raingauges include errors due to wind field deformation above the gauge orifice, errors due to wetting loss in the internal walls of the collector, errors due to evaporation from the container and errors due to in- and out-splashing of water. In addition, tipping bucket raingauges can underestimate rainfall at higher intensities because of the rainwater amount that is lost during the tipping movement of the bucket.

1.1.2 Weather Radar

Weather radars send out electromagnetic pulses to measure the location and intensity of precipitation, including rain, hail and snow, in real time.

The radar sends out a signal and measures the time and magnitude of a return signal from hydrometeors in the atmosphere. Depending on the frequency at which they radiate, weather radars can be of three main types (from lower to higher frequency): S-band, C-band and X-band. Lower frequency radars require larger dishes to achieve a small radar beam width, which ultimately determines the spatial resolution at which rainfall is measured. As such, S-band radars require the largest dishes and are therefore the biggest and most expensive type of weather radar, whereas X-band radars are the smallest and cheapest. Lower frequency radars are more powerful, and hence they can survey larger areas and are less susceptible to attenuation. Consequently lower frequency S-band radars tend to be used in tropical areas prone to very intense precipitation. C-band radars represent a good balance between power, size and cost, and are widely used in Europe. X-band radars tend to be used to monitor small mountainous and urban areas or for portable applications such as sporting events or research. X-band radars attenuate significantly in heavy rainfall.

The magnitude of the reflected signal is related to the intensity of precipitation, and the timing of the return gives the location. The radars commonly used by national meteorological services (C-band in the case of the UK) complete several scans every 5 minutes. Each scan is at a different predetermined angle to the horizontal. The surface precipitation rate is derived mainly from reflectivity data from the lowest elevation scan. Higher elevation scans are used where the lowest scan may be partially/totally blocked by surrounding topography, vegetation or manmade obstacles.

Weather radars observe rain, hail and snow, but drizzle can be more difficult to detect because the droplets are very small.

The UK and Ireland weather radar network operates continuously and at the time of writing the guide is composed of a total of 18 C-Band radars, of which 15 are operated and maintained by the Met Office. A composite data set is available from all the weather radars, at a timestep of 5 minutes and a resolution of 1km square. Intensity values are an average rainfall intensity over the 1 km square. Data is generally more accurate the closer the location is to the radar station.

This data undergoes a number of processing steps to correct for known sources of error in radar data (e.g. removal of spurious echoes or reflections from hills and building, removal of echoes caused by snow and hail melting to rain, and removal of anomalous propagation (anaprop) due to temperature inversion). This post processing is not guaranteed to remove all spurious echoes.

The calibration includes use of a number of local meteorological models and calibration from local real time raingauges. However this calibration is limited by the number of raingauges that can be used.

There are a number of advantages in using radar rainfall, the main ones being:

- Good spatial definition of rainfall at 1km grids
- Ability to track the spatial variation of rainfall across a catchment.
- Data available at individual catchment level, rather than limited to raingauge locations
- Data is available in near real time
- Data can therefore be used operationally in real time situations.
- Cheaper and less disruptive than installation of a high density raingauge grid on larger catchments.
- Since radars can survey large areas and capture the spatial-temporal variability of rainfall fields, they enable storm tracking and short-term rainfall forecasting based upon extrapolation of storm movement (i.e. nowcasting), which is not possible based upon raingauge measurements.

Instead of being a direct measurement, radar rainfall intensity is derived indirectly from measured radar reflectivity, often measured well above the ground. As a result, both radar reflectivity measurements and the reflectivity-intensity conversion process are subject to multiple sources of error, such as the following:

- Radar beam above the precipitation at long ranges. This would cause an under-prediction of rainfall values.
- Evaporation of rainfall at lower levels beneath the beam, if the rain falls through dry air before reaching the ground. This would result in an over-prediction of rainfall values.
- Orographic enhancement of rainfall at low levels. The rather light precipitation which is generated in layers of medium-level frontal cloud can increase in intensity by sweeping up other small droplets as it falls through moist, cloudy layers at low levels. This is particularly common over hills. This results in the radar under-reading actual rainfall.

These can cause both under and over reading of rainfall.

2. RAINFALL REQUIREMENTS FOR HYDRAULIC MODEL VERIFICATION

2.1 Introduction

The verification of hydraulic models is of fundamental importance to improve confidence in model predicted outputs. This is generally carried out by the use of short-term flow surveys, and historical verification against existing long-term monitoring or actual recorded incidents in the catchment.

This chapter provides details on current good practice for the collection of rainfall data through raingauge and radar techniques, data checking and analysis and application to hydraulic models.

Details are also provided on the strengths and limitations of raingauge and radar methods and an introduction to current research into addressing these limitations in the future.

2.2 Short-Term Flow Surveys

Historically short term flow surveys have generally been carried out to achieve three suitable rainfall events for verification purposes, with suitability assessed by the catchment response and the variability of the rainfall between adjacent raingauges. More recently there has been a move to include the whole period of the flow survey in the verification process. The duration of the short term survey is not fixed, as it is dependent on the quality of data obtained and the type of rainfall events, but they are usually two or three months in duration.

2.2.1 Raingauges

Rainfall data collection is most often undertaken through the deployment of a network of raingauges across a study area.

As previously discussed in section 1.1.1, for the majority of applications data is presented as an average intensity expressed in units of mm/hr within a 2 minute period.

Individual Site Location

The two main requirements for an individual site are that it is not sheltered from the true rainfall pattern by overhanging trees or nearby structures and is secure from vandals. Flat roofs are often chosen as sites either within schools, at police stations or in industrial complexes with one storey buildings. Where such sites are not available alternatives include locked water company owned compounds (such as pumping station sites and sewage treatment plants) or private gardens. Where such sites are used, however, it is important to ensure that the raingauge is not overlooked. Therefore it is recommended that the distance from neighbouring objects should exceed the heights of the neighbouring structures.

Raingauge Density

Ideally, raingauges should be installed in a catchment in a rough grid pattern in order to maintain a similar distance between sites and the density of the gauging increased to account for changes in topography and to minimise spatial variation between raingauges. Realistically, the locations of the raingauges tend to be limited to available sites that meet the individual site requirements described above.

As a rule of thumb, it is recommended that the existing guidance in the CIWEM UDG Code of Practice for the Hydraulic Modelling of Sewers (3rd Edition) (2002) is still applied for planning flow surveys. This is detailed in table 2.1 below.

Type of Terrain	Typical Number of Gauges
Flat	1 + 1 per 4km^2
Average	1 + 1 per 2km^2
Mountainous	1 + 1 per 1km^2

Table 2.1: Recommended raingauge density

The raingauge density is driven by the likelihood of significant changes in rainfall across a catchment due to orographic effects, the potential for localised cells of rainfall in convective rainfall, and to limit the potential for large variations in rainfall in adjacent raingauges. If there is variable topography across a modelled catchment, there may be a need for different raingauge densities in parts of the catchment. There may also be a case for increasing the number of raingauges in summer surveys due to the increased potential for convective rainfall.

It is good practice to install a minimum of 3 raingauges regardless of the size of catchment, in order to provide 2 gauges for measurements with the third operating as a backup should failure occur at one of the sites.

It should be noted that the number of raingauges required is driven by the area and type of catchment, not by the number of flow monitors. This may mean on some strategic modelling programmes there will be a need for more raingauges than flow monitors.

In large catchments even the minimum requirements for a flat catchment may not be possible to achieve due to the availability of sites and the cost of using a large number of raingauges. In these situations rainfall radar data can be used to supplement the raingauge network.

2.2.2 Radar Data

Radar data has been extensively used in meteorology and fluvial hydrology for decades. However it is only recently that it has been used more extensively in urban drainage modelling. The lack of use has been down to concerns about accuracy of data, issues with the cost of obtaining the data, the early spatial resolution of radar data to a 4 km^2 grid, and historically it has been easier to find suitable raingauge sites than is presently the case.

As detailed in section 1.1 the situation has improved in recent years. A number of water service companies now have access to close to real time data for their region, and radar resolution is now available as standard up to 1km^2 at a timestep of 5 minutes.

When using radar data for model verification purposes in short term flow surveys, the following issues should be taken into consideration:-

- As the data comes from one source, if the local radar is down for any reason all data will be lost. Checks should be made on the potential for any planned routine maintenance of the radar station during the period of the flow survey.
- As mentioned above, the accuracy of radar rainfall estimates may be poor and inconsistent due to the indirect nature of the estimates. The radar data will have been calibrated against raingauges which may be a considerable distance from the catchment being surveyed. As such it is good practice to include some raingauges in the catchment to be used for checking of the radar data, and as a possible back up if the radar data is lost for any reason.

2.2.3 Ongoing Radar Related Research Projects

There is significant ongoing research looking at improvements in both accuracy and spatial resolution of radar data. One such project is the RAINGAIN project (www.raingain.eu), an EU funded project with input from thirteen partner organisations from 4 countries in North-West Europe. UK partners include Imperial College London, the Met Office and the Local Government Information Unit.

The RainGain project has sought to obtain detailed rainfall data at an urban scale, to use these data to analyse and predict urban flooding and to implement the use of rainfall and flood data in urban water management practice to make cities more resilient to local rainfall-induced floods.

The main areas of work in the project have been:

- Testing of C-band and X-band radar technologies to obtain higher resolution rainfall estimates for cities, including associated costs and feasibility of obtaining such estimates;
- New techniques for further improving the accuracy and applicability of radar rainfall estimates, through combination with raingauge data and through temporal interpolation of radar images;
- Testing of high resolution models for simulation and forecasting of urban pluvial flooding;
- An investigation on governance and use of technology to improve place-based flood resilience.

2.2.4 Use of Both Raingauge and Radar Data

With the increased availability of radar data, and particularly where the data has already been purchased for other purposes, even if it is not intended to use the radar data directly for verification purposes, it may prove beneficial to still use the radar data.

The key advantage to the use of radar rainfall data in verification is increased accuracy of the spatial variation represented. Examination of the radar data may prove beneficial in the assignment of sub-catchments to raingauges, and also in the assessment of suitability of individual events for verification purposes if there is significant variance in rainfall totals between gauges.

By dynamically adjusting radar rainfall estimates based upon local raingauge records it is possible to combine the advantages and overcome the disadvantages of the two sensors, by retaining the accuracy of the point rainfall information provided by raingauges and at the same time retaining the broader description of the spatial and temporal variations of rain fields provided by radar. (Ochoa-Rodriguez et al, 2013; Wang et al, 2013; Wang et al, 2015).

2.2.5 Assessment of Suitability of Rainfall Data Collected for use in Verification

The key factors relating to the suitability of rainfall data collected for verification purposes are:

- There should have been enough rain to wet the catchment sufficiently so that initial losses are not a significant part of runoff.
- If raingauges are used, a comparison between the rainfall measured at each of the raingauges should be sufficiently consistent so that the rainfall at any point in the catchment can be determined by interpolation.
- The absence of lying snow during the rainfall event as the flow survey results may be affected by snow melt.
- There should be some variability of the duration and intensity of rainfall in the events in order that the model can be verified over as wide a range of rainfall types as possible.
- There should be sufficient periods in the duration of the flow survey when the catchment has returned to dry weather flow conditions.

It is becoming more common to carry out verification over the whole of the flow survey period, using continuous simulation techniques, rather than verifying the model over individual events. However the full period data will have identifiable rainfall events within it. Hence the guidance is still written on an individual event basis.

An event is defined as the period between dry weather flow conditions, and the return to dry weather flow conditions after the rainfall. In catchments where there is a significant period of slow response runoff after rainfall, or the rainfall results in an elevated base flow the event definition could be amended to end at the time that the fast response runoff has ended. For the assessment of rainfall depth and duration within the event, this shall be measured from the time of the first rainfall at any gauge or radar square, to the time of the last rainfall in any gauge or radar square.

As response to rainfall varies by catchment, the use of minimum recommended values for rainfall totals, event durations and variability can lead to satisfactory rainfall events being discarded and alternatively unsatisfactory rainfall events being accepted. These are therefore not included in the guide. Instead the suitability of rainfall for verification purposes should be assessed by an experienced practitioner taking account of the key factors above.

Where one raingauge is obviously faulty, the data should be discounted.

A minimum of three suitable events is considered satisfactory. However this will also need to take into account the suitability of the catchment response to the rainfall.

If verification for specific issues is required, e.g. CSO spill and flooding, far higher rainfall intensities may be required than would normally be used for general verification work. If slow response runoff is considered to be an issue then longer duration rainfall with higher rainfall depth may be required.

