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Influences on flood frequency distributions in Irish river catchments

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Abstract

This study explores influences which result in shifts of flood frequency distributions in Irish rivers. Generalised Extreme Value (GEV) type I distributions are recommended in Ireland for estimating flood quantiles. This paper presents the findings of an investigation that identified the GEV statistical distributions that best fit the annual maximum (AM) data series extracted from 172 gauging stations of 126 rivers in Ireland. Of these 126 rivers, 25 have multiple gauging stations. Analysis of this data was undertaken to explore hydraulic and hydro-geological factors that influence flood frequency distributions and whether shifts in distributions occur in the down-river direction. The methodology involved determining the shape parameter of GEV distributions that were fitted to AM data at each site and to statistically test this shape parameter to determine whether a type I, type II or type III distribution was valid. The classification of these distributions was further supported by moment and L-moment diagrams and probability plots. Results indicated that of the 143 stations with flow records exceeding 25 yr, data for 92 was best represented by GEV type I distributions and that for another 12 and 39 stations followed type II and type III distributions respectively. The spatial, hydraulic and hydro-geological influences on flood frequency distributions were assessed by incorporating results on an Arc-GIS platform with individual layers showing karst features, flood attenuation polygons and lakes. This data reveals that type I distributions are spatially well represented throughout the country. The majority of type III distributions appear in four distinct clusters in well defined geographical areas where attenuation influences from floodplains and lakes appear to be influential. The majority of type II distributions appear to be in a single cluster in a region in the west of the country that is characterised by a karst landscape. The presence of karst in river catchments would be expected to provide additional subsurface storage and in this regard, type III distributions might be expected. The prevalence of type II distributions in this area reflects the finite nature of this storage and the effects, in extreme conditions, when the karst is saturated and further storage is no longer available. Results therefore indicate

that in some instances assuming type I distributions is incorrect and may result in erroneous estimates of flood quantiles in these regions. Where actual data follows a type II distribution, flood quantiles may be underestimated and for type III distributions, overestimates may be expected.

1 Introduction

Flood studies often require the estimation of peak discharges for specified return periods. This is commonly based on a frequency analysis of a long record of annual maximum data at or near the site in question. It is generally recommended that the return period of the estimated flow in a single site analysis should not exceed the length in years of the available flow record by more than a factor of two (at least 50 yr of data should be used to estimate the 100-yr flood). In situations where record lengths do not meet this requirement or where the available hydrometric data is associated with poor confidence levels, a regional approach to flood frequency analysis is recommended. Much consideration has been given to the flood frequency model that best fits annual maxima series (e.g. Ahmad et al., 1988). In Ireland, as in many countries across the world, a Generalised Extreme Value (GEV) type I distribution is recommended for estimating flood quantiles. Phien (1987) notes that application of GEV type I models in flood frequency analysis is simple in that both the density and distribution functions are in closed form and the distribution has all useful moments that can be readily expressed in terms of its two parameters, also in closed form.

However, the recommendation of a GEV type 1/Gumbel two parameter flood frequency distribution at all locations in a drainage network is not sufficiently flexible to account for variations in the shape of the flood frequency distribution that potentially arise from climatic, hydraulic, hydrological and hydro-geological influences in Irish catchments. Climatic variations, influenced by the Atlantic Ocean and the warming effects of the Gulf Stream are reflected in the marked differences in rainfall across the country. Mountainous regions in the west and south-west of the country can experience annual rainfall totals in excess of 2800 mm that contrast sharply with rainfall totals of less that 1000 mm in large areas of the east of the country. Hydrological and hydraulic influences include the effects of attenuation arising from lakes and bogs and from floodplain effects. Hydro-geological influences include the likely effects on flood generation from carboniferous limestone and its associated karst features which are prevalent in over half of the country. Application of the GEV type I distribution without due consideration of the impacts of these features may produce errors in estimates of flood quantiles. Therefore, in some situations it may be appropriate to use a three-parameter GEV distribution that in addition to scale and location parameters, is also described in terms of a shape parameter (Jenkinson, 1969). Furthermore, and in the context of using groups of similar catchments or "pooling groups" to determine growth factors that can scale index floods to provide flow estimates of required return periods, data from floodplain-affected (FPA) areas has the capacity to contaminate growth curve estimates at non FPA sites. Similarly, it is unlikely that without detailed consideration of the physical and baseflow characteristics of the mechanics of flood generation, that data from a regional flood frequency analysis in a karst region, could be used to accurately predict a flood quantile at another site in the same region (Benzeden et al., 1993).

This paper explores primarily the hydraulic and hydro-geological influences in flood frequency distributions in Irish river catchments. Research that investigates this topic is somewhat limited, and when undertaken has tended to be limited to a specific river reach or particular region within a given river basin (e.g. Archer, 1980 and 1989; Mason et al., 1988; Mason, 1992; Woltemade and Potter, 1994; McCarthy and Naden, 1995; Benzeden et al., 1993). This study is considerably broader in scope and represents an assessment at national scale, in which hydraulic, hydrological and hydro-geological complexities are investigated. Furthermore, previous studies in which the hydraulic effects of floodplain inundation and storage were assessed have usually used detailed hydrodynamic models to define the extent of active floodplains. The extensive data requirements of these models make them suitable for specific sites but their application for more general studies is more problematic. The investigation of floodplain influences on flood frequency distributions presented in this paper is based on a more simple measure of floodplain activity or inundation, known as a floodplain attenuation indicator (FAI). FAIs are flood polygons that define the lateral extent of predicted floodplain inundation for specified return period floods. These were developed as part of the Flood Studies Update (FSU) programme (Reed and Martin, 2005) in Irish catchments for the 10-yr (Q_{10}), the 100-yr (Q_{100}) and the 1000-yr (Q_{1000}) floods from normal depth modelling at fixed nodes (approximate intervals of 500 m) on the main river network. The Q_{100} polygon was used in this investigation of annual maximum (AM) data sets of 172 gauging stations of 126 rivers in Ireland in which the GEV statistical distributions that best fit the hydrological data are identified. A total of 143 stations had historical flow records that exceeded 25-yr. The dataset covers a full range of climatic, hydrological, hydraulic and hydro-geological characteristics that are important for flood generation in Ireland. Of the 126 rivers studied, 25 have multiple gauging stations. A total of 104 rivers had observed records for longer than 25 yr and of these, 22 had multiple gauging stations. Spatial, hydraulic and hydro-geological influences on flood frequency distributions are assessed by incorporating results on an Arc-GIS platform with individual layers showing karst features, flood attenuation polygons and lakes. Analyses of the data facilitated an assessment of shifts in flood frequency distribution that occurs in the downstream direction and the role of floodplain attenuation on these changes in distribution.

2 Background

2.1 Hydro-geological influences

Over half of Ireland is underlain by Carboniferous limestone and lowland karsts occupy approximately 75% of this limestone area (Coxon, 1987; Williams 1970). The hydrology and geomorphology of Irish karstic terrain is intimately and genetically linked to perhaps a greater extent than with any other rock type (Drew, 1990). Conditions however, are not uniform throughout the country. Deposits of glacial drift mantle the bedrock over most low lying areas in central Ireland. The depth of these glacial deposits is generally lower in the west of the country (less than 3 m) than in the east (up to 10 m) and in many areas, rock outcrops are exposed (Drew, 2008; Jones and Gunn, 1982). The low gradient topography and high effective rainfall in these karst regions mean that river flooding and poor land drainage over large areas are acute problems (Drew and Coxon, 1988). Natural karst systems exhibit extremes in heterogeneity and variability of geologic, morphologic, hydro-geologic, hydrologic, hydraulic, ecological and other parameters in space and time (Denic-Jukic and Jukic 2002; Bonacci, 2004). A wide range of closed surface depressions, a well-developed underground drainage system (supported by an irregular network of pores, fissures and fractures of various size and form), and a strong interaction between the circulation of surface water and ground water are typical features of karst catchments (Bonacci et al., 2006).

Karst catchments behave differently with seasonal variations in rainfall. Zhou (2007) describes the types of flooding in karst terrains. In low flow conditions, transmission losses to the underlying limestone from well developed surface and underground karst landforms can be significant (Drew, 1976). In contrast, karst areas at wetter times can be characterised by high water tables and extensive groundwater flooding (discharge-related) for prolonged periods (Drew, 1980). For flash floods, hydrograph volume is important. Due to fast infiltration rates, overland flow and the existence of open water courses on karst terrains are low (Bonacci et al., 2006). A significant proportion of the initial rainfall is therefore used to fill karst voids. However, the volume of these voids is low and for high intensity, short duration rainfall, groundwater levels can rise rapidly with consequent recharge-related sinkhole flooding on the surface.

