5 Flood Flow Frequency Analysis

5.1 Introduction

Gauged and ungauged statistical methods will be required in order to provide flood flow magnitude estimates at the required hydrological estimation points within the hydraulic model domain. It is envisaged that for the working of the hydraulic flood model the hydrological inputs will be required at the upstream model boundary nodes representing the various rivers and tributaries. This will be specified as a hydrograph, with the hydrograph peak set to the estimated return period flood flow magnitude and the hydrograph shape defined using suitable hydrograph fitting methods described latter in this report.

There are numerous statistical distributions available and in use today for flood frequency analysis. The distributions vary in complexity from two parameter to multiple parameter equations that are based on the statistical moments of the distribution. The common distributions used in Ireland and the UK and in the FSU method are presented latter in Table 5-1.

5.2 Index Flood method

The return period flow estimates at a subject site are determined by multiplying the QMED estimate by the estimated Flood Growth Curve factors.

$$Q_T = Q_{MED} * X_T \qquad 5\text{-}1$$

Where, Q_T is the T-year flood quantile, Q_{MED} is the annual maximum median flood flow (Irish FSU and UK FEH use the median flood Q_{MED} as the index flood, previously it was the mean annual maximum flood QBAR that was used. An estimate of Q_{MED} can be obtained from the gauged annual maximum or POT flood data series or from ungauged flood estimation equations and X_T is the dimensionless flood growth factor obtained from either at-site or pooled frequency analysis.

5.3 FSU Flood estimation method of QMED

The Flood Studies Update (FSU) method determines the median flood magnitude as an index flood based on a number of its physical catchment descriptors (PCDs) parameters inputted the FSU PCD flood estimation equation. This FSU PCD equation is a regression equation that uses 8 PCDs parameters (refer to equation 5-2 and 5-3) and has a factorial standard error of 1.37 to estimate the median Flood Flow (2-year return period flow).

$$Qmed_{rural} = 1.237 \times 10^{-5} * AREA^{0.937} * BFISOIL^{-0.922} * SAAR^{1.306} * FARL^{2.217} * DRAIND^{0.341} * S1085^{0.185} * (1 + ARTDRAIN2)^{0.408} \qquad 5\text{-}2$$

$$Qmed = (1 + URBEXT)^{1.482} * Qmed_{rural} \quad \text{5-3}$$

To improve the reliability of this equation a gauged pivotal site can be selected which provides an adjustment for the ungauged QMED flood estimate. The return period estimates can then be determined by obtaining a flood growth curve from at-site or pooled analysis of selected reliable gauging stations and multiplying the Q_{MED} Value by the appropriate growth factor. For example, the Q_{100} is typically 1.8 to 2 times the Q_{MED} value for a lot of Irish gauging stations.

An Issue with the FSU method on the OPW FSU Web portal is that it is based on flood data only up to 2004/2005 and does not include the more recent data from 2006 onwards, which is 16 years of currently available flood data that has not been included. In many catchments this missing period, particularly in the Western, Southern and Shannon catchments has been the wettest period on record. For this study, as was done in the previous CFRAM hydrology studies carried out in 2012 - 2015, the relevant pivotal and pooling group stations AM series were updated to include the more recent available years. In respect to the River Corrib this includes three significant flood events, namely November 2009 and December 2015 and February 2020 and improves the reliability of the pooling group for flood growth curve determination over the FSU Web portal method.

In the case of the River Corrib at Galway a critical potential pivotal site is the Wolfe Tone Bridge gauge site and the possibly the Dangan gauge site whose rating relationships have been reviewed as part of this study, refer to chapter 4. The available AM Series for Wolfe Tone Gauge from the OPW hydrometric web site is restricted to the more recent 12years of AM flows giving a Q_{MED} of 279.5cumec. Consideration of the Dangan site with its 34years of estimated AM flows gives a Q_{MED} for the last 12 years of 274.7cumec and 260.8 cumec for the full AM 34year record period. The statistical error was also quantified in respect to the selected pivotal site and confidence intervals calculated. It should be noted that the FSU web portal method gives a Q_{MED} for Wolfe Tone Bridge of 248cumec based on a gauged AM series from 1972 to 2002, which the OPW hydrometric Section no longer consider reliable.

5.4 Flood Frequency Analysis to estimate Q_T

The general approach for conducting flood frequency analysis both in Ireland and the UK is based on the index flood method, using the median of the annual maximum flood series as the index flood. For a given subject site, a region-of-influence approach is used, involving the creation of a collection of either hydrologically or geographically similar catchments that comprise the pooling group from which a flood growth curve is developed. The index flood magnitude, when multiplied by the growth curve factors, produces the return period flood quantiles.

5.4.1 Gauged Sites

In some cases, a subject site may coincide with or be close to a gauging station location for which a reliably measured flood flow series over a sufficient number of years is available for statistical analysis. In reality, the majority of subject sites are unlikely to coincide with a gauging station, and consequently, such sites are referred to as ungauged sites.

At a gauged site, a probability distribution is fitted to the flood series with the assumption that the flood series is stationary, random and homogenous (i.e., random sample extracted from a single parent population of events). Single site analysis involves selecting a suitable probability distribution (such as a Gumbel or Weibull or other such extreme probability distributions) and either graphically or numerically fitting the selected distribution to the flood series. Generally, the distribution fitting is carried out through the use of either plotting positions and least square fit methods or numerical methods such as the ordinary method of moments, probability weighted moments, l-moments and maximum likelihood methods.

The statistical analysis for a gauged site may use a single-site distribution from the gauged site itself or may use a pooled analysis from suitable donor gauging stations or a combination of both to produce a flood growth curve from which to estimate the specific flood quantile Q_T. In the latter pooled analysis, which is generally the recommended method by the OPW Irish Flood Studies Update method (FSU), the flood data from several gauged river sites are in effect pooled together to provide a statistically more reliable estimate of the required flood quantile, particularly for the larger return periods as it represents a larger sample for the population of events and reduces the dependance on a single gauge site which may or may not well represent the estimation site and on the potential for measurement and sample error at that gauged site.

The pooling group of gauged stations is selected based on similarity both regionally and in their physical catchment descriptors such as catchment area, annual rainfall and soils and geology conditions, catchment and channel slope, etc. to the subject site. This pooling allows through the use of the index flood method a statistically more reliable and robust flood quantile estimate over the single site growth curve.

The general requirement for a pooling group in respect to estimating the return period flood flow quantile Q_T is that the group of selected stations provide at least 5T station years (e.g., 100year return period requires 500 station years). If too few stations are included the precision of the Q_T estimate is sacrificed, but if far too many stations are selected the assumption of homogeneity from a single representative parent of floods may be compromised. At larger return periods such as 500 and 1000 year, such a 5T requirement becomes unfeasible as a 1000year return period estimate under this rule would require 5000station years which would involve almost the entire available AM flood series and gauging stations for Ireland and would certainly compromise the homogeneity assumption.

Single-site analysis, either independent or in combination with pooled analysis, is acceptable where the gauge is reliable and the AM series is reasonably long. As a guide, such single-site analysis for estimating design flood flows can be applied where the record length would typically exceed 0.5T (i.e., a 50year record length for estimating the 100year flood).

A drawback with the pooled regional analysis for Ireland is that to achieve the 5T station years quite a number of gauging stations may be required, many of which may not be within the catchment or even the region and may not be as hydrologically similar to the subject site as desired, which is not consistent with the homogeneity assumption of originating from a single parent distribution. This can give rise to considerable scatter of the pooling group flood distribution characteristics (i.e., coefficient of variation, coefficient skewness and Kurtosis) and producing an average of the growth curve that may not be consistent with the gauged information if available near the site.

5.4.2 Ungauged Sites

Ungauged sites are all sites not located within close proximity to a reliable flood gauging station. The estimation of the flood quantiles depends completely on extrapolating from gauged donor sites both in respect to estimating the index flood quantile Q_{MED} and the flood growth curve X_T.

The standard method is to use an estimation equation that was calibrated by multiple regression analysis, which gives a relationship between the Q_{MED} and physical catchment descriptors (previously referred to in the FSR as catchment characteristic parameters). The normal approach for ungauged sites is the use of the index flood with a pooled or regional flood growth curve. The procedure in estimating the index flood (i.e., the median flood Q_{MED} or the mean annual maximum flood QBAR) involves deriving it from either a suitable donor or analog gauged site or to use an empirical flood estimation equation based on physical catchment descriptors.

A donor site is considered to be a gauging station site on the same river as the subject site and can be either upstream or downstream. An analog site is considered to be a gauged site not on the same river as the subject site, including being on another tributary within the same parent catchment. It is assumed that an analog site is chosen so that it is hydrologically similar (i.e., catchment descriptors are similar).

The empirical flood estimation equations available are the FSU Q_{MED} equation for physical catchment descriptors (PCDs), the IH124 QBAR equation for small ungauged catchments (<25km^2) or the original Flood Study Report (1975) QBAR catchment characteristic equation. The latter FSR QBAR method is generally considered redundant being replaced by better resolution FSU Q_{MED} method in respect to catchment descriptor mapping and also associated with more up to date (up to 2006 gauged AM flows in the FSU as opposed to up to 1974 gauged flows used in the FSR (NERC, 1975)).

5.4.3 Annual Maxima Series

In Ireland, flood frequency analysis is generally carried out on the Annual Maxima (AM) series of gauged flows. This represents a series of maximum flows that are extracted from the gauge record for each hydrological year (1st October to 30th September). Such flood frequency analysis can also be applied to the Peaks Over Threshold (POT) series of independent flood events, whose peak exceeds a minimum threshold value. This series can allow a number of flood peaks that exceed the threshold value in a given hydrometric year. The POT flood analysis is the preferred method in the UK and in the UK FEH (1998) method and for use with smaller AM records and smaller flashier catchments as it provides more sampling of floods.

For Ireland and particularly for the larger winter flooding catchments, where generally the river receives only one large independent flood per year and the record series is reasonable long, the AM series approach is sufficient. In flashy catchments where flooding is irregular or where the record length is short, a POT frequency analysis is likely to be more reliable as a greater sampling of floods and ensures all floods above the threshold are retained and also filters the low flood magnitudes below the threshold and thus eliminating some dry flood years from the series. The selection of an appropriate threshold value is important and often requires a sensitivity analysis to be performed on different thresholds values.

In this study the statistical analysis of the AM series was selected over a POT series as in a lot of cases there was sufficient sampling years available for accurate AM series analysis, the gauged data provided by the OPW hydrometric had AM series already separated and processed, the processing of AM series is much simpler and faster than the POT processing as independent flood events do not have to be identified as is the case with POT processing and the AM series is less sensitive to gaps in the record than the POT method.

5.4.4 Flood Frequency Distributions

Statistical data of random events such as flooding are produced from single parent probability distribution that governs the randomness of the events. All distributions can be defined by their statistical moments that include the mean (1st moment), variance (2nd moment), skewness (3rd moment), Kurtosis (4th moment), tail skewness (5th moment), etc. The variance measures the spread of values in the distribution about the mean and is a very important parameter in fitting distributions to data. The skewness measures the asymmetry of the data with positive skewness producing a longer right tail in the distribution, which is normally the case with flood data as theoretically there is a lower bound but no upper flood bound / limit. The kurtosis measures the size of the tails / extremes in the distributions and the fifth moment describes the asymmetry of these tails

The flood frequency distributions applied in hydrology vary in complexity and shape from two parameters to multiple parameter equations that are based on the statistical moments of the sampled flood series. The common distributions used in Ireland and the UK and in the FSU and FEH methods are presented below in Table 5-1. Other common distributions available are presented in

Table 5-2.

Table 5-1 Probability Distributions included in the flood frequency Analysis

Distribution name	**parameters**
EV1 Extreme Valve Type 1 (EV1 or also known as Gumbel), a	2 parameter location and scale Skewness of this distribution is set at 1.14
GEV General Extreme Value type distribution (which depending on skewness may also be known as EV2 (convex curve) or EV3 (concave curve))	3 parameter location, scale and shape parameter
LO Logistic Distribution	2 parameter location and scale (skewness is 0)
GLO General Logistic Distribution (	3 parameter location, scale and shape parameter (skewness)
LN2 Log Normal	2 parameter symmetrical distribution based on location and scale parameters. Generally, the logarithms of the AM flow series tend to have a symmetric distribution tendency i.e., skewness of 0.
LN3 Log Normal 3	3 parameter distribution of the log series having location, scale and shape parameters (symmetrical with kurtosis parameter defining the tail thickness of the distribution)
PE3 Pearson Type 3	3 parameter distribution of the log series having location, scale and shape parameters
WEI Weibull Distribution	3 parameter distribution having location, scale and shape parameters
WAK Wakeby Distribution	5 parameter distribution having location, scale and shape parameters

Table 5-2 Other Probability Distributions applicable to flood frequency analysis

Distribution name	**parameters**
LEV1 Log EV1 (Gumbel)	2 parameter location and scale Skewness of this distribution is set at 1.14 The logarithm of the AM series reduces the skewness and therefore the set skewness inherent in the EV1 of g=1.14 increases the upward curvature of the distribution fit to the data
LPE3 Log Pearson Type III	3 parameter location, scale and shape parameters of the Log of the series
LLO Log Logistic	2 parameter location, scale and shape parameters of the Log of the series suitable for positively skewed data
GAM Gamma	2 parameter location and scale
EXP Exponential	2 parameter location and scale
GPO Generalised Paerto	3 parameter distribution of the location, scale and shape parameters
KAP Kappa	4 parameter distribution of the location, scale and shape parameters including skew and kurtosis
NOR Standard Normal	2 parameter symmetrical distribution having location and scale parameters with a set Bell curve shape with rapidly decaying tails
GNO Generalised Normal	3 parameter symmetrical distribution having location, scale and shape parameters

5.4.5 Fitting of statistical distributions

Different statistical methods are available for fitting these distributions to the flood series with the most common methods using either plotting position and least-squares fit, ordinary method of moments, probability weighted moments and L-moment methods or maximum likelihood methods. The L-moments based on Hosting (1986, 1990) and Hosking and Wallis (1997) are generally the preferred methods in Ireland and in the FSU (2009) and consequently was applied to this study to fit the above distributions to annual maximum flood flow series at the selected gauges. The L-moment method suffers less from the effects of sampling variability and is generally unbiased and therefore more robust to the effect of outliers within the sample series than the conventional methods of method of moments and least squares fit.

