# COMMENT ON ESTIMATION OF GREENFIELD RUNOFF RATES

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## ABSTRACT

*In the context of Sustainable Urban Development it is often necessary to estimate design flood runoff from pre development (Greenfield) areas. At present such flood rates are calculated by either a rational method type approach or by a flood estimation formula which is based on catchment characteristics, such as those in FSR/FEH. These formulae are based on data from natural river catchments. Many development sites are of small area, relative to natural river catchments, and do not form complete natural catchments in themselves, many without any surface water features. These differences seriously weaken the applicability of such catchment type formulae to a typical development site. Results of a range of analyses are outlined which demonstrate the difficulties arising from the use of such methodology.*

## 1. INTRODUCTION

The estimation of peak flows on small to medium sized rural catchments is probably the most common design problem in flood estimation and often poses the greatest difficulty due to absence in the majority of cases of gauged (observed) flow data. Design flood estimates are needed for, among other things, the design of bridge openings and culverts, drainage networks and flood improvement schemes and determining flood risk and finish floor levels for developments. It is not possible to define precisely what is meant by small and medium sized catchments, but limits of 5 to 25km$^2$ and 100 to 1000km$^2$ can be taken as general guides. Ungauged flood estimation is considerably more difficult on smaller catchments than larger ones as the variability in runoff characteristics (slope, soil, land use, surface drainage network) become more pronounced and have a more significant effect.

The recent introduction of stormwater management for urban drainage systems has resulted in a requirement for flood estimation at much smaller scales, at the local drainage area scale of 1 to 2 km$^2$ down to the field plot scale of 1 to 10ha (0.01 to 0.1km$^2$). These are required to assess the pre-development (natural greenfield) and post-development runoff rates.

Unfortunately the flood estimation techniques available have not made nor in a lot of cases capable of making this transition to the finer scales. The difficulty becomes more pronounced when the scale is such that the project site does not exhibit any watershed features such as a watercourse or discharge outlet point causing some variables in these flood estimation formulations no longer have a meaning.

The focus of this research is to review commonly used flood estimation methods in terms of their accuracy at the scale for which they were derived and their applicability for estimating greenfield runoff at more refined field plot scales.

## 2. URBAN STORMWATER MANAGEMENT

In recent years it has become the norm to implement Sustainable Urban Drainage System (SUDS) policies to control the rate of storm runoff to watercourses from urban pavements. These systems use various methods to reduce and control storm run-off water as close to its origin as possible, before it enters a watercourse.

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The concept is to either divert surface water runoff from paved areas to groundwater via porous pavements, filter drains, infiltration fields and soakways or to attenuate individually on-site or communally off-site by providing stormwater attenuation storage (refer to CIRIA, 2000 & 2001 for description of options). Attenuation slows down the response time to storm events and reduces the peak runoff rate. It does not however, eliminate or even reduce the increase in runoff volume caused by the impervious area of the development. Infiltration, where feasible, works well as it diverts stormwater away from surface watercourses. The major drawbacks with infiltration devices is the limited design life of an infiltration field (requiring replacement every 10 to 15years) and scarcity of suitable free draining soil.

The objective of storm water management is to mimic the natural Greenfield runoff characteristics of the site. In Ireland and UK a somewhat crude, flood study catchment characteristic equation (IH No. 124 (1994) and FSSR No. 6 (1978) equations), originally devised for a much larger scale of application, is commonly used to define the natural greenfield runoff from a site. In reality natural runoff rates vary considerably from site to site depending on the local site characteristics such as slope, soil type, land-use, drainage features, etc. The catchment scale flood study equations are applicable if the desired effect is to restrict all development lands within the catchment to the catchment average greenfield runoff rate. In the USA and Australia (IEA, 1987) a Rational method type approach is normally adopted for such small scale applications.

Stormwater management through attenuation requires the storm runoff rate to be restricted to a permissible maximum outflow rate which is generally the natural greenfield or brownfield runoff rate from the site. Determining the required attenuation storage involves firstly estimating the greenfield runoff rate for various return periods and the post-development runoff at different return periods and storm durations. Often the policy is to restrict the outflow to the estimated mean annual maximum flood ($Q_{BAR}$) independent of the return period rainstorm event and to provide storage for 50year to 100year return period storm events (Dublin City Council (1998) and Faulkner (1999)).

Implementation of storm water management has in the majority of cases led to individual site-by-site attenuation via the construction of small ponds, underground storage tanks, large storm sewer pipes, and proprietary storm cell pavements with the outflows controlled by a vortex flow control, hydrobreak or other such proprietary devices. The difficulty with individual as opposed to communal storm water storage facilities is the ongoing maintenance and correct functioning of these storage facilities, which often are unable to empty as a result of blockages to the outflow device, and remain in a semi-permanent filled state overflowing without providing attenuation. This is a particular concern with small individual sites where permissible outflows are such that the flow control orifice has to be very small and consequently easily blocked by floating debris (such as paper bags or vegetation).

In certain cases, storm attenuation by storage can produce an adverse impact on streamflow, sufficiently slowing the storm runoff so as to coincide with the slower responding upstream rural catchment flood peak and thus for certain storm profiles producing higher combined flows (Faulkner,1999).

Table 1 presents the permissible outflows calculated by the IH 124 flood estimation equation for various site/catchment areas and Soil type classes. Also included is the storm attenuation storage based on a 50year storm event and an outlet permissible discharge equivalent to $Q_{BAR}$ from the impervious area. The critical rainstorm duration and the duration for the storage to empty are also calculated. In the storage calculations a simplistic approach which partitions the impervious and pervious (grassed) areas is adopted for illustration purposes. The impervious area is assumed to contribute at 100% to the storage whereas the pervious area is assumed to runoff at the natural greenfield rate and is not collected by the urban drainage. Within an urban development the soft/grassed areas are unlikely to exhibit the same pre-development runoff features as they are generally altered by landscaping, changes in soil drainage and the topography flattened. More detailed methods can be adopted to include the combined effect of urbanisation on pervious and impervious surfaces on runoff (refer to Packman, 1989, WaPUG (1996)).

