

## 08 – The importance of using time series rainfall for analysis or design of sewerage systems

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The use of time series rainfall, whether continuous or separate events, for analysing sewerage systems captures much more information than the use of design rainfall events. So why is the use of time series yet to become standard practice? Design events have been the principal method of analysis since simulation modelling was invented for two reasons; computational effort using time series was far greater than using time series information, and secondly because the length of recorded data is usually insufficient to carry out an effective analysis of the performance of sewers under extreme conditions. These two constraints no longer apply. All-nodes models of most sewerage systems run sufficiently quickly that run-time is rarely an issue, and stochastic time series generation provide very effective means of extending all the hydrological characteristics of recorded data sets.

What is equally important to understand is that the presumption that design rainfall provides accurate information on the exceedence frequency for a certain depth of a rainfall event of a particular duration is not necessarily accurate. Methods of extreme value analysis, curve fitting and extrapolation of information spatially as well as temporally can result in considerable uncertainty in the accuracy of the design depth. Other issues such as assumptions on the value of Areal Reduction Factor (ARF), seasonal correction factor (SCF) and selection of appropriate antecedent wetness condition (API) for runoff models all add to the uncertainty as to the accuracy of the analytical results obtained.

The paper will provide a complete overview on time series rainfall and why we should move to its use in preference to the use of design storms. Certain types of analysis can only be carried out using time series – vegetated SuDS systems, real time decision assessment, variability of Bathing Beaches compliance to water quality standards, present day or future performance of CSOs and much more.

### 1. INTRODUCTION

A paper on the benefits of using time series rainfall (TSR) for drainage design and analysis has to be made in the context of the alternative approach; the use of design storm events. This paper not only wants to promote the fact that time series is essential for most drainage analyses, it highlights the many limitations of the use of design events and challenges the industry by suggesting that they are not fit for purpose for many of the complex topics that drainage has become.

It is important to recognise that rainfall is not the actual input used by engineers in analysing drainage systems; a discussion on the merits of alternative rainfall methods cannot be made without including the subject of runoff models as it is surface water runoff rates and volumes which are used in the assessment of drainage systems.

This paper provides a holistic look at the subject of drainage analysis using rainfall and runoff models and includes:

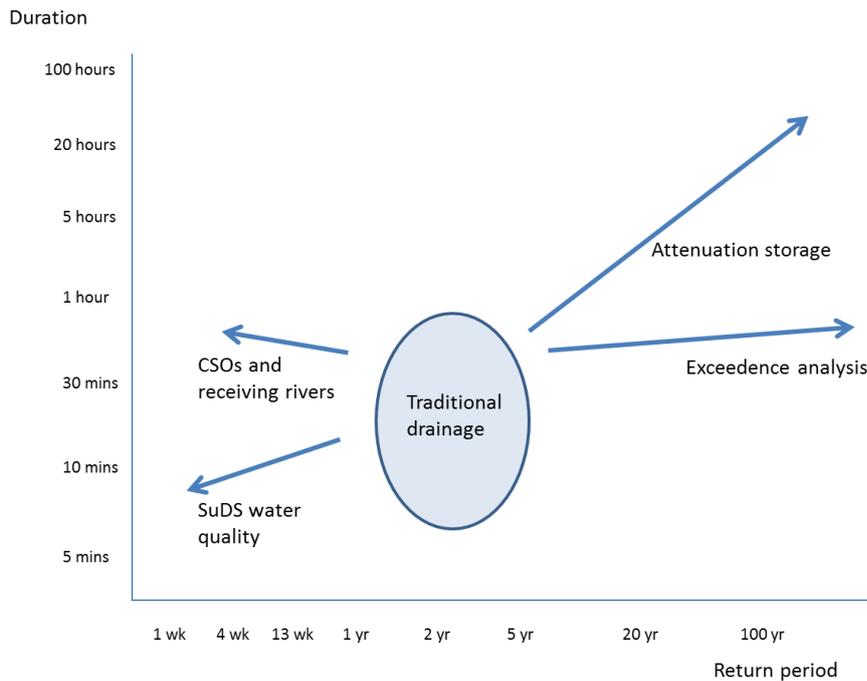
- A brief historical review of rainfall runoff drainage modelling with design storms;
- What drainage engineers need to be able to do with drainage models in order to provide appropriate solutions to meet environmental and societal requirements;
- How time series rainfall meets the needs of modern drainage engineering;
- How rainfall time series data is produced;
- How rainfall time series should be used;
- An example of the use of time series on SuDS systems performance.

Time series rainfall aims at replicating actual rainfall behaviour that takes place while design events are processed rainfall information to only provide information on the frequency of an extreme rainfall condition related to a specific duration. Drainage design in the past has been almost exclusively driven by the need to address flooding and as most events that occur are very small and will not cause flooding, it is quite reasonable to take the view that running a time series is largely a waste of time. Furthermore very few rainfall records are long enough to provide a data set with sufficient extreme events in them so as to test or design a drainage system for a specific extreme return period criterion. This simple logic is a valid argument where the objective is the simple one of urban flooding where drainage systems are designed to serve paved surfaces for short duration intense events.