5.4.6 Estimation of Flood Quantiles

The L-moments produce a location parameter u, a scale parameter α and a shape parameter k. These parameters are inputted to specifically derived equations for the particular distribution along with the non-exceedance probability F.

$$F = 1 - \frac{1}{T} \quad \text{5-4}$$

GEV
$$Q_T = u + \alpha\left(1 - (-LN(F))^k\right)/k \quad \text{5-5}$$

EV1
$$Q_T = u - \alpha LN(-LN(F)) \quad \text{5-6}$$

LO
$$Q_T = u + \alpha LN\left(\frac{F}{1-F}\right) \quad \text{5-7}$$

GLO
$$Q_T = u + \alpha\left(1 - \left(\frac{1-F}{F}\right)^k\right)/k \quad \text{5-8}$$

Refer to papers by Hosting (1986, 1990) and Hosking and Wallis (1997) for the L-moment expressions applicable to the above distributions and the other distributions considered. All of the distributions set out in Table 5-1 and

Table 5-2 were considered in this study, The L-moment analysis and the Q_T estimation was performed using in-house HEL-FFA statistical analysis software (Hydro Environmental Flood Frequency Analysis Software Package).

5.5 At-Site Frequency Analysis of River Corrib Gauges

5.5.1 River Corrib Wolfe Tone (30061) AM series

The River Corrib at its Wolfe Tone Bridge Gauge (30061) has hydrometric records extending back to 1950. However, the current approved and available record length for the flood flows from the OPW Hydro-Data site is limited to the most recent period from 2009 onwards, providing 12 years of AM flood flows. The record period pre 2009 is considered by OPW hydrometric to be potentially unreliable, pending further rating review by the hydrometric Section. The 12years of AM flows for the River Corrib provide a median flood flow estimate of 279.5cumec with a statistical standard error (s.e.) of 21.36cumec (8.52%). As part of this study a full rating review was carried out (refer to Section 4.4.2) and this review has allowed an Annual Maximum flood flow series for the full record length to be generated. A degree of caution, in respect to its overall reliability should be applied to this data. Notwithstanding that, little has changed in respect to the channel control at the Wolfe Tone gauge site such that the current rating is potentially applicable to the entire record once datums have been corrected for.

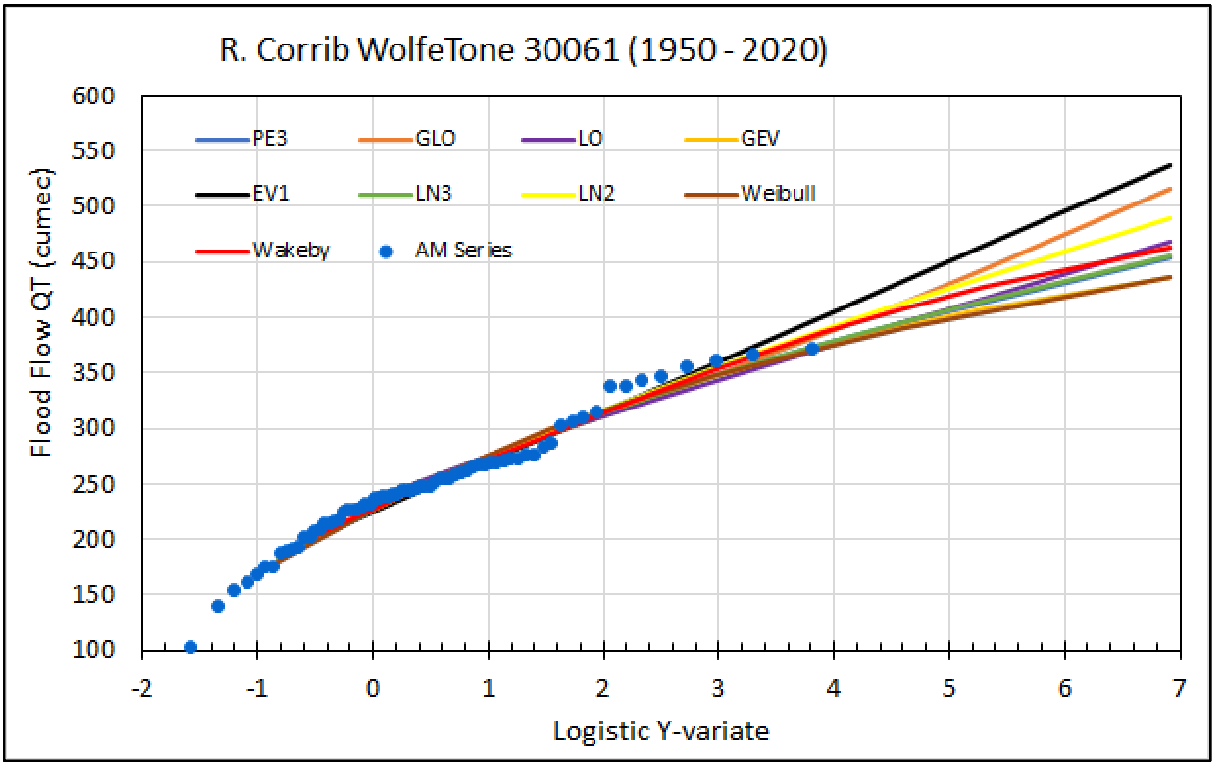

Figure 5-1 Statistical fit of selected probability distributions to the AM Flood data For River Corrib at Wolfe Tone Gauge (full series)

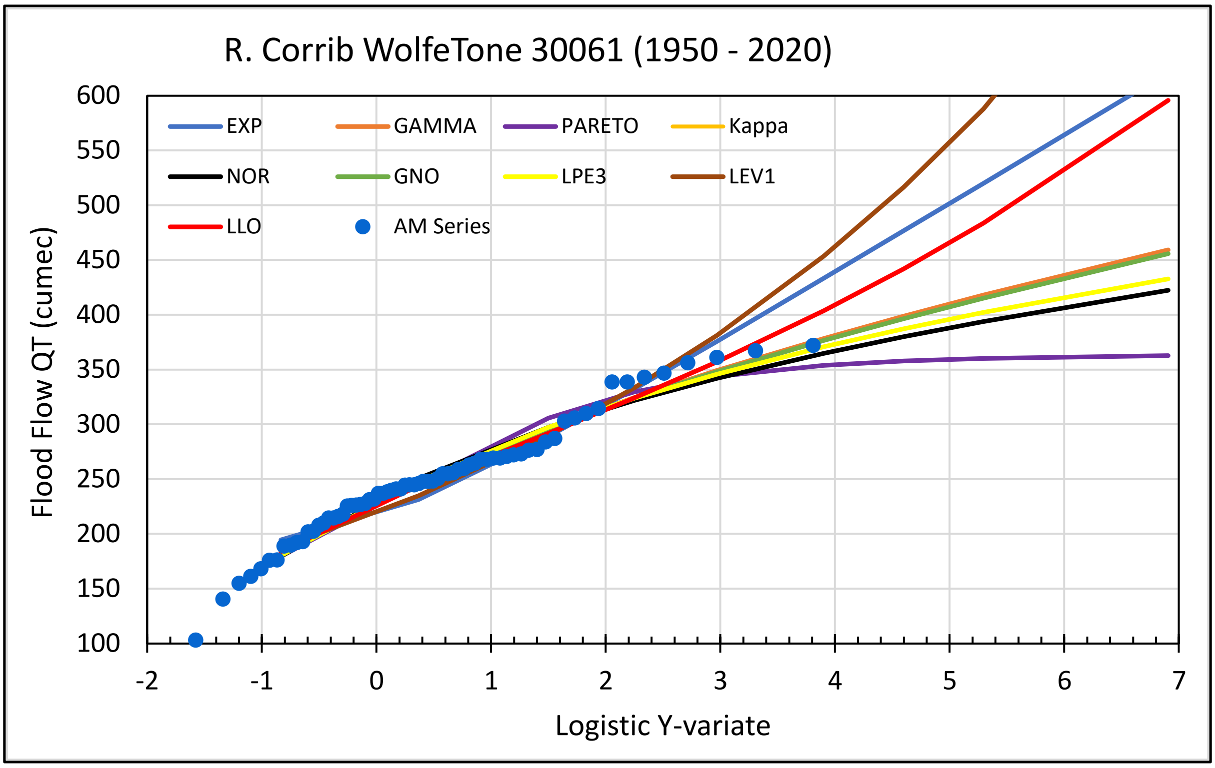

Figure 5-2 ***Statistical fit of other statistical probability distributions to the AM Flood data For River Corrib at Wolfe Tone Gauge (full series)***

Table 5-3 ***Computed Return Period Flood Flow Quantiles QT for the River Corrib at Wolfe Tone Gauge (30061) using different probability distributions (1950 to 2020)***

Return Period T	PE3 QT m3/s	GLO QT m3/s	LO QT m3/s	GEV QT m3/s	EV1 QT m3/s	LN3 QT m3/s	LN2 QT m3/s	Weibull QT m3/s	Wakeby QT m3/s
2	181.7	183.4	181.7	181.8	186.8	181.8	184.9	180.4	187.0
5	247.1	247.4	250.6	246.9	241.1	247.1	245.9	247.2	244.5
10	296.3	292.5	294.1	296.9	292.3	296.1	296.6	297.7	293.1
20	324.0	320.7	319.5	325.0	326.3	323.9	327.1	324.8	325.0
50	348.0	348.0	342.9	348.6	358.8	348.0	354.6	347.3	353.4
100	376.2	384.4	372.6	375.0	401.0	376.5	388.4	372.7	386.1
200	395.7	412.9	394.7	392.2	432.5	396.3	412.7	389.6	407.5
1000	414.0	442.4	416.5	407.3	464.0	415.1	436.3	405.1	426.6

The median flood flow Q_{MED} from the AM series for Wolfe Tone based on the estimated AM flows from 1950 to 2020 is 245.9 with a statistical error of 8.46cumec (3.44%). The computed L-CV is 0.1251, L-Skew is 0.0616 and L-Kurtosis is 0.1954.

Using the more recent record from 1972 onwards for which OPW have developed rating relationships for, as set out in Section 4.4.2, the QMED of the 49year AM series is 250.6cumec with a statistical error of 9.152cumec (3.65%). The computed L-CV is 0.1072, the L-Skew is 0.1563 and the L-Kurtosis is 0.1409.

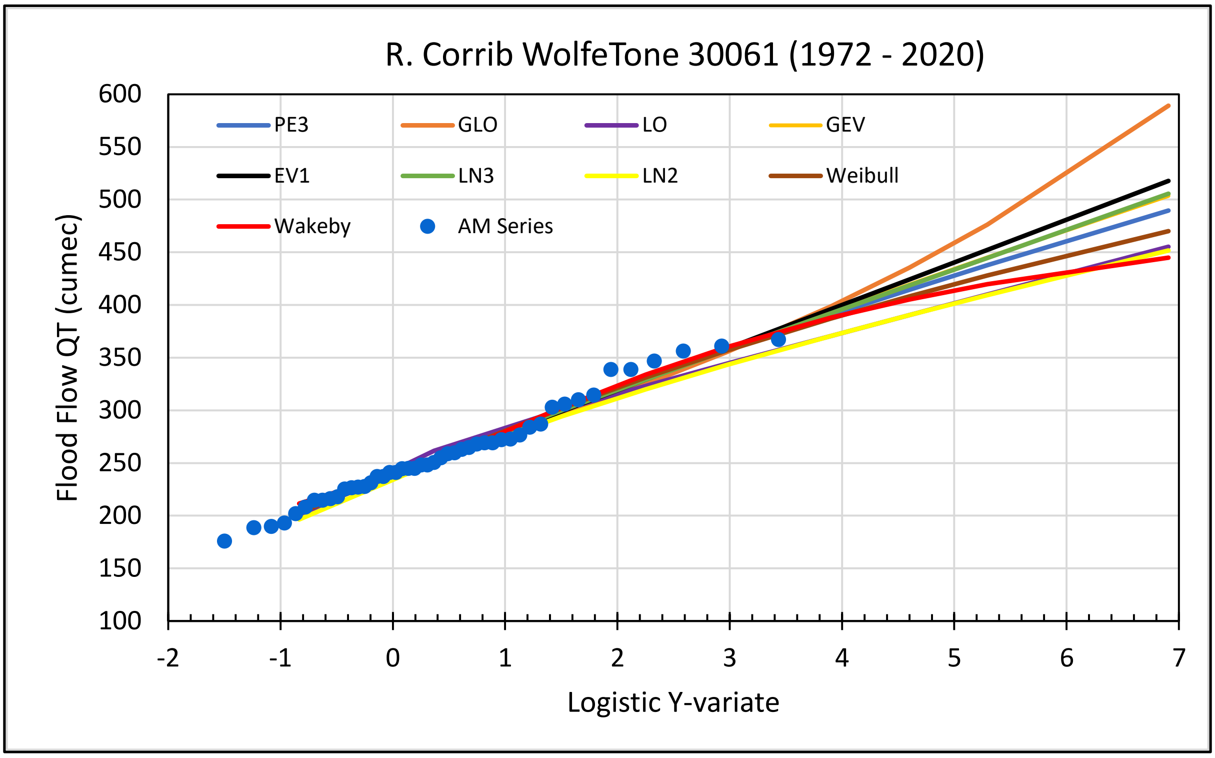

Figure 5-3 Statistical fit of selected probability distributions to the AM Flood data For River Corrib at Wolfe Tone Gauge (1972 to 2019)