A complex issue in karst hydrology, hydrogeology and geology is the delineation of catchment boundaries and the origins of springs and stream flows. A spring in one river catchment for example may receive water from a sinking stream in another catchment (Coxon and Drew, 2000). The hydrology of karst terrain is characterised by strong, direct and dynamic interactions between groundwater and surface water flows

(Bonacci and Zivaljevic, 1992). Because flow is mostly subsurface, direct hydrometric methods are difficult to use for monitoring and analysis (Bonacci, 2001: Bailly-Comte, 2008). Also, the catchment areas of springs cannot be defined in conventional hydrogeological terms. The surface catchments of losing and sinking rivers which contribute to spring flow must also be considered.

The limited research available that describes the influence of karst terrain on flood frequency analysis highlights the variable influences of such landscapes on these distributions. For example, Benzeden et al. (1993), in an investigation of various flood frequency distributions in 21 stations in seven karst river basins in Turkey, concluded that flood peaks follow no specified distribution. Although literature supports the assertion that underlying karst can significantly attenuate low to mean flows, its effects on flood flows, particularly in the context of high saturation levels, is less well understood. It is likely however, that the prevalence of karst features in catchments, together with karst influences on base flow contributions can affect the distribution of flood peaks in rivers (Benzeden et al., 1993).

2.2 Hydrological and hydraulic influences

Irish river catchments are characterised by an extensive network of bogs, lakes and topographical depressions which provide storage to flood flows. More importantly, the mild gradient of many river channels promotes additional attenuation in natural floodplains. These influences tend to be greater than in UK catchments and may, in part, explain why many growth curves in Ireland are mildly graded (e.g. NERC, 1975).

The shape, the size, extent and spread of natural floodplains reflect the dynamics of river systems (Bhowmik, 1984). Once overbank, the complexity of river flows is increased by 3-dimensional momentum exchanges between the main and floodplain channel zones (Sellin, 1964; Zheleznyakov, 1965). This is further increased by the patterns of relief which produce spatial and temporal variations in flood inundation for given discharge magnitudes. Lewin and Hughes (1980) noted that patterns of relief alter flow patterns of inundating waters through sequences of filling, transmission and drying-out of floodplains. Lewin and Manton (1975) highlight the role of vegetation, artificial structures, and development in restricting and compartmentalising overbank flow and storage. As a flood moves down the river it is subject to a series of influences that can alter the time of arrival and peak flow of a flood hydrograph. Vegetation and riparian forests can increase the infiltration and storage capacities of the soils and retard significantly the overland flow. Vegetation therefore, contributes to flood peak attenuation, the effect being most pronounced for small to moderate floods in smaller catchments (Subramanya, 1984).

Although a range of geometrical and hydraulic resistance properties of a river channel impact on storage and drainage efficiency (Archer, 1980), floodplains can act as a form of storage reservoir, providing additional storage for overbank flows. This storage and later release of the stored water can produce flood hydrographs that have lower peaks and longer durations compared to those from similar watersheds with no floodplain storage. The effects are likely to be more pronounced for low volume, moderate-frequency events (return periods of 4–50 yr) (Diehl, 1990; Woltemade and Potter, 1994) where floodplain depths are low. At higher return periods, conveyance rather than storage is likely to be the dominant influence and flood peaks will tend to be transferred downstream with less attenuation. Given that many bankfull recurrence intervals are in the order of 1–3 yr (see for example Richards, 1982; Petit and Paquet, 1997; Castro and Jackson, 2001) and that mean and median annual flows have return periods of 2.33 and 2 yr respectively (assuming GEV type 1 distributions), flows in natural channels can frequently be subjected to a combination of these complex storage and attenuation effects.

These physical processes and attenuating floodplain characteristics can significantly influence flood frequency distributions. Haider (1992), using a modular hydrological flood routing model based on non-linear Muskingum-Cunge routing, showed that floodplain inundation alters significantly, the characteristics of flood waves. Wolff and Burgess (1994) determined that the change in flood frequency distribution downstream of a floodplain is influenced by main channel and floodplain resistances, the width to depth ratio of the floodplain and both the floodplain width and longitudinal slope. Without being specific, Wolff and Burgess (1994) concluded that a GEV type I upstream flood frequency distribution ($C_V = 0.6$) could change to other GEV distributions when floodplain inundation occurred. Archer (1989), in a study if the River Tees in the UK, observed that floodplains could attenuate flood peaks by as much as 30% but that this was variable and dependent on floodplain geometry and hydrograph characteristics. The effect was more pronounced for sharply peaked, low volume floods. Furthermore, extensive floodplain inundation was shown to produce shifts from GEV type II distributions towards GEV type III distributions. A similar tendency for floodplain effects to produce GEV type III distributions, in this case from upstream GEV type I distributions, is also been reported in the literature (Mason et al., 1988; Mason, 1992; McCartney and Naden, 1995).

Although a specific flood frequency distribution is valid only at a specified site, it is common to assume that distributions for multiple sites within a geographically homogenous area are the same. Given that floodplain inundation can alter the shape parameter of an upstream flood frequency distribution, this assumption is likely to produce errors in estimates of flood quantiles at locations downstream of floodplains. Furthermore, in the context of using groups of similar catchments or "pooling groups" to determine growth factors that can be applied to index floods for estimating peak flows of required probabilities (return periods), data from floodplain-affected (FPA) areas has the capacity to contaminate growth curve estimates at non FPA sites.

3 Methodology

Annual maxima (AM) data series from 172 Irish gauging stations of 126 rivers with record lengths varying from 7 to 69 yr was obtained from the Irish Office of Public Works (OPW) and the Environmental Protection Agency (EPA). The OPW is the lead agency in Ireland with responsibility for monitoring and maintaining the Irish hydrometric network and the EPA monitors a smaller network of gauges. Of the 126 rivers investigated, 25 had multiple gauging stations. Analysis of these AM series was undertaken to identify the GEV distribution that best fits the data at each station and explore the hydraulic and hydro-geological factors that influence flood frequency distributions and whether shifts in distributions occur in the down-river direction. This was undertaken in three stages that involved:

1. Determining the summary statistics for each AM series;
2. Identifying GEV distributions for each AM series;
3. Assessing the spatial factors that influence distributions.

3.1 Summary statistics

Descriptive statistical parameters were determined for each station. For the limited record lengths that were available in this study, the theoretical product moments (ordinary and probability weighted) and L-moments (Eqs. A1a to A13a in Table A1, Appendix A) were equated to corresponding sample product moments and L-moments (Eqs. A1b to A13b).

The standard deviations (s), skewness (G), Hazen skewness (H-skewness), kurtosis (κ), coefficient of variation (C_v), $L-C_v$, L-skewness ($L-C_s$) and L-kurtosis ($L-C_\kappa$) of the flow data at each gauging stations was therefore estimated using (Eqs. A1b to A13b). All moments in Table A1 describe the summary statistics of observed samples (AM series). However, the ordinary moments in Table A1 are generally associated with relatively high standard errors, are biased downwards (Cunnane, 1985) and exhibit sample related boundness (Kirby, 1974). The Probability Weighted Moments (PWMs) and L-Moments in Table A1 are not prone to these issues and are more robust statistical descriptors.

3.2 Identification of GEV distributions

Probability plots and statistical tests are commonly used to determine the distribution for observed AM data at a given location. This study utilised three approaches of increasing statistical power for this purpose. These were:

1. Probability plots,
2. Moment and *L*-Moment diagrams,
3. The Hosking goodness of fit algorithm (Hosking et al., 1985).

The Hosking et al. (1985) algorithm was considered to be relatively simple to apply and was statistically quite powerful. Other statistical tests from Van Montfort (1970) and from Otten and Van Montfort (1978) were also considered. These however are based on ordinary moment estimates (rather than PWMs in Hosking et al., 1985) and have therefore less statistical power to discriminate for different GEV distributions.

3.2.1 Probability plots

Floodplain storage can have a significant effect on the shape of flood-frequency curves. The shape parameter, k, determines which Generalised Extreme Value (GEV) distribution is appropriate (Jenkinson, 1969). For $k = 0$, the Gumbel or GEV type I (EV1) distribution is fitted; when $k < 0$, the Frechet or GEV type II (EV2) distribution is appropriate; and with $k > 0$, the Weibull or GEV type III (EV3) distribution is arrived at. Probability plots were used in this paper to visually identify whether GEV type I, type II or type III distributions best fitted the AM data series at each of the 172 stations analysed.

Identification of the appropriate GEV distribution at a particular site is important for accurate predictions of flood flow. A probability plot is a graphical technique where the magnitude of a random variable is plotted against its cumulative probability. In this study, both GEV type I and GEV probability plots were prepared for the sites investigated.

Probability plots use an inverse distribution scale so that simple, 2-parameter GEV type I cumulative distribution functions plot as a straight line in the form:

$$x_i = \hat{u} + \hat{\alpha} y_i \tag{1}$$

where $\hat{u}$ and $\hat{\alpha}$ are location and scale parameters respectively and y_i is the Gumbel reduced variate for an ordered AM data series, given by:

$$y_i = -\ln(-\ln(F_i)) \quad \text{for} \quad i = 1, 2, \ldots\ldots, n \tag{2}$$

and where F_i is the Gringorten (1963) plotting position for the i$^{\text{th}}$ smallest of n observations from a Gumbel distribution, given by:

$$F_i = (i - 0.44)/(n + 0.12) \tag{3}$$

GEV type I model parameters of location ($\hat{u}$) and scale ($\hat{\alpha}$) as well as an estimated flood quantile, x_i, from Eq. (1) were determined from AM flow records at each gauging station using the method of probability-weighted moments. Flood quantiles (x_i) for a GEV type I distribution were plotted against the Gumbel reduced variate y_i at these stations. At stations where the linear relationship between x_i and y_i correlates closely with the measured data, it is likely that the sample is from a GEV type I distribution.