***Table 1 Mean Annual Maximum Runoff rate and Stormwater Attenuation requirement***

**Mean Annual Maximum Flood Flows using IH No. 124 Flood Equation**

| **Soil Class** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Soil Index | 0.15 | 0.3 | 0.4 | 0.45 | 0.5 |
| **Area (ha)** | **Runoff Rate l/s per ha** | | | | |
| **5** | 0.79 | 3.56 | 6.65 | 8.59 | 10.80 |
| **10** | 0.73 | 3.30 | 6.16 | 7.96 | 10.00 |
| **25** | 0.66 | 2.99 | 5.57 | 7.20 | 9.05 |
| **50** | 0.61 | 2.77 | 5.16 | 6.67 | 8.38 |
| **100** | 0.57 | 2.56 | 4.79 | 6.18 | 7.77 |
| **500** | 0.48 | 2.15 | 4.01 | 5.18 | 6.51 |
| **1000** | 0.44 | 1.99 | 3.71 | 4.80 | 6.03 |

**Storage Volume Calculations (50 year Storm Event)**

| **Soil Class** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Soil Index | 0.15 | 0.3 | 0.4 | 0.45 | 0.5 |
| Site Area ( ha) | **Required Storage Volume $m^3$** | | | | |
| 5 | 1573 | 1110 | 830 | 740 | 550 |
| 10 | 4630 | 2300 | 1720 | 1530 | 1130 |
| 25 | 7990 | 6030 | 4510 | 4000 | 3600 |
| Storm duration (hrs) | 170 | 20 | 7.5 | 5 | 3 |
| Duration to empty (hrs) | 351 | 39 | 16 | 11 | 6 |
| SAAR = 1000mm, M5-1hr = 15.6mm, M5-2day = 55.5mm | | | | | |
| Percentage Impervious Area 50% | | | | | |
| Permissible Outflow set to estimated Mean Annual Maximum Flow | | | | | |

## 3. ESTIMATION OF PEAK RUNOFF RATES

The two principal methods widely used for flood peak estimation at small ungauged study sites are:

Statistical based Methods
- Regional Flood Frequency by Catchment Characteristics using the Index Flood ($Q_{BAR}$)

Deterministic based methods
- Unit Hydrograph and design storm
- Rational Method type calculations

### 3.1 FSR Unit Hydrograph Method

The unit hydrograph method most widely used in Ireland and the UK for ungauged catchments is the FSR triangular unit hydrograph and design storm method. This method estimates the design flood hydrograph, describing the timing and magnitude of flood peak and flood volume (area beneath hydrograph). These methods require the catchment response characteristics (time to peak, $t_p$), design rainstorm characteristics (return period, storm duration, rainfall depth and profile) and runoff / loss characteristics (percentage runoff and baseflow).

The UK Natural Environmental Research Council (1975) carried out a comprehensive flood study involving a large number of catchments from throughout Britain including many Irish catchments. The unit hydrograph prediction equation was derived from 1631 events from 143 gauged catchments (the hydrograph method only included one Irish catchment) ranging in size from 3.5 to 500km$^2$. The result was a triangular Unit Hydrograph described by the time to peak $T_p$ of the catchment derived from catchment characteristics. The instantaneous triangular unit hydrograph is defined by a time to peak $T_p$, a peak flow in cumecs/100km$^2$ $Q_p = 220/T_p$ and a base length $T_B = 2.52T_p$.

Subsequent FSSR reports and in particular report No. 16 (1985) and IH 124 (1994) slightly modified the (Tp) equation and the calculation of percentage runoff (PR).

$$Tp = 283\ S_{1085}^{-0.33}\ SAAR^{-0.54}\ MSL^{0.23} \qquad \textit{(eqn 1)}$$

and

$$PR = SPR + DPR_{CWI} + DPR_{RAIN} \qquad \textit{(eqn 2)}$$

where

- $S_{1085}$ is the mainstream channel slope
- MSL is the mainstream length
- SAAR is the standard annual average rainfall depth
- SPR = 10S1 + 30S2 + 37S3 + 47S4 + 53S5
- $S_1$ to $S_5$ are the catchment fractions covered by the five winter rainfall acceptance potential (WRAP) classes and Su is the unclassified fraction which is covered either by standing water or a paved area.
- $DPR_{CWI}$ = 0.25(CWI – 125) and CWI = catchment wetness Index which is a function of SAAR.
- $DPR_{RAIN}$ = $0.45(R – 40)^{0.7}$ for storm depth R > 40mm and = 0 for R < 40mm.

The design rainstorm duration is obtained from the FSR formula $D = (1 + 0.001SAAR)T_p$. Using the prescribed FSR rules for computing the storm duration, profile and percentage runoff FSR a 140year return period design storm is required to produce the 100year design flood.

The FSR hydrograph method was tested on 36 Irish catchments and it was found that the $Q_{25}$ was overestimated in 30 of the 36 catchments with 24 of the 36 catchments being overestimated by over 150%. The mean value was 164% (Bree et al., 1989). The factors attributed to the overestimation were (i) underestimation of Tp, and storm duration D, (ii) overestimation of Qp caused by the factor 220, derived principally for UK catchments, being too large for Irish catchments and (iii) overestimation of percentage runoff, PR.

## 3.2 RATIONAL METHOD TYPE METHODS

### 3.2.1 Conventional Rational Method

The Rational Method remains in use, especially for small catchment work despite the advent of the FSR and other associated methods. With deterministic interpretation, the method was recommended for application to only small catchments below some arbitrary limit of 25km$^2$. In the USA and Australia this method is the most common method used for peak flow estimation in small ungauged catchments. The general form of the Rational equation is

$$Q_T = 0.278\ Cp\ Cr_T\ I_{tc,T}\ AREA \qquad \textit{(eqn 3)}$$

where

- T is the Return period (average recurrence interval (ARI) in years)
- Cp is a peaking factor often taken as 1.3
- $Cr_T$ = runoff coefficient for Return Period T years
- AREA = area of catchment (km$^2$)
- $I_{tc,T}$ = average rainfall intensity (mm/hr) for design duration of $t_c$ hours and return period T years.
- $T_c$ = time of concentration defined as the travel time from the furthest point on the catchment to the outlet (hrs)

The rational method equation can be derived from applying a rectangular unit-hydrograph to a uniform rainfall (NERC, 1978). The two methods differ in their estimated peak flow through the definition of the percentage runoff/ runoff coefficient and the design rainstorm duration and profile. The FSR set-out a procedure for evaluating percentage runoff based catchment wetness, soil type and storm intensity. In the conventional Rational method runoff coefficients are based on empirical tables of values based on a general description of the site (pavement time, landuse, etc.) Latter modifications to the Rational method have introduced flood study type procedures to evaluate the runoff coefficient.