However the drainage engineer's remit has changed significantly in the last 50 years and many aspects of drainage analysis are not adequately served by the use of design rainfall events. The key issues which start to challenge the effectiveness of just using design storms are:

- The influence of pervious runoff which is dependent on not only the size and length of rainfall event of interest, but also the antecedent conditions prior to an event;
- The joint probability aspects of any event as this is not independent of other system states and processes; and
- The change in approach to drainage in addressing the various challenges of protecting people and the environment.

Figure 1 illustrates the expanding hydrological range of relevance to present day drainage engineering.



**Figure 1:** The expanding range of the drainage engineer's hydrological domain

In addition to drainage practices changing and making the use of time series more relevant, it is also worth challenging the assumption that design rainfall is necessarily the benchmark against which everything has to be measured. Design rainfall depths are derived by processing rainfall data and hyetograph profiles are used to reflect the best approximation for representing the intensities of real rainfall. Processing of any data and making assumptions automatically introduces the approximations and loses information from the original data. A recognition that design storms are not necessarily an accurate measure of rainfall at any location is also required, especially for more extreme rainfall. As for the limitations of a time series due to the length of a record from a gauge, this also applies to design rainfall and is only overcome by aggregating rainfall data from different gauges and making suitable assumptions regarding independence of the information.

Table 1 is a comparison rainfall depths for several locations in the southeast of England for the three rainfall models: FSR, FEH and FEH13. Although they are based on different data periods, FEH13 is only based on an extension of the original FEH data and the differences are therefore rather greater in some instances than one might expect. This illustrates the need for a degree of scepticism that a design rainfall depth is “gospel” for any given return period and duration.

**Table 1:** A comparison of the 1:30 year rainfall depths for several locations in south England

	FEH13 Rainfall depth (mm)	FSR 1:30 yr, 1 hour Rainfall depth (mm)	Percentage increase in rainfall to FSR %	FEH 1:30 yr, 1 hour Rainfall depth (mm)	Percentage increase in rainfall to FEH %
Colchester: 1hr	28.0	27.3	+2.6%	35.2	<u>-20.5%</u>
Colchester: 6 hr	46.7	43.3	+7.9%	50.8	-8.1%
Milton Keynes: 1hr	32.3	27.3	<b>+18.3%</b>	32.5	-0.1%
Milton Keynes: 6hr	51.3	43.3	<b>+18.5%</b>	50.1	+2.4%
Peterborough: 1hr	35.2	28.7	<u>+22.6%</u>	33.7	+4.5%
Peterborough: 6hr	61.7	45.4	<u>+35.9%</u>	52.2	<b>+18.2%</b>
Norwich: 1hr	34.6	28.7	<u>+20.6%</u>	34.6	+0.0%
Norwich: 6hr	56.5	45.4	<u>+24.4%</u>	49.1	<b>+15.1%</b>
Gt. Yarmouth: 1hr	33.2	30.4	+9.2%	34.9	-4.9%
Gt. Yarmouth: 6hr	54.1	48.1	<b>+12.5%</b>	52.9	+2.3%
Skegness: 1hr	36.7	27.3	<u>+34.4%</u>	32.4	<b>+13.3%</b>
Skegness: 6hr	57.9	43.3	<u>+33.7%</u>	53.9	+7.4%

Addressing the point regarding the limitation of insufficient data in a record for time series, there are now many gauges in the UK and Ireland which extend to 10 years or more, but which are not sufficient for meeting the 30 year flooding criteria which is commonly used for sewerage flood analysis. In addition data is often limited to hourly data which is an inadequate level of resolution for drainage analysis. These limitations are no longer an issue with the development of stochastic rainfall models which have been shown (Audacious 2006) to be accurate in replicating and extending data records to 100 years.

## 2. THE (RECENT) HISTORY OF URBAN RUNOFF MODELLING

This section looks briefly at the history of urban drainage modelling and runoff models associated with the last century and particularly the Wallingford Procedure models. The paper is extremely brief in covering only the key salient points associated with this paper.

### 2.1 Mulvaney (1850) and the Rational Method

Life has moved on a long way since Mulvaney (1850) and Lloyd Davies (1906) and the early version of Sewers for Adoption which specified pipe-full sizing to return periods of 1, 2 or 5 year return periods. Although drainage has been built back to the Romans and beyond, current practices of sizing pipes in relation to estimated rates of runoff effectively originated in Ireland with Mulvaney. The credit for the Rational Method is often associated with Lloyd Davies (1906), but I think the Irish should take the credit of providing the cornerstone of the science of drainage.

Runoff factors were, (and still are) normally applied as 100% and 0% for paved and pervious surfaces which is reflected in Sewers for Adoption to the present day (issued by Sewerage Undertakers in the UK for adopting sewers built by developers). The logic for this is perfectly sound; times of concentration for most drainage systems are measured in minutes so pervious contribution is unlikely to be significant for these design events.

#### **Key Points / lessons learnt**

- Urban drainage traditionally assumed 100% and 0% for paved and pervious surfaces respectively.
- This means that the return period of the flood event is the same as that of the rainfall event.

## **2.2 The Wallingford Procedure (1983)**

The Wallingford Procedure was led by HR Wallingford (Hydraulics Research Station at the time) with the support of the Institute of Hydrology (IoH). IoH led the work on the rainfall and runoff work. This research work resulted in a step change in the approach to drainage analysis by introducing hydrodynamic simulation modelling.