A strong deviation from this line indicates that the sample is not from a GEV type I distribution and comes therefore from an alternative GEV distribution (type II or type III). GEV model parameters of location ($\hat{u}$), scale ($\hat{\alpha}$) and shape ($\hat{k}$) as well as an estimated flood quantile, x_i, were therefore also determined from AM flow records using the method of probability-weighted moments. Flood quantiles (x_i) for a GEV distribution are given by:

$$x_i = \hat{u} + \frac{\hat{\alpha}}{\hat{k}}\left(1 - (-\ln(F_i))^{\hat{k}}\right) \tag{4}$$

The inclusion of the additional shape parameter in GEV distributions provides the added flexibility for the distribution to better fit the observed AM data.

A major statistical drawback in the method of probability plots is that no allowance is made for the fact that not all members of an ordered sample are subject to the same amount of sampling variation. The observations at the upper end of a sample, in particular, have large sampling variance (NERC, 1975). Therefore, uncertainty exists when a distribution is identified from probability plots, particularly when limited data is available in the high flow range.

3.2.2 Moment and L-moment diagrams

A widely used technique for identifying appropriate frequency distributions to observed data is the method of moments and L-moments. Values of skewness (γ) (Eq. A3a) and kurtosis (κ) (Eq. A4a) together with L-skewness (τ_3) (Eq. A12a) and L-kurtosis (τ_4) (Eq. A13a) depend on the shape parameter of a particular distribution and are thus related. Moment ratio diagrams of kurtosis against skewness and L-moment diagrams of L-kurtosis against L-skewness were used to identify the parent population from which the AM data for the 172 gauging stations analysed is derived. Sample estimates of skewness (G), kurtosis (κ), L-skewness ($L-C_s$) and L-kurtosis ($L-C_k$) were derived from the AM data for the 172 gauging stations and plotted in Fig. 5 with theoretical moments and L-moments for GEV type 1 and GEV distributions.

The distribution occupying a greater proportion of the measured data in the moment or L moment ratio diagram is expected to be a suitable candidate distribution to model the measured data. The two parameter GEV (type I) distribution has fixed moments of skewness (1.1395), kurtosis (5.400) as well as fixed L-skewness (0.1699) and L-kurtosis (0.1504) values. However, in practice where samples are finite, moment and L-moment ratios are biased and therefore exact values of these ratios for GEV type 1 distributions are rarely obtained.

As a result of this bias in finite samples, moment and L-moment diagrams by themselves are unlikely to be sufficient for identifying the distribution from which a sample has come. To assist in this regard, a Monte Carlo simulation was undertaken to generate 200 synthetic samples of 50-yr from a GEV type I population. Comparison of measured data from the 172 sites investigated with these synthetic samples allowed distributions to be identified. If data from the analysed station is shown on moment and *L*-moment diagrams to fall within the cluster of synthetic GEV type I samples, it is then probable that it comes from a GEV type I population. If plotted data is outside of this cluster, it is likely to be from an alternative GEV distribution (type II or III).

As the method of moments suffers from bias and sample size related bounds for samples from skewed populations, it has reduced discriminating power to identify appropriate distributions among potential candidate distributions for AM data series (Vogel and Fennessey, 1993). As a result and to overcome these issues, the method of L moments is now also extensively used for distribution identification. Hosking (1990) noted that *L*-moment ratios are more robust in the presence of extreme values and do not have sample size related bounds. These represent considerable benefits over product moment ratios.

3.2.3 The Hosking goodness of fit algorithm

The third and statistically most rigorous method used to identify flood frequency distributions was to estimate the shape parameters, $\hat{k}$, for the AM series at each site using the algorithm from Hosking et al. (1985). The shape parameter, $\hat{k}$, from this algorithm for a limited sample size recommended to have at least 25 of AM data is determined from:

$$\hat{k} = 7.8590c + 2.9554c^2 \tag{5}$$

where

$$c = \frac{2\hat{\mathrm{M}}_{110} - \hat{\mathrm{M}}_{100}}{3\hat{\mathrm{M}}_{120} - \hat{\mathrm{M}}_{100}} - \frac{\log 2}{\log 3} \tag{6}$$

and where $\hat{\mathrm{M}}_{100}$, $\hat{\mathrm{M}}_{110}$ and $\hat{\mathrm{M}}_{120}$ are determined from Eq. (A6b) in Table A1.

Whether $\hat{k}$ is positive or negative is important in fully assigning a distribution to a given AM series. A positive value indicates either a GEV type I or type III distribution and for a negative value, the distribution will be either type I or type II. The Hosking et al. (1985) algorithm provides a further statistical test to investigate the GEV type I null hypothesis with another GEV distribution as the alternative. In the null hypothesis, H_0: $\hat{k} = 0$, the PWM estimate of $\hat{k}$ is taken to be asymptotically distributed as:

$$N\left[0, \frac{0.5635}{n}\right] \tag{7}$$

where N is a normal distribution with a mean (μ) of 0 and a sampling variance (σ^2) of 0.5636 and n is the sample size. The test consists of comparing the standardised normal variate, Z, with the critical values of the standardised normal distribution (determined from statistical tables). The standardised normal variate is given by:

$$Z = \hat{k}\left(\frac{n}{0.5635}\right)^{1/2} \tag{8}$$

Statistically significant positive values of Z imply rejection of H_0 in favour of the alternative $k > 0$, and statistically significant negative values of Z imply rejection in favour of $k < 0$. Values are statistically significant when the estimated test statistics fall outside of the 95% confidence interval. Hosking et al. (1985) recommends that for sufficient discriminating power, test sample sizes (n) should be greater than 25. The record length of the 172 gauging stations used in this study is shown in Fig. 1 and indicates that 143 stations satisfy this requirement. The 29 that did not have the required record length were excluded from further analyses.

3.3 Assessing the spatial factors that influence distributions

Spatial factors that influenced flood frequency distributions were observed by incorporating the analysed data in an ArcGIS platform with individual layers that contained Irish karst features, lakes and flood attenuation indicators (FAIs). The 100-yr (Q_{100}) FAI was used in this study and represented a flood polygon determined from normal depth modelling at nodes (approximate intervals of 500 m) on the main river network. The polygons represented the lateral extent of flooding for the 100-yr flood and therefore provided an indication of floodplain inundation in a particular catchment.

FAIs are based on the assumption that the median flood, Q_{med} with a return period of 2 yr is equivalent to the bankfull flow in all rivers. Given that bankfull recurrence intervals in many rivers are in the order of 1–3 yr (see for example Richards, 1982; Petit and Paquet, 1997; Castro and Jackson, 2001), this simplying assumption is considered reasonable. The median flood for Irish catchments is determined using an FSU relationship for ungauged catchments given by:

$$Q_{\text{med}} = 1.237 \times 10^{-5} \text{AREA}^{0.937} \text{BFI}^{-0.922} \text{SAAR}^{1.306} \text{FARL}^{2.217} \text{DRAIND}^{0.341} \\ \text{S1085}^{0.185} (1 + \text{ARTDRAIN 2})^{0.408} \tag{9}$$

where AREA (km^2) is the catchment area of the river to the outlet point being considered, S1085 (m km^{-1}) is the average slope of the river between 10% and 85% of its length from the outlet, SAAR (mm) is the annual average rainfall on the catchment, FARL is a flood attenuation factor for reservoirs and lakes, BFI is the baseflow index, DRAIND (km^{-1}) is a simple index that relates the length of the upstream hydrological network (km) to the area of the gauged catchment (km^2) and ARTDRAIN 2 is the percentage of the catchment river network that has been included in national drainage schemes.

Simple multiplication of Q_{med} by a growth curve factor appropriate to particular regions in Ireland defined the magnitude of Q_{100} flows. Floodplain flows were determined by subtracting Q_{med} values from these flood quantiles and corresponding floodplain flow depths were determined iteratively at all nodes using the Manning equation based on the geometry at that node and a resistance coefficient that was consistent with the land use at the node. Incorporating these depths into a revised Digital Terrain Model (DTM) facilitated the production of flood polygons for a range of return periods for the Irish river network (Fig. 2).