2.3 Verification against Historical Data

Historical data can take various forms. However in most cases available historical data will be some form of long term monitoring, (for example continuous flow measurement data at treatment works, depth monitors at CSOs and pumping stations, spill recorders etc.) or historical flooding records.

2.3.1 Verification using Long-term Monitoring

Short term flow surveys can only be used to verify the antecedent conditions at the time of the flow survey. Hence summer flow surveys will tend to have less infiltration and slow response runoff, with winter surveys having higher values. However this is not always the case, and there can be exceptionally dry winters and very wet summers. A model verified during a wet winter will in most instances generate more permeable runoff in use than a model verified in a dry winter. For that reason, short term flow surveys are more effective in verifying the fast response from impermeable areas.

Improvements can be made in the model by carrying out verification against long term data in the catchment, as due to the long term nature of the records, the data will cover various antecedent conditions. However it is unlikely that a high density of raingauges will be available for the verification period.

Available options for rainfall measurements will generally be the use of historical raingauge data from one or more of the permanent quality controlled network of raingauges, or the use of weather radar data if the dataset extends for a long enough period. Due to the need for a comparison of modelled performance with observed measured data it is not possible to use stochastically generated rainfall for this purpose.

The main disadvantages of using historical raingauge data are the spacing and location of raingauges. It is likely that the historical verification will only use one raingauge, or in very large catchments two or three, which may not necessarily be in the urban area being verified, and could be located in an elevated position in relation to the urban area. This needs to be taken into account when comparing model performance with observed data.

The use of historical raingauge data is discussed further in Section 4 of the guide.

A rainfall series could be developed using weather radar for this comparison if a long enough record is available. This will allow more spatial variability and the use of catchment specific data. Comparisons of the radar data with raingauge data will be limited to the historically available data from the permanent raingauge network.

2.3.2 Verification against Flooding Records

There are two possible methods for verification against flooding records. If the exact time and date of a flooding occurrence is known, the individual event can be analysed. Rainfall data available would be the same as detailed in section 2.3.1.

If information is known on the frequency of flooding, then a general assessment can be made using design storms or a rainfall time series. These are considered in detail in sections 3 and 4 of the guide.

2.4 Application to Hydraulic Models

Where raingauge data or radar data is being utilised, there is a need to assign the relevant rainfall to individual runoff surfaces (sub-catchments) in the model. Where radar data is being utilised, rainfall data is an average over the grid square of the rainfall. Hence assignment of the rainfall will be to those surfaces in the rainfall grid.

Where raingauge data is used, as these are point locations, there has been no averaging of rainfall values. The simplest method to assign rainfall to a runoff surface (sub-catchment) is to use the data from the gauge at closest proximity to the centroid of that sub-catchment. This is normally calculated by using the Thiessen polygon approach, but some software will do this automatically.

However this process does not take into account variations in catchment topography, and spatial variation between the gauges. Hence there may be instances where the rainfall at the closest raingauge to a sub-catchment is unlikely to be representative of the rainfall actually falling at that location. In situations like this, then the allocation of raingauges should be amended.

There are a number of interpolation techniques, such as Kriging or inverse distance weighting, which will lead to improved rainfall distribution. These interpolation techniques enable the creation of a grid of raingauge-based rainfall estimates, which better represents rainfall variability across the catchment, based upon known values at point locations. Once a spatial grid of gauge-based rainfall estimates is obtained, it can be applied to subcatchments in the same way as radar data.

2.5 Antecedent Conditions

Information on antecedent rainfall and in some cases soil moisture data is required to ensure that the catchment wetness conditions are correctly modelled. In addition evapotranspiration will need to be included in the modelling.

Evaporation and Soil Moisture information is available from the Met Office MORECS data.

MORECS is an acronym for the Meteorological Office Rainfall and Evaporation Calculation System. It uses daily meteorological data to produce amongst other things estimates of evapotranspiration and soil moisture deficit (SMD) for each square of a 40 × 40 km grid superimposed upon Great Britain. Grid square estimates of meteorological data are found using interpolation methods. A modified version of the Penman—Monteith equation is used to calculate evapotranspiration; a two-reservoir model is used to simulate the extraction of water in the SMD calculations.

2.5.1 Antecedent Rainfall

Dependent on the type of runoff model used in the model, antecedent rainfall data will be required for up to 30 days prior to the first rainfall event, to allow initial catchment wetness parameters to be calculated.

For short term flow surveys, actual rainfall data will be required for this period. If using raingauges for the rainfall, this can be obtained by the following methods:

- Deployment of all raingauges 30 days prior to the commencement of flow monitoring.
- Use of radar rainfall data to provide rainfall data 30 days prior to commencement of flow monitoring
- Deployment of a limited number of raingauges 30 days prior to commencement to gain an understanding of average rainfall.
- Use of permanent raingauge data if a suitable location is available.

If radar data is being used for the flow survey, this should be collected for the 30 day period prior to the flow survey. For verification against historic data, the processes outlined in sections 3 and 4 of the guide should be used.

2.5.2 Soil Moisture Deficit (SMD)

SMD data is used in the Standard Wallingford Runoff model. The data is available as an average figure for a 40 x 40 km grid, on a daily, weekly or monthly average. The grid is relatively coarse, with average rainfall data being used in the calculations, some of which is an interpolation of rainfall from gauges up to 100km away from the grid. If the SMD is known at the commencement of the survey period, it is possible to calculate the SMD using the site specific rainfall data. However in most instances the use of the standard MORECS data will be sufficient for the verification process.

A newer alternative dataset at a finer resolution is available from the Met Office Surface Exchanges Scheme (MOSES) system.

2.5.3 Evapotranspiration

Evapotranspiration is the sum of water transferred to the atmosphere by evaporation from wet surfaces and transpiration from vegetation. The impact of evaporation is a net reduction in runoff and a drying out of depression storage.

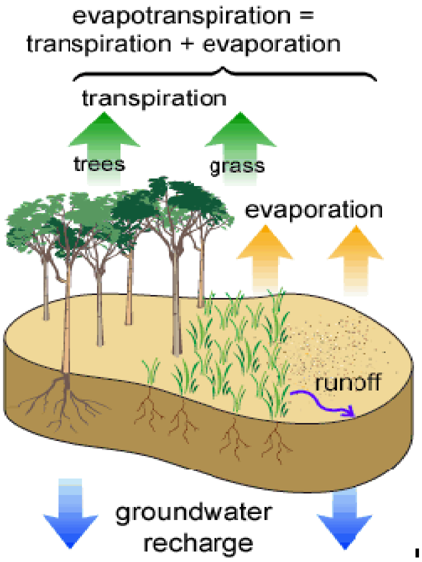

Figure 2.1 Evapotranspiration (Image by Mwtoews, GFDL).

There are two parameters, Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET). Figures are given in mm/day for both parameters. PET is the amount of evapotranspiration there would be if there was no limit to the amount of water available to evaporate, and AET takes account of the limited availability of soil moisture.

It is normal in modelling to use PET values. These typically range between 0mm/day in winter to 3mm and above in summer. Values of PET tend to be higher in the south of the UK, going progressively lower the further north. However the variation is not large. For short term flow surveys, the MORECS PET data should be used for the relevant grid square. For checks against historical data the relevant processes outlined in sections 3 and 4 should be used.

3. USE OF RAINFALL IN DESIGN – DESIGN STORMS

3.1 Design Storm Overview

A design storm is an artificial rainfall event whose total rainfall depth has a specified return period.

As well as the depth of rainfall, it is necessary to specify the duration of the storm, its time profile (known as a hyetograph) and its spatial pattern. These are generally set to simplified average values, often with the aim of ensuring that the runoff generated from modelling the design storm has a similar return period to that of the rainfall depth.

Design storms represent the statistical characteristics of rainfall derived from analysis of many years of actual rainfall records. They are easier to use than observed rainfall and can approximate a catchment's rainfall in just a few storms. In sewer modelling these storms may be used for peak flow, surcharge and flooding analysis and for the development of flooding solutions and peak screening rates for CSOs.

3.1.1 FEH and FSR rainfall

Design storms are typically generated for return periods of 6 months to 100 years for urban drainage applications, but may be generated for much higher return period events where required e.g. for reservoir design.

Two main methods have been used historically for the generation of design storms:

- Flood Studies Report (FSR)
- Flood Estimation Handbook (FEH)

Flood Studies Report (FSR)

The Flood Studies Report was published in 1975 and was primarily intended for use with major river catchments rather than small urban catchments. Between 1977 and 1988 a total of 18 Supplementary Reports (FSSR's) were produced. The methods included in the Flood Studies Report were adapted for other purposes, in 1978 for Reservoir safety, in 1979 for urbanised catchments and it was not until 1981 when it was adapted for use in storm sewer design. The original research was based on 96,000 years of daily raingauge data and 2300 years of hourly raingauge data.

The FSR method for determining design storms was incorporated into the Wallingford Procedure and was then built into hydrological simulation programs.

There has always been some criticism of the Flood Studies Report that it was too over-generalised, that it did not take sufficient account of local features and that important local or regional variations were masked. In spite of these problems the methods used and embodied within the mainstream simulation programs were widely used for storms with return periods of less than 1 year to over 100 years. Although the use of the FSR has been superseded by the Flood Estimation Handbook, it is still used in some circumstances.

Flood Estimation Handbook (FEH)

The Flood Estimation Handbook (FEH; Institute of Hydrology, 1999) amongst other things provides design storm data for both point locations and river catchments throughout the UK. The FEH design rainfall depths are provided by a model of depth-duration-frequency (a DDF model). Design rainfall depths from the FEH cover a range of durations from 1 hour up to 8 days. The range of return periods extends up to 1,000 years or longer.

The preparation of the Flood Estimation Handbook was undertaken between 1994 and 1999 and was based on a far more extensive data set than was available for the Flood Studies Report including 6106 daily raingauges and 375 hourly raingauges. The amount of hourly data available at 7389 station years was over 3 times that available for the FSR.

Although FEH rainfall statistics can be extended to storm durations as short as half an hour, for shorter durations the FEH recommended reversion to rainfall statistics from the Flood Studies Report (FSR; NERC, 1975). As part of the research work on the development of FEH13, a recent pilot study (Prosdocimi et al, 2014) of short duration extreme rainfall has found that the FEH (1999) rainfall frequency model gives less biased results than the FSR statistics when applied at sub-hourly durations. This finding was based on analysis of data from 19 raingauges across England and Wales. The study aimed to examine the feasibility of extending the FEH rainfall statistics to shorter durations, as part of the Environment Agency's project, “Estimating flood peaks and hydrographs for small catchments”. In the light of these findings, it is recommended that there is now no need to revert to FSR rainfall for short durations.

The FEH also provides guidance on storm durations and time profiles, which is identical to that given in the FSR.

FEH13 DDF Rainfall Model

There were concerns expressed by reservoir engineers over the apparent high rainfall estimates produced by the FEH DDF model when it was applied to return periods in excess of its recommended upper limit of 1,000 years. In many locations, the FEH model was giving 10,000-year estimates considerably higher than the Flood Studies Report (FSR) probable maximum precipitation (PMP), a parameter used in the calculation of the probable maximum flood as a statutory part of the spillway design procedure for major reservoirs.

A major research project was instigated by DEFRA / EA to develop a new statistical model of point rainfall DDF for the UK (Reservoir Safety – Long Return Period Rainfall, Project: FD2613). This was intended to replace both the FEH DDF model for extreme rainfall analysis and the then current guidance for spillway design that the FEH rainfall estimates should not entirely replace the old FSR estimates.

Data were available for over 6,500 daily raingauges (a slight increase in the number used in the FEH), and for 969 hourly gauges, which is more than twice the number used in the FEH.

Although the project aimed to develop an improved DDF model to replace the FEH model for the return periods relevant to reservoir flood risk assessment (that is return periods from 100 to 10,000 years), it was found that the final revised DDF model could be applied over the full range of return periods from 2 to over 10,000 years.

Subsequent work has refined the model and smoothed the results across the UK on a 1-km grid, and this now forms the FEH13 DDF rainfall model.

3.2 Generating Design rainfall

3.2.1 Urban Drainage Modelling Software

Design storms can typically be generated using modules provided in urban drainage models. Software packages need the user to provide values for the parameters that describe the rainfall statistics.

Figure 3.1 below outlines a typical sequence used to generate a set of design storms for a catchment, in this case using the FEH web service.