The storm duration which influences the rainfall amount is based on the time of concentration which is defined as the travel time from the most remote point on the catchment to the outlet. Over the years numerous empirical formulas have been developed based on the stream length, slope and area. A. The Bransby-Williams formulation is commonly used

$$Tc = L/D\ A^{2/5}S^{1/5} \qquad \textit{(eqn 4)}$$

where L is catchment length, D is the diameter of a circle whose area is equal to the catchment area A. Other formulations in use are :-

$$T_c = 58L/(A^{0.1}S^{0.2}) \qquad \textit{(eqn 5)}$$

$$T_c = 0.76AREA^{0.38} \qquad \textit{(eqn 6)}$$

$$T_c = 7.06\sqrt{\left(L/\sqrt{S}\right)} - 1 \qquad \textit{(eqn 7)}$$

The Rational formula will yield flood peaks typically twice as large as those from the FSR hydrograph method for small lowland catchments subject to an assumed use of identical runoff coefficients. For the larger and steeper catchments greater similarity is found. The primary source of difference between the methods is the estimation of design storm duration.

### 3.2.2 ADAS Report No. 5 method (MAFF, 1980)

This method is essentially a rational method type approach but with specific emphasis on site assessment of percentage runoff that is consistent with the FSR winter rainfall acceptance (SOIL) classes and also allows the effect of land drainage, prolonged saturated catchments and flat catchments to be included.

The flood estimation equation is

$$Q_T = 2.78\ M_F^{2.0}\ F_A\ A\ I_{tc,T} \qquad \textit{(eqn 8)}$$

Where

- A is the catchment area in ha
- $F_A$ is the annual rainfall factor = 0.00127SAAR – 0.321 (dimensionless) and SAAR the annual average rainfall is in mm.
- Lc the characteristic length = $0.0001(L^2/Z)$
- L the catchment length measured as the distance from the outlet to the watershed passing through the middle of the catchment (m)
- Z is the average elevation of the catchment above the outlet (m)
- $I_{tc,T}$ Design Rainfall intensity of Duration $t_c$ and return period T obtained from the rainfall intensity-duration-frequency relationship
- $t_c$ the time of concentration = $6.09(Lc)^{0.39}$ (hrs)
- $M_F$ is Soil permeability modifying factor = $4.938\ S_m^{2.0}$
- Sm is the soil index = $(0.15S_1 + 0.3S_2 + 0.4S_3 + 0.45\ S_4 + 0.50\ S_5)/(1 - S_u)$

The method used for arriving at the site WRAP class fractions is the 1975 FSR method which lends itself to site specific description taking account of the soil permeability, depth to impermeable horizon, depth to winter water table and land slope.

This method, unlike the FSR methods, is not dependent on poor resolution mapping for describing its parameters allowing the inclusion, be it somewhat subjective, of the site specific drainage characteristics and local/regional rainfall statistics. This method lends itself to small drainage scale applications, which have sufficient watershed features to allow the above parameters to be measured.

The overall accuracy of this method at small scales has not been extensively tested and similar to all other estimation methods at these scales the caveat should read "to be used as a guideline indicator only".

### 3.3 Flood Frequency Methods

These methods use certain catchment descriptors to determine an index flood magnitude, such as the annual maximum flood (FSR methods) or median Flood (FEH method), which can then be multiplied by an appropriate regional flood frequency growth factor to yield a return period flood estimate (i.e. $Q_{100}$). A variety of empirical equations for various catchment regions (Benson (1962), Nash & Shaw(1966)) were available in UK prior to the publication of the Flood Studies Report (FSR) in 1975.

The Office of Public Works prior to the FSR equations occasionally used formulae (Lynn, 1971) such as

$$Q = 10.68\ A^{2/3}\ S^{1/2} \qquad \textit{(eqn 9)}$$

$$Q = 190\ A^{3/4}\ S^{1/4} R\ N^{1/5} \qquad \textit{(eqn 10)}$$

These equations were converted into SI units with Q the design flood in cumec, A the catchment area in $km^2$, S the median overland slope, R is the most frequently occurring maximum daily rainfall (mm) per annum and N is discharge return period (years). The first equation was considered to give satisfactory discharges, of about one to two year return period for small catchments (less than 2000 acres (≈ 800 ha) ) of moderate slope. The other gives roughly equivalent results for these conditions but can be used more generally for defined frequencies.

The flood estimation methods presented in this section progress from the original 1975 FSR equations to the 1978 FSSR Report No. 6 revision for small catchments, to the Institute of Hydrology No. 124 equations for small catchments (which is now widely used in Ireland for estimation of greenfield runoff) and finally to the recent Flood Estimation Handbook FEH (1999) method, which is specific to the UK.

#### 3.3.1 1975 Flood Studies Report Catchment Characteristic Method

The original 1975 FSR investigation involved flood frequency analysis of some 5500 record years from 430 British gauging stations and 1700 record years from 112 Irish sites. The catchment areas varied from 0.05 to 9868$km^2$ and annual maximum flows from 0.06 to 997cumec. Cunnane and Lynn (1976) provide a detailed examination of flood estimation in Ireland following the 1975 FSR.

The FSR six-variable equation for the mean annual maximum flood $Q_{BAR}$ is

$$Q_{BAR} = C\ AREA^{0.95} F_S^{0.22} SOIL^{1.18} SAAR^{1.05} S_{1085}^{0.16} (1{+}LAKE)^{-0.93} \qquad \textit{(eqn 11)}$$

where the multiplier $C = 0.00042$ for Ireland. This equation has a standard factorial error of about 1.5.

The three parameter equation for the same data set gives

$$Q_{BAR} = 4.53 \times 10^{-7}\ AREA^{0.84} F_S^{0.51}\ SAAR^{1.34} \qquad \textit{(eqn 12)}$$

and has a standard factorial error of 1.77.

The two-variable equation for the same data set gives

$$Q_{BAR} = 2.242 \times 10^{-7}\ AREA^{0.84}\ SAAR^{2.09} \qquad \textit{(eqn 13)}$$

and has a standard factorial error of 1.96.