4 Results

4.1 Summary statistics

Results of the statistical analysis for the 172 stations analysed are shown in Fig. 3. Figure 3a, b and c indicates that there is a reasonable relationship between catchment area and the mean, median and standard deviation of the annual maxima flow series. The least squares regression equations shown, indicate respectively that the mean, median and standard deviation of the analysed AM series is proportional to $A^{0.68}$, $A^{0.69}$ and $A^{0.62}$, A being the catchment area. The coefficient of variation, C_v in Fig. 3d describes the standard deviation as a proportion of the mean for the annual maximum flow record at each site. Estimated values of C_v vary typically from 0.1 to 0.4 for most gauging stations with a small number being outside of this range. The average value of 0.27 in this analysis is based on data from 172 stations and is marginally lower than the value of 0.3 in the Flood Studies Report (FSR) (NERC, 1975 p. 122) that was determined from significantly shorter records at 63 stations. Low C_v values at most locations reflect the low permeability of Irish catchments and the high annual rainfall which does not vary significantly from year to year. The higher values observed in Fig. 3d may result from either or a combination of uncharacteristic rainfall or errors in the flow record (Cunnane, 1989). Skewness is very sensitive to sample size, n, and is a measure of the symmetry in hydrological data. Figure 3g indicates that skewness for the AM series analysed varies from 1.4 to 3.0 with the majority of values occupying the band from 0 to 2.0. *H*-skewness provides an unbiased estimation of skewness and reduces the sensitivity associated with small sample sizes. The average *H*-skewness in Fig. 3i, determined by multiplying skewness values by $(1+8.5/n)$ is 0.77. This value is considerably lower that the value of 1.63 reported in the FSR (NERC, 1975 p. 122) for Irish catchments and again reflects differences in the number of data years in the FSR analyses compared to that presented in this paper. The *H*-skewness value provides an indication of the distribution that best fits the data at a particular station. A GEV type I distribution is a fixed skew (H-skewness = 1.14) statistical model. Samples from

GEV type II and type III distributions therefore exhibit higher and lower skew values respectively. In general, if the parent population has a lower or higher H-skewness than an assumed fixed skew model, the upper quantile estimates will be biased upwards or downwards respectively. The kurtosis is a measure of the peakiness of the distribution fitted to the AM series. Figure 3b shows that the estimated kurtosis range from -1 to 3. Lower values indicate that the distribution is concentrated about the mean value and is characterised by a short tale; higher values reflect lower, more even distributions that portray longer tails.

Values of C_v, skewness and kurtosis obtained from individual hydrological records of the usual length (circa. 25 yr) have relatively large standard errors as well as being biased downwards (Cunnane, 1985). Another drawback in using product moment estimators is that they have sample related boundness. Kirby (1974) showed that these bounds depend upon sample size so that C_v is bounded by the interval (0, $(n-1)^{1/2}$) and sample skewness is bounded by $|G_n| \leq (n-2)/(n-1)^{1/2}$.

To overcome these limitations, Probability Weighted Moment (PWM) and L-Moment estimates are also used in this paper to describe the summary statistics of observed samples. PWMs are derived from a ranked sample. For a random variable X, with a cumulative distribution of $F(X)$, the order r PWM can be defined as in Eq. (A6a) (Greenwood et al., 1979). For practical purposes however, the unbiased estimates of PWMs are obtained from Eq. (A6b) for a finite ordered sample of size n. Both PWMs and L moments (from Hosking, 1990) include sample estimators that are linear functions of the data (Hosking, 1986). These moments are not influenced to the same extent from the effects of sampling variability and bias that results from higher order exponents of the ordinary moment equations (Eq. A2b to A4b) (Hosking, 1990; Vogel and Fennessey, 1993). The first L-moment, l_1, is the arithmetic mean, while the second L-moment, l_2, is a measure of dispersion and is analogous to the standard deviation. The L-coefficient of variation, $L-C_V$, is defined in Eq. (A11b). The standardised higher L-moments of L-skewness and L-kurtosis are determined using Eq. (A12b) and Eq. (A13b). The L-moment ratio estimators of $L-C_V$, $L-C_S$, and $L-C_\kappa$ are analogous to the ordinary moment ratio estimators, C_V, G and κ. $L-C_V$, $L-C_S$ and $L-C_\kappa$ are shown for the 172 gauging stations in Fig. 3f, h and j respectively.

4.2 Identification of GEV distributions

4.2.1 Probability plots

Indicative probability plots for four of the 172 gauging stations that were analysed are shown in Fig. 4. Plots relate to Stations 07012 (River Boyne – 69 data years), 25022 (River Camcor – 55 data years), 20002 (River Bandon – 50 data years) and 24013 (River Deel – 49 data years). Figure 4a and b indicates that the observed AM data is reasonably well aligned to the GEV type I (Gumbel) distribution. Figure 4c and d however, shows that the shape of the probability plot is concave upwards for Station 20002 and convex downwards for Station 24013 suggesting that the data follows GEV type II and type III distributions respectively. Visually identifying specific distributions for observed AM series is subjective and therefore not statistically robust. Furthermore, observed data at the upper end of a sample is derived from events of low frequency with a resulting large sampling variance (NERC, 1975). Given that no allowance is made for the fact that members of the ordered sample (AM series) have different sampling variation, an incorrect distribution could be assigned to an observed data series. The method however, can provide an initial estimate of the distribution of an AM series at a given location.

4.2.2 Moment and *L*-moment diagrams

Estimated skewness and kurtosis as well as *L*-skewness and *L*-kurtosis for the 172 stations analysed together with the 200 simulated samples from a GEV type I distribution are shown in Fig. 5. The proximity of observed data to both the theoretical GEV type I value and the simulated type I cluster in Fig. 5 indicates that data from the majority of stations comes from a GEV type I population. However, as shown (particularly for the moment ratio diagram where data is densely clustered), appropriate distribution identification is not always clear.

4.2.3 The Hosking goodness of fit algorithm

Results from an application of the Hosking et al. algorithm (1985) are shown in Table B1 and Table B2 for the OPW monitored catchments with multiple and single gauging stations respectively. Table B3 of Appendix B contains findings from the EPA gauges analysed in this study.

Results show that of the 143 stations analysed, data for 89 was best represented by type I distributions and that for another 11 and 39 stations followed type II and type III distributions respectively.

As mentioned, GEV type I distributions are recommended for flood frequency analysis in Ireland. The 100-yr GEV type I (shape parameter, $\hat{k} = 0$) flood quantiles (X_{100}) for all stations analysed in this study were determined from calculation of scale ($\hat{\alpha}$) and location parameters ($\hat{u}$) using:

$$\hat{\alpha} = \frac{\left(2\hat{\mathrm{M}}_{110} - \hat{\mathrm{M}}_{100}\right)}{\ln 2} \tag{10}$$

and

$$\hat{u} = \hat{\mathrm{M}}_{100} - \varepsilon.\hat{\alpha} \tag{11}$$

where ε is Euler's constant given as 0.5772 and $\hat{\mathrm{M}}_{100}$ and $\hat{\mathrm{M}}_{110}$ are the sample PWMs from Table A1. X_{100} was determined from the inverse of the cumulative distribution function (cdf) of the GEV type I distribution, given by:

$$X_{100} = \hat{u} + \hat{\alpha}\left\{-\ln\left(-\ln\left(1 - \frac{1}{100}\right)\right)\right\} \tag{12}$$

Standard errors, $\mathrm{Se}(X_{100})$, for calculated values of X_{100} were determined from:

$$\mathrm{se}(Q_T) = \frac{\sigma}{\sqrt{n}}\theta_T \tag{13}$$

where σ is the standard deviation of the of the AM flow series of sample size, n and where:

$$\theta_T = \left\{1 + 1.14K_T + 1.10K_T^2\right\}^{0.5} \tag{14}$$

in which K_T is Chow's frequency factor, given by:

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right]\right\} \tag{15}$$

Values of $\hat{\alpha}$, $\hat{u}$, X_{100} and Se(X_{100}) for assumed GEV type I distributions are shown in Tables B1, B2 and B3.

In order to quantify the error in the 100-yr flood quantile that would arise from incorrectly assuming that a sample from a particular gauging station conforms to a GEV type I population, flood quantiles assuming a GEV population (shape parameter, $\hat{k} \neq 0$) were also calculated. GEV scale ($\hat{\alpha}$) and location parameters ($\hat{u}$) were determined from:

$$\hat{\alpha} = \frac{\left(2\hat{\mathrm{M}}_{110} - \hat{\mathrm{M}}_{100}\right)\hat{k}}{\Gamma\left(1 + \hat{k}\right)\left(1 - 2^{-k}\right)} \tag{16}$$

and

$$\hat{u} = \hat{\mathrm{M}}_{100} + \hat{\alpha}\left\{\Gamma\left(1 + \hat{k}\right) - 1\right\}\Big/\hat{k} \tag{17}$$

where Γ is the standard gamma function. X_{100} for the GEV distribution was determined from the inverse of the cdf of a GEV distribution given as:

$$X_{100} = \hat{u} + \frac{\hat{\alpha}}{\hat{k}}\left(1 - \left(-\ln\left(1 - \frac{1}{100}\right)\right)^{\hat{k}}\right) \tag{18}$$

Standard errors, Se(X_{100}), for calculated values of X_{100} were determined from the approach in Lu and Stedinger (1992). This approach however, is valid only for shape parameters in the range $-0.3 < \hat{k} < 0.3$. Standard errors for values of $\hat{k}$ outside of this range were not determined. Values of $\hat{\alpha}$, $\hat{u}$, X_{100} and Se(X_{100}), where calculated, are again shown in Tables B1, B2 and B3.