### **2.2.1 The Old PR equation**

The Wallingford Procedure runoff model (DoE, 1983) was developed at the time of the original simulation model WASSP. Unlike the Rational Method runoff model which requires selection of an educated guess at a suitable runoff coefficient by the drainage modeller, the Wallingford Procedure concept was to provide the user with a fixed “correct” value for the proportion of runoff based on the correlation parameters of the proportion of paved area, the catchment area and the soil characteristics which also dictated the catchment wetness factor. A calculation of PR was made for each of the observed events for verification of the network and then for a design value by based on the appropriate value for the wetness term UCWI.

The Wallingford Procedure runoff model (referred to as the Old PR equation) is:

$$PR = 0.829PIMP + 0.078UCWI + 25SOIL - 20.7$$

Where:

PR = percentage runoff

PIMP = percentage of impervious area within catchment

SOIL = an index of soil characteristics

UCWI = urban catchment wetness index

The original runoff model produced a value which was used as a constant proportion of runoff throughout the event with all the runoff allocated to the paved areas unless it exceeded 70%, above which the percentage increase in runoff was split equally from paved and pervious surfaces (so a model with a paved runoff coefficient of 73% would also have runoff from pervious surfaces of 3%).

The design value UCWI was set initially as 100, but this was changed later to produce separate summer and winter curves related to SAAR to take account of the higher levels of wetness in winter.

#### **Key Points / lessons learnt**

- The Old PR equation was shown to under-predict pervious runoff during wet conditions and also that the assumption of a constant runoff rate through the event was incorrect.
- Addition of pervious area did not increase runoff significantly and sometimes reduced it.

### 2.2.2 Variable UK (New UK) runoff model

The New UK runoff model was developed in response to the shortcomings of the Old PR equation.

The model introduced the concept of effective impervious area (the proportion of paved area which generates 100% runoff) and the remaining non-effective paved surface is lumped in with the pervious area which is all treated equally as the pervious component. Although the runoff proportions for paved and pervious runoff were now being produced by the runoff model rather being distributed in the network simulation analysis, the pervious area runoff factor is still a combination of paved and pervious surfaces.

$$PR = IF \times PIMP + (100 - IF \times PIMP) \times \left( \frac{NAPI}{PF} \right)$$

Where:

*PR* = percentage runoff

*PIMP* = percentage of impervious area within catchment

*IF* = effective impervious area factor

*NAPI* = net antecedent precipitation index

The calculation of wetness of an event was changed significantly being entirely a function of the soil type and the last 30 days of rainfall. The analysis also differentiated between soil types by using different decay factors in the calculation of NAPI.

Key differences between the Old and New PR equations are:

- There is variable runoff (normally increasing depending on intensity) from pervious surfaces as the event progresses;
- Although guidance on the value of IF was given and a default value for PF provided, the engineer has to make educated guesses on these factors; this started blurring the line of verification rather than calibrating models;
- More pervious area resulted in more runoff taking place. The 10m rule was turned on its head to avoid too much runoff taking place from pervious surfaces.
- The wetness term NAPI was well defined in calculating its value for observed events, but a formally agreed method for a design value has never been arrived at. The Margetts paper (2002) is generally used. Design values of NAPI are derived for each soil type and correlated with SAAR. Two seasonal values are used for summer and winter design events.

#### Key Points / lessons learnt

- The New PR equation addressed the limitations of the Old PR equation, but opened the Pandora's box of pervious runoff becoming a dominant feature in modelling;
- The concept of verification rather than calibration remained even though there was a need for engineers to define certain runoff parameters;
- The '10m rule' was still recommended though auto-creation of models was encouraging all-area take-off methods to be used;.
- A demand for a new runoff equation to address limitations of the New PR equation resulted in the commission of the UKWIR equation in 2012.

## 2.5 The UKWIR UK runoff model (2014)

The UKWIR UK runoff model was produced in 2014 to address a number of limitations of the variable UK (New PR) runoff model. The following are some of the key points addressed:

- Models calibrated using summer conditions generally under-predicted runoff for winter conditions;
- There were no scientifically approved value for the parameter NAPI for use with design storms;
- There are improved soil characteristic datasets (HOST categories) available digitally for the UK;
- The variable UK runoff model incorrectly assumes that runoff occurs from pervious areas for all events, however small the event;
- It is not correct to assume that the non-effective paved surface component contributes runoff in the same way as a pervious surface.

As well as addressing these issues, the development of the UKWIR equation also took into account the current and likely future development of runoff tools in urban drainage modelling for both 1D and 2D modelling, and the trend towards the use of continuous rainfall time series and away from design storms. The UKWIR UK runoff model is shown below.

$$PR = \sum_{n=1}^N \left[ IF_n \times PIMP_n + (1 - IF_n) \times PIMP_n \times \frac{PI_{pv}^\beta}{PF_{pv}} \right] + \left[ (1 - PIMP_{TOTAL}) \times \frac{((NAPI_s + PI_s)^{Cr} \times SPR)}{PF_s} \right]$$

Where:

PR = percentage runoff

PIMP = percentage impermeability of the sub-catchment

IF<sub>n</sub> = effective impermeability factor for a particular paved surface type

β = power coefficient for paved surface

PI<sub>pv</sub> = precipitation index for paved surface with rapid decay coefficient

PF<sub>pv</sub> = soil store depth for paved surface

SPR = standard percentage runoff (for both WRAP and HOST soil classes)

PI<sub>s</sub> = precipitation index for pervious surface with decay coefficient

NAPI<sub>s</sub> = antecedent precipitation index for a particular pervious surface type (with 30-day decay coefficient)

Cr = power coefficient for pervious surface

PF<sub>s</sub> = soil store depth for a particular pervious surface type

The UKWIR model has not yet been taken up into mainstream use and the New PR equation is still generally used. This may be because the model looks complex and there are many more parameters in it. In practice it is very similar in concept to the New PR equation but it splits the paved area runoff completely from the pervious area, and allows both surfaces to have variable runoff characteristics.