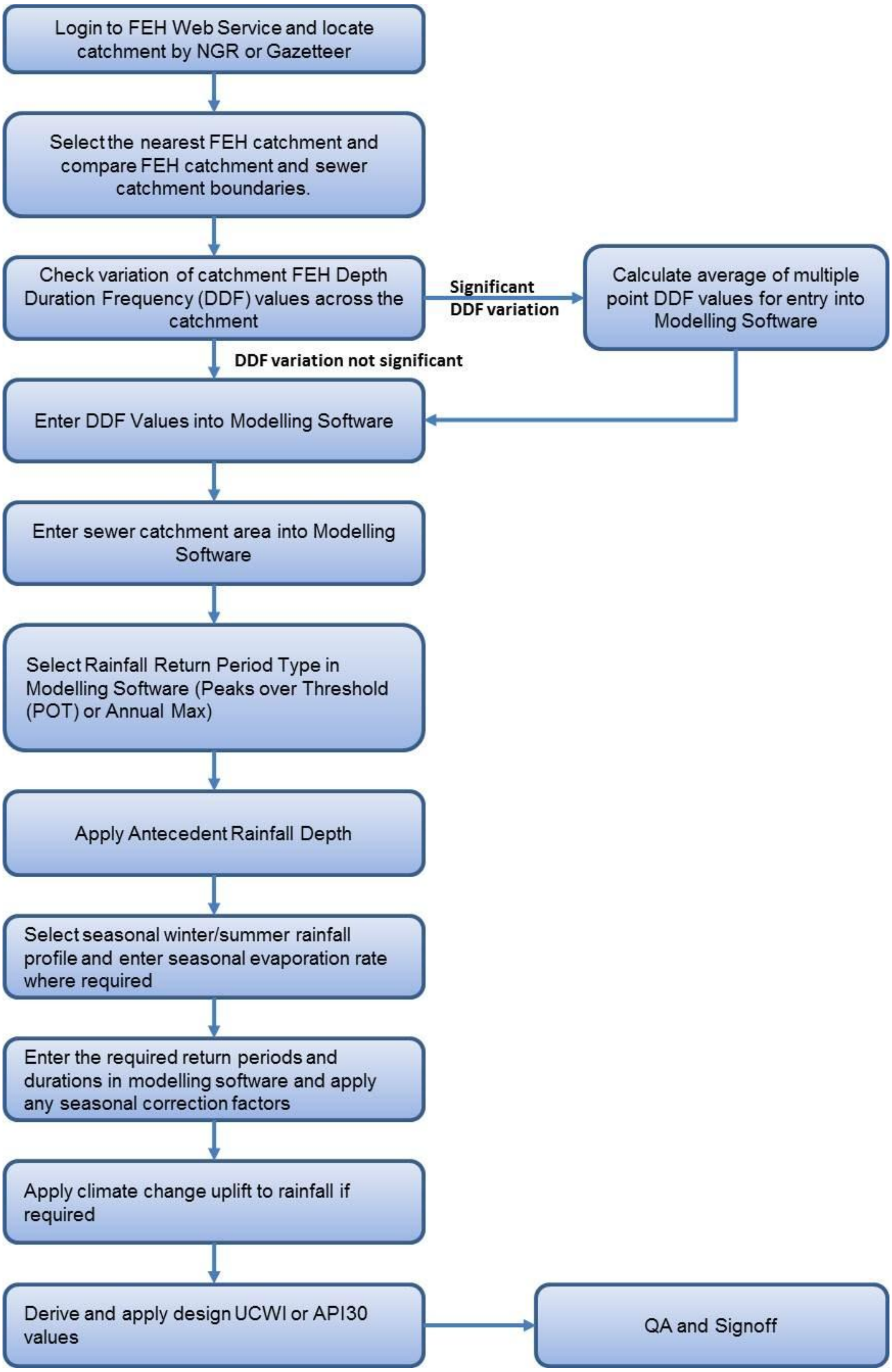

Figure 3.1: Typical Design Storm Generation Process (Courtesy of MWH)

3.2.2 FSR Rainfall

Design storms are generated using the FSR methods with just 3 variables:

- 2-day rainfall for a return period of 5 years (M5-2day rainfall),
- The ratio of the 60 minute rainfall for a return period of 5 years (M5-60 rainfall) to the M5-2day rainfall (r),
- The catchment area which applies the Areal Reduction Factor

Location is accounted for by the use of plans with the above data for the whole of the UK plotted on individual maps in the FSR. At best the above factors can be interpolated on these plans to one significant decimal place.

The Wallingford procedure uses the M5-60 value as the index which in conjunction with the rainfall ratio (r) is used to calculate the M5-2D value and generate a set of rainfall growth curves, detailed in figure 3.2, which may be used to derive rainfall depths for all return periods and durations.

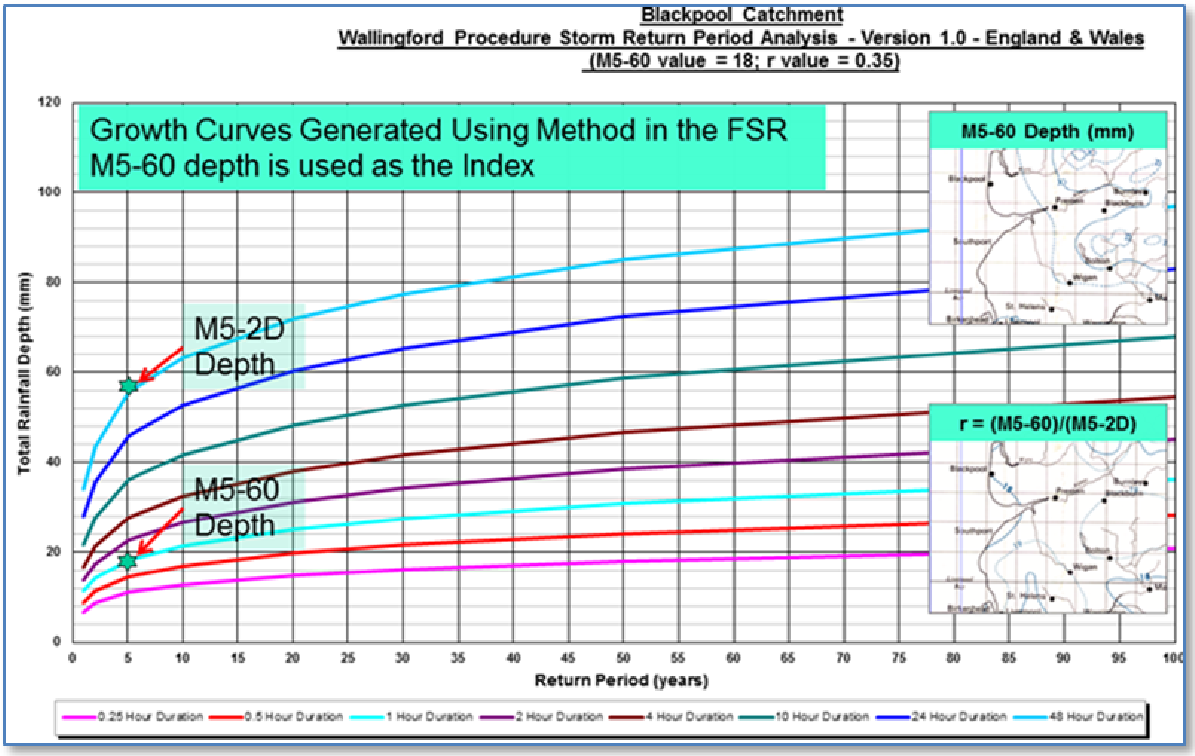

Figure 3.2: FSR Rainfall Growth Curves (Courtesy of MWH)

3.2.3 FEH Rainfall

FEH Depth Duration Frequency – DDF Models

As detailed in section3.1.1 there are now two FEH DDF Models, the original FEH model (FEH1999) and the FEH13 model. The FEH13 model is based on a larger dataset and more up-to-date analysis methods. However, at the time of writing it has just been released and it has not yet been evaluated for urban drainage modelling. Work is planned to extend it to cover rainfall durations shorter than 1 hour.

In many areas of England, FEH13 gives lower design rainfalls at short durations than FEH 1999. Results are higher than FEH 1999 in some areas such as parts of Cornwall, Hampshire and Lincolnshire. In much of Wales and Scotland FEH13 gives substantial increases in short-duration design rainfall.

In the FEH99 model the design rainfall depths are provided by a DDF model with six parameters. The model is represented in figure 3.3 below, which plots depth against duration, with several lines representing different frequencies (return periods). The six parameters d1, d2, d3, c, e and f control the slope and position of the lines on the DDF plot and their variation with return period. The parameters are defined in Volume 2 of the FEH.

In the FEH13 model the DDF model is represented by a family of gamma distributions, with 14 parameters in total.

The parameters of the FEH1999 model and the results of the FEH13 model have been evaluated at every point on a 1-km grid covering the UK, and as catchment averages for all natural catchments draining an area of at least 0.5 km2. These are provided in the FEH web based service together with software to calculate design rainfalls or estimate the return period of observed rainfalls.

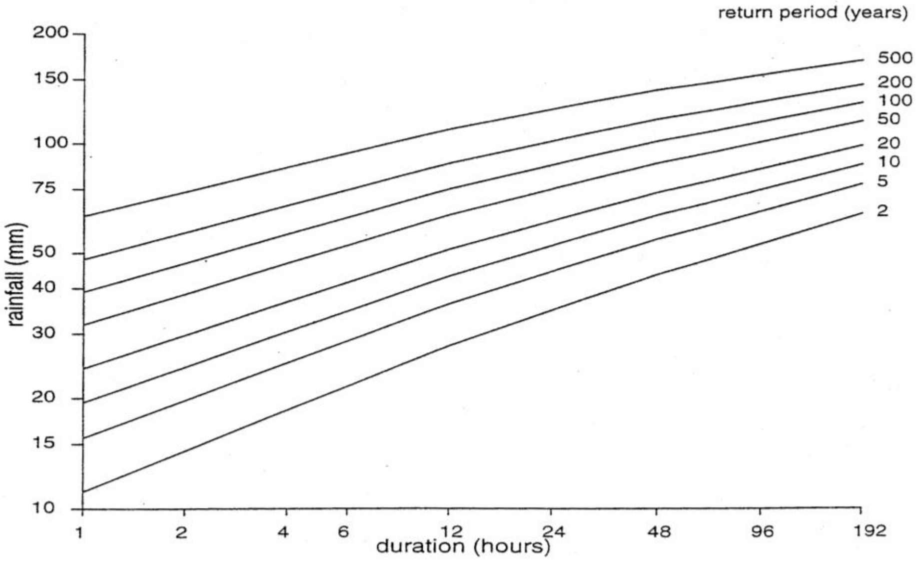

Figure 3.3: FEH rainfall DDF model plot for an example location (Courtesy of CEH)

Generating FEH DDF Values

Historically the six parameters of the FEH 99 DDF model were extracted from the FEH CD-ROM and then imported to urban drainage models.

The FEH CD-ROM was one of a suite of software packages that implement aspects of FEH methods. There were three releases of the FEH CD-ROM but all three contained identical design rainfall statistics.

The use of the FEH CD-ROM is being superseded by the implementation of the FEH web service, although it is still supported for the duration of existing licences. The FEH web service can generate rainfall data for FEH13, FEH99 and FSR DDF models. Results from FEH99 are identical to those obtained from the FEH CD-ROM.

It is not possible to obtain parameter values from the FEH13 model. Instead, the FEH web service can output a table of design rainfall depths for a wide range of durations and return periods, or calculate a design rainfall for a user-specified duration and return period.

A Catchment Average calculation will generate rainfall for the whole river catchment. This is inclusive of the Areal Reduction Factor (ARF) (see Section 3.2.4.). The alternative is a 1km grid point calculation which will generate point rainfall for the location, not inclusive of an ARF.

In most circumstances the 1km point value for the centre of the sewer catchment under consideration should be used in the generation of FEH rainfall. This is because the topographic catchment boundaries shown in the FEH web service often do not match those for the sewer catchment. However, it is often possible to find a small topographic catchment in the FEH dataset which overlaps much of the area of interest and may enclose only one 1km grid point and so have catchment-average parameters that are very close to the point values. The minimum catchment size shown is 0.5km2.

Large sewer catchments should be checked for spatial variation of DDF values or design rainfall and an average of a number of point values calculated where it is not possible to find a topographic catchment with a similar catchment boundary. For many urban drainage catchments this will not be necessary.

The most common way to calculate design rainfalls from FEH99 is to import the DDF model parameters to the sewer modelling software, where this is supported, taking care to ensure that the correct set of values (catchment-wide or 1km point values) are being used.

For estimation of design rainfall for short return periods, it is important to understand the difference between the **annual maximum return period** and the **peaks over threshold (POT) return period**, sometimes known as the average recurrence interval.