Figure 6 indicates that assuming a GEV type I distribution at locations where an GEV type II distribution is valid can result in underestimated 100-yr flood quantiles (X_{100}) of up to 35% (Station 20002 – River Bandon). Correspondingly, the assumption of type I distributions at locations where GEV type III distributions are appropriate can produce overestimates of the 100-yr flood quantile that are in the order of 25% (Station 24013 – River Deel).

4.3 Assessing the spatial factors that influence distributions

Hydrograph shape is influenced in broad terms by climatic and physiographic factors. Climatic factors generally control the rising limb of the hydrograph but the recession limb is independent of storm characteristics and is influenced by catchment characteristics only. To further explore how GEV distributions vary across the country and to assess the underlying hydrological, hydro-geological and hydraulic conditions that are known to influence flood frequency distributions, the analysed data was presented in an ArcGIS platform (Fig. 7). Figure 7a reveals that GEV type I distributions are reasonably well distributed throughout the country. However, the majority of GEV type III distributions appear in four distinct clusters in well defined geographical areas of the Shannon, South-Eastern and Eastern river basins. GEV type III distributions are representative of strong attenuation influences in respective catchments.

It may have been expected therefore that significant lake areas may have characterised the catchments where GEV type III distributions were observed. Although lake storage was associated with Type III distributions in Scotland (Acreman and Sinclair, 1986), no obvious link was observed in the Irish catchments investigated (Fig. 7b). The three GEV type III clusters in the south-eastern and eastern river basins are observed in reasonably low gradient catchments where considerable floodplain inundation, as reflected by FAIs with significant lateral width dimensions (Fig. 7c), is likely. The attenuating effect of floodplains and the capacity of floodplains to produce shifts in distribution from GEV type I to GEV type III is consistent with findings from other studies (Mason et al., 1988; Mason, 1992; Archer, 1989; Wolff and Burges, 1994 and McCartney and Naden, 1995). As an example, Archer (1989) observed floodplain attributed peak flow attenuations of up to 30% in a 36.4 km reach of the River Tees in the UK. Archer also observed a break in slope in the downstream flood frequency curve at the bankfull level after which the flood frequency relationship is more mildly graded than for the inbank flow range. In a previous study, Archer (1980) attributed floodplain storage effects in the River Coquet at Rathbury and the River Skerne at Preston, both in the UK, to low flood growth rates and to GEV type III distributions. McCartney and Naden (1995) also showed that floodplain inundation promoted shifts from GEV type I distributions to GEV type III distributions in the River Severn, UK.

The majority of type II distributions appear in a single cluster in a region that straddles the Shannon and Western river basins. As shown in Fig. 7d, these basins are underlain with karst terrain. The flow in karst regions is composed of three components; surface flow, subsurface flow and groundwater flow. During low to median floods, a substantial proportion of the flow is used to recharge the subsurface and groundwater flows and overland flow magnitudes tend to be low. For more intensive and prolonged rainfall periods, of the type expected in the west of Ireland, overland flow rates are likely to be significantly higher than karst percolation rates and consequently, overland flow can dominate. Furthermore, and perhaps more importantly, the karst in these regions, as opposed to elsewhere in the country, is characterised by thin glacial overburdens with regular exposures of bare rock outcrops. These features promote the formation of karst springs where water can be withdrawn from the surface flow only to re-emerge through groundwater conduits and contribute to surface streams at later stages of a flood episode (White, 2002). These springs however, have limits that are independent of catchment conditions, rainfall depths and intensities and rises in groundwater levels

(Bonacci, 2001). The influence of karst features on small, medium and large floods is therefore very different. A reasonable AM flow record is likely to contain a range of low to high flows. Therefore, it is likely that low to moderate floods may be represented by a given GEV distribution but more extreme events, given the increased overland flow together with groundwater and subsurface contributions, may be more suitably described by a flood frequency distribution that curves upwards. Such distributions are typical of GEV type II distributions and karst influences may in part explain the spine of Type II distributions observed in the north-south direction in Fig. 7d.

The variable and complex hydrological mechanisms that characterise karst terrains are significant influences in these regions. The results presented support the assertions of Benzeden et al. (1993) and Bonacci (2001) that the complexities of karst hydrology are such that the fitting of flood frequency distributions to maximum or extreme annual discharges and relating these to flood recurrence intervals is meaningless.

To further investigate influences on flood frequency distributions, variations in the GEV shape parameter of distributions fitted to the analysed AM data series for a range of catchment properties are shown in Fig. 8. Figure 8 suggests that contrary to what might be expected, the characteristics of Irish catchments do not have well defined influences on flood frequency curves in Irish catchments. Small catchments, due to lower concentration times, would be expected to produce steeper flood frequency curves (NERC, 1975) and these would be reflected in increasingly positive shape parameters. Figure 8a indicates that for the range of catchment areas from 10 km^2 to 2460 km^2, such a trend has not been verified. Reduced attenuation of flood peaks is expected in steeply graded catchments where high conveyance capacities are generally associated with a reduction in storage volume in the river reach. Figure 8b shows the variation of S1085 values with shape parameter. S1085 represents the slope of the main stream (m km^{-1}) at 10% and 85% of its length from a given outfall and values for Irish rivers investigated vary from 0.2 m km^{-1} to 25 m km^{-1}. Although scatter is significant, Fig. 8b is consistent with predicted behaviour at high slopes (S1085 > 10 m km^{-1}) but at lower channel gradients, results are less conclusive. Although rainfall is the primary driver in generating stream discharge, Figure 8c indicates that there is no clear relationship between annual rainfall and shape parameters of flood frequency curves in Irish catchments. Ireland experiences very significant spatial variations in annual rainfall totals across the country. Totals in the east of the country range from 750 mm to 1000 mm per year, while those in the west typically vary from 1000 mm to 1250 mm. Results suggest that frequency, as opposed to volume, is important in defining the shape of flood frequency distributions. The Irish climate produces an annual rainfall that is reasonably well distributed throughout the year with the consequence that year on year variations in the magnitudes of large floods is small, possibly contributing to the shallow nature of probability plots that are typical of Irish catchments. The lateral extent of an active floodplain in river flows is reflected in the area over which alluvium material deposits on floodplains (alluvium area). For a discharge in a given river, the width of the active floodplain determines whether floodwater flows slowly as a thin layer spread over a wide valley or whether it will rise within the confines of a narrow valley to depths at which even overbank water is rapidly flowing. The floodwater gets more attenuated in wider floodplains than in narrow valleys. Fig. 8d indicates that there is an increased tendency towards GEV type III distributions in catchments with larger areas of alluvium deposits. This is consistent with Fig. 7c and is supported by findings in literature (Mason et al., 1988; Mason, 1992; Archer, 1989; Wolff and Burges, 1994 and McCartney and Naden, 1995). Approximately 16% (1.2 m hectares) of the Irish landscape is peat. Blanket bogs are most common in the west of Ireland where rainfall is greatest and raised bogs feature in the Shannon River basin. Peat is naturally hydrophobic and peat areas are characterised by shallow water tables and ground water flows that can be multi-dimensional (Katimon and Wahab, 2003). Figure 8e indicates that there is no clear indication that peat landscapes are influencing flood frequency distributions. The high and sustained rainfall totals, particularly in the west of the country may contribute to this in that if saturated, the influence of the peat on high flows would be low. The influence of urbanisation on shape factors of flood frequency distributions is shown in Fig. 8f. Increasing impervious areas inhibit infiltration, reduce surface retention and result in a greater proportion of incident rainfall appearing as direct runoff. This, combined with sewers, gulleys and culverting of natural streams that accompany development, results in a more rapid conveyance of the runoff through the drainage network and produces hydrographs that are considerably more flashy than would have occurred prior to urbanisation. Consequently, flood frequency curves of reduced slope might be expected in urbanised catchments. However, these effects are not constant, and will vary with the degree of urbanisation in given catchments, storm characteristics (duration, profile, relative severity) and prevailing antecedent catchment conditions. These complexities are reflected in Fig. 8f where no clear relationship between distribution shape factors and urban fractions of catchments is observed.

Figure 6 indicates that assuming a GEV type I distribution at locations where type II or type III distributions are valid can produce errors in the estimates of flood quantiles. The basis of assuming GEV type I distributions in Irish catchments is therefore questionable and is likely to become more so with climate change impacts that are expected to result in greater flood risks in future years (Wang et al., 2006). Climate change intensifies the hydrological cycle with more evaporation and more intense precipitation but the extra precipitation will be unequally distributed around the globe (Arnell, 1999). In Ireland, climate change impacts are producing changes in the volume and timing of runoff, changes in soil water storage, groundwater-surface water interactions as well as in the variability of hydrological processes which produce extremes of flooding and low flows (Kiely, 1999; Cawley and Cunnane, 2003; Murphy and Charlton, 2006; Wang et al., 2006; Steele-Dunne et al., 2008; Hall and Murphy, 2010). Since 1975, the Western and Southern river basins of Ireland have experienced episodes of extreme flooding contributed to by the enhanced hydrological cycle (Kiely, 1999).