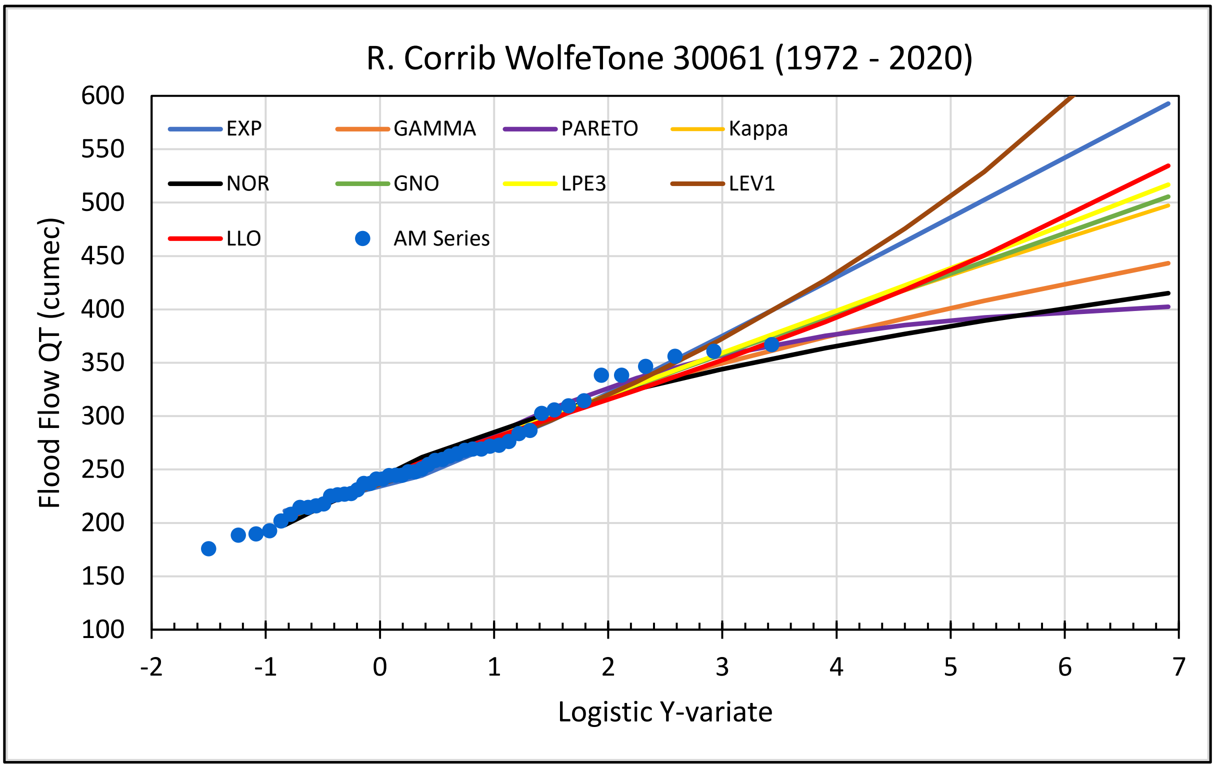

Figure 5-4 Statistical fit of other statistical probability distributions to the AM Flood data For River Corrib at Wolfe Tone Gauge (full series)

Table 5-4 Computed Return Period Flood Flow Quantiles QT for the River Corrib at Wolfe Tone Gauge (30061) using different probability distributions (hydrometric years 1972 to 2020)

Return Period T	PE3 QT m3/s	GLO QT m3/s	LO QT m3/s	GEV QT m3/s	EV1 QT m3/s	LN3 QT m3/s	LN2 QT m3/s	Weibull QT m3/s	Wakeby QT m3/s
2	253.5	254.4	261.5	253.6	253.0	253.7	250.6	253.5	251.3
5	300.5	296.1	300.4	299.4	298.8	299.7	294.2	302.0	302.4
10	330.0	325.0	323.1	329.2	329.2	329.2	320.0	331.1	333.7
20	357.0	355.1	344.1	357.3	358.3	356.9	342.9	356.7	359.9
50	390.4	398.7	370.7	393.0	396.0	392.2	370.7	387.1	388.0
100	414.4	435.4	390.4	419.3	424.3	418.4	390.5	408.1	405.3
200	437.6	476.2	410.0	445.1	452.4	444.6	409.5	427.9	419.7
1000	489.5	589.2	455.2	503.5	517.6	505.5	451.7	470.0	444.7

5.5.2 River Corrib Dangan (30098) AM series

The flood rating review for the Dangan Gauge presented in Section 4.4.3 provides a moderately reliable AM flood flow series for the hydrometric period 1986 to 2020 and provides a reliability check on the AM data for Wolfe Tone Gauge and vice versa.

A review of the annual maximum water level series for the Dangan gauge found that for the 35-year record, a single AM year for the hydrometric year 2005 was missing due to recorder malfunction and this missing year was extracted from the downstream Wolf Tone gauge. This gauge provides 35 years of River Corrib AM flood flows for flood frequency analysis. The estimated River Corrib AM flows for the Dangan Gauge are based on the rating relationship set in Section 4.4.3 and give a Q_{MED} of 260.8cumec and a statistical error of 9.32cumec (3.57%). It should be noted that for the Wolfe Tone AM record for this same record period, the Q_{MED} is 254.9cumec and the statistical error is 12.06cumec (4.73%). The estimated Wolfe Tone AM flows are on average 2.25% lower than the estimated Dangan flows which is within an acceptable range of measurement accuracy. The computed L-CV is 0.0914, l-Skew is 0.1201 and L-Kurtosis is 0.1378.

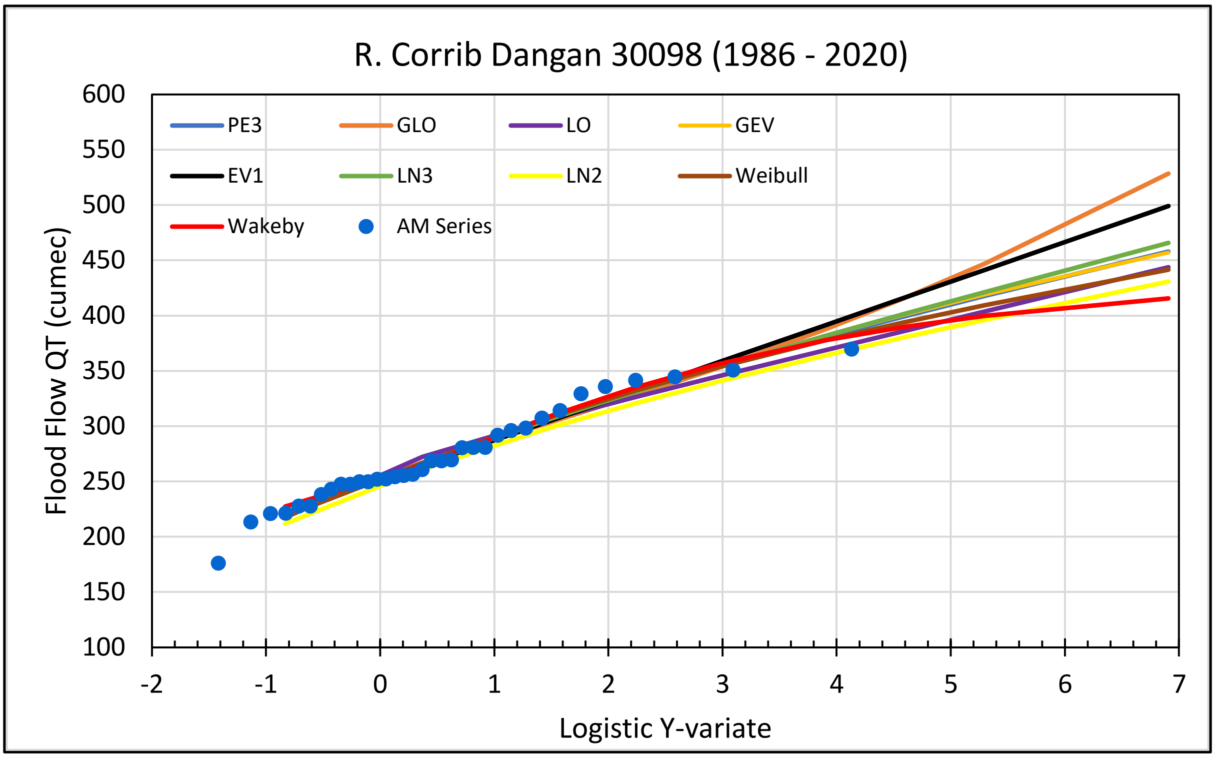

Figure 5-5 ***Statistical fit of selected probability distributions to the AM Flood data For River Corrib at Dangan Gauge (1986 to 2020)***

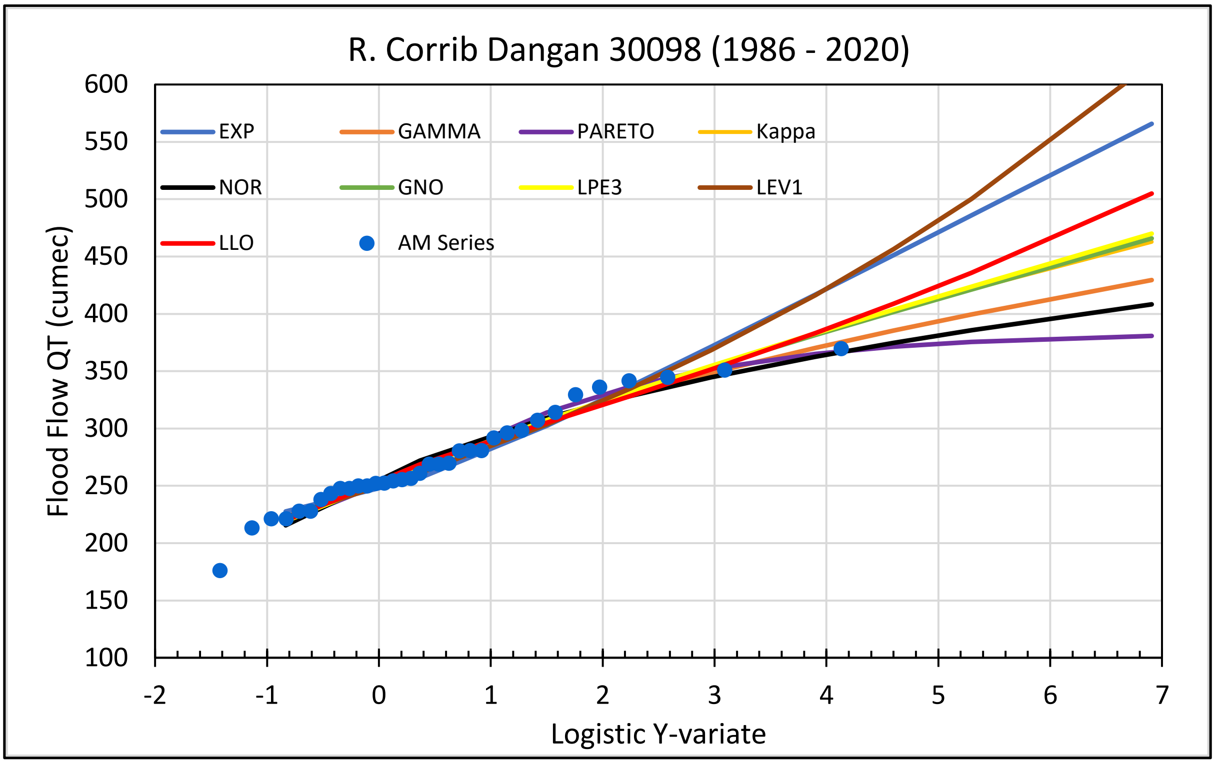

Figure 5-6 ***Statistical fit of other statistical probability distributions to the AM Flood data For River Corrib at Wolfe Tone Gauge (full series)***

Table 5-5 Computed Return Period Flood Flow Quantiles QT for the River Corrib at Dangan Gauge (30098) using different probability distributions (hydrometric years 1986 to 2020)

Return Period T	PE3 QT m3/s	GLO QT m3/s	LO QT m3/s	GEV QT m3/s	EV1 QT m3/s	LN3 QT m3/s	LN2 QT m3/s	Weibull QT m3/s	Wakeby QT m3/s
2	266.6	267.2	272.1	266.6	264.5	266.7	260.8	266.6	264.3
5	307.3	303.8	306.5	307.0	305.2	306.9	299.0	308.6	309.4
10	331.9	328.2	326.7	331.9	332.1	331.4	321.1	332.7	335.5
20	353.9	352.9	345.3	354.3	357.9	353.8	340.6	353.5	356.4
50	380.6	387.6	368.8	381.6	391.3	381.6	364.0	377.6	377.6
100	399.6	416.1	386.3	400.8	416.4	401.7	380.5	394.1	390.0
200	417.8	446.8	403.7	418.8	441.3	421.3	396.2	409.4	399.8
1000	457.9	528.4	443.8	457.1	499.1	465.8	430.7	441.6	415.7

5.5.3 River Corrib At-Site Return Period Q_T Estimates for Galway City

The AM series at both Wolfe Tone Bridge and at Dangan gauges when plotted on a logistical plot (refer to Figure 5-1 and Figure 5-5) suggest a concave downward curving behaviour in the flood growth curve. This suggests an upward limiting flood frequency distribution which may be due to the large attenuating effect of the Corrib by its large lakes and its significant karstic catchment basin. The best fit to the AM flood flow data for the River Corrib at both Dangan and Wolfe Tone is produced by the Wakeby (5 parameter distribution and the generalised Pareto (3 parameter) distributions. Such behaviour is considered not to be hydrologically realistic as it represents an upper bound on the maximum flood which is unlikely as some future unprecedented rainfall event could generate significantly higher runoff rates and flood peak than previously recorded. Under such concave downward behaviour in the AM data, it is recommended (OPW,2009 FSU wp2.2) that possibly a straight line 2-parameter growth curve be used with such at-site data (i.e. EV1 or Log Normal)) so as to avoid upper limit on the flood growth curve. Such upward limit on return period flows is generally not considered realistic and often with more years of AM Flows the distribution straightens to be represented more by a 2-parameter distribution such as EV1. For the at-site Corrib AM flow data an EV1 distribution will be used refer to Table 5-6 below.

Table 5-6 Computed Return Period Flood Flow Quantiles QT for the River Corrib at Wolfe Tone Gauge and Dangan Gauges for EV1 distribution

Return Period T years	Wolfe Tone (30061) (1972-2020) EV1 QT m^3/s	Dangan (30098) (1986 – 2020) EV1 QT m^3/s	Average EV1 QT m^3/s
2	252.99	264.50	258.74
5	298.84	305.16	302.00
10	329.20	332.08	330.64
20	358.32	357.90	358.11

50	396.02	391.32	393.67
100	424.26	416.37	420.31
200	452.41	441.32	446.86
1000	517.60	499.12	508.36

5.5.4 River Corrib At-Site Standard Error for Q_T

The standard error (*se*) of the mean annual flood flow (QBAR) from an AM series of size N can be estimated from the following expression where σ is the standard deviation and N the AM sample number.

$$se(QBAR) = \sigma/\sqrt{N} \qquad \text{5-9}$$

The standard error of the median of the AM series is approximately 25% larger at

$$se(QMED) = 1.253\,\sigma/\sqrt{N} \qquad \text{5-10}$$

The standard error estimate can also be expressed in terms of Q_{MED} as follows

$$se(QMED) = 0.36\,QMED/\sqrt{N} \qquad \text{5-11}$$

The EV1 statistical error (SE) by the method of L-moments has been given by Liu & Stedinger (1992) as follows:

$$SE[\hat{Q}_T] = \frac{\alpha}{\sqrt{N}}\sqrt{\left(1.1128 + 0.4574Y_T + 0.8046{Y_T}^2\right)} \qquad \text{5-12}$$

where $\hat{Q}_T$ is the estimate for the T-year flood flow event α is the EV1 scale factor and Y_T is the EV1 reduced variate = -ln(-ln(1-1/T)) and N is the number of observations (AM flows) in the sample.