The **annual maximum return period** is the average interval between years containing an exceedance of a given rainfall depth over a different duration.

The POT return period is the average interval between exceedances of a given rainfall depth over a different duration.

The difference between the two definitions is only important at short return periods, i.e. less than about five years. The two types of return period are related using Langbein's formula, included in Appendix A of FEH Volume 1.

Return periods of 1 year or less are meaningless on the annual maximum scale. So, for example if a design storm for a return period of 0.5 years is required, this POT-scale return period value must first be converted to the corresponding annual maximum-scale return period, which, from Langbein's formula, is 1.16 years. This can then be entered into the DDF model to calculate a rainfall depth. The FEH web service and CD-ROM carries out this conversion of return periods automatically.

Standard practice is generally to use the POT return period for storms of up to 5 years and annual maximum for storms of 5 years and above.

3.2.4 Areal Reduction Factor

The Areal Reduction (ARF) is a factor used to reduce the depth of rain in synthetic storms to convert from a typical point rainfall to a rainfall across an area such as a river or sewer catchment.

$$\text{ARF} = \frac{\text{T-year catchment rainfall}}{\text{T-year point rainfall}}$$

The reduction factor varies with catchment area and storm duration.

Catchment Area (km²)	Event Duration (minutes)						
	15	30	60	120	240	360	1440
0.01	0.99	0.99	0.99	0.99	1.00	1.00	1.00
0.1	0.97	0.98	0.98	0.99	0.99	0.99	0.99
1	0.93	0.95	0.96	0.97	0.98	0.98	0.99
5	0.88	0.91	0.93	0.95	0.96	0.96	0.98
10	0.85	0.88	0.91	0.93	0.95	0.96	0.97
15	0.82	0.87	0.90	0.92	0.94	0.95	0.97
50	0.71	0.79	0.84	0.88	0.91	0.93	0.96
100	0.62	0.72	0.80	0.85	0.89	0.91	0.95

Table 3.1: Areal Reduction Factors for various catchment areas and event durations

It can be seen from table 3.1 that the areal reduction factors are lower the larger the catchment area and the shorter the event duration. Hence there will be a significant reduction in peak rainfall intensities in a short duration event on a very large catchment.

To apply an ARF, an area must be entered into the modelling software based on the catchment area being studied. For the reasons above, care must be taken when defining the appropriate area. For instance, the area of the whole sewer catchment will be appropriate when assessing flows at a treatment works but would not be correct when looking at a flooding location in a small sub-catchment on the periphery of the sewer network. When assessing the performance of the whole catchment for Drainage Area Study work, no single value will be correct and a compromise must be reached.

For drainage area planning purposes some specifications set a maximum size of catchment area for ARF calculation such that areal reduction factors will be within the range of 0.9 to 1 for all event durations.

Another alternative may be to base the ARF on the time of concentration of the catchment, as the critical event duration is generally proportional to the catchment size. For example, assuming a velocity of 0.75m/sec, the time of travel in a 5km2 catchment could be in the order of 60 minutes, leading to a critical 120 minute storm. This would equate to an ARF of 0.95. The time of travel for a 0.1km2 area may be in the region of 8 minutes, with a critical duration of 15 minutes. This would equate to an ARF of 0.97. Hence fixing the ARF at 0.96 for all event durations could be a reasonable compromise to make.

Testing of the catchment with varying fixed ARFs could be carried out to check how sensitive the catchment response is to ARF, particularly if storage is being included in the catchment.

Table 3.2 below shows a suggested methodology for assessment of ARFs, based on expert judgement, but other methods could be used to suit individual circumstances.

Study Type	**Area to be used for ARF**
Wastewater treatment works	Total catchment area
Localised flooding study or single Combined Sewer Overflow (CSO)	If local capacity problem, use sub-area upstream of the study area. If backing up from downstream use larger sub-area.
Strategic CSOs and Flooding Schemes with multiple sites	Consider fixed ARF based on time of travel analysis.
Drainage Area Planning and other whole catchment studies	Consider fixed ARF based on time of travel analysis.

Table 3.2: Possible catchment areas to be used for Areal Reduction Factor (ARF) calculation

Important points to note on setting the catchment area for design rainfall in modelling software

Always check that the correct unit is used. The FEH Web Service exports the catchment area in km^2, whereas some modelling software packages use hectares.

If using a catchment area, the catchment area entered in the modelling software should be the area contained within the model boundary extents. This is not necessarily the sum of the modelled areas that contribute flow to the sewer network which may be much less, for example in an area which is predominantly drained by a separate system.

3.2.5 Design Storm Return Periods

If overall system performance is being assessed a full range of storm return periods will normally be used. However if the model is being used for a specific design purposes, return periods will usually be specified.

Concerns have been raised about how realistic it is for a high return period storm to impact on the whole of a large catchment at the same time, particularly in convective storms. In situations like this, methodologies have been developed for using multiple design storm return periods over parts of the catchment, with for example a 30 year return period being used for a localised area, and a 5 year return period being used for the trunk sewer catchment. However this approach should not be used without a detailed analysis of local spatial rainfall records.

A spatio-temporal stochastic rainfall model would be a more robust way of allowing for this effect.

3.2.6 Storm Durations

Design events are simulated through varying storm durations, as each duration will have a different impact on the sewer system. The critical duration is determined by identifying the event which causes the highest risk or cost, based on the parameter under consideration. It must be noted that a single storm duration will not be enough for considering all areas of the catchment:

Different areas of a catchment will have different critical durations. Critical duration typically increases where the upstream catchment is larger or flatter, or for example where the contribution from infiltration and permeable surfaces is greater.

There may be different critical durations for the same location, depending on the criteria used to assess "critical". For example, one duration may give a worst case flood risk, but a different duration may be critical when sizing below-ground storage solutions.

To assess critical duration:

- Decide upon the assessment criteria which will define critical. This will vary by type of assessment or model.
- For a 1D sewer model, critical duration may for example be assessed as the duration causing the greatest volume of flooding in the area of interest, the largest CSO spill, or some other parameter.
- For a 1D-2D model (coupled or uncoupled) critical duration may for example be equated to the duration leading to the greatest extents of flooding.
- Where a risk-based approach is being followed, critical duration would be that event duration leading to the greatest impact, for example monetised flood damage costs.
- When assessing a storage design, critical duration will be the duration requiring the greatest volume of storage.

An assessment of critical duration would typically include design storm durations for the 15, 30, 60, 120, 180, 240, 360, 480, 720, 900 and 1440 minute events for the design return period.

Note that:

- Critical duration may change with return period
- The upper limit of storm duration tested is catchment-specific. Consideration should be given to running longer duration events where the assessed impact is continuing to increase at the longest duration run.

Critical duration should be checked following significant changes to a model, and for each option assessed.

3.2.7 Critical Input Hyetographs (Superstorms)

As detailed in section 3.2.6, the number of simulations that are required to assess the performance of a sewer system for a range of rainfall durations and return periods can be large.

In order to reduce the number of simulations, it is possible to develop a Critical Input Hyetograph (CIH), or Superstorm. This is a long duration single synthetic rainfall hyetograph that encompasses the critical intensity and critical volume for a given set of rainfall hyetographs. By applying this synthetic rainfall hyetograph, only one simulation per return period is required, rather than running multiple rainfall events with varying durations and intensities. This approach is often referred to as the Chicago Method, which originated in a paper by Keifer and Chu (1957).

Newton et al (2013) discussed a number of CIH generation methodologies that have been developed, either using historic recorded rainfall datasets or generated from synthetic FEH or FSR derived storms.

One potential drawback of the CIH or Superstorm method is that the resulting rainfall hyetograph does not necessarily reflect a realistic typical storm profile. It involves applying a storm which has a much longer duration than that likely to be the critical duration in some parts of the drainage network. In portions of the network that are sensitive to rainfall over a relatively short storm duration, there will already be some storm flow before the relevant critical duration part of the design storm event starts. There will also be more rainfall after the end of the relevant part of the storm.

Superstorms have been successfully used on a number of surface water management plans, but the method is not universally accepted.

3.2.8 Seasonal Correction Factors (SCFs)

As it is recognised that in winter months the catchments will be generally wetter and generate more slow response runoff, there is a tendency to make use of winter storm events as well as summer events in modelling.

Outputs from the FEH DDF model are based on annual data, with no means of deriving seasonal rainfall depths. As the maximum rainfall depths tend to be in the summer periods, this can lead to an over-prediction of rainfall depths in winter periods. Table 3.9 in volume 2 of the Flood Studies Report (1975) showed seasonal correction factors based on different seasons and months for 5 year return period storms, for a range of average annual rainfall values. The correction factors were as low as 43% of the annual values for short duration storms in low annual rainfall areas, so over-prediction of maximum winter rainfall depths can be significant.

As part of the research into the "Revitalisation of the FSR/FEH rainfall runoff method" (Kjeldsen et al, 2006), a more comprehensive seasonal analysis was developed, which required the availability of estimates of seasonal design rainfall. The following is an extract from the report:-

"The seasonal design rainfall is derived from the FEH DDF-model by multiplying FEH estimates of design rainfall with a seasonal correction factor, where the seasonal correction factor depends on the Standard Average Annual Rainfall (SAAR) of the considered catchment. With the introduction of the seasonal correction factor, the catchment-average seasonal design rainfall depth (**R**) is calculated as

$$R = RDDF*ARF*SCF$$

where **RDDF** is the point estimate of design rainfall obtained from the FEH DDF model, **ARF** is the areal reduction factor transforming point rainfall to catchment average rainfall and **SCF** is the seasonal correction factor transforming annual maximum rainfall to seasonal maximum rainfall."

As part of the research, functional relationships between the seasonal correction factors and SAAR were developed. The relationships were selected to be able to produce realistic estimates of the seasonal correction factors for all values of SAAR encountered in the UK and, at the same time, to have a limited number of parameters to facilitate user friendliness.

The winter seasonal correction factor is modelled using an exponential type relationship, and the summer correction factor is a linear relationship.

Parameter values for the relationship between SAAR and SCF were developed for durations of one hour, two hours, six hours and 24 hours, with the recommendation that for intervening durations, simple interpolations of the parameter values should be carried out.

The SCFs developed by this process are similar to those published in the Flood Studies Report.

It can be seen from table 3.3 that summer correction factors reduce as SAAR increases, and winter correction factors increase with SAAR. The two factors converge at SAARs of between 1500mm and 2500mm depending on the event duration.

Osborne (2012) recommended that a value of 1 should be used for Summer SCFs, although there is no such recommendation by Kjeldsen et al.

SAAR (mm)	Duration (hrs)	Seasonal Correction Factor	
		Summer	Winter
500	1	1.00	0.51
800	1	0.98	0.60
1000	1	0.96	0.64
1500	1	0.92	0.73
2000	1	0.88	0.79
500	2	1.00	0.55
800	2	0.98	0.65
1000	2	0.96	0.70
1500	2	0.93	0.79
2000	2	0.89	0.85
500	6	1.00	0.62
800	6	0.98	0.73
1000	6	0.97	0.78
1500	6	0.95	0.87
2000	6	0.92	0.92
500	24	1.00	0.63
800	24	0.97	0.75
1000	24	0.95	0.81
1500	24	0.90	0.89
2000	24	0.84	0.94

Table 3.3: Example Seasonal Correction Factors generated by ReFH process.

3.2.9 Design Storm Profiles

Although there are a number of possible profiles, as part of the FSR a decision was made to use two standard time profiles for design storms: the 75% winter profile and the 50% summer profile. The summer period is defined as May to October and winter as November to April. The percentiles are based on the peaked-ness of the storms. A number of storms were analysed, and the summer 50%ile profile is such that 50% of the analysed storms in summer were less peaked than this profile. In winter a profile was chosen such that 75% of winter storms were less peaked. The profiles are the same for each return period and duration, being based on a factor of mean intensity and proportion of the duration of the event. As mean rainfall intensity reduces with duration of event, although a longer duration of rainfall has more total rainfall, the peak intensities will reduce. The FEH has continued with these profiles. It is good practice to test critical duration using both summer and winter profiles with corresponding SCFs, taking account of variation in antecedent conditions between summer and winter.