Uncertainties are likely to be increased given that the impact of climate change on subsurface hydrology and storage capacities is predicted to vary considerably between catchments and also to vary seasonally (Murphy and Charlton, 2006). Annual rainfall, experiencing upward trends in excess of 1.0 mm per year (with increases in excess of 2 mm since 1977) is expected to increase national average rainfall totals from levels in 2000 by 10% by 2050 (Cawley and Cunnane, 2003). There is evidence to suggest that climate change impacts are already having an adverse effect on flood frequencies with 4 and 5 of the six largest floods in the River Fergus and Shannon catchments respectively observed in the last 80 yr, occurring since 1993 (Cawley and Cunnane, 2010). These trends, should they persist, will have significant implications in the context of how flood frequency analysis in Irish catchments is currently approached. However, this will require continued investigation.

5 Conclusions

Quoting Gumbel (1891–1966), where he stated that "*It seems that the rivers know the theory. It only remains to convince the engineers of the validity of this analysis*" is particularly apt for the analysis presented. This analysis involved identifying the GEV flood frequency distributions for annual maximum (AM) data sets in Irish catchments. The statistical test of Hosking et al. (1985) was used but results were also supported by probability plots and Moment and L-moment diagrams. Although data from 172 gauging stations in 126 rivers was analysed in the study, the Hosking et al. algorithm was applied only to the 143 stations where AM flow records exceeded 25 yr. Results indicated that of the 143 stations with these longer flow records, data for 89 was best represented by type I distributions and that another 12 and 39 stations followed type II and type III distributions respectively.

GEV type II distributions were primarily observed in a single cluster in the west of the country in a region underlain by pure carboniferous limestone with extensive karst features together with relatively thin quaternary deposits that overlie the bedrock. Persistent rainfall in the region results in high annual rainfall totals compared to elsewhere in the country and thus, conditions are conducive to the generation of high volume flood hydrographs. For karst floods the volume of the hydrograph is more important than in cases of non-karst floods. For low to moderate floods, a significant proportion of flow can penetrate into the karst underground and fill voids and fissures, with the effect that overland flow is quite low. For larger volume floods, the relative capacity of the voids fissures is not large. Groundwater levels can therefore rise rapidly, pressurising karst conduits and producing groundwater springs that break through on the surface in unexpected locations, producing more significant overland flows. Therefore, although intuitively, the additional subsurface storage provided in karst terrain may be expected to provide conditions consistent with GEV type III distributions, the type II distributions in this area reflect the finite nature of this storage and the effects, in extreme conditions, when the karst is saturated and further storage is no longer available.

The majority of GEV type III distributions appear in four distinct clusters in well defined geographical areas of the Shannon, South-Eastern and Eastern river basins where attenuation influences attributable to floodplains appear to be influential. For moderate floods with relatively high peak to volume ratios, floodplain attenuation effects can be more significant and are influenced by channel-floodplain morphology, valley width, stream slope and hydraulic resistance. The floodplain extent that potentially alters the progression of a flood wave along a valley was represented in the study both in terms of a Flood Attenuation Indicator (FAI) based on both normal depth modelling using the Manning equation and the area adjacent to rivers where alluvium material is known to deposit. The presence of a GEV type III clustering in areas where floodplain activity is high suggests that when gauging stations are separated by wide shallow floodplains without significant intervening tributaries inflow, there is increased tendency for flatter GEV type III flood frequency distributions at downstream gauging stations.

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Table A1. Summary Statistics: relationships used for calculating descriptive statistics. μ, σ^2, γ, and κ denote the theoretical mean, variance, skewness, and kurtosis, respectively, and m, s^2, G, and κ denote the sample mean, variance, skewness, kurtosis. n and x_i are the record length and the individual AM flow values of the particular gauging station respectively.

Theoretical product moments		Sample product moments	
$\mu = E[X]$	A1a	$m = \frac{1}{n}\sum_{i=1}^{n} x_i$	A1b
$\sigma^2 = \mathrm{Var}[X] = E[(X-\mu)^2]$	A2a	$s^2 = \left[\frac{1}{n}\sum_{i=1}^{n}(x_i - m)^2\right]$	A2b
$\gamma = \frac{E[(X-\mu)^3]}{\sigma^3}$	A3a	$G = \frac{1}{s^3}\left[\frac{1}{n}\sum_{i=1}^{n}(x_i - m)^3\right]$	A3b
$\kappa = \frac{E[(X-\mu)^4]}{\sigma^4}$	A4a	$\kappa = \frac{1}{s^4}\left[\frac{1}{n}\sum_{i=1}^{n}(x_i - m)^4\right]$	A4b
$C_V = \frac{\sigma}{\mu}$	A5a	$C_V = \frac{s}{m}$	A5b
Theoretical probability weighted moments		**Sample probability weighted moments**	
$\beta_r = E\left\{x[F(x)]^r\right\}$	A6a	$b_r = \frac{1}{n}\sum_{j=1}^{n}\frac{(j-1)(j-2)....(j-r)}{(n-1)(n-2).....(n-r)}X_j$	A6b
		$\hat{\mathrm{M}}_{100} = b_0$ $\hat{\mathrm{M}}_{110} = b_1$ $\hat{\mathrm{M}}_{120} = b_2$ $\hat{\mathrm{M}}_{130} = b_3$	
Theoretical L moments		**Sample L moments**	
$\lambda_1 = \beta_0$	A7a	$l_1 = b_0$	A7b
$\lambda_2 = 2\beta_1 - \beta_0$	A8a	$l_2 = 2b_1 - b_0$	A8b
$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0$	A9a	$l_3 = 6b_2 - 6b_1 + b_0$	A9b
$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0$	A10a	$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0$	A10b
$\tau_2 \equiv \frac{\lambda_2}{\lambda_1}$	A11a	$L - C_V = \frac{l_2}{l_1}$	A11b
$\tau_3 \equiv \frac{\lambda_3}{\lambda_2}$	A12a	$L - C_S = \frac{l_3}{l_2}$	A12b
$\tau_4 \equiv \frac{\lambda_4}{\lambda_2}$	A13a	$L - C_\kappa = \frac{l_4}{l_2}$	A13b

Table B1. Statistical Data: summary of statistical analysis of OPW monitored gauges where multiple stations exist along a river.