The standard error presented in Table 5-7 was determined through conducting Monte Carlo simulation of the sampled L-moments for Wolfe Tone and Dangan AM series fitted to an EV1 distribution and generating 5000 random samples of size N (N = 49 for Wolfe tone and N = 35 for Dangan) generated from the respective EV1 population distribution. The return periods by l-moments for each of the 5000 random sample determined and finally the standard deviation of the Q_T values at each the return period computed which represent the statistical standard error.

Table 5-7 Computed EV1 statistical error of flow Quantiles QT for the River Corrib at Wolfe Tone and Dangan Gauges

Return Period T years	Wolfe Tone (30061) EV1 SE(Q_T) m³/s	Dangan (30098) EV1 SE(Q_T) m³/s	Average EV1 SE(Q_T) m³/s
2	6.63	6.87	6.75
5	6.79	7.02	6.91
10	10.94	11.41	11.18
20	14.37	15.04	14.71
50	17.84	18.70	18.27
100	22.47	23.58	23.02
200	25.98	27.28	26.63
1000	37.76	39.68	38.72

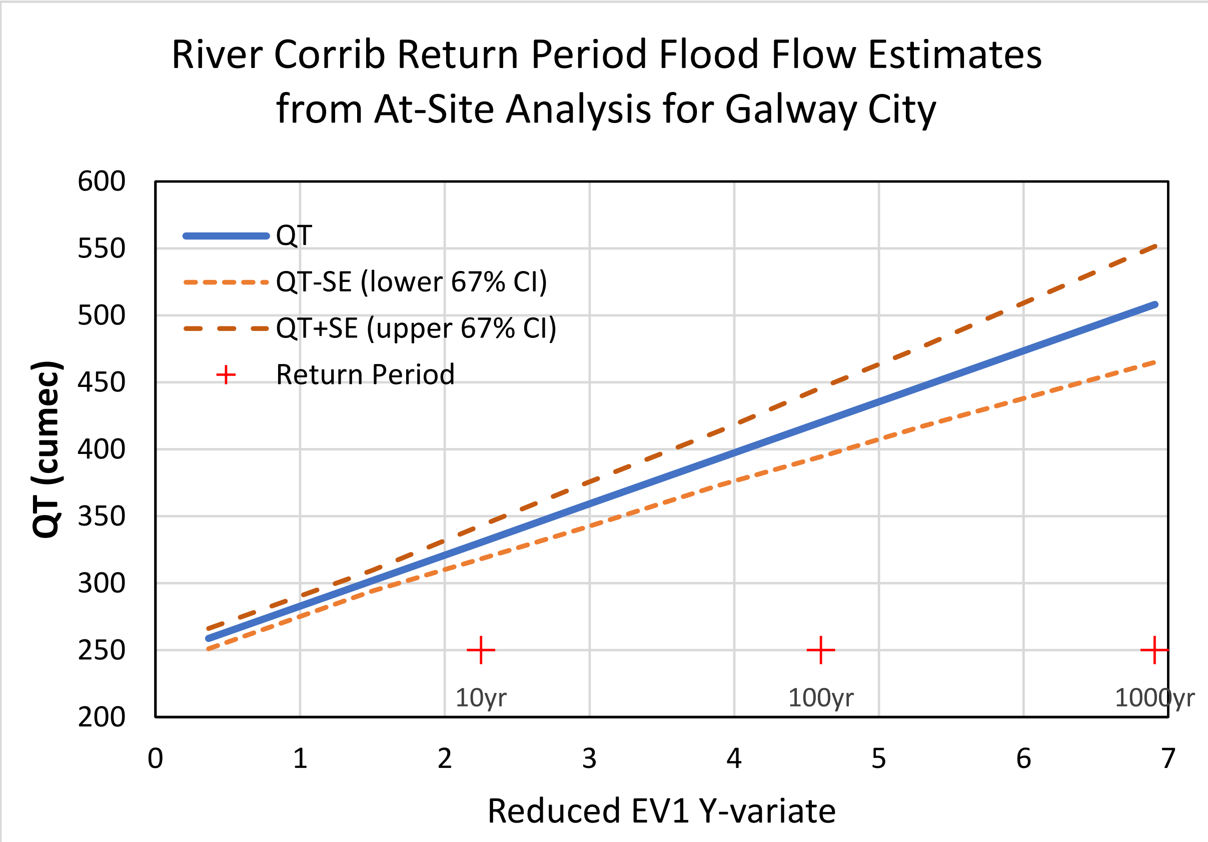

Figure 5-7 Estimated Return Period Flood Flows QT for River Corrib at Galway City with 67-percentile statistical confidence intervals from at-Site EV1 statistical Analysis (representing average between Wolfe Tone (N=48) and Dangan (N=34) Stations).

5.5.5 River Corrib flood Growth Curve from at-Site analysis

The computed L-moments for the Dangan Gauging Site is an L-CV = 0.09139, l-Skew = 0.1201, L-Kurtosis = 0.1378 and for N=35. The computed L-moments for the Wolfe Tone Bridge Gauge L-CV = 0.1072, l-Skew = 0.1563, L-Kurtosis = 0.1409 and for N=49. The average L-CV = 0.0993, l-Skew = 0.1382 and L-Kurtosis = 0.139 for the two stations combined. The return period growth factors are presented below in Table 5-8 for an EV1 distribution with an L-CV of 0.0993.

Table 5-8 Computed EV1 flood Growth factor for the River Corrib from At-site Statistical Analysis

Return Period T years	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Growth Factor XT	1.00	1.18	1.29	1.40	1.54	1.64	1.74	1.98
S.E. (%)	2.61	2.29	3.38	4.11	4.64	5.48	5.96	7.62

5.6 River Corrib Pooled Analysis

5.6.1 Introduction

The flood growth curve from pooled analysis uses the concept of a region-of-influence approach involving the creation of a collection of hydrologically similar catchments. To avoid over reliance on a single gauge site it is recommended in the FSU and in the UK FEH to select a pooling group of hydrologically similar gauges. The assumption that is inherent in the pooling group is that they represent a homogenous group from a single statistical population (i.e., single population L-CV, L-Skewness and L-Kurtosis).

In theory the standard error of the flood growth factor X_T should be reduced by the order of $\sqrt{m}$, where m is the number of homogenous gauges in the pooling group. In reality, however, the selected group is often not very homogenous and therefore the real statistical error is not likely to achieve anywhere close to the above reduction and can in many cases be significantly less reliable with an averaging effect occurring in respect to its L-CV and L-Skewness due to the inclusion of unsuitable pooling sites. These sites may even have reasonably similar PCDs, but their AM series may not reflect this, possibly due to measurement / rating error or regional/location differences. Consideration of the spread of L-CV and L-skewness within the pooling group is important before recommending the final selection of candidate sites and the use of a pooling growth curve.

To provide for increased reliability of the return period estimates in the Corrib a pooling group of hydrologically and geographically similar gauging stations are selected to generate a pooled growth curve estimates for the Corrib. The pooling groups are extended out so as to generate, where feasible, a total station-years in excess of 500 years of AM flows (i.e., 5T with T equal to 100year return period).

5.6.2 Selection of Pooling Group

5.6.2.1 Corrib Regional Pooling Group Flood Growth Curve

A regional pooling group of Corrib gauging stations was developed with 9 stations selected providing a total of 374 station years of AM data. The majority of these stations, namely 6 of the 9 are located upstream of the large attenuating lake bodies of Lough Corrib, Mask and Carra and as such are unlikely to be very representative of the flood Growth characteristics of the Corrib at Galway City. The selected stations PCD's and flood statistics are presented in Table 5-9. The AM data for these stations is best represented by an EV1 distribution and is likely to be reasonably conservative for the estimating return period Flood Magnitudes in the River Corrib at Galway City, refer to Figure 5-8.

Table 5-9 Regional Pooling group from available Corrib gauges

Station Reference	Location	Waterbody	AREA (km^2)	SAAR (mm)	FARL (index)	URBEXT (Prop)	BFIsoil (index)	DRAIND (km/km^2)	MSL (km)	S1085 (m/km)	ART-DRAIN2 (Prop)
30061	Wolfe Tone	Corrib	3126.8	1422.4	0.663	0.0065	0.7791	0.940	122.78	0.5675	0.4115
30031	Cong Weir	Cong Canal	890.9	1710.0	0.629	0.004	0.7670	1.185	79.61	0.6588	0.3126
30101	Oughterard	Owenriff	66.12	1910.4	0.746	0.0066	0.4851	1.703	22.72	5.6895	0.0705
30098	Dangan	Corrib	3120.7	1423.6	0.661	0.004	0.7809	0.942	119.51	0.5654	0.4112
30012	Claregalway	Clare	1072.9	1099.1	0.994	0.0052	0.5390	0.663	84.54	0.7421	0.7132
30004	Corofin	Clare	699.3	1103.7	0.992	0.0073	0.6062	0.796	65.66	0.8684	0.7018
30008	Ballygady	Clare	469.9	1115.1	0.989	0.005	0.6455	0.810	50.33	1.0855	0.6865
30005	Foxhill	Robe	237.8	1172.5	0.985	0.0082	0.5637	0.943	44.81	1.0262	0.6873
30002	Ower Br.	Black (Scrule)	194.1	1143.2	0.992	0.0000	0.5743	0.942	22.73	1.3847	0.8238

Station Reference	Location	Waterbody	N AM years	L-CV	L-Skewness	L-Kurtosis
30061	Wolfe Tone	Corrib	49	0.1072	0.1563	0.1409
30031	Cong Weir	Cong Canal	41	0.1376	0.0123	0.1874
30101	Oughterard	Owenriff	17	0.1365	0.3265	0.1346
30098	Dangan	Corrib	35	0.0914	0.1201	0.1378
30012	Claregalway	Clare	25	0.0920	0.1857	0.0674
30004	Corofin	Clare	54	0.1031	0.2703	0.2948
30008	Ballygady	Clare	46	0.1175	0.1521	0.1780
30005	Foxhill	Robe	63	0.1855	0.1576	0.1270
30002	Ower Br.	Black (Scrule)	46	0.1097	0.1474	0.1421
Pooled			**376**	**0.1201**	**0.1698**	**0.1567**

Note the L-Skewness of an EV1 distribution is 0.169 and therefore an EV1 is a good fit to this data and very similar results to the GEV.

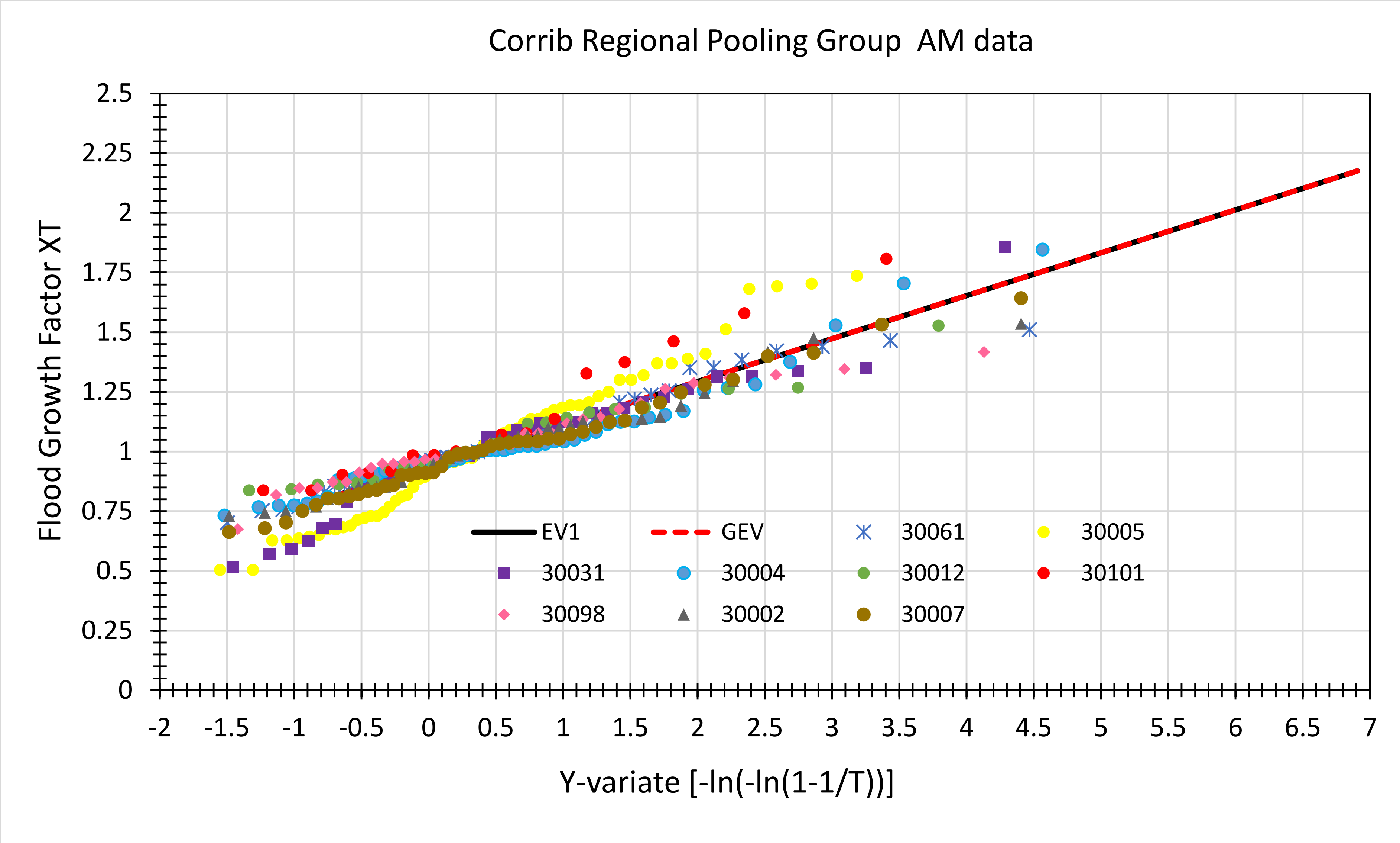

Figure 5-8 Fitting of GEV (3-parameter) and EV1 (2-parameter) Distributions to Corrib Regional Pooling group

5.6.2.2 Pooling Group Selection from Hydrologically Similar Stations

The selection of suitable pooling group is based on hydrologically similar gauged flow stations to the subject site in respect to a number of selected PCD's. The number stations selected is generally increased until a combined sample of 5T station years of AM flows is produced, where T is the return period. In Ireland the return period T used in developing the flood growth curve is generally selected as the 100year return period and thus 500 station years is required. In many cases the more stations required to achieve the 500 station years of AM data the poorer the similarity becomes, and tradeoff exists between the desired 5Tstation years and the suitability of selected stations.