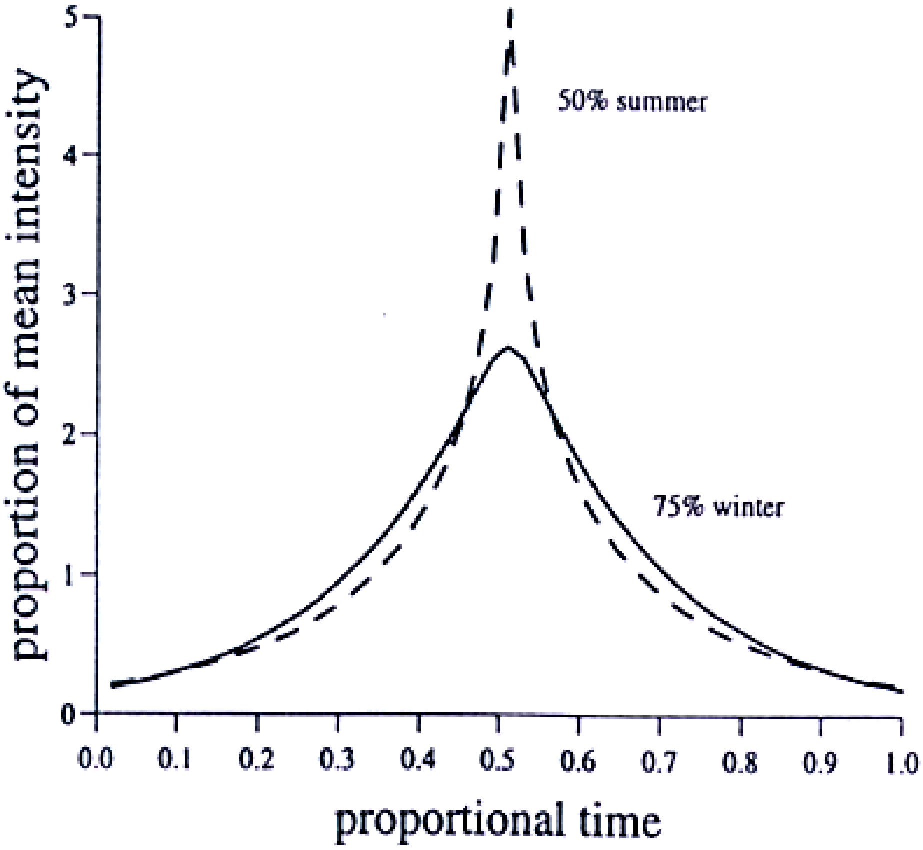

Figure 3.8: Winter and Summer Design Profiles (Image courtesy of CEH)

3.3 Initial Conditions

3.3.1 Urban Catchment Wetness Index (UCWI)

The Urban Catchment Wetness Index defines the antecedent wetness of the catchment for the Standard Wallingford Runoff model. Figure 3.9 below from the Wallingford Procedure provides curves of UCWI against annual average rainfall (SAAR). SAAR is obtained from the map in Volume 3 of the Wallingford Procedure.

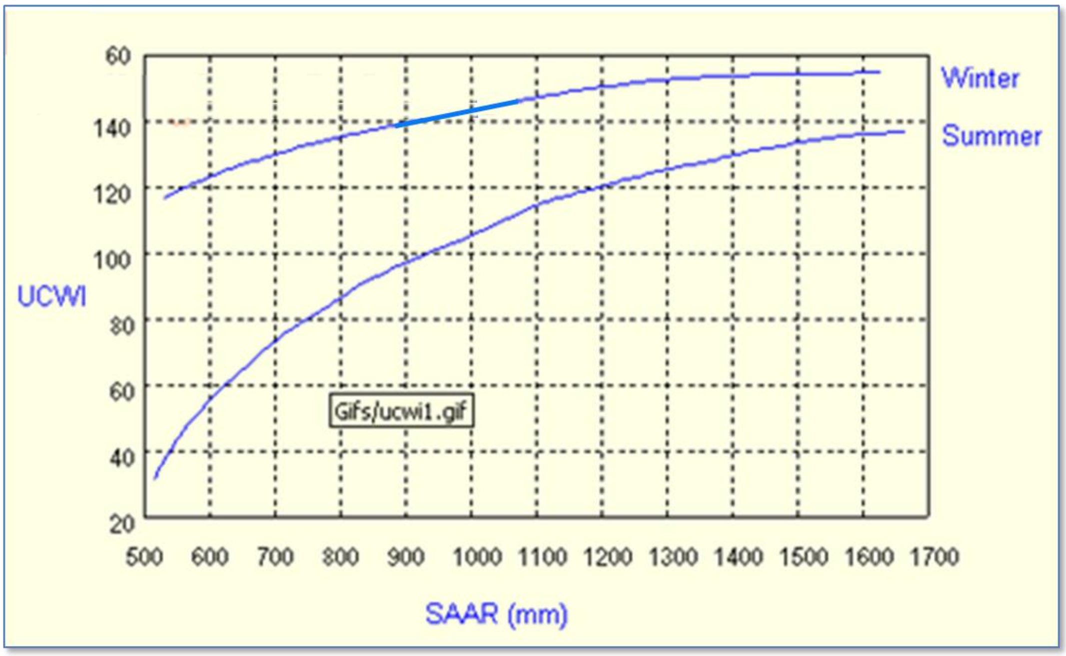

Figure 3.9: Winter/Summer UCWI vs SAAR (Image courtesy of Innovyze.)

3.3.2 Antecedent Precipitation Index (NAPI/API30)

This is the initial precipitation index value to be used with the New UK Runoff Model. Unlike the Wallingford Runoff Volume model, there are no maps available with Average NAPI values.

There is no industry standard process for the calculating design values of NAPI.

One possible method for calculation of design NAPI values is detailed below, based on using a long term rainfall series:

- Split the rainfall series into individual events with a suitable inter event period.
- For each event, calculate API30 values for each of the five soil types.
- Split the events into Winter (October to March) and Summer (April to September)

  Calculate percentile values from all the API30 values for each of the seasons and soil types.

The table below is the outputs of the analysis from a location in the North West of England

	Summer					Winter				
Soil Type	1	2	3	4	5	1	2	3	4	5
Mean	0.3	2.1	4.7	16.5	46.0	0.6	3.6	8.1	28.9	84.3
25%	0.0	0.2	1.0	7.4	24.7	0.0	0.7	2.6	15.2	49.9
75%	0.3	2.9	7.1	23.7	66.3	0.7	5.2	11.7	40.2	112.3
90%	0.9	5.7	11.2	32.2	81.3	1.9	8.8	17.5	54.2	148.7

Table 3.4 Example NAPI values for a location in the North West of England (Courtesy of United Utilities)

The percentile value to use would depend on the level of risk taken on the use of the model. If a low risk of failure is required, a high percentile value could be taken. Alternatively the mean values could be used.

Terry and Margetts (2005) suggested an approach based on analysis of long term rainfall records, with the calculation of daily NAPI values from the records. From these median graphs were produced for winter and Summer NAPI values for each soil type, varying by SAAR.

3.4 Antecedent Rainfall Depth

This is the depth of rainfall (in mm) which has fallen immediately prior to the event. If a worst case scenario of depression storage being full at the start of an event is required, this will be set to a high value.

3.5 Evapotranspiration (Evaporation)

Evapotranspiration is the loss of water to evaporation and transpiration during and between rainfall events.

Potential evaporation in the UK generally varies between about 0mm/day in mid-winter and 3mm/day in mid-summer. As these are the extremes of the range, the following ranges of values are generally applied in design storms:

- Winter Evaporation 0-0.5 mm/day
- Summer Evaporation 2.5-3.0 mm/day

It should be noted that evaporation should only be included if the original model was verified with evaporation being specifically included in the rainfall files. If evaporation was not included in the verification, the effects will already have been factored in to the model by amendment of other parameters, particularly if the verification was carried out in summer.

3.6 Rainfall Event Naming Conventions and Quality Assurance

3.6.1 Design Event Naming Conventions

Rainfall events should have a naming convention applied which is consistently followed, and is intuitive of the design event return period, season and duration.

3.6.2 Rainfall Data Checks and Quality Assurance

The incorrect application of rainfall is one of the most common and serious causes of modelling errors. At best this can lead to significant re-work and at worst, the failure to accurately identify needs, failure of solutions or costly over design. It is therefore imperative that the generation of the rainfall is clearly documented and quality checked.

The checks may include:

- UCWI/API30 values checked and appropriate to runoff model
- Winter and Summer Profiles
- Appropriate storm return periods/durations
- Rainfall profiles applied correctly in model
- Application of areal reduction factor
- Application of evapotranspiration
- Application of antecedent depth
- QA form completed and signed off
- Application of climate change uplift if any

4. RAINFALL TIME SERIES

4.1 Introduction

Long term rainfall time series are generally required for use in the Urban Pollution Management (UPM) process, general CSO assessments and also in some instances for flood risk assessment and flooding resolution project design.

Depending on the length of series required and the availability of data, the series can be developed directly from historic data, either from raingauge or radar rainfall, or stochastically generated synthetic rainfall.

4.2 Length of Series

The length of rainfall series required is dependent on the use of the rainfall series.

For use in CSO and UPM studies, due to the variability of rainfall it is recommended that a rainfall series up to 25 years is used, particularly where designs are based on frequency of discharges. The rainfall series must have a minimum duration of ten years but a longer record is preferred. If insufficient historical rainfall is available a synthetic rainfall series will need to be developed.

For use in flooding design and assessment, the length of series will need to be significantly longer. It is usual to design sewerage systems to a 1 in 30 – 50 year no flooding criteria. In order to use long rainfall series for this type of assessment a series significantly longer than 50 years is required. This will mean that a synthetic rainfall series will have to be developed due to the lack of high resolution rainfall records for such a long period of time.

4.3 Historical Rainfall Series

Historic rainfall data is available from raingauges which have been audited, a radar rainfall record or as gridded data from the Met Office. Raingauge data is generally available from the Met Office, the environmental regulator and in some instances from the local authority or Water Service Company. Raingauge data is generally more accurate and has more checking if it is from a Met Office registered station. Radar rainfall is available from the Met Office, other commercial providers and a number of Water Service Companies.

Selection of the most appropriate raingauge site to represent the catchment to be modelled needs to take account of the distance of the gauge from the catchment in question, the elevation of the gauge compared to the catchment, and the appropriateness of the annual rainfall at the site compared to the catchment.

The rainfall record length needs to be long enough to take account of the inherent variability of rainfall. In assessing discharges from CSOs and storm tanks both intensity and duration of rainfall is important and some discharges are very sensitive to changes in antecedent conditions. Hence as wide a range of rainfall is required over as long a time period as possible. If a relatively short rainfall record is available, then reviews should be undertaken of long rainfall records to ensure the period of the rainfall record is consistent with long term trends. This could be done for example by comparison with a daily rainfall record.

4.3.1 Data Formats and Timesteps

Rainfall from raingauges can be obtained at a variety of timesteps, or as a record of actual tips of the gauge.

The various elements of modelling require rainfall in a range of formats. The main requirements are for values in hourly or shorter timesteps for deterministic modelling. Five minute timestep data has been used, and some CSO and UPM related studies have used 15 minute timestep data with no significant detriment to modelled sewer system performance. Long time series of hourly data are generally needed as input for simplified sewer flow models. If only daily or hourly data is available, these will need to be disaggregated to a shorter timestep using stochastic methods, preferably five minutes for use in detailed models. There is commercially available software that can carry out this task.

If tip data is available, this is preferable as the data can be converted to any timestep required. Radar rainfall data is generally available at a 5 minute timestep.

4.3.2 Infilling of Missing data

The historic rainfall data must be checked for missing or un-reliable data. This is easier to do if the data is quality controlled and flagged by the supplier. Missing or unreliable data can be replaced with data from another raingauge with similar characteristics.

4.3.3 Evapotranspiration

There is a need to consider evapotranspiration in rainfall series. If there is a long term record of potential evaporation of the same length as the rainfall series, this could be used directly. Otherwise it is standard practice in development of rainfall series to calculate daily potential evaporation using a sinusoidal equation detailed below.

$$Et = f[1 + \sin(2\pi j / 365 - \pi/2)] + a$$

where:

Et is the potential evaporation rate (mm/day)

j is the day number since start of the year.

f is the seasonal amplitude value

a is the amplitude shift value

The default value for **f** is 1.5 and the default value of **a** is 0.

If the default values of **f** and **a** are used, the equation gives a range of values from 0 on January 1st to a peak of 3mm/day on 1st July.

Other values of "**f**" and "**a**" have been used, based on locally calculated data.

It should be noted that evaporation should only be included if the original model was verified with evaporation being specifically included in the rainfall files. If evaporation was not included in the verification, the effects will already have been factored in to the model by amendment of other parameters, particularly if the verification was carried out in summer.

4.3.4 Splitting Continuous Rainfall into Events

In some circumstances there is a need to split long term rainfall series into individual events. In the UK this will be required where the Standard Wallingford Procedure is used for runoff due to the need for event specific UCWI calculations.