No.	Stn.	River	n	M_{100}	M_{110}	M_{120}	c	$\hat{k}$	Z	Dist	EV1				GEV				% Error
											$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	X_{100}
1	20001	BANDON	50	151.65	89.42	64.96	0.35	−0.014	−0.13	EV1	39.23	129.01	309.47	29.22	38.73	128.77	312.68	26.02	−1.04
2	20002	BANDON	36	146.47	88.06	65.79	0.43	−0.374	−2.99	EV2	42.77	121.78	318.54	41.30	26.16	116.23	437.00		−37.19
3	14005	BARROW	51	52.24	29.70	21.25	0.29	−0.079	−0.75	EV1	10.32	46.28	93.76	8.21	9.55	45.93	98.83	8.26	−5.41
4	14006	BARROW	56	84.03	46.54	32.89	0.20	−0.096	−0.96	EV1	13.06	76.49	136.58	8.78	11.86	75.95	144.52	10.52	−5.82
5	14018	BARROW	67	149.83	86.55	62.06	0.28	0.072	0.79	EV1	33.58	130.45	284.91	20.08	35.74	131.60	271.49	15.01	4.71
6	14019	BARROW	57	105.57	60.47	43.25	0.26	0.038	0.38	EV1	22.18	92.77	194.81	14.39	22.94	93.16	190.04	11.84	2.45
7	14022	BARROW	12	136.17	74.45	51.88	0.16	0.180	0.83		18.36	125.58	210.02	25.16					
8	14029	BARROW	14	182.39	105.23	75.25	0.26	0.130	0.65		40.51	159.01	345.35	50.63					
9	07004	BLACKWATER (KELLS)	22	23.31	12.63	8.72	0.15	0.455	2.84		2.82	21.68	34.67	2.91					
10	07010	BLACKWATER (KELLS)	49	52.31	32.50	23.74	0.42	0.325	3.03	EV3	18.31	41.75	125.96	12.26	22.87	44.85	99.44	5.18	21.06
11	18002	BLACKWATER (Munster)	53	350.34	191.33	133.34	0.16	0.156	1.51	EV1	46.64	323.42	537.96	30.58	52.84	326.98	500.54	18.94	6.96
12	18003	BLACKWATER (Munster)	49	282.76	159.46	113.29	0.23	0.017	0.16	EV1	52.17	252.64	492.65	36.53	52.99	253.06	487.46	31.87	1.05
13	18006	BLACKWATER (MUNSTER)	30	316.01	173.01	121.35	−0.01	−0.047	−0.35	EV1	43.29	291.02	490.18	38.22	41.36	290.11	502.68	41.05	−2.55
14	18055	BLACKWATER (Munster)	7	356.29	196.33	137.14	0.17	0.229	0.81		52.49	325.99	567.44	89.82					
15	26012	BOYLE	51	39.34	23.32	16.84	0.32	0.177	1.69	EV2	10.54	33.25	81.75	7.00	12.12	34.18	72.30	4.15	11.57
16	26108	BOYLE	20	58.01	34.22	24.93	0.37	−0.067	−0.40		15.05	49.32	118.57	19.00					
17	07005	BOYNE	34	105.14	59.48	41.71	0.23	0.480	3.73	EV3	19.93	93.64	185.30	16.16	26.45	98.84	147.89		20.19
18	07007	BOYNE	42	33.43	19.19	13.62	0.26	0.282	2.43	EV3	7.13	29.31	62.13	5.18	8.72	30.35	52.83	2.43	14.97
19	07009	BOYNE	32	163.31	98.78	72.64	0.37	−0.028	−0.21	EV1	49.42	134.78	362.11	42.11	48.12	134.16	370.46	42.80	−2.31
20	07012	BOYNE	69	209.87	130.90	97.46	0.44	−0.013	−0.14	EV1	74.92	166.63	511.26	43.56	74.02	166.19	517.00	42.19	−1.12
21	25006	BROSNA	55	86.53	49.10	34.94	0.24	0.056	0.55	EV1	16.84	76.81	154.27	11.18	17.68	77.25	149.01	8.70	3.41
22	25011	BROSNA	54	86.84	51.28	37.17	0.34	0.050	0.49	EV1	22.67	73.76	178.04	15.54	23.70	74.29	171.60	11.99	3.62
23	25050	BROSNA	31	4.04	2.45	1.79	0.39	0.123	0.91	EV1	1.26	3.31	9.09	1.10	1.39	3.39	8.27	0.72	9.02
24	30004	CLARE	44	98.54	56.06	40.39	0.29	−0.236	−2.09	EV2	19.60	87.23	177.38	16.70	14.94	85.42	209.63	27.12	−18.18
25	30007	CLARE	26	56.61	30.56	21.03	0.14	0.526	3.57	EV3	6.50	52.85	82.75	5.98	8.74	54.73	69.87		15.57
26	16003	CLODIAGH	55	31.87	17.62	12.41	0.19	−0.018	−0.18	EV1	4.86	29.07	51.41	3.16	4.77	29.03	51.94	3.11	−1.03
27	25016	CLODIAGH	51	23.60	13.26	9.36	0.13	0.147	1.40	EV1	4.20	21.18	40.49	1.62	4.73	21.48	37.28	1.77	7.92
28	06013	DEE	33	27.35	15.81	11.29	0.19	0.183	1.40	EV1	6.14	23.81	52.06	3.51	7.09	24.37	46.40	2.96	10.87
29	06025	DEE	33	18.43	10.02	6.94	0.16	0.363	2.78	EV3	2.33	17.08	27.82	1.95	2.97	17.53	24.16		13.14
30	07002	DEEL	49	19.56	11.57	8.35	0.32	0.180	1.68	EV3	5.17	16.58	40.35	3.51	5.95	17.04	35.65	2.06	11.64
31	24011	DEEL	36	79.40	43.99	30.70	0.19	0.348	2.78	EV3	12.37	72.26	129.17	9.96	15.62	74.52	110.34	3.83	14.58
32	24012	DEEL	44	111.66	60.97	42.43	0.16	0.217	1.91	EV3	14.84	103.09	171.35	10.74	17.48	104.71	155.63	5.73	9.17
33	24013	DEEL	49	95.73	56.08	39.62	0.31	0.640	5.97	EV3	23.71	82.04	191.10	16.55	32.66	90.56	138.90		27.31
34	34007	DEEL	56	89.75	53.86	39.24	0.35	0.091	0.91	EV1	25.92	74.79	194.04	16.49	28.00	75.91	181.20	12.06	6.61
35	29002	DUNKELLIN	39	30.66	18.78	14.04	0.44	−0.231	−1.92	EV2	9.95	24.92	70.68	8.50	7.63	24.01	86.67	14.41	−22.62
36	29007	DUNKELLIN	27	29.49	17.12	12.45	0.33	−0.209	−1.45	EV2	6.84	25.54	57.01	7.26	5.41	24.97	66.82	11.16	−17.21
37	29011	DUNKELLIN	25	33.92	19.77	14.45	0.32	−0.277	−1.85	EV2	8.10	29.24	66.51	8.46	5.81	28.39	82.53	16.78	−24.08
38	36011	ERNE	52	18.05	10.00	6.97	0.19	0.401	3.85	EV3	2.82	16.42	29.39	1.86	3.64	17.03	24.66		16.07
39	36019	ERNE	51	93.62	53.15	37.68	0.26	0.175	1.67	EV3	18.30	83.06	167.24	13.41	21.01	84.65	150.97	7.23	9.73
40	06011	FANE	53	16.03	8.96	6.33	0.21	0.078	0.75	EV1	2.74	14.45	27.04	1.85	2.93	14.55	25.87	1.36	4.32
41	06012	FANE	53	15.28	8.93	6.46	0.30	−0.004	−0.04	EV1	3.72	13.13	30.25	2.48	3.71	13.13	30.33	2.33	−0.27
42	06014	GLYDE	33	22.35	12.77	9.17	0.26	−0.104	−0.79	EV1	4.59	19.70	40.83	3.97	4.13	19.50	43.86	4.93	−7.42
43	06021	GLYDE	53	21.51	12.17	8.63	0.23	0.128	1.24	EV1	4.08	19.15	37.94	2.67	4.54	19.40	35.18	1.77	7.27
44	25021	LITTLE BROSNA	47	27.99	15.13	10.44	0.14	0.395	3.61	EV3	3.28	26.10	41.18	2.27	4.22	26.79	35.74		13.22
45	25023	LITTLE BROSNA	55	12.44	7.30	5.25	0.29	0.137	1.35	EV3	3.11	10.65	24.93	1.88	3.47	10.85	22.70	1.30	8.94
46	24004	MAIGUE	55	54.16	32.81	24.13	0.38	−0.016	−0.15	EV1	16.54	44.61	120.68	10.87	16.30	44.49	122.21	10.52	−1.27
47	24008	MAIGUE	31	120.38	69.27	49.43	0.26	0.157	1.17	EV1	26.20	105.25	225.77	22.30	29.71	107.28	204.56	13.86	9.39
48	24082	MAIGUE	31	135.17	77.37	54.75	0.25	0.334	2.48	EV3	28.23	118.88	248.76	24.10	35.43	123.82	207.02		16.78
49	19044	MARTIN	12	20.65	12.03	8.53	0.28	0.494	2.28		4.92	17.81	40.45	6.62					
50	19046	MARTIN	9	31.09	17.97	12.76	0.26	0.357	1.43		6.99	27.06	59.23	10.52					
51	34003	MOY	33	174.80	96.679	67.859	0.014	0.1104	0.845	EV1	26.775	159.34	282.51	22.9427	29.363	160.77	266.67	15.42	5.61
52	34010	MOY	12	105.04	61.79	44.88	0.00	−0.033	−0.15		26.75	89.60	212.65	36.16					
53	25001	MULKEAR	53	124.07	67.07	46.30	0.14	0.387	3.75	EV3	14.54	115.67	182.56	9.59	18.67	118.67	158.76		13.03
54	25003	MULKEAR	54	68.83	37.34	25.88	0.15	0.251	2.45	EV3	8.42	63.97	102.72	5.43	10.13	65.05	92.69	2.72	9.76

Table B1. Continued.