### 3. A CHANGING WORLD OF DRAINAGE ANALYSIS REQUIREMENTS

It can be seen from the review of the use of design storms that the convenience of using one rainfall event (of an appropriate duration) is very convenient, it has become more and more obvious that the antecedent conditions are fundamental in many instances to obtaining an accurate assessment of the runoff. However in using design storms not only is the issue of antecedent wetness an important issue, there are many other aspects that are discarded by using design events.

Time series rainfall captures all the characteristics of rainfall, which are often essential for many of the challenges faced by today's drainage engineer. These include:

- Seasonal characteristics of rainfall events;
- Antecedent conditions (previous rainfall and dry periods) providing catchment wetness;
- Variability of rainfall (wet and dry years / seasons);
- Spatial rainfall.

These characteristics enable various forms of analysis to be carried out using time series rainfall where design events cannot be used. These include:

- Pervious runoff is more likely to be correct as the seasonal characteristics of rainfall automatically captures aspects such as antecedent conditions, rainfall size and evaporation as well as preserving the periods when events might be intense or long periods of drizzle. There is no need to consider design wetness factors, seasonal correction factors and hyetograph profiles;
- UPM assessments of SWO impacts on rivers (Intermittent or Fundamental standards) or other river impact studies requires the information captured in the variability of TSR;
- Bathing Beaches water quality compliance takes into account annual variability in recognition of there being wet and dry years;
- The joint probability issue rainfall following dry periods (with low river flows and high build-up of pollutants on the surface) is automatically captured. this avoids the issue of using rainfall return periods and choice of an antecedent dry period or wetness parameter value. This means that catchments with different types of soil, and proportions of pervious area and runoff characteristics can be analysed for flood frequency (or other performance measure such as infiltration or pollution) rather than assume it to be the same as that of the rainfall frequency;
- The joint probability issues of having rainfall taking place and concerns over river levels can be established if models of both systems are used rather than trying to determine the statistical dependency relationships. Time series will enable the representation of all aspects of the seasonal or other characteristics of a second or third system state;
- Time series rainfall captures rainfall shapes and therefore the attenuation during less intense periods. More accurate volumetric and frequency analysis for systems such as

SWOs can be made. In some networks reverse flow takes place to SWOs and spills can be very different to that assessed using design events;

- Spatial rainfall is now possible by combining radar and raingauge information and has been shown to achieve high levels of accuracy using recently developed techniques. It is not possible to use design storms for assessing spatial rainfall impact. Research has shown that spatial rainfall is essential for analysis of large catchments (greater than 350 to 500ha (R. Kellagher 2010));
- Time series rainfall assists in more accurate water quality modelling due to varying concentrations in sewerage flows as well as the mass build-up of sediment and washoff of pollutants on the surface;
- The use of time series rainfall enables the development of RTC rules for active sewer system management which design rainfall cannot be used to develop.

#### **4. HOW TO DEVELOP TIME SERIES RAINFALL**

Time series rainfall can comprise either recorded data or using the data to produce a calibrated stochastically generated series. In Ireland, unlike the UK, data is free and therefore the choice between the two approaches is based on technical merit of which approach is best. In either case there is a need for a minimum of 10 years of data; 10 years is desirable for obtaining an adequate representation of annual and event variability. 10 years is also the minimum duration needed to produce an accurately calibrated stochastic rainfall data set.

Theoretically a recently recorded rainfall data set is the most accurate information available to assess the performance of a drainage system. The main limitation is whether the information is available as tipping bucket or processed 5 minute information, as any lower resolution (usually 1 hour) is inadequate for assessing the performance of drainage systems. However there is a greater need to check the information more closely to capture any anomalies of the raingauge data.

Any processing of data results in a loss of some information and accuracy. However stochastic model testing (Audacious 2006) has shown that these tools are quite accurate and checks should always be made to show that the stochastic data reflects the characteristics of the original data. There are several advantages of producing stochastic rainfall data and these include:

- Aberrations of a few events in an observed data set get “smoothed” out as the tool measures various characteristics of shape, intensity and other measures to reproduce a stochastic series;
- Hourly data is used to generate a 5 minute series so if a gauge does not have high resolution information it does not preclude its use;
- Generated data can be extended to 100 years allowing analysis of flooding performance, flood exceedence duration and depths, design of attenuation storage systems, assessment of interaction with tides and extreme river flows and so on.

Having generated or produced a time series data set it is important to carry out a range of analyses to understand its characteristics, and these include:

- Making an assessment of the annual and seasonal variability in rainfall depth for both stochastic and observed data;
- Comparison of extreme value analysis for 1 and 6 hour events (and possibly others depending on the use of the rainfall data) against FSU information and the observed data set;
- Assessment of the number of events in bands of total depths;
- Assessment of the largest 10 events and checking their approximate return periods against FSU information.