Many of the gauged stations used in the original FSU are no longer considered to be suitable candidates for inclusion in pooling group analysis due to the unreliability of the AM series and the rating relationships. The number of stations currently considered by the OPW as sufficiently reliable for growth curve development has dramatically decreased to only 51 stations (OPW Q-T Atlas 2021). The original number of gauged stations available to the FSU study was 115 (considered as Grade A1 (excellent) and A2(good)) for pooling group growth curve analysis, A further 67 grade B (moderate) stations combined with the 115 A1/A2 stations were used to develop the Q_{MED} PCD regression equation.

In this study the flow gauging stations used in developing the pooling group flood growth curves is based on the FSU A1 and A2 stations using the most up to date data where available from the OPW and EPA Hydronet sites. A number of selected additional stations were included In order to provide a better sample of the larger attenuated catchments similar to the River Corrib catchment. The following stations 26075 (Boyle River at Cuppanagh), 26030 (ESB Lough Allen outflow at Bellantra Sluices) and 26027(Shannon River at Athlone Weir) were included with their AM flow series based on recent rating reviews and analyses presented in the Ballinasloe (2021), Carrick-on-Shannon (2021) and Athlone (2019) Flood Relief Scheme Hydrology Reports. The AM flood series (1972 to 2019) for Corrib at Wolfe Tone gauge was also included based on the satisfactory rating review of this gauge presented earlier in Chapter 4.

The FSU (2006) pooling group method used the following Euclidean distance measure based on three selected PCD's of AREA, SAAR and BFI for hydrological similarity. The hydrology report (FSU Flood Frequency Estimation Volume II) for the FSU examined other PCD combinations and the use of weighting factors to best select hydrologically similar pooling stations. The recommended Euclidean distance measure from the FSU is presented below in equation (5-13). The lower the Euclidean distance magnitude the higher the station similarity is to the subject site (i.e., zero represents identical).

$$d_{ij} = \sqrt{\left(\frac{ln(AREA_i)-ln(AREA_j)}{\sigma_{lnAREA}}\right)^2 + \left(\frac{ln(SAAR_i)-ln(SAAR_j)}{\sigma_{lnSAAR}}\right)^2 + \left(\frac{ln(BFIsoil_i)-ln(BFIsoil_j)}{\sigma_{lnBFIsoil}}\right)^2} \qquad \text{5-13}$$

Where the standard deviations of the complete FSU gauged PCD dataset is σ_{lnAREA}=1.265, σ_{lnSAAR}=0.173 and $\sigma_{lnBFIsoil}$= 0.219.

Table 5-10 presents the FSU selected catchments based on FSU 3-parameter distance measure for AREA, SAAR and BFISOILS. A number of catchments selected by this method are quite remote from the Corrib catchment with Slaney at Scarawalsh and the River Suir at Cahir Park and Clonmel gauges included. This measure does not include for a specific allowance for attenuation by lakes and as a consequence the majority of stations included have steeper growth curve relationships than the Corrib. An EV1 distribution is found to represent reasonably well this data, refer to Figure 5-9.

To include for attenuation from lakes a fourth PCD FARL parameter is included in the distance measure, refer to Equation (5-14). Testing of this approach has generated a more representative pooling group for the River Corrib, over the 3-parameter FSU method. The selected gauging stations and their PCDs and L-moment statistics are presented in Table 5-11. The AM -data for these stations plotted on a logistic plot, refer to Figure 5-12 shows much smaller spread in the data points over the previous Corrib regional pooling group and the FSU 3-parameter pooling group. This indicates that this pooling group is more homogenous and satisfies better the requirement for the pooling stations to originate from a single parent population of known statistical distribution. An EV1 distribution fits reasonably well this data, refer to Figure 5-12.

$$d_{ij} = \sqrt{\left(\frac{ln(FARL_i) - ln(FARL_j)}{\sigma_{lnFARL}}\right)^2 + \left(\frac{ln(AREA_i) - ln(AREA_j)}{\sigma_{lnAREA}}\right)^2 + \left(\frac{ln(SAAR_i) - ln(SAAR_j)}{\sigma_{lnSAAR}}\right)^2 + \left(\frac{ln(BFIsoil_i) - ln(BFIsoil_j)}{\sigma_{lnBFIsoil}}\right)^2} \qquad \textit{5-14}$$

Table 5-10 Pooling group selected using Euclidean distance based on FSU method using AREA, SAAR, and BFISOIL

Station Reference	Location	Waterbody	AREA (km^2)	SAAR (mm)	FARL (index)	URBEXT (Prop)	BFIsoil (index)	DRAIND (km/km^2)	MSL (km)	S1085 (m/km)	ART-DRAIN2 (Prop)
30061	Wolfe Tone Br.	R, Corrib	3126.8	1422.4	0.663	0.0065	0.779	0.940	122.8	0.568	0.412
34001	Rahans	R. Moy	1974.8	1322.7	0.825	0.0083	0.776	1.352	88.9	0.719	0.336
16011	Clonmel	R. Suir	2143.7	1125.0	0.998	0.0073	0.670	1.045	116.5	0.953	0.000
12001	Scarawalsh	R. Slaney	1030.8	1167.3	0.999	0.006	0.716	1.068	89.3	2.099	0.000
30031	Cong Weir	Cong Canal	890.9	1710.0	0.629	0.004	0.767	1.185	79.6	0.659	0.313
26027	Athlone Weir	R. Shannon	4600.7	1058.4	0.670	0.0061	0.692	0.858	177.0	0.315	0.228
27002	Ballycorey	R. Fergus	564.3	1336.4	0.835	0.0008	0.697	0.537	40.4	1.218	0.000
16009	Cahir Park	R. Suir	1582.7	1078.6	0.998	0.0077	0.631	1.002	85.4	1.005	0.000
26007	Bellagill	R. Suck	1207.2	1045.6	0.983	0.0021	0.653	0.753	107.4	0.413	0.000

Station Reference	Location	Waterbody	N AM years	L-CV	L-Skewness	L-Kurtosis
30061	Wolfe Tone Br.	R. Corrib	49	0.1072	0.1563	0.1409
34001	Rahans	R. Moy	51	0.0968	0.0887	0.2635
16011	Clonmel	R. Suir	47	0.1533	0.1190	0.0436
12001	Scarawalsh	R. Slaney	64	0.1930	0.1832	0.1842
30031	Cong Weir	Cong Canal	41	0.1023	-0.0191	0.1290
26027	Athlone Weir	R. Shannon	67	0.1218	0.0797	0.1298
27002	Ballycorey	R. Fergus	66	0.1217	0.1805	0.2156
16009	Cahir Park	R. Suir	66	0.0939	-0.0809	0.0517
26007	Bellagill	R. Suck	68	0.1349	0.2008	0.2363
Pooled			**518**	**0.1250**	**0.1009**	**0.1550**

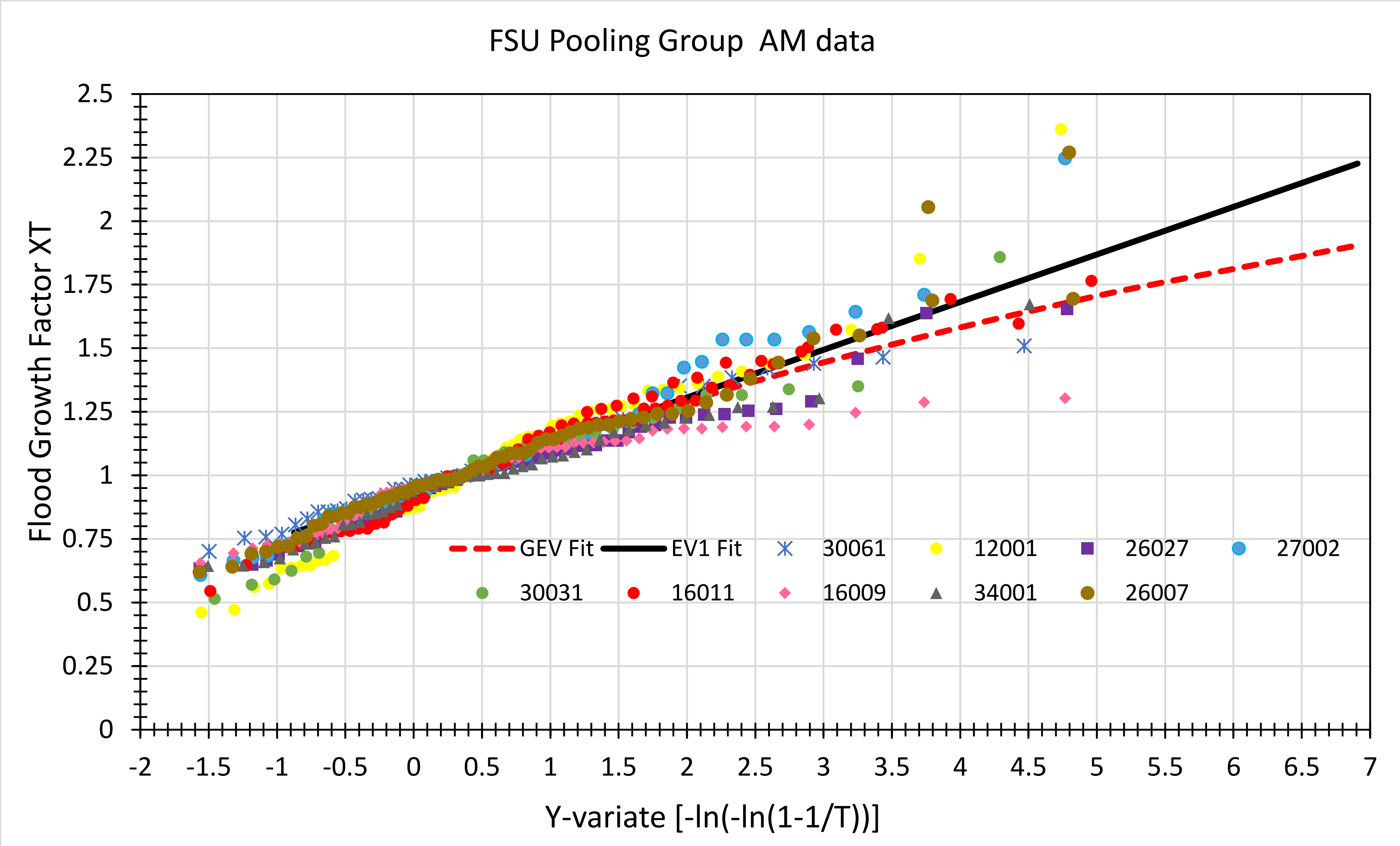

Figure 5-9 Fitting of GEV (3-parameter) and EV1 (2-parameter) Distributions to Pooling group based on FSU 3-parameter selection

Table 5-11 Pooling group selected using Euclidean distance based on modified FSU method using AREA, SAAR, BFISOIL and FARL

Station Reference	Location	Waterbody	AREA (km^2)	SAAR (mm)	FARL (index)	URBEXT (Prop)	BFIsoil (index)	DRAIND (km/km^2)	MSL (km)	S1085 (m/km)	ART-DRAIN2 (Prop)
30061	Wolfe Tone Br	R. Corrib	3126.8	1422.4	0.663	0.0065	0.779	0.940	122.78	0.5675	0.4115
30031	Cong Weir	Cong canal	890.9	1710.0	0.629	0.004	0.767	1.185	79.61	0.6588	0.3126
26027	Athlone Weir	R. Shannon	4600.7	1058.4	0.67	0.0061	0.692	0.858	177.02	0.3148	0.2284
34001	Rahans	R. Moy	1974.8	1322.7	0.825	0.0083	0.776	1.352	88.86	0.7194	0.3359
36019	Belturbet	Erne River	1491.8	971.2	0.761	0.0067	0.787	1.010	78.58	1.1912	0
25017	Banagher	River Shannon	7980.4	1024.1	0.786	0.0082	0.654	0.806	214.61	0.2465	0.2093
22035	Laune Br.	Laune R.	559.7	2009.9	0.731	0.0097	0.637	1.363	56.30	7.5797	0
26030	Bellantra Sl.	R. Shannon	416.6	1561.0	0.673	0.009	0.522	1.366	40.20	2.7970	0
27002	Ballycorey	Fergus R.	564.3	1336.4	0.835	0.0008	0.697	0.537	40.39	1.2183	0

Station Reference	Location	Waterbody	N AM years	L-CV	L-Skewness	L-Kurtosis
30061	Wolfe Tone Br	R. Corrib	49	0.1072	0.1563	0.1409
30031	Cong Weir	Cong canal	41	0.1023	-0.01909	0.12905
26027	Athlone Weir	R. Shannon	67	0.1218	0.07970	0.12978
34001	Rahans	R. Moy	51	0.0968	0.08865	0.26349
36019	Belturbet	Erne River	61	0.1041	-0.02857	0.06384
25017	Banagher	River Shannon	70	0.1139	0.01331	0.09482
22035	Laune Br.	Laune R.	28	0.1183	-0.15299	0.02724
26030	Bellantra Sl.	R. Shannon	80	0.1166	0.23790	0.10953
27002	Ballycorey	Fergus R.	66	0.1217	0.18052	0.21561
Pooled			**513**	**0.1114**	**0.0618**	**0.1305**