Various tools have been developed to split rainfall files into events. The main criterion for definition of events is usually the Inter Event dry period. This value will be driven by the purposes the rainfall is being used for, any limitations there may be to the overall duration of rainfall events, and the characteristics of the wastewater network that the rainfall series will be used on.

It is good practice to use an inter event dry weather period that is sufficiently long enough to allow the wastewater network flows to return to base flow conditions, with all network storage empty. However this may result in an inter event dry period of a number of days resulting in very long rainfall events. When using the Standard Wallingford Runoff model this may cause some problems of under-predicting runoff. In these instances there will need to be a compromise made.

4.3.5 Antecedent Conditions

Generally there are three elements of antecedent conditions that need to be considered when using historic or stochastic time series in the UK, namely API30, UCWI and how wet the catchment is for depression storage and initial wetting calculation.

It is possible to calculate API30 and API5 directly from the long term series, as long as there is a 30 day period before the start of the series for API30 calculation.

For the UCWI calculations there is a need to have long term Soil Moisture Deficit (SMD) data. SMD data is obtainable from the MET Office. Data is available as a monthly long term average or as actual recorded values at daily, weekly or monthly intervals.

If there is a long term record the actual SMD values can be used. Otherwise there will be a requirement for development of a rainfall series for long term monthly average data. If this is used directly, all SMD values in a month will be the same regardless of the rainfall. Alternatively SMD data can be calculated using a suitable SMD model calibrated against the historical long term average monthly SMD values. Overall runoff is not very sensitive to SMD values so in most cases monthly average values will be acceptable.

Initial catchment wetness for depression storage purposes can be calculated from the rainfall series, using a reasonable antecedent period.

4.3.6 Observed Rainfall from Radar

Radar rainfall data is a further source of historic rainfall. It is generally available at a 1km2 resolution making it very good for assessment of spatial variation. However if it is to be used for rainfall series generation some reviews against raingauge data should be carried out.

4.3.7 Spatial Variation

When undertaking analysis of large catchments, it may be possible to use more than one raingauge to provide rainfall inputs, dependant of course on the availability of data. This will allow the consideration of an element of spatial variation of rainfall across the catchment. The advantage of using historical data for this purpose is that the data is dated, and therefore rainfall events are linked. For this reason it may be preferable to accept a shorter rainfall series based on historical data than a single site stochastically generated longer rainfall series, providing there is sufficient variability in rainfall in the historic rainfall series.

Although use of radar rainfall data resolves any spatial variation issues, the duration of the available rainfall radar data set usually precludes its use in long time series development. If there is a suitable duration of data available, checks should be made on the perceived accuracy of the data when compared to raingauge data and missing data.

4.3.8 Areal Reduction Factor

Rainfall time series developed from raingauge data and stochastically generated are derived from point source data. As such they are the equivalent to design storms and when used as catchment wide rainfall would require the use of ARFs. However the derivation of ARFs is based on catchment area and event duration. By the nature of rainfall time series, there is no defined storm duration, and hence ARFs cannot be calculated, certainly when using the series in continuous simulation form.

If using individual rainfall events from the series, it is possible to analyse the event to determine the duration in the event giving the worst case storm return period, and ARFs could be calculated on this basis. However this could mean that other parts of the event are over compensated.

As events in rainfall time series tend to be longer in duration than design storms, calculated ARFs will be at the high end of the scale. Hence given the difficulties in calculation, and the limited reduction in rainfall by their use, it is recommended that ARFs are ignored in rainfall time series.

If radar rainfall series are used, the rainfall is already averaged over the rainfall grid, and as such there is no requirement for ARFs.

4.4 Synthetic Rainfall

4.4.1 Introduction

Stochastically generated synthetic rainfall is required when there is a need to develop a long rainfall series and there is no local raingauge information of a suitable length or timestep interval.

A stochastic rainfall model generates artificial rainfall data with statistical characteristics that are intended to be similar to real rainfall. Some models also simulate other types of climate data such as temperature. An important distinction is between “point” rainfall models, which produce a single time series of rainfall, which is taken as representative of a wider area or catchment, and spatial-temporal models which represent differences in the timing and depth of rainfall at different locations.

The possibility of using synthetic rainfall data for urban drainage modelling was investigated by Cowperthwaite et al, (1991) and Cowperthwaite and Threlfall, (1994). This resulted in the development of modelling techniques to generate long rainfall time series containing all of the characteristics of historical data, for all areas of the UK, for use in the UPM processes. The first tool developed was StormPac. Since then other commercially available tools have been developed. TSRSim was developed as part of an UKWIR project "Climate Change and the Hydraulic Design of Sewerage Systems", and the UKCP09 weather generator was developed as part of the development of the UKCP09 suite of climate change tools.

Generally the software consists of two elements. The first is the stochastic rainfall generator which is used to develop a rainfall series at hourly intervals, and a disaggregator which disaggregates the rainfall series from hourly data to generally 5 minute data for use in a detailed deterministic model.

The disaggregator can also be used on its own to disaggregate observed rainfall available at hourly or daily timescale.

Current commercially available software is limited to the development of a single rainfall series, and stochastically generated spatially varied rainfall series are currently not available commercially. The commercially available software can disaggregate multiple location historic data.

4.4.2 Length of Stochastic Series

The length of stochastic rainfall series required is dependent on the use of the rainfall series.

For use in CSO and UPM studies, due to the variability of rainfall it is recommended that a rainfall series up to 25 years is used, particularly where designs are based on frequency of discharges.

For use in flooding design and assessment, the length of series will need to be significantly longer. There are limits to the lengths of series that can be developed in currently available commercial software. A rainfall series of a minimum of 100 years is required for flood risk assessment and design up to a 30 year return period, and preferably longer.

4.4.3 Use of Observed Data to Improve Parameters of Stochastic Series.

In all cases it is recommended that observed rainfall data, either from a local raingauge or gridded data available from the Met Office, is used as an input into the software to improve the parameters of the stochastic series. This dataset should be as long as possible, with the recommendation to have a dataset of at least ten years or if possible longer of either hourly or daily rainfall. If a significantly longer record of data is available then for UPM purposes it may be preferable to disaggregate data and use the historic series directly rather than develop a stochastic rainfall series.

Care should be taken on the choice of historic rainfall site to use. The characteristics of the historic rainfall need to be similar to the catchment that the series is being developed for. This is particularly relevant in situations where the raingauge may be in an elevated location, and the urban catchment is in a valley.

The following assessments will therefore be required in assessing the suitability of a historic rainfall series for use as an input into the stochastic rainfall generator:

- Duration of rainfall record.
- Geographic location of the raingauge in relation to the catchment to be assessed.
- Comparison of the SAAR of the raingauge with the SAAR of the catchment.
- Amount of missing data in the historic series.

4.4.4 Checks of the Stochastic Rainfall Series

Once the rainfall series has been developed, a series of checks and statistical analyses should be undertaken to ensure that the measured and stochastic rainfall series generated were sufficiently representative of the rainfall for the catchment. This may mean that multiple runs are needed to obtain a distribution of the extremes and selection of the appropriate generated series.

The recommended checks/analysis and rainfall series acceptance criteria are detailed in the table below.

Check	Check Details	Acceptance Threshold
Measured series length (1)	Check measured series for suitability as input for Series Generator	Minimum 10 Years
Measured series length (2)	Check measured series for suitability for using in modelling analysis as an alternative to a 25 Year stochastic series	Minimum 15 Years or as agreed with Regulator
Measured series comparison with SAAR	Check Measured series AAR against catchment SAAR	± 5%
Stochastic series vs measured series average annual rainfall (AAR)	Check measured series AAR against Stochastic Series AAR	± 5%
Stochastic series vs measured series summer rainfall depth (ASR)	Check measured series ASR against Stochastic Series ASR	± 5%
Stochastic series vs. measured series annual rainfall depth variability	Check to ensure that the stochastic series has the expected variability in annual rainfall totals	Visual check of variability using graphical analysis
Stochastic series vs measured series average monthly rainfall totals	Check measured series average monthly rainfall totals against stochastic series average monthly rainfall totals	Visual check using graphical analysis
Stochastic series vs. measured series daily rainfall totals	Check to ensure the that the stochastic series has the expected number of rain days and the expected frequency distribution of daily rainfall totals	Visual check using graphical analysis
Stochastic vs. measured vs. FEH rainfall depth for standard return period and durations	Check that the stochastic series contains storms that are comparable to FEH storms for standard return period from 1 to 100 years and durations of 30 mins to 360 minutes	Visual check using graphical analysis

Table 4.4: Rainfall Series Checks and Analysis

4.4.5 Antecedent Conditions

As stochastic rainfall series are synthetic, there is no actual SMD antecedent data available and long term monthly average data is generally used. If this is used directly, all SMD values in a month will be the same regardless of the stochastically derived rainfall. Alternatively SMD data can be calculated using a suitable SMD model calibrated against the historical long term average monthly SMD values. Overall runoff is not very sensitive to SMD values so in most cases monthly average values will be acceptable.

4.4.6 Spatial Variation

The use of a single uniform rainfall series over large urban catchments is a significant simplification, particularly in catchments with large variation in topography. The result of this limitation is generally an averaging of rainfall across a catchment, and no account being taken of the movement of the storm across the catchment. This can lead to an over-prediction of rainfall in low lying areas, an under-prediction in higher altitudes, and a potential over-prediction in runoff due to the assumption that rain is falling over the whole of the catchment at the same time.

Kellagher et al (2009) reported that the use of uniform rainfall tends to overestimate flood volumes and locations for large catchments. Although only based on one catchment, the results seem to indicate that the spatial nature of rainfall becomes important in producing significantly different results for catchments larger than 350 to 500ha.

Currently there are no commercially available software packages that can be used to develop stochastically generated spatially varying rainfall. However there are available research tools that have been used for specific projects. An example is RAINSim (v3). RainSim is an implementation of the Spatial Temporal Neyman Scott Rectangular Pulses (STNSRP) stochastic rainfall model for simulating rainfall (Burton et al, 2008). A further example is documented by McRobie et al (2013), outlining the production of a stochastic generator of spatially varied rainfall for the Counters Creek catchment in the London region.

Further development of these tools is required before they are generally accepted in urban drainage applications, including processes for validation of the spatial series developed.

5. CLIMATE CHANGED RAINFALL

5.1 Introduction

There is a need to understand how the impacts of climate change can be analysed in wastewater network models. This requirement is both for the impact on foul and surface water flooding and also the impact on water quality and spill frequency.

Elements that are modelled and could be altered by climate change are precipitation, evaporation and temperature. Of these the most important element is precipitation.

The latest information on climate change is from the UK Climate Change Projections, UKCP09, although there have been a number of research projects either ongoing or completed since its development. It should be noted that there is a significant limitation in UKCP09, as it cannot be used to assess the potential for higher rainfall intensities in convective storms. This will be discussed further in section 5.2.1.

As the assessment of climate change impact on future precipitation is a constantly changing area, with ongoing and recently completed research, and the potential for requiring considerable processing power and resources, there are currently no standard ways of using data. This guide does not therefore make specific recommendations on how to carry out climate change assessments, but instead attempts to identify approaches that could be taken.

5.2 UKCP09

The UKCP09 projections are significantly more sophisticated than previous scenarios both in terms of the scientific methods used in their creation and in the tools and outputs available to the user. The principal feature of the projections is that they are probabilistic, although no probabilities can be attached to emissions scenarios, and so three separate probabilistic projections are provided for three corresponding different emissions scenarios. The probabilities represent the strength of evidence for changes in variables.

One of the outputs of UKCP09 was the production of a weather generator. The weather generator produces 'synthetic' timeseries of baseline and future daily and hourly weather conditions for 5km grid squares across the UK. The data are described as 'synthetic' because they do not represent predictions of future weather for specific dates, but instead simulate weather conditions that could occur, consistent with natural variability and the UKCP09 projections. As such the weather generator is a valuable resource, providing a unique source of spatially detailed, hourly or daily synthetic weather data for the whole UK, both for the historical baseline (1961-1990) and for future timeslices.

Although weather generators can be designed to provide hourly time series, within UKCP09 the decision taken was to have the weather generator provide daily time series. Hourly time series can be requested, however, rather than generating this separately, these hourly time series are created from the daily time series using simple disaggregation rules. These rules (e.g. no change in the diurnal cycle, day-time temperatures are generally higher than night-time temperatures, etc.) are used to convert the generated daily time series into sensible hourly time series that are consistent with the daily totals (e.g. that hourly rainfall totals add up to the daily rainfall total) and averages. These rules are based on the observed climate and are assumed not to change in future time periods. The result of this is there is no climate signal for rainfall intensity in the hourly data.