Single-variable equation is

$$Q_{BAR} = 0.667 AREA^{0.77} \qquad \textit{(eqn 14)}$$

and has a standard factorial error of 2.73.

These factorial errors apply to the middle of the data set and consequently will be significantly higher at both ends of the data set, which has implications for applicability to small catchments.

The parameter description in the FSR methods are based on mapped information compiled as part of the FSR study. The SOIL parameter is provided on a 1:625,000 scale mapping for the UK and Ireland. The SAAR based on meteorological records from 1941 to 1970 stations is also provided on 1:625,000 scale mapping. The stream junction frequency Fs, the Slope S1085, and mainstream length MSL are extracted from 1 : 25,000 O.S. contour mapping for the UK and 1 : 63,360 for Ireland (1:50,000 discovery series mapping now available for Ireland). These scales and particularly the SOIL mapping do not lend themselves to accurate description of small catchments.

### 3.3.2 FSSR No. 6

The original 1975 FSR equation when tested showed that floods on small catchments were less well predicted than on large ones. Experience found that the common usage of the FSR equation was for small catchments and consequently this merited a re-examination of the FSR equation for such applications. The FSSR Report No. 6 study carried out regressions on 53 small catchments from the FSR data set (small defined in this case as catchments with areas less than 20km$^2$) and produced the following 4 and 3-parameter equations.

$$Q_{BAR} = 0.0288\ AREA^{0.90}\ RSMD^{1.23} SOIL^{1.77}\ F_s^{0.23} \qquad \textit{(eqn 15)}$$

Factorial Error = 1.53, N = 53

$$Q_{BAR} = 0.00066\ AREA^{0.92}\ SAAR^{1.22} SOIL^{2.0} \qquad \textit{(eqn 16)}$$

Factorial Error = 1.58, N = 53

A large operational difficulty in using the FSR equations for small catchments is the difficulty in measuring a number of the catchment characteristics, in particular the slope of the mainstream S1085, the stream junction density $F_S$ and the SOIL Factor. Therefore the three parameter equation (*eqn 16*) is favoured.

These equations performed well for the sample catchments with SOIL indices greater than 0.45 (Soil types 4 and 5) but less well on catchments with SOIL types 1, 2 and 3 (very low to moderate runoff). This can be explained by the fact that Soil types 4 and 5 (high and very high runoff) represent 41 of the 53 catchments used in the regression analysis.

This method still retains the 1975 FSR mapping to describe the estimation parameters, which is not appropriate for small catchments.

### 3.3.3 Institute of Hydrology Report No. 124

In 1994 the Institute of Hydrology carried out further regression studies on small catchments (< 25km$^2$). A total of 87 catchments ranging from 0.9km$^2$ to 24.7km$^2$ were available. 71 of these catchments were chosen as completely rural having urban fractions of less than 0.025.

The following 3-parameter equation was derived by regression analysis

$$Q_{BAR} = 0.00108\ AREA^{0.89}\ SAAR^{1.17} SOIL^{2.17} \qquad \textit{(eqn 17)}$$

Factorial Error = 1.65, N = 71

The regression statistics for this equation are presented in Table 2.

This equation is now widely used in the UK and more recently in Ireland to estimate Greenfield runoff for stormwater management of development sites and is the basis on which attenuation storage is sized.

***Table 2 Regression Statistics***

| | |
|---|---|
| Multiple R | 0.921 |
| R Square | 0.847 |
| Adjusted R Square | 0.841 |
| Standard Error | 0.218 |
| Observations | 71 |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* |
|---|---|---|---|---|---|---|
| Intercept | -2.967 | 0.4978 | -5.96 | 1.03E-07 | -3.961 | -1.974 |
| AREA | 0.887 | 0.0676 | 13.12 | 3.50E-20 | 0.752 | 1.022 |
| SAAR | 1.170 | 0.1469 | 7.96 | 2.79E-11 | 0.877 | 1.464 |
| SOIL | 2.169 | 0.2314 | 9.37 | 8.22E-14 | 1.707 | 2.631 |

Given its current relevance to Ireland a closer examination of the data on which the IH 124 equation was derived was carried out. This revealed that both the catchment area and the annual average rainfall (SAAR) were evenly distributed over the sample range but the SOIL parameter was not well distributed with only 16 (22%) of the 71 catchments being represented by SOIL types (1, 2 and 3) and 39 (55%) catchments having Soil type 5 (refer to Table 3).

***Table 3 Parameter distribution within sample population***

| **AREA** | | **SAAR** | | **Soil Category** | |
|---|---|---|---|---|---|
| < 5km2 | 25% | < 800mm | 16% | Type 1 (SOIL = 0.15) | 6% |
| 5 to <10km2 | 15% | 800 - 1200mm | 29% | Type 2 (SOIL = 0.3) | 6% |
| 10 to <15km2 | 21% | 1200 - 1600mm | 21% | Type 3 (SOIL = 0.4) | 10% |
| 15 to < 20km2 | 18% | 1600 - 2000mm | 11% | Type 4 (SOIL = 0.45) | 23% |
| 20 < 25km2 | 22% | > 2000mm | 23% | Type 5 (SOIL = 0.5) | 55% |

If we examine catchment areas less than $5km^2$, which totals 17 catchments, we find the soil classes 1 and 2 are not represented at all, soil classes 3 and 4 have 4 catchments each and Soil class 5 has 9 catchments.

If three catchments which had originally been excluded (their Urban fractions are 0.05 and 0.06 and 0.03 which exceed the arbitrary 0.025 limit) with soil classes 1, 2 and 3 respectively were included to improve the representation of the lower SOIL classes, then the regression equation would become

$$Q_{BAR} = 0.001\ AREA^{0.89}\ SAAR^{1.15} SOIL^{1.88} \qquad \textit{(eqn 18)}$$

having a factorial error of 1.71, N = 74.

A two-parameter equation without the SOIL parameter was tested against the IH 124 equation for catchments less than $5km^2$ and found little improvement in the prediction as a result of including the SOIL parameter.