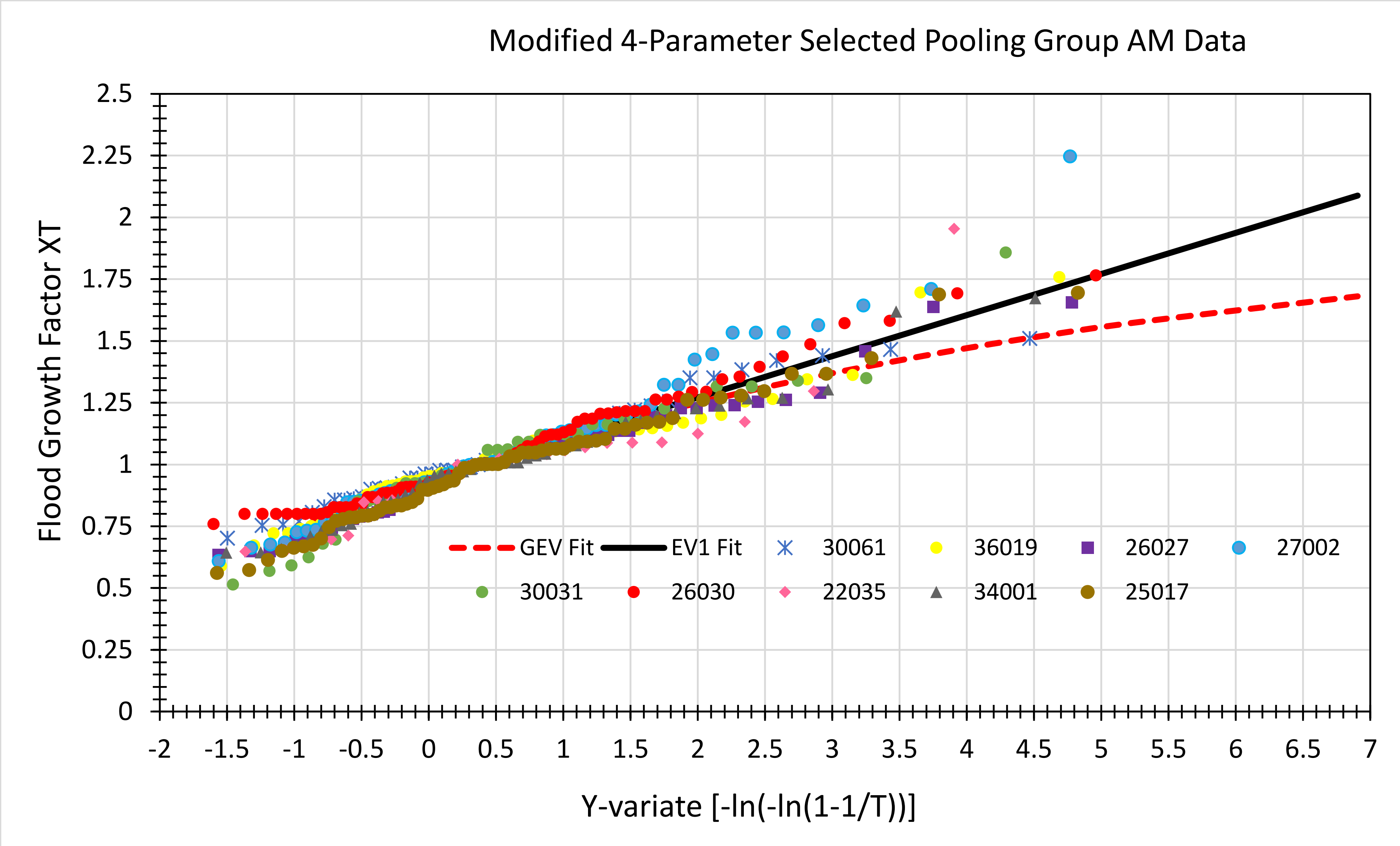

Figure 5-10 Fitting of GEV (3-parameter) and EV1 (2-parameter) Distributions to Pooling group based on 4-parameter Selection

5.7 OPW FSU 2021 Q-T Atlas

The OPW have recently produced a draft 2021 Q-T Atlas which includes return period estimates at all FSU hydrological Estimation points throughout the 26 counties. The following is a description of the Q-T Atlas method from the Hydrology Section of the OPW. The development of the 2021 Q-T Atlas involved the following steps:

1. A new Q_{MED} equation was developed using the most recent Amax data from 109 FEMI only Stations + 73 FSU Stations. The Nash Sutcliffe Efficiency (NSE) for this equation was 0.942.

2. The adjustment of the initial Q_{MED} estimate by using the concept of pivotal sites was examined and a of pooling schemes that looked at three main variables were trialled, the number of pivotal sites to be used, the PCDs to be used to define hydrologically similar gauged sites and their associated weightings that are applied to the hydrological distance measure (i.e., inverse weighting on distance inverse distance squared etc.). In total 600 combinations of PCDs and associated weightings were examined to achieve the best NSE score. The best of these combinations (pooling schemes) used 3 pivotal sites (the FSU method only uses one) with an NSE of 0.957.

3. A generalised likelihood uncertainty estimation (GLUE) Monte Carlo simulation approach of the ensemble of pooling schemes NSE results was performed to further improve the NSE. The results from this gave an NSE score of 0.959 of the average outputs from the top six pooling schemes.

4. This pooling approach for Q_{MED} adjustment was then applied to all ungauged locations in Ireland to provide estimates of Q_{MED} at all ungauged locations. A certain amount of 'jumpiness' (i.e., flows sometimes reduced when moving downstream on a segment of river reach) was observed in the estimated Q_{MED} values. A smoothing rule was used to remove this. The rule was not applied across lakes seeing as it is possible for Q_{MED} values to be smaller after passing through lakes due to flood attenuation.

5. Selection method of pooling group for Flood growth curve estimation involving Euclidean similarity distance measure based on selected PCDs . Similar to the approach for Q_{MED} estimation, a number of combinations of PCDs and weightings were examined and optimised to minimise the pooled uncertainty measure (PUM). The best result was a PUM of 0.1556, using the weightings shown in Table 5-12 below. It's worth noting that the PUM for the FSU pooling scheme was 0.189, so this represents an improvement on the FSU pooling scheme. However, the number of stations considered suitable for growth curve pooling has been dramatically reduced due to flood rating reliability concerns by the OPW to only 51 stations, 48 from within the 26 counties and 3 from Northern Ireland stations. This relatively low number of pooling group stations limits the availability of potentially hydrologically similar catchments to the subject site and potentially produces a more generic average flood growth curve. This is a concern for

the application of this method to the Corrib catchment which is a large attenuated catchment and such characteristics are not well represented in the available pooling stations with no River Corrib stations (i.e., Wolfe Tone or Dangan downstream of Lough Corrib) included.

$$d_{ij} = \sqrt{1.7\left(\frac{ln(FARL_i)-ln(FARL_j)}{\sigma_{lnFARL}}\right)^2 + 1.3\left(\frac{ln(S1085_i)-ln(S1085_j)}{\sigma_{lnS1085}}\right)^2 + 0.5\left(\frac{ln(DRAIND_i)-ln(DRAIND_j)}{\sigma_{lnDRAIND}}\right)^2 + 0.9\left(\frac{ln(SAAR_i)-ln(SAAR_j)}{\sigma_{lnSAAR}}\right)^2 + 1.1\left(\frac{ln(BFIsoil_i)-ln(BFIsoil_j)}{\sigma_{lnBFIsoil}}\right)^2} \quad \text{5-15}$$

Table 5-12: Selected PCDs and weightings used in Q-T Atlas Pooling group selection.

PCD:	*BFI*	*SAAR*	*FARL*	*DRAIND*	*S1085*
Weighting:	*1.1*	*0.9*	*1.7*	*0.5*	*1.3*
LN(Stdeviation)	*0.2153*	*0.2201*	*0.099*	*0.3554*	*1.0668*

6. The above pooling scheme in equation (5-15) is used to generate pooled L-moment ratios at all ungauged sites in Ireland. This requires 5T years of data to form the pooling group using at T=100years as the return period of interest.

7. In order to select the most suitable growth curve distribution, we compared the location of the pooled L-moment ratios for ungauged sites to theoretical L-moment diagrams. The majority of locations were found to follow LN2 and EV1 (2-parameter distributions), and GEV (3-parameter distribution).

8. The final Q values for each return period, T were then calculated by multiplying Q_{MED} by the Growth Factor for all ungauged locations. Again, a smoothing rule was applied to ensure continuity of flow magnitudes in the downstream direction.

The OPW consider the 2021 Q-T atlas as a quick reference guide for flood estimation at ungauged locations, and do not deem it suitable for detailed design.

The main draw backs of this method for the River Corrib at Galway is that no River Corrib gauging stations w(i.e. Wolfe Tone Gauge 30061) were included as a pivotal site for the Q_{MED} estimation and that the pool of available gauge stations for pooling selection are two few (currently only 51 stations deemed suitable by OPW for growth curve development) and not these stations are generally not very representative of the River Corrib in respect to catchment area and lake attenuation effects. The selection parameters in Equation (5-15) do not include the catchment AREA, which is problematic as small catchments can be selected to represent a very large catchment such as the Corrib, refer to Table 5-14. In this case of the 12 sites selected three had catchment areas of 9.7km^2 (Mournebeg), 66.1km^2 (Owenriff) and 127.2km^2

(Kiltimagh) relative to the subject site of 3125km^2 and therefore, not very applicable to the Corrib. The performance and wide scatter of the AM data from this method (refer to Figure 5-12) is no better than that produced by the regionally selected Corrib catchment pooling group, refer to Figure 5-8.

The Q-T atlas results for the subject site at FSU node 30_3419_2 are presented below in Table 5-13 below and the location of the node point is shown in Background Map Data © 2023 Google, DigitalGlobe

Figure 5-11.

Table 5-13 Estimated Return Period Flood Flows River Corrib at Galway City (Node 30_3419_2) from OPW 2021 Q-T Atlas

Return Period T years	Reduced Yvariate = -ln(-ln(1-1/T))	Growth Factor XT	Return Period Flow QT (cumec)
2	0.37	1	209.9
5	1.50	1.200	251.9
10	2.25	1.336	280.5
20	2.97	1.475	309.7
50	3.90	1.673	351.3
100	4.60	1.838	385.8
200	5.30	2.018	423.6
1000	6.91	2.505	525.9

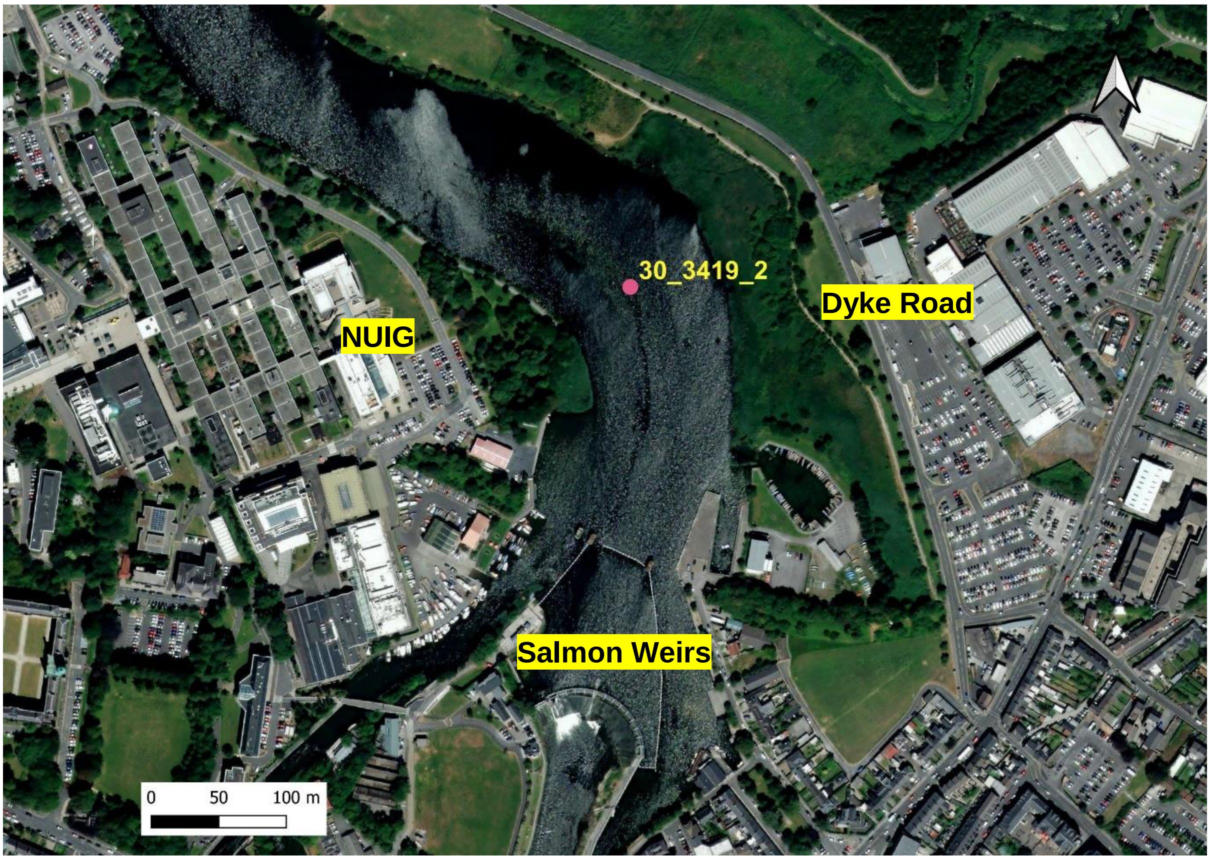

Figure 5-11 Location of Node 30_3419_2 located upstream of the Salmon Weir Barrage adjacent to NUI Galway and Dike Road

These results suggest a Q_{MED} of 209.9 cumec which is well shy of the gauged Q_{MED} of 258.9cumec (i.e., 19% lower). The estimated 100year growth factor from this method is X_{100} = 1.84 whereas the at site statistical analysis gives a 100year growth factor X_{100} = 1.62 and the pooled analysis gives an X_{100} = 1.70.