The weather generator at hourly periods will synthesise 100 different 30 year period rainfall for both control and climate changed perturbed conditions. Hence there is 3000 years of data generated. At daily timesteps the weather generator can generate between 100 and 1000 series of up to 100 years length.

In the UK, although annual precipitation totals are projected to remain largely unchanged, the seasonal variability across the country is substantial. Winter precipitation is projected to increase across the country, but particularly along the western side of the country; summer precipitation, by contrast, is projected to decrease under central estimates for the whole country. Precipitation on the wettest day of the season is projected to increase in winter – by up to 40-50 percent for southern England – but decrease in summer – by up to 10 percent for most of the country, under medium emissions for the 2080s. Under the same scenario, central estimates for heavy rain days (rainfall greater than 25 mm) over most of the lowland UK is projected to increase by a factor of between 2 and 3.5 in winter, and 1 to 2 in summer.

5.2.1 Limitations of UKCP09

Alongside the benefits of UKCP09, there are a number of limitations, including issues of joint probability between variables and months and constraints on spatial averaging of change factors. The volumes of data produced are also significant, particularly from the weather generator.

The most significant limitation of UKCP09 is it cannot be used to assess the potential for higher rainfall intensities in convective storms.

UKCP09 used regional climate models (RCMs) to infer short duration rainfall intensity changes in the future. The fundamental problem with using RCMs for this purpose is that the main type of rainfall resulting in sewer flooding events is convective – a type of rainfall caused by the vertical movement of an ascending mass of air that is warmer than its environment. Most of the sewer flooding in summer resulting from hydraulic under-capacity occurs as a result of convective rainfall that is generally of higher intensity than other rainfall types. Hand et al (2004) identified 50 extreme rainfall events in a UK-wide survey of the 20th century, of which 30 were convective storms; they also note that they all occur in the summer months (June, July & August). UKCP09 does not quantify changes in convective, localised and intense rainfall events because such processes occur on a much finer scale than the RCM resolution (25km) used in UKCP09. The general message of drier, hotter summers and milder wetter winters coming from UKCP09 relates predominantly to the frequency of large scale (frontal) rainfall events that occur at a spatial scale that climate models can simulate quite realistically.

In 2010, the Met Office (2010) produced a report for OFWAT on rainfall extremes in which they concluded that “there is no clear signal for the change in frequency of summer rainfall events. The range of possible changes means that summer rainfall events could become much less frequent, or that that they might be much more frequent.” The report drew conclusions about summer extreme rainfall intensity changes but acknowledges that these estimates were drawn from UKCP09, which cannot simulate convective rainfall intensities well. Limits to observational records mean that the weather generator cannot provide reliable high return period (>10 year) estimates of short duration rainfall; therefore, as with current design storm approaches, growth curves may be required to extrapolate beyond this return period.

5.2.2 UKCP09 Probability Projections.

The IPCC uses the following probability levels to describe the proposed likelihood associated with a particular outcome (note that this is different from the amount of confidence that the IPCC places in the projection):

Virtually Certain	> 99%
Very Likely	> 90%
Likely	> 66%
About as likely as not	33-66%
Unlikely	< 33%
Very Unlikely	< 10%
Extremely Unlikely	< 1%

UKCP09 general guidance suggested that users should be able to use the distribution from the 10% to the 90% probability levels, but not outside this range. Probability levels associated with a given change should be interpreted as indicating the relative likelihood of the projected change being at or less than the given change.

UKCP09 recommended that users should not limit their considerations to a single probability value. There is no special significance associated with the central estimate. An adaptation strategy that addresses the climate risks associated with a single projection leads to acceptance of a higher risk than necessary. Users should consider strategies across the probabilistic projections which would allow development of resilient and adaptive strategies that recognise the levels of uncertainty.

There are obvious limitations to the number of probability values that can be assessed when using deterministic models.

5.3 Research Outputs

There have been a number of relevant studies carried out investigating how the use of climate change data can be used in modelling. The following are a summary of work undertaken at the time of publication of the guide.

5.3.1 UKWIR Climate Change Modelling for Sewerage Networks (10/CL/10/15)

The project:

- Reviewed the UKCP09 projections and the weather generator and the latest science on climate change and extreme rainfall;
- Developed guidance on how to assess impacts of climate change on sewer networks, for design events and timeseries applications; and
- Tested the approaches presented in the guidance through twelve case studies

The table below from the research project sets out the alternative approaches, their applicability to design and timeseries methods, and their limitations.

Approach	Applicability to design and timeseries methods	Limitations
Comprehensive set of Weather Generator (WG) runs	Widely applicable and theoretically robust	Requires significant effort
Limited WG run(s)	Advised only where impact of climate change on investment decision is limited or Company has chosen to adopt a specific position on climate change (e.g. conservative / no regrets)	Takes little or no account of uncertainty in climate change projections
Perturbation of historical event/series based on UKCP09 wettest day statistic	Easy to obtain but advised only as crude approximation (daily uplifts found to be different from hourly).	Only applicable to daily critical periods. No information on return period and natural variability uncertainty.
Perturbation of historical event/series based on monthly change factor	Relatively easy to obtain and apply but very crude.	Theoretical limitations in relation to temporal scale. No information on return period and natural variability uncertainty.
Defra (2006) indicative sensitivity range (NB. Since updated in 2011).	Standard national uplift easy to apply to design events. Not suitable for timeseries modelling.	Takes no account of location, event duration and return period.

Table 5.1: Alternative Climate Change Approaches

There was a tool, WRAPT, developed as part of the project that allows some analysis of weather generator output. The tool analyses hourly weather generator outputs, and can develop both climate changed design storms and timeseries based on the 100 different 30 year period UKCP09 rainfall outputs for both control and climate changed perturbed conditions. Design storms can be analysed for return periods of 2, 3, 5 and 10 years at durations of between 1 hour and 24 hours for both control and climate change scenarios, with an uplift being calculated based on the difference between the two. For timeseries analysis the tool identifies the 30 year timeseries which is the closest match to the average of the 100 outputs based on up to three user identified metrics.

5.3.2 Modifying Existing Rainfall Design Sets for Climate Change - WRc.

This was a portfolio project developed with support from three water service companies. The Project commenced in May 2009 and reported in March 2010.

The following information is extracted from the project report:-.

"An innovative methodology to adapt rainfall design sets for climate change using change factors derived from the UKCP09 Weather Generator hourly rainfall outputs has been developed. The Revised Historical series can be used to test the impact of climate change alone on sewer network model predictions when compared against results derived from the Historical series. The prototype tools that have been developed will be useful for analysing rainfall files and UKCP09 data files in other applications.

The approach has been tested on three datasets from contributors and by applying the change factors, on a seasonal basis, to the number of historical events in depth/duration categories a revised historical rain series has been generated. The total rainfall ratios for Revised Historical/Historical have been compared with the ratios for Scenario/Control and the matches were generally good across the Seasons."

The project involved the following steps:

- Identification of a range of statistical measures to describe rainfall events and evaporation series for Historical and UKCP09 (Hourly Weather Generator) datasets.
- Development of a procedure to calculate the event changes in the UKCP09 data (from Control to Scenario) for a particular site and for a particular time period. These changes are calculated as differences and ratios for different depth/duration categories.
- Production of an optimisation procedure that modifies the historical datasets to give 'future' datasets. The procedure allows 'future' datasets to relate to the historical datasets by these climate change factors, whilst retaining as much of the historical structure as possible.
- Calculation of revised UCWI and API30 for each rainfall event.
- Application of the procedure to collaborators' historical datasets to produce a perturbed rainfall series with appropriate changes to antecedent conditions.
- Production of a report describing the development and testing of the procedure.

This process has since been used to develop a number of climate change perturbed rainfall series.

The approach can be used for any emission standard and probability projection. A limitation of the process is it will develop a perturbed rainfall series based on average climate change factors from the range of weather generator series.

5.3.3 Future Flows and Groundwater Levels Project

The Future Flows and Groundwater Levels (FFGWL) project carried out a consistent assessment of the impact of climate change on river flows and groundwater levels across England, Wales and Scotland using the latest projections from the UKCP09 Programme, including the UKCP09 probabilistic climate projections from the Met Office Hadley Centre.

FFGWL developed two unique datasets for Great Britain, both of which are available to the public under specific licensing conditions:

Future Flows Climate (FF-HadRM3-PPE), an 11-member ensemble 1km gridded projection time series (1950-2098) of precipitation and potential evapotranspiration for Great Britain specifically developed for hydrological and hydrogeological application based on HadRM3-PPE run under the Medium emission scenario SRES A1B. There are 11 series developed, one for each of the ensemble at a daily timestep.

Future Flows Hydrology (FF-HydMod-PPE), an 11-member ensemble projection of daily river flow and monthly groundwater levels time series (1951-2098) for 282 rivers and 24 boreholes in Great Britain.

Future Flows Climate and Future Flows Hydrology represent a nationally consistent ensemble of 11 plausible realisations (all equally likely) of nearly 150 years of climate, river flow and groundwater regime. They enable the investigation of the role of climate variability on river flow and groundwater levels nationally and how this may change in the future. Some climate change uncertainty is accounted for by considering all ensemble members together.

The Future Flows Project was a partnership project co-funded by the Environment Agency of England and Wales, Defra, UK Water Industry Research, the Centre for Ecology & Hydrology, the British Geological Survey and Wallingford Hydrosolutions.

There are no examples known of these outputs being applied to wastewater and surface water sewerage systems.

5.3.4 Research Funded on a Project Basis by WASCs

Due to the need to develop climate changed rainfall, some water companies have carried out their own funded research on the development of climate change approaches.

5.3.5 UKWIR Project CL10A205

In 2014, UKWIR commissioned research to provide “practical, quantitative estimates of future intensities in rainfall” using high resolution rainfall data from other countries that are currently experiencing climates similar to those that are likely to occur in the UK in the future under climate change projections. The project team undertaking this research, CH2M, adopted this ‘climate analogue’ approach and complemented this approach by using recently available, high resolution climate model output. The latter was provided through a research project called CONVEX, led by Newcastle University and the Met Office (http://research.ncl.ac.uk/convex/).

CONVEX makes use of new, powerful Met Office supercomputers that have enabled climate simulations to be made at a resolution of 1.5km – much higher than the 25km RCM used in UKCP09 and able to simulate convective processes well (Chan, Kendon et al, 2014).The research project has examined:

- changes in design storm rainfall depths under climate change (for 1, 3 and 6-hour durations) and the impacts of these changes on sewer flooding
- impacts of using time series rainfall derived from the CONVEX project for 13-year current and future climate periods on CSO spills. Full details of this research and the outputs are available from UKWIR.

Key messages documented in the research were:

- Both approaches show that there is good indication that estimates of rainfall intensity changes ('uplifts') are greater than the allowances for rainfall intensity change produced by Defra and the Environment Agency
- The estimates produced by the two approaches show that there is a reasonable degree of spread in the results, pointing to the need for more detailed analysis to corroborate the findings and add more confidence to the estimates.
- Time series data from the high resolution CONVEX model show, for one location, that flooding frequency and CSO spill frequency is likely to increase at all times of year, including during the bathing season, despite very little change in overall rainfall on an annual basis. However, further research is required to examine whether this trend is exhibited in other parts of the UK and other sewer models.
- The rainfall and sewer modelling results produced in this project suggest that significantly increased storage provision will be required to maintain spill frequency outcomes and, most probably, environmental water quality outcomes.
- International sewer design practice examined has shown that cities or regions in other countries (Spain, France, Australia, USA, Netherlands) use similar design values of rainfall rarity as in use in the UK, though other locations experience significantly higher rainfall values for the same rainfall return period. Institutional arrangements differ in these countries and in some cases result in a more holistic approach to managing excess water in an urban drainage environment.
- Further research and access to / analysis of increased quantities of data would benefit the water industry and recommendations are provided.

5.3.6 EA / Defra Guidance

Defra/ EA guidance is mentioned in the alternative approaches to climate change in section 5.3.1. This has since been updated.

EA Guidance is now outlined in the document "Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities, September 2011". At the time of writing the guide, this document was under review and further guidance will be given.

This guidance outlines new climate change factors for Risk management Authorities to apply to investment planning decisions. Change factors are given for extreme rainfall, river flood flows, sea level rise and storm surges. The change factors quantify the potential change (in mm or percentage increase depending on the variable) to the baseline.

The change factors are based on UKCP09 or research using UKCP09 data. Upper and lower end estimates of change are provided to help represent the range of the future risks. Government recommends that when considering climate change a full appreciation of emission scenario and climate uncertainty is taken into account. The upper and lower end estimates are designed to achieve this within flood and coastal erosion risk management applications.