The following 3-parameter catchment characteristic equation was fitted to the original IH 124 data set by minimising the sum of proportional errors eqn(20) as opposed to the sum of the squares of the errors in the log domain. This equation produces a marginally lower percentage error between observed and computed $Q_{BAR}$ than the IH 124 equation and is more accurate in 41 out of the 71 catchments.

$$Q_{BAR} = 3.6 \times 10^{-5}\ AREA^{0.94}\ SAAR^{1.58} SOIL^{1.85} \qquad \textit{(eqn 19)}$$

$$MIN\left[\sum_{i=1}^{71}\left|\frac{\left(LogQ_{BAR_i} - Log\hat{Q}_{BAR_i}\right)}{LogQ_{BAR_i}}\right|\right] \qquad \textit{(eqn 20)}$$

A comparison between the two methods is presented in Figure 1 showing proportional error against Catchment Area for the IH 124 Data set.

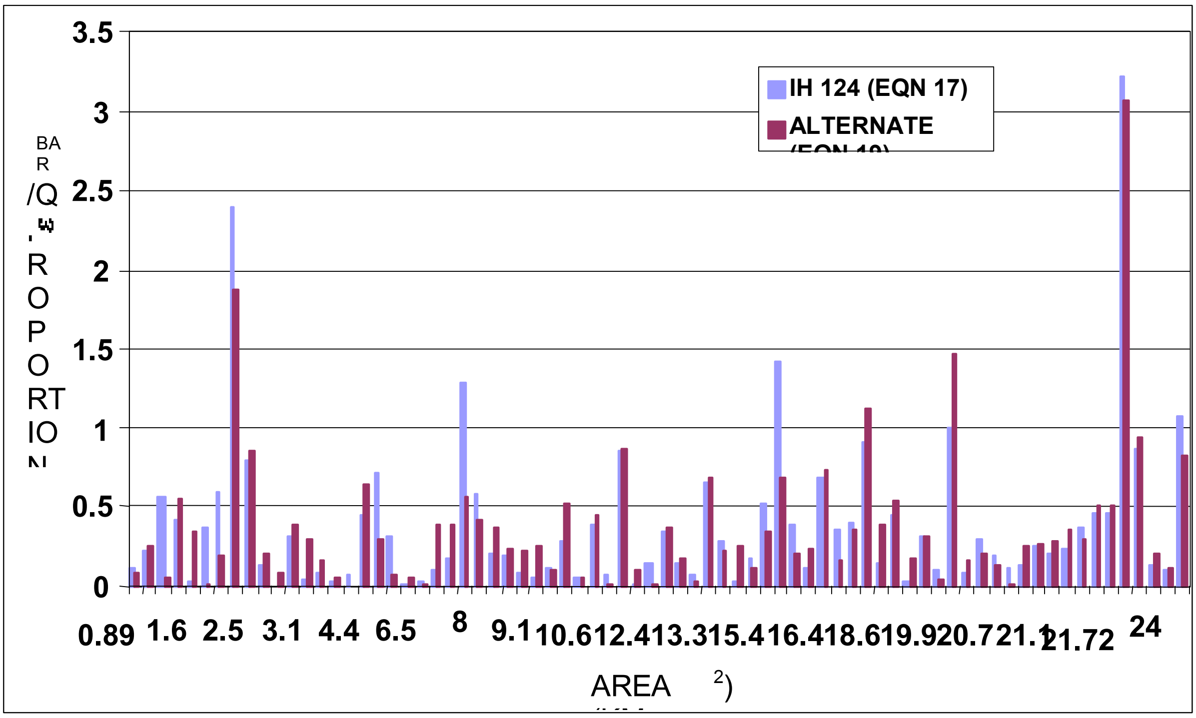


***Figure 1 Error comparison between IH124 and alternate flood estimation equations***

The mean annual maximum runoff rate for different catchment sizes and soil classes are presented in Table 4. Significant difference exists between both equations when applied to the small catchment sizes (100 ha and lower) and to higher soil classes (Class 2 and higher).

In conclusion the poor representation of lower soil classes in the sample and the sensitivity of the regression equation when either three additional catchments of the lower soil types or an alternate minimisation function are included seriously questions of the validity of the IH 124 equation to small catchments and also for soil classes 1 to 3. SOIL Classes 1,2 and 3 are the most common categories for Ireland and particularly in the low-lying urban centres. This method also retains the 1975 FSR poor resolution mapping to describe the estimation parameters, which is not appropriate for small catchments.

### 3.3.4 FEH Method of Design Flood Estimation

The statistical flood estimation procedures in the Flood Estimation Handbook (NERC, 1999), are largely based on the index flood method, $Q_T = Q_{index} \cdot X_T$ where $X_T$ is a growth factor. However, the details of implementation have changed from those of FSR. The median annual flood (= 2 year return period flood) is used as $Q_{index}$ instead of mean annual flood. $X_T$ is obtained individually for each project location from a pooled analysis, based on L-Moment techniques, of data from catchments which are most similar to the project catchment rather from a single growth curve for each geographical region.

In the case of ungauged catchments Qmed is estimated from catchment descriptors, relating to catchment size, wetness, soils and lakes, i.e.

$$QMED_{rural} = 1.172\ AREA^{AE} \left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642} \left(\frac{SPR\ HOST}{100}\right)^{1.211} 0.098^{REHOST} \quad \textit{(eqn 21)}$$

Where

| | | |
|---|---|---|
| AREA | = | catchment area |
| SAAR | = | standard average annual rainfall (1961-90) |
| FARL | = | flood attenuation by reservoirs and lakes factor |

| | | |
|---|---|---|
| SPRHOST | = | standard percentage runoff based on hydrology of soil types map |
| AE | = | area exponent (which varies with area) |
| RESHOST | = | a factor based on baseflow index (BFIHOST) and SPRHOST which reflects relative flashiness or sluggishness of the catchment. |

***Table 4 Mean annual flood runoff rates by IH124 and Alternate equations (eqn 17 & 19)***

Mean Annual Maximum Flood Flow based on IH 124

| Soil Category | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Soil Index | 0.15 | 0.3 | 0.4 | 0.45 | 0.5 |
| Area (ha) | Flood Runoff l/s per ha | | | | |
| 5 | 0.79 | 3.56 | 6.65 | 8.59 | 10.80 |
| 10 | 0.73 | 3.30 | 6.16 | 7.96 | 10.00 |
| 50 | 0.61 | 2.77 | 5.16 | 6.67 | 8.38 |
| 100 | 0.57 | 2.56 | 4.79 | 6.18 | 7.77 |
| 500 | 0.48 | 2.15 | 4.01 | 5.18 | 6.51 |
| 1000 | 0.44 | 1.99 | 3.71 | 4.80 | 6.03 |