Table 5-14 Pooling group selected using Euclidean distance based on new OPW Q-T Atlas method using S1085, DrainD, SAAR, BFISOIL and FARL (note number of gauged pooling stations considered suitable reduced to 51 stations)

Station Reference	Location	Waterbody	AREA (km^2)	SAAR (mm)	FARL (index)	URBEXT (Prop)	BFIsoil (index)	DRAIND (km/km^2)	MSL (km)	S1085 (m/km)	ART-DRAIN2 (Prop)
25017	Bangaher	R. Shannon	7980.4	1024.1	0.786	0.0082	0.654	0.806	214.61	0.247	7980.4
34001	Rahans	R. Moy	1974.8	1322.7	0.825	0.0083	0.776	1.352	88.86	0.719	1974.8
26108	Boyle Abbey Br.	R. Boyle	527.3	1142.7	0.825	0.0042	0.725	0.876	70.03	0.369	527.3
26021	Ballymahon	R. Inny	1098.8	945.3	0.807	0.0041	0.828	0.744	90.24	0.199	1098.8
22035	Laune Br.	R. Laune	559.7	2009.9	0.731	0.0097	0.637	1.363	56.30	7.580	559.7
26008	Johnston's Br.	R. Rinn	280.3	1035.5	0.855	0.0026	0.611	1.130	34.79	1.106	280.3
30101	Oughterard d/s	Owenriff R	66.1	1910.4	0.746	0.0066	0.485	1.703	22.72	5.690	66.1
36010	Butler's Br.	Annalee R	771.7	967.6	0.861	0.0045	0.632	1.005	64.31	1.581	771.7
07010	Liscartan	Kells Blackwater	699.7	948.3	0.911	0.0058	0.658	0.976	69.07	1.801	699.7
07002	Killyon	Deel [Raharney]	285.0	920.5	0.929	0.0034	0.780	0.788	36.55	0.962	285.0
01055	MourneBeg W.	MourneBeg	9.7	1975.8	0.737	0.0000	0.446	1.552	5.88	13.632	9.7
34024	Kiltimagh	Pollagh	127.2	1177.5	0.922	0.0075	0.521	1.361	31.92	1.518	127.2

Station Reference	Location	Waterbody	N AM years	L-CV	L-Skewness	L-Kurtosis
25017	Bangaher	R. Shannon	70	0.1304	0.0911	0.1577
34001	Rahans	R. Moy	51	0.1218	0.0937	0.1706
26108	Boyle Abbey Br.	R. Boyle	30	0.1248	0.2533	0.3274
26021	Ballymahon	R. Inny	45	0.1133	0.0544	0.1619
22035	Laune Br.	R. Laune	27	0.1298	0.1523	0.2766
26008	Johnston's Br.	R. Rinn	65	0.1125	0.1858	0.1609
30101	Oughterard d/s	Owenriff R	18	0.1342	0.2913	0.1144
36010	Butler's Br.	Annalee R	65	0.1370	0.2422	0.2249
07010	Liscartan	Kells Blackwater	34	0.1256	0.1571	0.2639
07002	Killyon	Deel [Raharney]	41	0.1549	0.0149	0.0690
01055	MourneBeg W.	MourneBeg	23	0.1930	0.2326	0.1499
34024	Kiltimagh	Pollagh	43	0.1100	-0.0855	0.2726
Pooled			**512**	**0.1291**	**0.1289**	**0.1922**

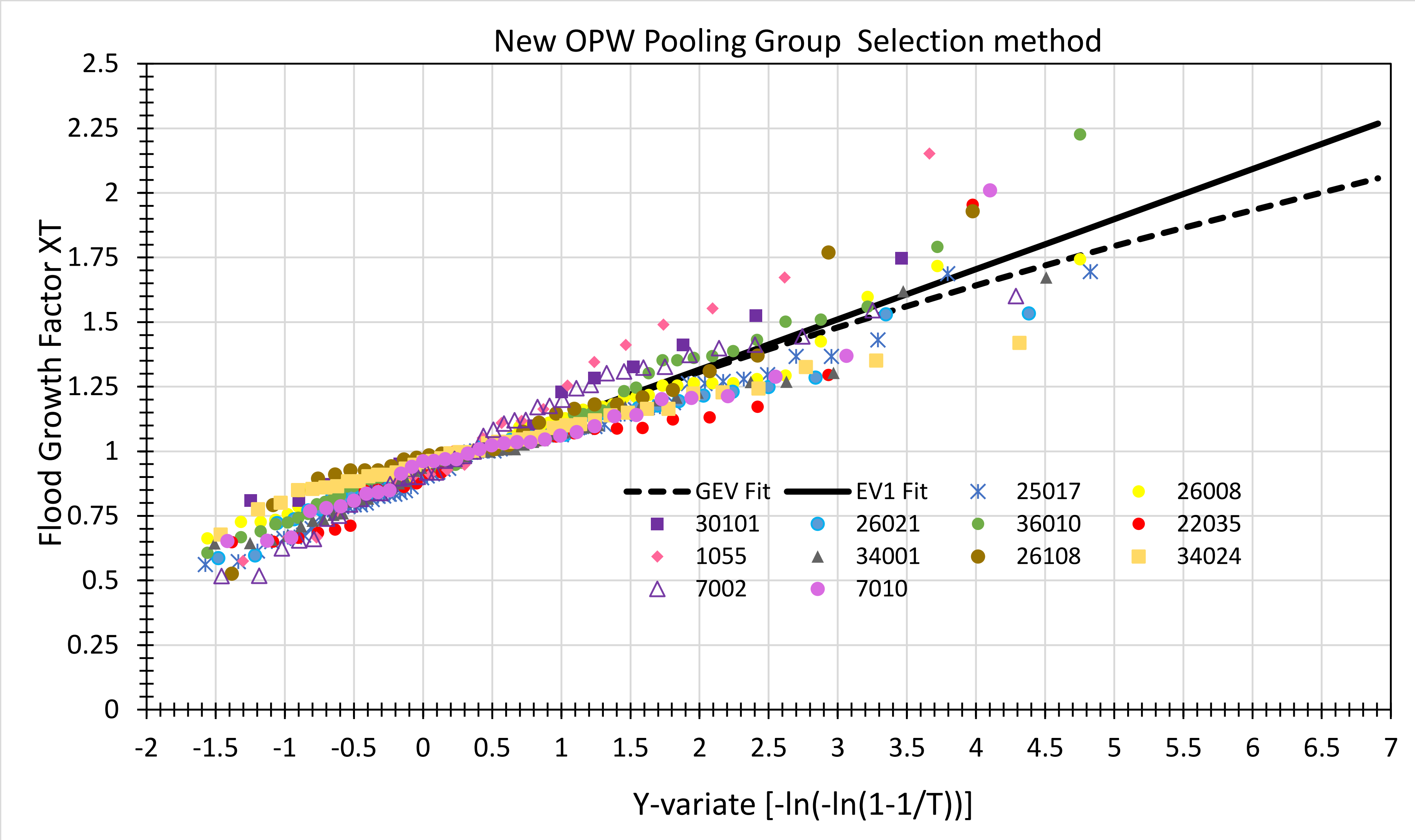

Figure 5-12 Fitting of GEV (3-parameter) and EV1 (2-parameter) Distributions to Pooling group produced from the OPW Q-T atlas 2021 Method

5.8 Q_{MED} Pivotal Site Adjustment Estimate

The Corrib reference site for setting the pivotal adjustment factor for the FSU PCD method is FSU node 30_3419_2 located 290m upstream of the Salmon Weir Barrage, refer to Table 5-15 below for details of site's PCDs:

Table 5-15 Details of PCDs for River Corrib Reference Node 30_3419_2 (Corr_06)

NODE 30_3419_2 c. 300m Upstream Salmon Weir Galway 129656E, 226036N		
AREA	3122.6	km2
SAAR	1422.5	mm
URBEXT	0.0062	
BFISOIL	0.7793	
DrainD	0.940	km/km2
S1085	0.5662	m/km
ARTDRAIN2	0.4117	
FARL	0.664	
MSL	121.6	km

The Q_{MED} estimate from the FSU PCD equation for the above nodal point 30_3419_2, based on the PCD values in Table 5-15 and using Equations 5-2 and 5-3, is 159.0cumec. The previous FSR catchment characteristic equation (NERC 1975) gives a QBAR estimate for the Corrib at this node of 204.6cumec which is equivalent to a Q_{MED} of 196.4cumec.

The gauged Q_{MED} estimate at this reference location based on combining the gauged Q_{MED} from Wolfe Tone (Q_{MED} = 250.6cumec for AM period 1972 – 2020) and from Dangan (Q_{MED} = 260.8cumec for AM period 1986 – 2020) is 255.7cumec with a S.E. of 9.234 cumec (or 3.612%). This represents a FSU pivotal adjustment factor of 1.608 ($QMED_{gauged}/QMED_{PCD}$) for all of the Corrib HEPs within the scheme area.

5.9 Recommended Design Flows and Growth Factor for River Corrib

The estimated Growth Factors for the River Corrib to Galway City from the various statistical methods are presented in

Table 5-16. The recommended Flood Growth curve for the Galway City Flood Relief Scheme is the pooled analysis using the HEL 4 – parameter Selection and fitting an EV1 distribution with an L-CV of 0.1123. This gives a growth curve very similar to the average of the at-site, Corrib regional, FSU and HEL Pooling group curves. The new OPW Atlas method is not considered to be very reliable for the Corrib flows as many of the stations collected are considerably smaller in area and have limited flood attenuation effect (FARL).

Table 5-16 Estimated Flood Growth factors for River Corrib to Galway City from at-site and various pooled analyses.

Return Period T years	EV1 Yvariate	At-Site Analysis	Corrib regional Selection	FSU 3-parameter Selection	HEL 4-parameter Selection	OPW 2021 Q-T Atlas method
		EV1	EV1	EV1	EV1	unknown
2	0.37	1.010	1	1	1	1
5	1.50	1.179	1.204	1.212	1.189	1.200
10	2.25	1.291	1.339	1.353	1.313	1.336
20	2.97	1.398	1.468	1.488	1.433	1.475
50	3.90	1.537	1.636	1.663	1.588	1.673
100	4.60	1.641	1.761	1.794	1.704	1.838
200	5.30	1.744	1.886	1.924	1.820	2.018
1000	6.91	1.984	2.176	2.226	2.088	2.505

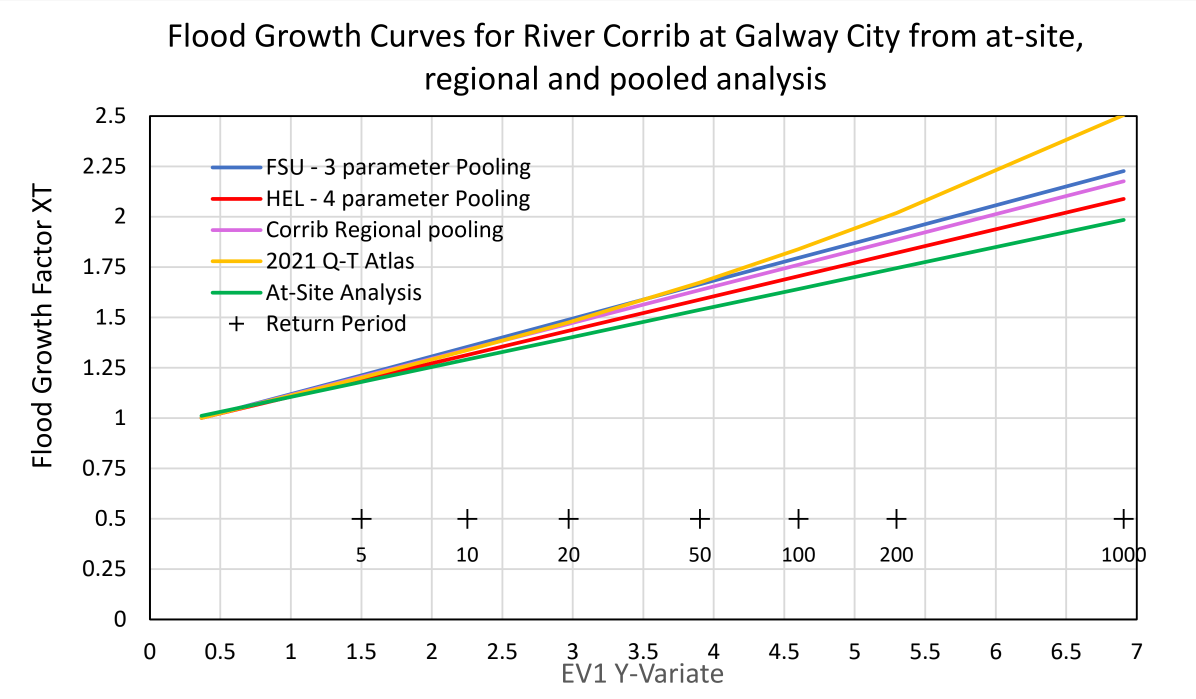

Figure 5-13 Estimated Flood Growth Curves for River Corrib from at-site and Pooled statistical analysis

The recommended return period design flows for the River Corrib are presented below in

Table 5-17. It is expected that these design flows developed by fitting an EV1 distribution will be reasonably conservative for the Corrib due to the attenuating effect from Lough Corrib.

Table 5-17 Recommended Return Period Growth Factor and Design Flows for the River Corrib to Galway City (Node 30-3419-2)

Return Period T years	X_T	QT m^3/s
2	1.000	255.7
5	1.189	304.0
10	1.313	335.7
20	1.433	366.4
50	1.588	406.0
100	1.704	435.7
200	1.820	465.3
1000	2.088	533.8

The statistical error (SE) associated with pooled analysis theoretically reduces by a factor of $\sqrt{m}$, where m is the number of pooling stations. Therefore, in respect to the selected pooling group which had 9 stations the reduction in statistical error should be threefold. This assumes that the stations are all from the same single statistical distribution and that their AM series are independent and random, which may not be the case as a number are clearly from different distributions based on the probability plots and furthermore many of AM series in the pooling group are produced by the same meteorological rainfall events.

A more meaningful estimate would be to assume a single distribution based on the average sample length N (station years/ no. of stations) and the mean pooled L_CV. In the case of the study pooling group of 513 station years and 9 stations the average sample length is N = 57 and the weighted average L_CV = 0.1114. By Monte Carlo simulation the statistical error is calculated and presented below for both Standard error calculations and are combined with the percentage statistical error of 3.61% associated with the gauged Q_{MED} estimate. It is considered prudent that the larger standard error be used for hydrological uncertainty associated with the recommended design flows.

Table 5-18 Estimated Statistical Error associated with Corrib Design Flows

Return Period T years	Q_T	Relative Standard Error of 9 station pooling group as % of Q_T	Recommended Standard Error for pooling group represented by single best fit site as % of Q_T
2	255.7	3.612	3.612
5	304.0	4.215	5.410
10	335.7	4.520	6.319
20	366.4	4.762	7.042
50	406.0	5.021	7.816
100	435.7	5.184	8.305
200	465.3	5.326	8.729
1000	533.8	5.594	9.532

Included in the above standard errors presented in Table 5-18 is the 3.612% standard error associated with the gauged Q_{MED} value that represents the pivotal Site. The relative standard error is considered not realistic as it represents the statistical sampling error for the 9 pooling stations with average sample size of 57 from a single identical distribution which clearly is not the case. It is therefore considered that a more realistic statistical sampling error is produced for a single average distribution of the 9 stations with a sample number of 57, represented in the fourth column in the above Table.