It is important to recognise that the results of an extreme value analysis will often show a difference to FSU values. FSU data is processed gauge data and smoothed across the country. It is therefore no more likely to be right (and probably less so) than the specific gauge analysis as long as the gauge has been checked and shown to have recorded good data.

## **5. HOW TO USE TIME SERIES RAINFALL**

As with any data, time series rainfall must be used correctly. Some examples of misuse are:

- Selection and use of a ‘typical’ year by basing the selection on the year which sums to a depth closest to that of SAAR and or the number or events or other single measure;
- Selection of a few events as being ‘typical’ based on a measure of its effect on a particular part of the drainage system;
- Use of an inter-event dry period such as one hour to divide up storms; this is too short for systems with long travel times and systems with storage.

Rainfall that takes place in any month of any year will tend to be very different to that month in the subsequent two or three years. The variability of rainfall each year is now recognised in many regulatory requirements such as the Bathing Beaches or Water Framework Directives. Assessments of compliance to some Directives specifically cater for an analysis based on a continuous period of years. Therefore the representation and use of rainfall in a series should reflect this and the variability in rainfall that occurs. This means the mean and distribution of rainfall depths, numbers of events etc. (annual / seasonal / monthly) should all be evaluated to show that it is representative.

This does not preclude the use of a selection of some rainfall events from a series. Limiting the selection to events greater than say 3mm or 5mm for SWOs spills analysis or greater than 30mm from an extreme series for flooding analysis will reduce the number of events to be run dramatically without losing any accuracy in the analysis of the system state. The choice of the threshold should be based on an understanding of the drainage system being analysed so that all spills or flood events are captured.

## 6. AN ILLUSTRATION OF THE DEVELOPMENT OF TSR IN IRELAND

Buncrana (R. Kellagher 2017) has recently been studied for improvements needed to comply with the Wastewater Treatment Directive and the performance of the SWOs have had to be evaluated using a 10 year time series. Unfortunately there was no gauge data close to Buncrana and there was a choice of four gauges in the region that might have been suitable. Some of these were in Northern Ireland.

The gauges were assessed for their data availability (resolution and length), as well as key metrics from FSU data for both the town and the gauge locations. In addition comparisons were made of depths for a range of return periods and durations. As a result of this the gauge at Finner was selected even though the data duration was for only 6 years.

**Table Error! No text of specified style in document.:** Buncrana FSU rainfall depths (mm)

Return period	Rainfall Duration		
	1 hour (mm)	3 hour (mm)	6 hour (mm)
2 year	11.7	17.6	22.9
5 year	15.7	22.9	29.1
10 year	18.7	26.8	33.5
30 year	24.1	33.4	41.1
100 year	31.4	42.2	50.8

Source: Flood Studies Update web portal <http://opw.hydronet.com/> at coordinates (236000, 432000)

**Table 3:** Finner FSU rainfall depths

Return period	Rainfall Duration			
	1 hour (mm)	3 hour (mm)	6 hour (mm)	24 hour (mm)
2 year	12.1	18.2	23.7	38.2
5 year	16.5	24.1	30.6	48.0
10 year	19.8	28.3	35.5	54.9
30 year	25.9	35.8	44.1	66.7
100 year	34.1	45.9	55.3	81.7

Source: Flood Studies Update web portal <http://opw.hydronet.com/> at coordinates (192000, 360000)

The hourly data was then used to produce a 100 year rainfall time series using TSRsim. A rolling period of 10 years through the 100 year data set was used to select the most appropriate 10 year period based on the mean and distribution of the data for various metrics as well as assessment of the values of the top 5 events. Extreme value analysis of rainfall depths for a range of return periods and durations was also carried out and compared with observed data and FSU values.

The “peaks over threshold” analysis shows that the FSU values are well above the best fit of the gauged data for the 1 hour events, it is quite close to both the 3 hour and 6 hour events (particularly for the low return periods), but below for the 24 hour events. Although it is important to highlight that the gauged data is only 6 years in length and therefore the fit above a two or three year return period must be treated with caution, the difference to the FSU values for the short duration rainfall and more extreme rainfall is surprisingly large (see Figures 2, 3, 4 and 5). Usually fits are closer than this.

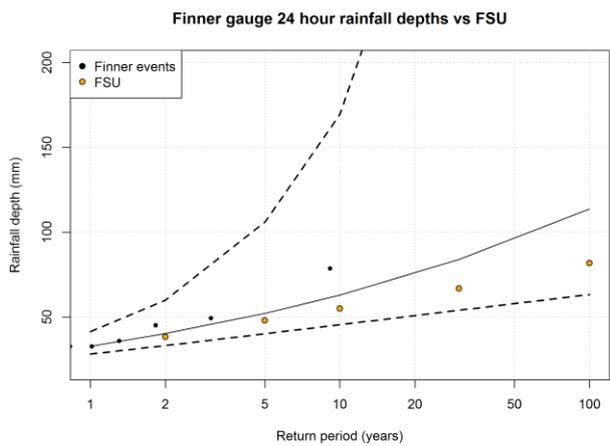


Figure 2: GPD fitted to Finner 24 hour event depths compared to FSU 24 hour rainfall depths.