The following is an extract from the report relating to changes to extreme rainfall:

"Although we are able to make qualitative statements as to whether extreme rainfall is likely to increase or decrease over the UK in the future, there is still considerable uncertainty regarding the magnitude of these changes locally. UKCP09 provides useful information on change to rainfall across the UK accessible through the user interface. This information is most robust for more common events such as changes to the wettest day of a season. Typically, for flood management purposes the concern is much rarer events such as those that have a 1 in 20 year chance of occurring or rarer. Developing quantitative predictions of future changes for such extreme rainfall at the local scale remains a key challenge for climate scientists.

It is recommended that where projection of future rainfall is required for events more frequent than those with a 1 in 5 year chance of occurrence, information is taken from the UKCP09. Where rarer events are being considered, it is recommended that changes to rainfall presented in the table 5.2 below are used.

Only maximum daily total rainfall data have been considered from the climate model projections, and so it is not possible to provide any guidance on how rainfall at hourly timescales may change.

Applies across all of England	Total potential change anticipated for 2020s	Total potential change anticipated for 2050s	Total potential change anticipated for 2080s
Upper end estimate	10%	20%	40%
Change factor	5%	10%	20%
Lower end estimate	0%	5%	10%

Table 5.2: Change to extreme rainfall intensity compared to a 1961-90 baseline

It is recommended that the 2080s changes are used beyond 2100. The 2020s covers the period 2010 to 2039, the 2050s the period 2040 to 2069, and the 2080s the period 2070 and 2099.

The peak rainfall intensity ranges should be used for small catchments and urban/local drainage sites. For river catchments over, say 5km^2, the peak flow ranges should be used. "

It should be noted that this is based on UKCP09 outputs and has the inherent limitations on UKCP09 when assessing the potential changes in convective rainfall.

5.4 Review of Alternative Approaches

5.4.1 Flooding Analysis

For design rainfall analysis the requirement is for an understanding of the change in the return periods of extreme rainfall. Hence changes in low intensity rainfall are not relevant. Historically these changes have been modelled as an uplift to existing FEH or FSR rainfall, where the rainfall intensities at each timestep are multiplied by the climate change factor. Hence a projected increase in rainfall intensities of 20% would mean the uplift factor would be 1.20. There is no reason to change that approach, as this provides a link to existing climate analysis.

Alternatives that could be considered in the provision of uplifts are:

- Use UKCP09 data for changes in wettest winter day
- Use EA / Defra guidance.
- Use of the recommendations of the UKWIR CL10/A205 report.

The percentage change on the wettest day is a direct output from UKCP09, at a 25 km grid level. The analysis is available at seasonal level, either Spring (March, April, May), Summer (June, July, August), Autumn (September, October, November) or Winter (December, January, February). The change in wettest day is the change in the future 99%ile of 30 year daily precipitation rate from the baseline climate (1961-1990) long term average. The change is a percentage difference from the baseline climate.

The use of changes in wettest day, rather than changes in sub daily rainfall, is possible as the rainfall and other variables in the UKCP09 Weather Generator are primarily estimated at the daily level, with simple disaggregation rules used for generating hourly resolution data. These rules are taken from the current climate and fixed for future time periods. Hence it is variations in the daily rainfall data that actually drive the Weather Generator outputs, as the disaggregation for future climate is the same as current climate.

Values are available for a full range of probabilities for all three emission scenarios.

Tables 5.3 and 5.4 below are the wettest day percentage changes in rainfall for medium and high emission scenarios for the 2030s and 2050s at a 10%ile, 50%ile and 90%ile probability at various locations in the UK, based on UKCP09 outputs.

Scenario	Medium						High					
Season	Summer			Winter			Summer			Winter		
Probability	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Leeds	-17.9	0.1	21.9	-4.3	6.7	19.2	-19.3	-1.7	19.6	-4.5	6.7	20.1
Manchester	-11.6	3.5	21.2	-5.5	5.9	19.0	-13.5	1.7	19.6	-5.7	6.1	19.4
Birmingham	-14.5	2.7	24.4	-6.9	6.4	22.2	-16.1	1.4	22.3	-9.0	4.6	20.6
London	-22.3	-0.2	27.9	-5.9	7.0	22.9	-24.1	-2.9	23.3	-5.7	7.0	22.8
Glasgow	-12.1	0.4	15.0	-3.9	4.7	14.9	-11.0	1.4	15.6	-6.0	3.5	13.9
Canterbury	-22.0	-0.4	27.3	-6.3	7.1	22.8	-24.2	-3.3	23.2	-6.9	6.8	22.4
Newcastle	-16.4	-0.2	18.9	-6.3	7.6	23.6	-17.8	-2.1	16.8	-6.2	7.6	24.2

Table 5.3: 2030’s percentage changes in rainfall based on wettest day analysis

Scenario	Medium						High					
Season	Summer			Winter			Summer			Winter		
Probability	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Leeds	-22.0	-3.9	18.0	-0.8	12.0	27.5	-21.9	-3.3	18.5	-0.3	13.1	29.6
Manchester	-16.9	0.6	21.3	-2.4	10.5	25.8	-16.9	0.9	22.5	-1.9	11.4	27.5
Birmingham	-18.4	0.4	23.2	-5.4	10.5	28.6	-18.6	0.7	24.4	-5.4	11.5	32.6
London	-28.6	-6.3	21.0	-2.7	12.2	31.4	-28.5	-6.1	22.5	-3.8	13.1	35.8
Glasgow	-13.4	0.1	15.1	-3.2	7.4	19.4	-12.9	1.0	16.2	-3.1	8.0	21.8
Canterbury	-29.3	-7.0	21.2	-2.6	11.5	28.5	-29.0	-6.8	22.2	-5.1	10.2	28.2
Newcastle	-20.9	-4.2	15.2	-2.0	13.6	32.3	-20.5	-3.8	15.5	-1.5	14.8	34.7

Table 5.4: 2050’s percentage changes in rainfall based on wettest day analysis

Due to the current inability of the UKCP09 projections to adequately predict changes in convective rainfall, the summer values are not realistic, and this is borne out by the summer 50% probability values which are low, and in a number of cases negative. The winter rainfall values will be more realistic due to the preponderance of frontal rainfall in winter.

There are variances in the change factors across the UK, with the Glasgow figures being lower than the rest. For the 2030s the range in winter 50%ile uplifts is between 5% and 7.6%, and between 15 and 24% for the 90%ile probability.

For the 2050s the range in winter 50%ile uplifts is between 8% and 15%, and between 22 and 35% for the 90%ile probability. The equivalent EA/DEFRA guidance (2011) for uplifts for this period would have been 10%, with an upper end estimate of 20% and a lower end estimate of 5%.

The recommended uplifts from the CL10/A205 project, Rainfall intensity for sewer design, 2015, are considerably higher than either of the EA/Defra guidance or the UKCP09 wettest day analysis, due to the attempts in the research to take account of potential changes in convective rainfall intensities. Potential uplifts for varying event durations have been shown, but there is some inconsistency in the changes. The values are annual values and no attempt has been made to split the values between seasons."

Given the wide range of potential uplifts, it is recommended that sensitivity analysis is undertaken with a final choice being taken based on the consequences of failure.

5.4.2 Time Series Analysis

The following are the requirements for a climate changed rainfall series:

- It would be preferable for the climate change series to be based on the existing rainfall series. A number of historic rainfall series may be available, and to use a different version of reality may be confusing, giving a different version of the base climate.
- The new rainfall series must be usable. Due to the run times associated with deterministic models, it is not practical to run extremely long timeseries. The UKCP09 weather generator develops 100 number 30 year rainfall series for both the current climate and the future climate, so the direct use of the weather generator outputs will not be possible with deterministic models.
- Some models use multiple linked historic rainfall series which allows an element of spatial variability across the catchment. The climate changed rainfall series must keep this spatial variability.
- The new time series must take account of changes in antecedent conditions due to increases or decreases in catchment wetness and changes in evaporation.
- The new time series must be capable of taking into account changes in the frequency and duration of rainfall events, and not just changes in rainfall intensity.
- The climate changed rainfall series should use as much of the probabilistic nature of the climate change projections as possible, taking account of the run-times of deterministic models.

It is recommended that an approach based on the perturbation of baseline rainfall series using climate change factors is used. This would require the development of a set of adjustments that can be applied to historic rain gauge observations to produce synthetic future time series data. The adjustments would need to relate to both intensity change for specific durations and periodicity and frequency of change in rainfall events.

This approach is consistent with an approach described by Olsson et al (2009) in which Delta Change Factors (DCFs) are calculated to represent the expected future change of some key precipitation statistics. In Olsson's study, short-term precipitation from climate projections were analysed in order to estimate DCFs associated with different percentiles in the frequency distribution of non-zero intensities. The DCFs can then be applied to an observed time series, producing a realisation of a future time series.

It is likely at the present time this will be based on UKCP09 outputs, either based on daily rainfall or hourly rainfall.

It has generally been assumed, and recent research has confirmed that any use of UKCP09 data will show an under-prediction of convective rainfall intensities, particularly in summer. At present there is insufficient data from models explicitly representing convection to provide a robust alternative to UKCP09 outputs, but this will change as more information becomes available.

The use of the tools developed in the UKWIR project 10/CL/10/15 does not meet the requirements for a usable time series, the use of the existing rainfall series or the multiple location series.

The use of a standard uplift in intensities is not an option as it takes no account of the change in frequency and duration of rainfall events.

The use of the tool developed in the WRc portfolio project meets the requirements except that it will only give an average change in climate. The user could use the tool with a particular subset of probabilities (e.g. 90%) from UKCP09 to take account of the probabilistic nature of the climate change projections but in practice this would be time consuming.

A recent project for a WASC has developed climate changed perturbed series based on the use of a sample of 100 number 100 year daily series from the weather generator at seven strategic locations. A total of twelve series have been developed, with a 10%, 50% and 90% probability series being developed for the 2030s and 2080s, for both the medium and high emission scenarios. Each series is 25 years in length. In practice the use of twelve rainfall series with a large model will be extremely time and resource consuming, and it is anticipated that the modelled scenarios will be based on attitude to risk, sensitivity of location and current understanding of emissions.

It is recommended that the development of climate change perturbed rainfall timeseries are carried out by experienced individuals with expert knowledge of the subject, due to the possibilities of making inappropriate use of the climate changed data.

There will be a need to recalculate antecedent conditions for the new series. This will require a re-assessment of evaporation and in certain instances calculation of SMD values. This can be done with the use of a simple MORECS type soil model. Evaporation changes are discussed in section 5.7.

5.5 Changes in Temperature

When carrying out water quality studies, changes in temperature can be significant in dissolved oxygen calculations.

An output from UKCP09 is change in mean air temperature. Up to 10,000 samples of monthly climate changed temperature can be obtained on a monthly level for each of the three emissions scenarios, for any of the seven time periods. From this dataset, mean changes and any other percentile probabilities can be determined.

5.6 Changes in Evaporation

PET is a parameter available in the UKCP09 projections, as part of the weather generator output. As temperatures are projected to increase, so evaporation is projected to increase also. Data is calculated at a daily timestep.

It is recommended that an average value of the change in evaporation is calculated, based on the variance between control values and scenario values.

As an indicator of the potential changes in PET, outputs from a regional climate change assessment has been included in Table 5.5. This assessment has been made of the changes in evaporation for each of five areas in the North West of England for the 2030s medium emission scenario, based on UKCP09 projections. Calculations have been rolled up to monthly averages.

As a rule there is little change in evaporation in winter and up to 0.5mm/day increase in summer.

Suitable amendments can be made to the sine curves detailed in section 4.3.3.

	Average changes in daily evaporation (mm)					
MONTH	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
1	0.03	0.05	0.03	0.02	0.02	0.03
2	0.06	0.07	0.06	0.05	0.06	0.06
3	0.15	0.17	0.16	0.15	0.17	0.16
4	0.20	0.22	0.20	0.18	0.18	0.20
5	0.25	0.28	0.26	0.27	0.31	0.27
6	0.44	0.45	0.44	0.41	0.49	0.45
7	0.38	0.42	0.40	0.40	0.41	0.40
8	0.40	0.42	0.41	0.43	0.40	0.41
9	0.18	0.20	0.18	0.21	0.22	0.20
10	0.09	0.12	0.09	0.11	0.12	0.10
11	0.07	0.10	0.08	0.08	0.10	0.09
12	0.07	0.08	0.07	0.06	0.07	0.07

Table 5.5: Example changes in daily evaporation in the North West of England for 2030s medium emission scenario.

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Amendments

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