Mean Annual Maximum Flood Flow based on alternate equation (19)

| Soil Category | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Soil Index | 0.15 | 0.3 | 0.4 | 0.45 | 0.5 |
| Area (ha) | Flood Runoff l/s per ha | | | | |
| 5 | 0.71 | 2.55 | 4.35 | 5.41 | 6.57 |
| 10 | 0.68 | 2.45 | 4.17 | 5.18 | 6.30 |
| 50 | 0.62 | 2.22 | 3.79 | 4.71 | 5.72 |
| 100 | 0.59 | 2.13 | 3.63 | 4.52 | 5.49 |
| 500 | 0.54 | 1.94 | 3.30 | 4.10 | 4.98 |
| 1000 | 0.52 | 1.86 | 3.16 | 3.93 | 4.78 |

The FEH approach avoids catchment descriptors which use channel length or slope because these do not lend themselves to unique determination from digital mapping databases. All of the quantities in the $Q_{MED}$ equation are spatial or area based quantities which are determined from digital databases, which hold gridded data for each variable for each 0.5 km$^2$ grid square in the UK. In particular it should be noted that the SOIL variable used in the FSR has been replaced by a completely new, and more extensively classified and calibrated variable called HOST (Hydrology of Soil Types).

Equation (21) was calibrated from the data of 728 catchments and the smallest area for which it is applicable is 0.5 km$^2$ (50 ha) and the catchment should have an urban extent of <0.025.

**FACTORIAL STANDARD ERROR**

The $Q_{MED}$ equation was determined using a linear relationship between the logarithms of the variables which leads to the power law form in eqn (21) when converted back into the original domain. In the log-domain the standard error of an estimate is added/substracted from the estimated value to provide a 66% confidence interval on the assumption that the model residuals are normally distributed. These additive terms ($\pm$e) become multiplicative terms, $10^{\pm e}$ in the original domain and are referred to as Factorial Standard Errors (FSE).

In FEH, eqn (21) has FSE = 1.55 so that the 66% confidence interval is (0.65 $Q_{MED}$ to 1.55 $Q_{MED}$) where $Q_{MED}$ is the value obtained from eqn (21). This confidence interval is very wide and reflects the fact that flood estimation from an ungauged catchment is imprecise notwithstanding the apparently comprehensive inclusion of relevant controlling variables in eqn (21).

**3.2.5 Flood Frequency Growth Curve for Ireland**

The design flood magnitude for a given return period can be estimated by multiplying the Index flood $Q_{BAR}$ (mean annual maximum flood) by the T-year return period growth factor ($X_T$) :

$$Q_T = Q_{BAR}\, X_T \qquad (eqn\ 22)$$

The FSR derived the following flood frequency growth curve for Ireland from statistical analysis of 112 Irish catchments having an average of 15 record years per station:

$$X_T = Q_T/QBAR = -3.33 + 4.2e^{0.05YT} \qquad (eqn\ 23)$$

where $Y_T = -\ln(-\ln(1-1/T))$

***Table 5 FSR Flood Frequency Growth Curve Ordinates***

| Return Period T years | 2 | 5 | 10 | 25 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|
| $X_T$ | .95 | 1.2 | 1.37 | 1.6 | 1.77 | 1.96 | 2.14 |

The FSR derived 9 regional and a national average flood frequency growth curves for the UK. They are generally steeper than the Irish curve and exhibit significant variations regionally. The flatter growth curve for Ireland reflects the comparatively lower variability between small and large floods, as is usually found in more humid regions. Recent research has indicated that the east of Ireland has more variability than the west and so appropriate values for the east might be expected to be higher than the overall national values.

***Table 6 Regional and Revised National Flood Frequency Growth Curve for Ireland***

| Return Period T years | 2 | 5 | 10 | 25 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|
| Ireland East | .96 | 1.21 | 1.38 | 1.59 | 1.74 | 1.90 | 2.05 |
| Ireland South | .96 | 1.19 | 1.35 | 1.55 | 1.70 | 1.84 | 1.99 |
| Ireland West | .96 | 1.18 | 1.33 | 1.51 | 1.64 | 1.78 | 1.91 |
| National (revised) | .96 | 1.20 | 1.35 | 1.55 | 1.70 | 1.84 | 1.99 |

Statistical flood frequency analysis was carried out on a total of 56 reliable OPW stations having a combined record length of 2096years. Regional growth curves for the west, south and east of Ireland and a revised National growth curve were determined. In the west 13 stations were used having an average record length of 35years per station, in the East Region 17 stations were used having an average record length per station of 36years and in the south Region 25 stations were used having an average record length of 39years.