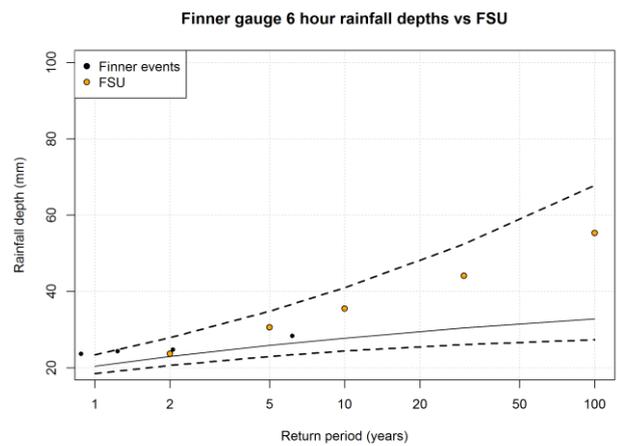


Figure 3: GPD fitted to Finner 6 hour event depths compared to FSU 6 hour rainfall depths

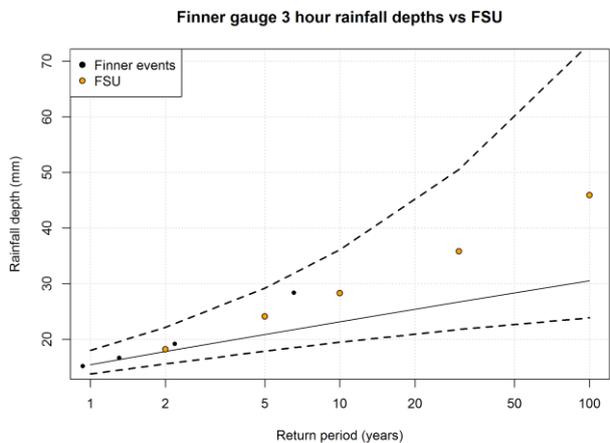


Figure 4: GPD fitted to Finner 3 hour event depths compared to FSU 3 hour rainfall depths.

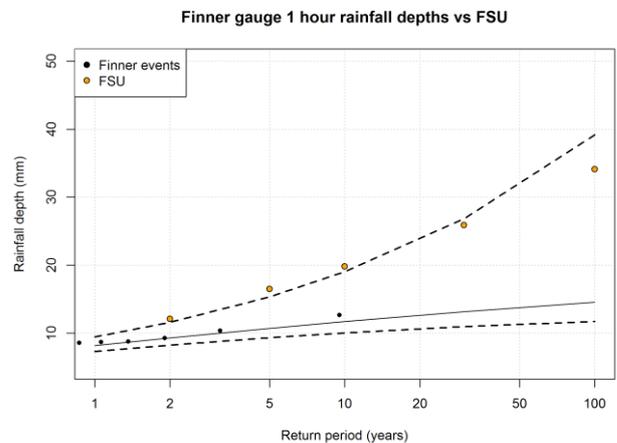
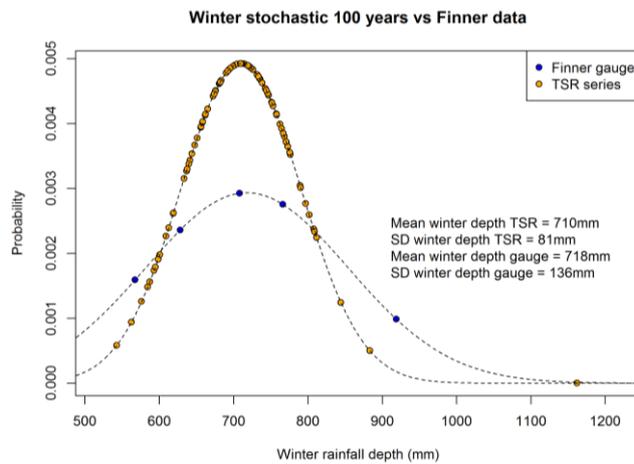
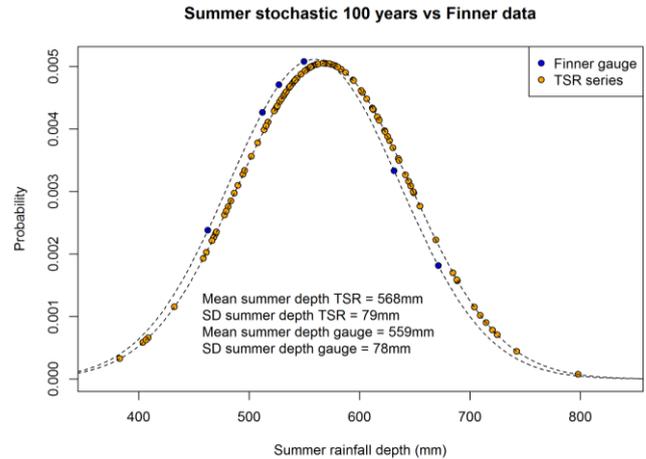


Figure 5: GPD fitted to Finner 1 hour event depths compared to FSU 1 hour rainfall depths.



**Figure 6:** Winter rainfall normal distribution for 100 year data series vs Finner rainfall gauge.



**Figure 7:** Summer rainfall normal distribution for 100 year data series vs Finner rainfall gauge.

As for the observed data, the stochastic 100 year time series was also analysed for extreme values for the four durations. The results were very similar.