5.10 Flood Estimation for Small Ungauged Catchments

5.10.1 Introduction

Flood flow estimation for the small ungauged catchments entering the Corrib of which there is only one within the Galway City area, namely Sruffaunacashlaun Stream that discharges to the Distillery Stream at NUI Galway. This is a small, urbanized stream of catchment area 2.54km^2. The Sruffaunacashlaun Stream catchment is significantly modified by urban development over many decades with the entire catchment draining to piped storm network drainage system. Currently there is only a small section of open channel (c. 80m) remaining on the Sruffaunacashlaun Stream located between the Seamus Quirke Road and the Newcastle Road through Snipe Lawn. A lot of the older urban areas within the upstream catchment at Rahoon, Newcastle and Shantalla are serviced by combined and separated storm sewers that discharge downstream to the Distillery channel at NUI Galway campus and the combined sewer to Mutton Island WWTP. This catchment is a fully urban drained catchment whose drainage systems are under the control of Irish Water (foul and combined) and Galway City Council (Roads Section). The portion of natural stream channel is very small at only 80m, and the drainage flows to the stream are limited by the storm network capacity. As a consequence, this catchment does not behave like a natural catchment and therefore standard flood estimation methods (IH124 Equation, FSU equations, Rational Method) for this small ungauged, highly urbanized catchment may not be very accurate. To fully understand and improve the accuracy of estimating the flood hydrographs for this stream rainfall-runoff modelling of the sewer network would be required which does not form part of the brief for this study. A Galway City drainage study by Irish Water and Galway City Council is being carried out at present, but is not sufficiently advanced at time of writing to input to the hydrology study.

5.10.2 Flood Flow estimates – IH124 Equation

5.10.2.1 Background

Generally, for small ungauged catchments (< 25km^2) the IH124 Equation (Institute of Hydrology, 1993, Cawley et al., 2003) is applied with an urban factor to estimate the mean annual maximum flood QBAR. Such equations are considered to be less reliable than a single year's annual maximum flow estimate. The IH124 equation is presented below:

$$QBAR_{rural} = 0.00108AREA^{0.89}SAAR^{1.17}SOIL^{2.17} \quad \text{5-16}$$

Where $QBAR_{rural}$ is mean annual maximum flood discharge for a natural rural catchment (i.e. without the presence of urbanization), AREA is catchment area in km^2, SAAR is the standard average annual rainfall over the catchment area in mm and SOIL is the soil index for the catchment based on the winter rainfall acceptance potential class (five classifications: very high, high, medium, low, very low). This equation was developed from 71 gauged small UK catchments, varying in size from 0.5 to 25km^2, with no Irish catchments represented, and predominantly for SOIL types 4 and 5 (high and very high soil runoff) with little representation of low and very low soil runoff catchments (type 1 and 2) only 12%, (Cawley et al., 2003). The factorial standard error (FSE) of the $QBAR_{rural}$ regression equation is 1.65, which is generally applied to the $QBAR_{rural}$ estimates due to the high degree of uncertainty.

The CIRIA guide to the design of Flood Storage Reservoirs (Hall et al.,1993) sets out a method of estimating QBAR for a catchment subjected to partial urbanization from the $QBAR_{rural}$ estimate and is based on an earlier FSSR report no. 5 method (NERC,1979).

A catchment index CIND is Defined as a function of SOIL and catchment wetness index (CWI) as follows:

$$CIND = 102.4SOIL + 0.28(CWI - 125) \quad \text{5-17}$$

And a further index NC representing the rainfall continentality factor is defined at be a function of SAAR as follows:

$$NC = 0.92 - 0.00024SAAR\ for\ [500 \le SAAR \le 1100\ mm] \quad \text{5-18}$$

$$NC = 0.74 - 0.000082SAAR\ for\ [1100 \le SAAR \le 3000\ mm] \quad \text{5-19}$$

The ratio of $QBAR_{urban}$ to $QBAR_{rural}$ is

$$F = \frac{QBAR_{urban}}{QBAR_{rural}} = (1 + URBAN)^{2NC}\left(1 + URBAN\left(\frac{21}{CIND} - 0.3\right)\right) \quad \text{5-20}$$

Where URBAN is the urban fraction of the catchment.

The conversion factor F is based on the assumption that 30% of the mapped urban area is impervious from which 70% of the runoff is anticipated, refer to FSSR No. 5 (NERC, 1979). The CWI for West of Ireland is taken as 125mm in this study which represents winter conditions without soil moisture deficit.

5.10.2.2 Sruffaunacashlaun Stream

In the case of the Sruffaunacashlaun stream the catchment mapped as urbanized is the majority of the catchment except for the large public green areas associated with playing field and pitches giving an Urban factor of 0.85. The SOIL factor for this catchment which is located west of the Corrib in the granite bedrock area is based on a type 2 WRAP (high WRAP) with a SOIL index = 0.3. The SAAR for this catchment is 1160mm and the total catchment area is 2.54km^2.

The above method without inclusion of the FSE produces:

$QBAR_{rural}$ = 0.698cumec and $QBAR_{urban}$ = 1.231cumec

With inclusion of the factorial standard error the QBAR estimate for the Sruffaunacashlaun Stream is

$QBAR_{rural}$ = 1.152cumec and $QBAR_{urban}$ = 2.031cumec

Applying the FSR National Growth Factor for Ireland based on a GEV distribution, refer to Table 5-19 below for return period factors expressed in terms of QBAR and alternatively QMED. This growth curve is found to be more conservative than the FSU and the recent QT Atlas growth curves with a the X_{100} = 2.06 and the X_{1000} = 2.74.

Table 5-19 FSR (NERC 1975) National Growth Curve For Ireland

T (years)	2	5	10	20	50	100	200	1000
X_T^* = QT/QBAR	0.95	1.20	1.37	1.54	1.77	1.96	2.14	2.60
$X_T = Q_T/Q_{MED}$	1.00	1.26	1.44	1.62	1.86	2.06	2.25	2.74

Table 5-20 Estimated return period flood flow and runoff rates for the Sruffaunacashlaun Stream (without inclusion of FSE)

Return Period T (years)	2	5	10	20	50	100	200	1000
Q_T (cumec)	2.047	2.586	2.952	3.319	3.814	4.224	4.612	5.603
Runoff rate (l/s per ha)	8.07	10.19	11.64	13.08	15.04	16.65	18.18	22.09

Table 5-21 Estimated return period flood flow and runoff rates for the Sruffaunacashlaun Stream (with inclusion of FSE of 1.65)

Return Period T (years)	2	5	10	20	50	100	200	1000
Q_T (cumec)	3.378	4.267	4.872	5.476	6.294	6.970	7.610	9.245
Runoff rate (l/s per ha)	13.32	16.82	19.20	21.58	24.81	27.47	29.99	36.44

These estimated flows represent extreme flows well beyond the capacity of the storm drainage network within the Sruffaunacashlaun catchment particularly at 10year and greater.

5.10.2.3 Terryland Stream

The Terryland Stream has a mapped total drainage basin with a catchment area of 9.0km^{2}and an urban fraction of 38%. The direct surface runoff catchment based on the lidar DTM is only 4.58km^2 and an urban fraction of 75%. The catchment is karstic with no surface drainage features present except within the Terryland Stream basin itself. This is a modified arterial drainage channel of reasonably regular trapezoidal geometry, c. 5 to 6m in width maintained by the OPW and of very mild bed slope. A large portion of the channel is tidally influenced. The FSR SOIL index mapping shows SOIL type 1 classification, associated with karst catchment having very high winter rainfall acceptance potential (i.e., very low runoff). This general classification applies to an extensive area of County Galway east of the Corrib channel as far as Ballinasloe. The FSU BFIsoil index, by inference as it is not a direct measure of SOIL index, suggests that the is SOIL index is more equivalent to type 2 as opposed to type 1 for this catchment. The Teagasc soil types and the catchment slopes and wetness suggest that Soil type 2 is more appropriate for this catchment. It has been generally found that for West of Ireland catchments SOIL type 1 produces unrealistically low flood runoff rates as it assumes that majority of the effective rainfall percolates to groundwater through free draining till and karst bedrock and does not contribute to flood runoff which is often not the case during persistent rainfall associated with winter flooding conditions.

Using the IH124 equation (5-16) and the FSR Growth Curve presented above in Table 5-19 for the surface runoff catchment of area 4.58km^2, SAAR is 1163mm, URBAN is 0.71 and SOIL is set at 0.3 (Soil type 2) gives the following return period peak flood flow estimates and runoff rates:

Table 5-22 Estimated return period design flows and runoff rates for the Terryland Stream (without inclusion of FSE)

Return Period T (years)	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Q_T (cumec)	3.012	3.804	4.343	4.882	5.612	6.214	6.785	8.243
Runoff rate (l/s per ha)	6.58	8.31	9.48	10.66	12.25	13.57	14.81	18.00

Table 5-23 Estimated return period design flows and runoff rates for the Terryland Stream (with inclusion of FSE of 1.65)

Return Period T (years)	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Q_T (cumec)	4.970	6.277	7.167	8.056	9.259	10.253	11.195	13.601
Runoff rate (l/s per ha)	10.85	13.71	15.65	17.59	20.22	22.39	24.44	29.70

5.10.3 Other flood study ungauged catchment flood estimation equations

Other Catchment characteristic/ PCD methods used in the estimation of the annual Flood Flow (QBAR/Q_{MED}) are the FSSR No. 6 3-parameter equation for small ungauged catchments

(NERC, 1978), the FSU 3-parameter equation and the FSU 5-parameter equation for small ungauged catchments and the general FSU 7-parameter equation. For comparison purposes with the IH124 estimates presented in above in Section 5.10.2 these flood equations were applied to both the Sruffnacashlaun and the Terryland Streams, refer to Table 5-25 for the Q_{MED} estimates without the SFE applied and Table 5-24 for the PCD parameter values used in the calculations. The Q_{MED} estimates without the SFE by the various methods range from 0.885 to 2.365cumec for the Sruffaunacashlaun stream and 0.730 to 3.542cumec for the Terryland.

The flood flow estimates by the various method range by a factor in excess of 3, indicating the degree of uncertainty associated with predicting runoff rates within small ungauged catchments.

Table 5-24 Summary of the PCD parameters for the Sruffaunacashlaun and Terryland Streams

PCD's	AREA	SAAR	BFIsoils	SOIL	Farl	S1085	URBAN	DrainD	ART-DRAIN2
Sruffaunacashlaun	2.537	1160	0.598	0.3	1	3.45	0.85	1.214	0
Terryland	4.58	1163.4	0.610	0.3	1	0.3587	0.71	0.812	0.239

Table 5-25 QMED Estimates for the Sruffaunacashlaun and Terryland Streams by various Flood Study Estimation Equations

PCD's	IH 124 (3var)	FSSR (3var)	FSU (3Var)	FSU 4.2a (5var)	FSU (7 var)
Sruffaunacashlaun	2.155	2.365	2.026	0.885	1.686
Terryland	3.170	3.542	2.859	0.730	1.524

Note the FSU (7 var) equation is the standard FSU PCD Urban estimate for QMED.

5.10.4 Flood Flow Estimates - Rational Method

5.10.4.1 Sruffaunacashlaun Stream

A rational method calculation using a critical storm duration of 2.7hours for the Sruffaunacashlaun catchment (refer to hydrograph analysis in Section 9.5), a catchment area of 2.54km^2 and using a peaking factor of 1.3 and applying the FSSR No. 16 method (NERC, 1985) the catchment was modelled at 85% urbanised and the estimated percentage runoff was based on the FSSR Report No. 16 method that assumes that 30% of the urbanised area is impervious and that the remaining 70% of the urban area runs off at the natural greenfield SOIL rate (i.e. 30%). This method estimates the QMED at 2.38cumec and the Q at 5.11cumec.

Table 5-26 Peak Flood Flows in the Sruffaunacashlaun Stream by the Rational Method

Return Period T (years)	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Rain depth (mm)	17.4	21.9	25.1	28.4	33.3	37.4	42.0	52.0
Percentage Runoff (%)	40.2	40.2	40.2	40.2	40.2	40.2	40.74	42.11
Q_T (cumec)	2.38	2.99	3.43	3.88	4.55	5.11	5.81	7.43

5.10.4.2 Terryland Stream

Rational method calculations using a computed critical storm duration of 7.75hours for the Terryland basin based on its estimated Tp of 3.75 hours, a peaking factor of 1.3 and an urban fraction of 71% with 30% impervious and the remainder running off at natural greenfield rates based on a SOIL factor of 0.3 and using the FSSR NO. 16 percentage runoff method were carried out. This method estimates the Q_{MED} at 2.12cumec and the Q_{100} at 4.38cumec.

Table 5-27 Computed Peak Flood Flows in Terryland Stream by the Rational Method

Return Period T (years)	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
Rain depth (mm)	25.8	31.7	35.7	39.9	45.8	50.8	56.3	68.4
Percentage Runoff (%)	38.52	38.52	38.52	38.52	39.73	40.39	40.50	42.20
Q_T (cumec)	2.12	2.61	2.93	3.28	3.88	4.38	4.87	6.16

5.10.5 Conclusion

In conclusion, both the IH124 Equation and the Rational Method equations produce moderately high estimates of return period flood flow magnitudes for the two significantly urbanised small ungauged catchments. Such peak flows, particularly in the Sruffaunacashlaun Stream catchment, are likely to significantly exceed the storm drainage network capacity within the catchment, resulting in such flow magnitudes never reaching the downstream outlet of the catchment. In the Terryland catchment the stream channel and drainage basin provide considerable storage that will attenuate the flood hydrograph and limit the peak flow rate in the stream discharging to the Castlegar swallow-holes. Both the IH124 and the Rational Method flow estimates are recommended for consideration in the hydraulic modelling of these streams. However, hydraulic sensitivity analysis should reflect the high degree of uncertainty associated with the design flood flows for these small, highly urbanised catchments given that the various methods examined produced significantly varying magnitudes with a factor of 3 between the highest and lowest estimate.