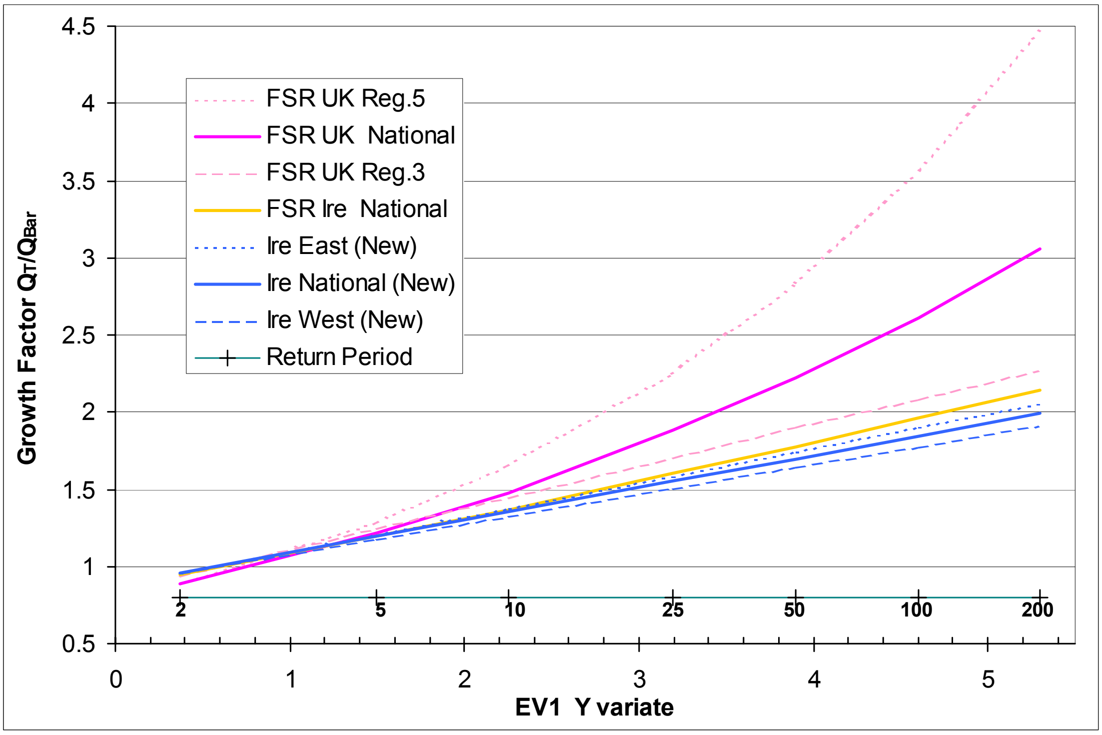


***Figure 2 Irish and UK Regional & National Flood Growth Curves***

The outcome is that the West region (predominantly SOIL types 1 and 2) has a slightly lower growth curve than the national average while the East region is slightly higher. These recently derived curves, based on almost 40 years of data per station, are all below the FSR national growth curve, which was based on an average record length of 15 years. Thus continued use of the FSR curve should prove to be a little conservative.

## 4. CLIMATE CHANGE

Climate change scenarios produced by the UK Hadley centre suggest fluvial floods in the 2080's increasing by up to 10% (low and medium low scenarios) or by up to 20% (medium high and high scenarios). Present recommendations are to include in the design flow a 20% increase in flood peaks over 50years return period as a result of climate change. This scenario based on the Irish growth curve will result in a present day 100year flood becoming a 25year flood in 50 years time, See Figure 3.

Other predicted climate change effects for the UK are

- A 4 to 5mm per annum rise in mean sea level
- Additional intensity of rainfall of 20%
- An additional 30%winter rainfall by the 2080's
- A reduction of 35/45% Rainfall in summer
- The 1 in 100year rainfall storm to increase by 25%

Kiely (1999) published results which indicate significant changes in rainfall totals at several Irish locations since the mid 1970's. He attributes this to changes in the North Atlantic Oscillation (NAO), a quantity based on seasonal pressure difference between Iceland and the Azores. Kiely (1999) also found differences in rainfall frequencies at a number of the synoptic weather stations – for Valentia he found that, for several durations, 10 and 30year return period rainfall depths are increased by approximately 20% when calculated from the most recent data (1976 – 96) as compared to values calculated from the entire period of record (1940 –1996). While such changes in rainfall regime provide a warning it is strange that changes in flood behaviour and in particular increase in flood magnitudes were not noticed in many rivers until the 1990's.

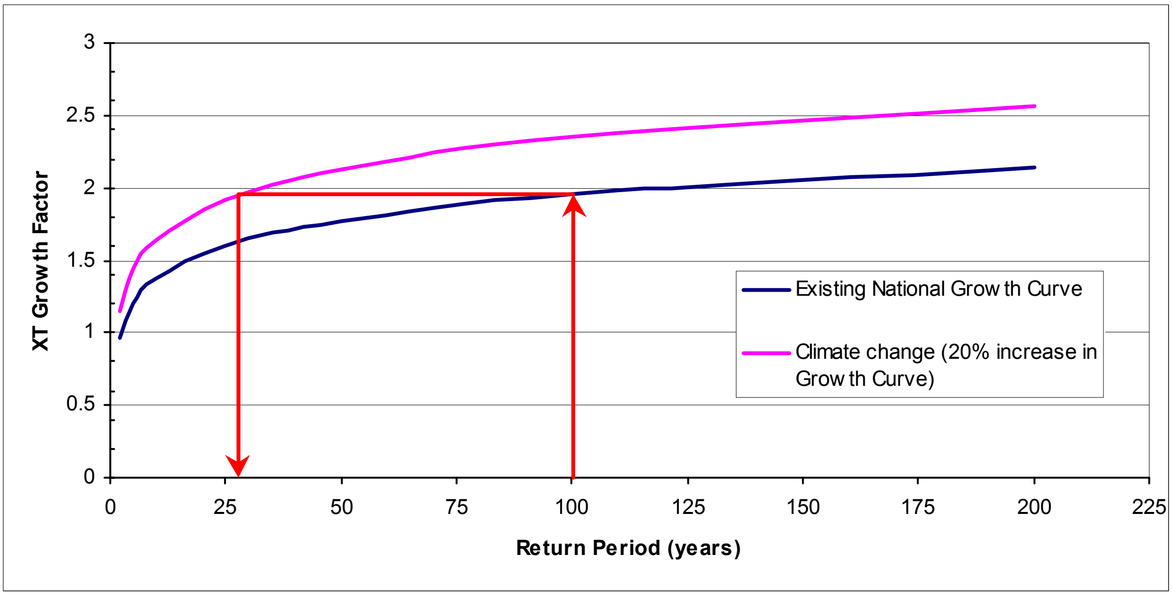


***Figure 3 National Flood Growth Curve for Ireland including climate change effect.***

Changes in circulation patterns across Europe have been linked to changes in flood frequency and hence increased risk of flooding in parts of southwest Germany. The circulation pattern known in Germany as "West Cyclonic" during the winter months has increased over the last century giving rise to increased risk of flooding. Caspary (2003) has shown flood magnitudes that were once deemed to be 100year return period floods, would be deemed to have much smaller return periods (5 to 30years) if judged on data of the past 25 years.

The changes observed in SW Germany may not be replicated in Ireland but it is clear that account must be made for climate change impact in view of the above findings.

**TRENDS IN IRISH ANNUAL RAINFALLS**

Met Eireann provided 4147 station years of annual rainfall totals at 80 stations from 1941 and 2000. The time series of average combined annual rainfall for these stations, (assumed to represent the national annual rainfall total, exhibited a slight upward trend of 1.1mm per annum between 1941 and 2000. From 1977 onward this upward trend is more pronounced at 2.1mm per annum. At this rate of increase the National Average rainfall will have increased by 10% by 2050. Two thirds of the stations showed an increase in rainfall; 14 stations showed significant trends (at 90% level) all of which have positive trends and a tendency for greater trends as one moves north and west.