Annual and seasonal rainfall depths were calculated for the 100 year time series and compared with the Finner gauged data. The results were plotted as normal distributions and are shown in **Error! Reference source not found.** The summer normal distribution of the 100 year time series and the gauged data match almost perfectly with negligible differences between standard deviations and means. The winter normal distributions have close mean values (710mm and 718 mm respectively), but very different standard deviations which means that the variability of winter rainfall depths for the stochastically generated data is less than experienced in practice.

## 7. INTERCEPTION ANALYSIS - AN ILLUSTRATION OF THE USE OF TIME SERIES RAINFALL

An analysis was carried out (R. Kellagher 2014) on four different types of SuDS: Rainwater harvesting, permeable pavements, swales and green roofs. Data from a continuous period of 10 years of rainfall at 2 minutes resolution was used to carry out a probabilistic approach to Interception analysis. Evaporation rate is an important parameter for the analysis of small events. 3 mm/day was used at mid-summer through to 0 mm/day at mid-winter.

The analysis of each of the four SuDS components was carried out with detailed representation of their characteristics in terms of soil store, depression losses, evaporation and infiltration (unless lined) below the SuDS component. Several arrangements such as varying the contributing loading condition (area served) or infiltration rate of each SuDS were tested. Each analysis was run to assess the capability of each arrangement to retain the first 5 mm of any rainfall event using the whole 10 years of rainfall.

A probabilistic criteria for Interception was set that the SuDS needed to retain (prevent any runoff) for the first 5mm of rainfall for 80% of events in summer and 50% of events in winter.

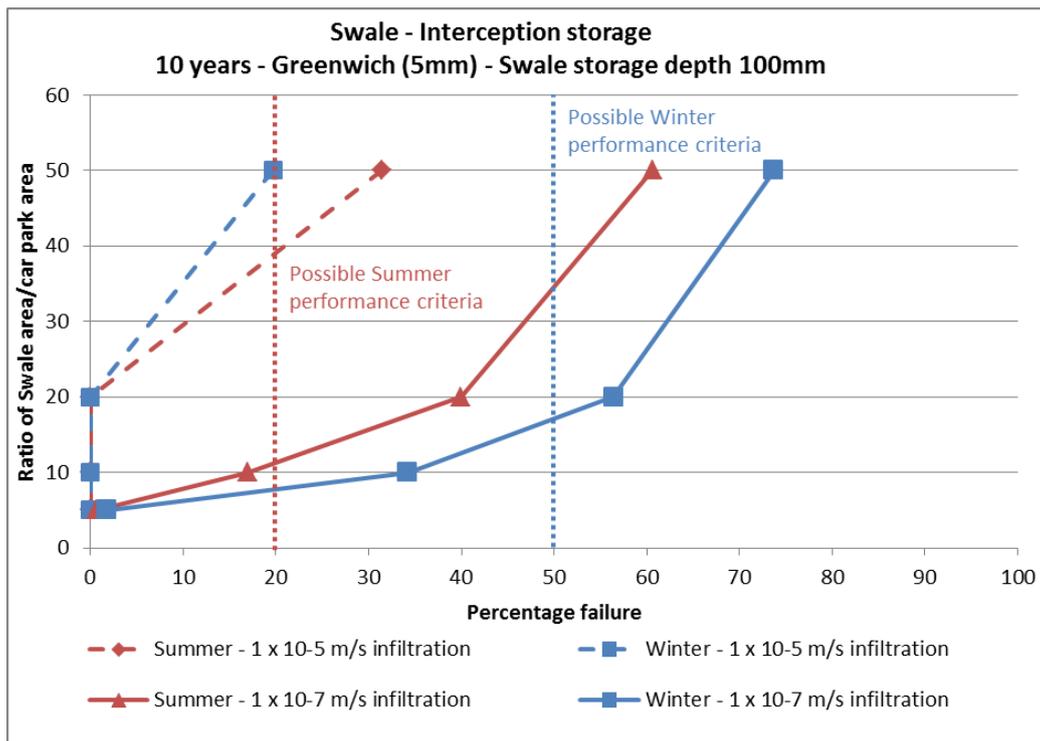


Figure 8: Interception effectiveness of a swale.

Only two illustrations are provided from the study. Figure 8 illustrates summer and winter Interception performance for a swale, based on two assumptions of infiltration rates; one poor one good. The soil store was set at 100mm. The vertical dotted lines are the retention criteria set for compliance. The figure shows that a swale can successfully serve an area of car park equal to 40 times the area of the swale if there is good infiltration below the swale, while nominal infiltration indicates that it would only meet the criteria if it served 11 times its surface area.