To incorporate a climate change allowance into the flood estimation methods either the mean annual maximum flood estimate is increased by introducing an additional climate change multiplier or the regional growth curve be adjusted by increasing its ordinates (refer to Figure 3).

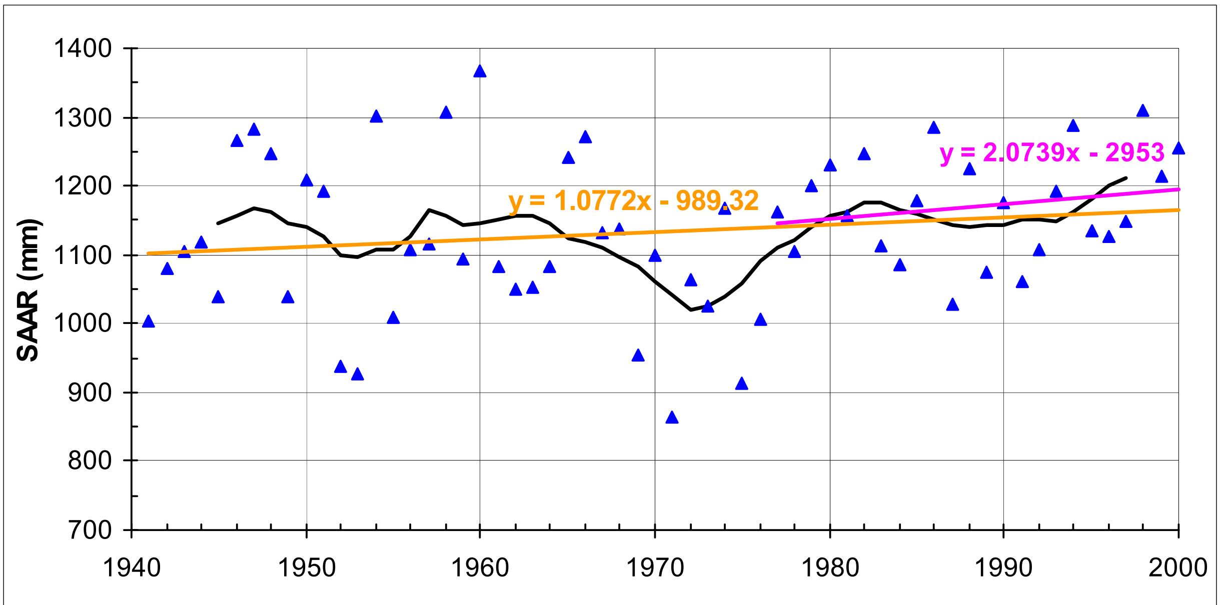


***Figure 4*** ***The National Average Annual Rainfall Series (based on 80 Met stations and 4147 station years)***

## 5. CONCLUSIONS

Methods of estimation of greenfield runoff rates for use in sustainable urban drainage systems are reviewed. These include rainfall - runoff type methods and flow frequency type methods. The rainfall runoff methods reviewed include the rational method, the FSR unit hydrograph + design rainstorm method and the MAFF method while the flow frequency methods include those described in FSR, FSSR 6, IH 124 and FEH.

One source of concern is the consequence of mismatches between the circumstances of the derivation of ungauged catchment formula and the circumstances of their use in SUDS. The formulae in these methods for estimation of model parameters, such as $T_p$, %Runoff or $Q_{BAR}$, from catchment characteristics are based on regression equations calibrated from the data of what are, by the standards of SUDS applications, <u>large</u> catchments. Further these catchments are <u>whole</u> natural catchments extending from source to point of gauging. The IH 124 Report is dedicated to small catchment hydrology but nevertheless its formula for $Q_{BAR}$, which is in widespread use for SUDS applications, is based on data of 71 catchments < 25 km$^2$, only one of which is <1 km$^2$. Since many SUDS applications are for areas much less than 1 km$^2$ there is an immediate mismatch between the circumstances from which the formula is calibrated and its range of application. Further many SUDS applications are for areas which are not natural catchments but rather, in many cases, merely truncated portions of catchments which may be at upstream, middle or downstream end of the natural catchment to which they belong. This is another possible form of mismatch between the derived formula and its point of application. Further 75% of the 71 catchments used in derivation of the $Q_{BAR}$ formula in IH 124 have soil type 4 and 5 while soil types 1 and 2 are not represented at all among the 17 smallest catchments, < 5km$^2$. Hence the applicability, with confidence, of the $Q_{BAR}$ equation to small catchments of soil types of 1 to 3 is questionable especially as it has been found that the index or power of SOIL is very sensitive to the catchments which are included in the calibration.

The reliance of the IH 124 $Q_{BAR}$ estimation method in small catchments on poor resolution FSR SOIL mapping, particularly for Ireland, further reduces the confidence that can be placed on its predictions. The continued use of this method and other methods relying on the FSR SOIL parameter should incorporate a site determination of the SOIL parameter rather than relying solely on FSR mapping.

The implementation of stormwater management based on a site by site evaluation of greenfield runoff would be fraught with difficulty given the high variability of runoff characteristics at such scales. The stormwater management policy should adopt the average greenfield runoff rate (l/s per ha) at the local drainage area scale as it is generally at this scale that the impact reduction of urbanisation is required and at which the available estimation methods are more valid.

It is felt that the MAFF (1980) method, which allows for use of more site-specific runoff characteristics, is deserving of more widespread consideration.

Growth curves are also examined and it is found that the curves derived recently from record lengths which average almost 40 years are slightly lower than the national FSR growth curve derive in 1975 from record lengths which averaged just 16 years. Hence continued use of the FSR growth curve is slightly conservative. However when the effects of global warming and climate change are taken into account then use of even steeper growth curves may have to be considered. The paper also reports a slight trend in annual rainfall totals.

**Acknowledgements**: The data on which Figure 3 is based were obtained from the OPW hydrometric web-site. Tom Sheridan of Met Eireann kindly provided the data on which Figure 4 is based.

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