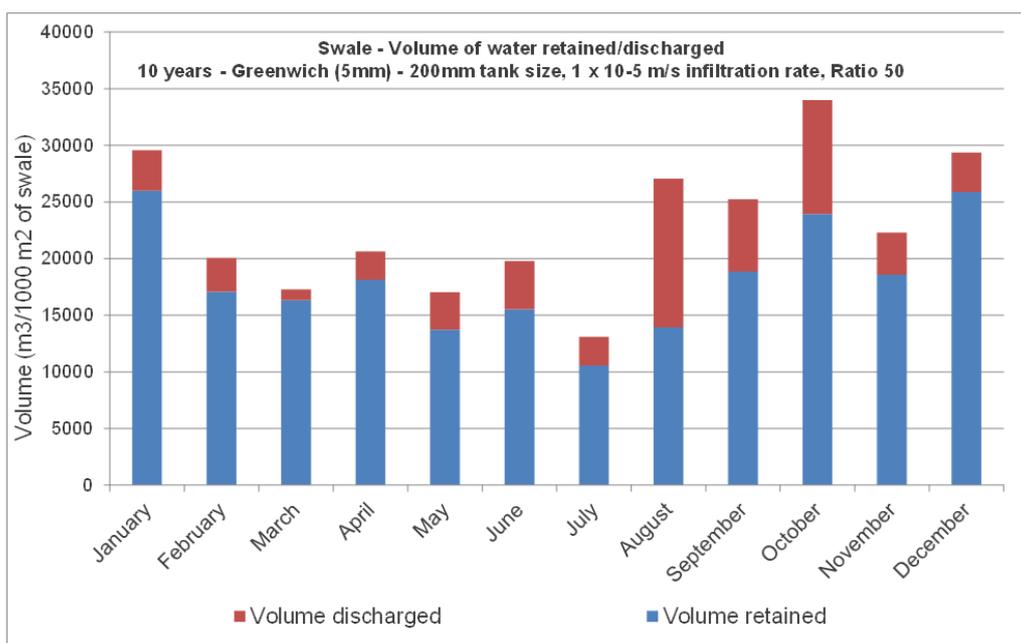


Figure 9: Volumetric reduction of runoff of a swale

Figure 9 shows how the total much of the runoff has been evaporated and infiltrated (the blue bars) with only approximately 15% (the red bars) passing to the outfall. The soil moisture depth in this case has been assumed to be 200mm and infiltration rate is good. The contributing area loading ratio is 50 times the swale area. The graph also illustrates that although winter is traditionally wet, the runoff volume reduction is very high in winter while the bigger storm events in August through to October result in more runoff during these months.

## 8. REFERENCES

- Centre for Ecology and Hydrology (2007). The revitalised FSR/FEH rainfall-runoff method, Supplementary report 1, section 4.3.5 Seasonal correction factors.
- Lloyd-Davies, D.E. (1906). The elimination of stormwater from sewer systems. Proc. Inst. Civ. Engrs. Vol. 164(2) pp 41-67.
- Defra. 2013. Reservoir Safety – Long Return Period Rainfall, Volume 1 Technical Report (Parts 1 and 2), Project: FD2613 WS 194/2/39.
- DOE 1983. The Wallingford Procedure: Winter Rain Acceptance Potential Maps – WRAP maps. (Based on NERC, 1975, Vol. V, 1.4.18(S), revised 1978: FSSR 7). Hydraulic Research Ltd.
- EU Bathing Water Directive (2006).
- EU Water Framework Directive (2000).
- Faulkner, D (1999) Rainfall Frequency Estimation. Flood Estimation Handbook Vol. 2, Institute of Hydrology, Wallingford.
- Fitzgerald, D (2007). Flood Studies Update: Technical Research Report. Vol.1 Rainfall frequency. Met Eireann.
- Institute of Hydrology (1995). The hydrology of soil types: a hydrologically based classification of soils of the United Kingdom. Report IH 126.
- Kellagher, R. (2000). Dublin time series rainfall. Report EX4294. HR Wallingford.
- Kellagher, R. (2005). Audacious - Adaptable Urban Drainage. Comparison on RainSim and TSRsim stochastic rainfall generators benchmarked against observed data. Report SR675. HR Wallingford.
- R. Kellagher (2010). Use of spatial rainfall in urban flood modelling. DTI SAM - System Based Analysis and Management of Urban Flood Risks. Technical Note MCS0441-01. HR Wallingford.
- Kellagher, R. (2014). Supermarket representation for SuDS guidance. Interception storage analysis. MAM7091-RT001-02-00. HR Wallingford.
- Kellagher R. (2014b). Development of the UKWIR runoff model: Main report. 14/SW/01/6. UKWIR.

Kellagher, R. (2016). Urban drainage best practice – A review for Anglian Water. MAR5568-RT001-R03-00. HR Wallingford Ltd.

Kellagher, R. (2017). Wastewater modelling in Ireland – Guidance on rainfall. MAM7651-RT003-R03-00. HR Wallingford Ltd.

Kellagher, R. (2017b). TSR stochastic rainfall generation for Buncrana. 10 year series. MAM7949-RT001-R01-00. HR Wallingford Ltd.

Margetts, J. (2002). IF the NAPI fits.... WaPUG conference, Coventry.

Met Eireann Rainfall Frequency - FSU Volume 1 (2007).

Mulvaney, T.J. (1850). On the use of self registering rain and flood gauges in making observations on rainfall and flood discharges in a given catchment. Trans. ICE Ireland. Vol. 4. No. 2 P. 18.

NERC (1975). The Flood Studies Report, Vol. 2. Meteorological studies.

NERC (1975). FSR Vol. 2, Table 3.9. Variation of M5 ratio of annual rainfall to monthly and seasonal depths as a function of duration and AAR.

Packman, J C (1990). New Hydrology model, WaPUG conference, Coventry, 1990.

WRc plc, (2013). Sewers for Adoption. WRc plc on behalf of Water UK.