No.	Stn.	River	n	M_{100}	M_{110}	M_{120}	c	$\hat{k}$	Z	Dist	EV1				GEV				% Error
											$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	X_{100}
55	16005	MULTEEN	34	23.01	12.63	8.86	0.18	0.007	0.05	EV1	3.24	21.14	36.04	2.73	3.26	21.15	35.92	2.45	0.35
56	16006	MULTEEN	37	30.14	18.37	13.42	0.38	0.158	1.28	EV1	9.52	24.65	68.43	7.40	10.80	25.39	60.67	4.59	11.33
57	15002	NORE	53	230.88	136.57	98.98	0.32	0.070	0.68	EV1	60.97	195.69	476.17	40.31	64.77	197.69	452.61	30.86	4.95
58	15004	NORE	54	36.67	21.20	15.20	0.28	0.084	0.83	EV1	8.28	31.89	69.97	5.50	8.90	32.22	66.15	3.99	5.46
59	15006	NORE	52	301.02	170.51	120.27	0.23	0.304	2.92	EV3	57.71	267.71	533.19	37.80	71.35	276.80	453.68	16.74	14.91
60	15011	NORE	55	332.76	187.39	131.53	0.23	0.390	3.86	EV3	60.64	297.76	576.69	39.71	77.96	310.36	476.88	13.29	17.31
61	12001	SLANEY	53	162.53	95.52	69.02	0.33	0.071	0.69	EV1	41.12	138.80	327.96	29.01	43.74	140.19	311.71	20.72	4.96
62	12002	SLANEY	29	250.11	157.61	119.43	0.51	−0.226	−1.62	EV1	93.93	195.89	627.97	92.85	72.59	187.52	775.16	155.48	−23.44
63	26002	SUCK	58	57.61	32.29	22.96	0.24	−0.102	−1.03	EV1	10.05	51.81	98.05	7.17	9.07	51.37	104.55	8.09	−6.63
64	26005	SUCK	56	94.20	52.55	37.11	0.23	0.036	0.36	EV1	15.72	85.12	157.45	11.36	16.24	85.39	154.20	8.50	2.06
65	26006	SUCK	58	30.12	18.05	13.33	0.39	−0.200	−2.03	EV2	8.62	25.15	64.81	6.13	6.90	24.45	76.57	9.35	−18.15
66	26007	SUCK	58	93.88	53.14	37.99	0.27	−0.107	−1.08	EV1	17.89	83.55	165.83	13.20	16.05	82.73	178.01	14.63	−7.35
67	16002	SUIR	55	55.30	32.05	23.05	0.30	0.037	0.37	EV1	12.70	47.97	106.37	8.70	13.12	48.19	103.68	6.91	2.53
68	16004	SUIR	54	21.93	12.51	8.99	0.21	−0.146	−1.43	EV1	4.45	19.36	39.82	2.48	3.81	19.09	44.08	4.25	−10.72
69	16008	SUIR	55	91.48	49.16	33.87	0.13	0.361	3.56	EV3	9.88	85.77	131.24	6.30	12.55	87.65	115.83		11.74
70	16009	SUIR	56	158.58	86.92	60.21	0.17	0.485	4.84	EV3	22.00	145.88	247.10	13.96	29.25	151.70	205.51		16.83
71	16011	SUIR	53	247.12	142.53	102.09	0.27	0.084	0.81	EV1	54.74	215.53	467.34	35.60	58.80	217.71	442.23	26.68	5.37

Table B2. Summary of statistical analysis of OPW monitored gauges.

No.	Stn.	River	n	M_{100}	M_{110}	M_{120}	c	$\hat{k}$	Z	Dist	EV1				GEV				% Error
											$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	X_{100}
72	29010	AGGARD	26	5.65	3.47	2.60	0.42	−0.198	−1.35	EV1	1.87	4.57	13.16	1.82	1.50	4.43	15.68	3.00	−19.11
73	16007	AHERLOW	55	79.71	46.96	33.90	0.31	0.121	1.20	EV1	20.49	67.88	162.15	13.12	22.66	69.09	148.96	8.89	8.14
74	30001	AILLE	18	32.67	17.66	12.15	0.07	0.556	3.14		3.81	30.47	48.02	4.25					
75	36010	ANNALEE	55	68.94	39.27	28.17	0.27	−0.105	−1.04	EV1	13.86	60.94	124.69	9.99	12.45	60.32	134.00	11.59	−7.47
76	16010	ANNER	37	45.43	25.43	17.93	0.02	0.160	1.29	EV1	7.85	40.89	77.03	6.07	8.92	41.51	70.58	3.78	8.37
77	18004	AWBEG	49	30.73	16.71	11.61	0.17	0.223	2.08	EV3	3.89	28.48	46.39	2.99	4.60	28.92	42.17	1.41	9.09
78	25025	BALLYFINBOY	34	10.41	6.14	4.44	0.32	0.099	0.77	EV1	2.70	8.85	21.28	2.21	2.94	8.98	19.83	1.58	6.81
79	35005	BALLYSADARE	60	80.78	45.60	32.44	0.23	−0.012	−0.13	EV1	15.03	72.11	141.23	9.51	14.85	72.03	142.35	9.06	−0.79
80	25004	BILBOA	29	42.25	23.73	16.66	0.21	0.341	2.45	EV3	7.52	37.91	72.52	6.60	9.47	39.25	61.24	2.65	15.56
81	26009	BLACK	38	13.62	7.40	5.17	0.16	−0.062	−0.51	EV1	1.70	12.63	20.47	1.35	1.60	12.59	21.12	1.50	−3.19
82	07003	BLACKWATER (ENFIELD)	16	11.88	6.82	4.84	0.26	0.268	1.43		2.54	10.41	22.08	3.00					
83	18001	BRIDE	43	72.52	40.44	28.15	0.20	0.560	4.89	EV3	12.06	65.56	121.03	8.88	16.35	69.30	96.28		20.45
84	08008	BROADMEADOW	28	45.28	30.97	24.30	0.69	−0.216	−1.52	EV1	24.05	31.39	142.04	23.21	18.86	29.33	177.72	39.27	−25.12
85	25022	CAMCOR	55	27.62	15.40	10.89	0.20	−0.002	−0.02	EV1	4.59	24.97	46.07	2.99	4.58	24.97	46.14	2.80	−0.14
86	26019	CAMLIN	56	22.28	12.67	9.08	0.25	−0.098	−0.97	EV2	4.41	19.74	40.02	2.92	3.99	19.55	42.75	3.57	−6.83
87	34018	CASTLEBAR	32	11.99	6.78	4.83	0.23	−0.074	−0.56	EV1	2.25	10.70	21.04	1.94	2.09	10.62	22.08	2.24	−4.92
88	29004	CLARINBRIDGE	35	10.05	5.50	3.82	0.16	0.314	2.47	EV3	1.36	9.27	15.53	1.09	1.69	9.49	13.61	0.47	12.37
89	27001	CLAUREEN	33	20.79	11.42	8.02	0.18	−0.018	−0.14	EV1	2.96	19.08	32.69	2.63	2.91	19.06	33.00	2.44	−0.96
90	30061	CORRIB ESTUARY	19	260.03	141.91	99.71	0.17	−0.178	−1.03		34.30	240.23	398.03	40.61					
91	14009	CUSHINA	28	6.72	3.81	2.72	0.25	−0.030	−0.21	EV1	1.30	5.97	11.95	1.23	1.26	5.95	12.19	1.21	−1.97
92	25005	DEAD	47	27.90	14.79	10.11	0.11	0.475	4.34	EV3	2.44	26.49	37.69	1.69	3.23	27.12	33.15	0.37	12.06
93	15003	DININ	55	142.92	80.19	55.85	0.22	0.626	6.18	EV3	25.18	128.39	244.21	16.53	34.61	137.20	189.41		22.44
94	16001	DRISH	36	16.14	9.22	6.59	0.01	0.040	0.32	EV1	3.32	14.22	29.51	2.87	3.44	14.28	28.75	2.22	2.55
95	36018	DROMORE	52	15.28	8.59	6.06	0.02	0.191	1.86	EV3	2.72	13.71	26.24	1.78	3.16	13.97	23.63	1.02	9.93
96	15005	ERKINA	53	28.51	16.79	12.20	0.34	−0.016	−0.15	EV1	7.33	24.27	58.01	5.20	7.23	24.22	58.70	4.75	−1.19
97	26015	ESLIN	36	6.52	3.53	2.45	0.02	0.150	1.20	EV1	0.78	6.08	9.66	0.63	0.88	6.13	9.05	0.39	6.27
98	26022	FALLAN	36	6.54	3.83	2.76	0.30	0.093	0.75	EV1	1.62	5.60	13.06	1.28	1.75	5.68	12.23	0.93	6.30
99	23002	FEALE	62	401.06	234.32	170.26	0.32	−0.118	−1.24	EV1	97.49	344.79	793.25	63.90	86.32	339.89	867.46	79.86	−9.35
100	27002	FERGUS	56	35.23	20.03	14.35	0.26	−0.108	−1.07	EV1	6.97	31.21	63.26	4.86	6.24	30.89	68.04	5.81	−7.57
101	14004	FIGILE	51	21.49	12.50	9.02	0.29	0.009	0.08	EV1	5.07	18.57	41.89	3.42	5.11	18.59	41.63	3.11	0.61
102	22006	FLESK(LAUNE)	55	166.45	94.60	67.06	0.24	0.191	1.89	EV3	32.83	147.50	298.51	21.53	38.08	150.63	267.11	12.03	10.52
103	18005	FUNSHION	53	56.75	32.44	23.30	0.27	−0.099	−0.96	EV1	11.73	49.98	103.96	8.22	10.62	49.48	111.30	9.79	−7.06
104	23001	GALEY	48	111.13	66.99	49.31	0.38	−0.078	−0.72	EV1	32.97	92.10	243.78	23.77	30.52	90.98	259.87	27.16	−6.60
105	34005	GWEESTION	13	32.49	18.30	13.01	0.22	−0.024	−0.11		5.92	29.08	56.29	7.85					
106	28001	INAGH	49	52.11	29.82	21.50	0.30	−0.178	−1.66	EV2	10.86	45.85	95.80	8.86	8.95	45.06	108.78	11.99	−13.55
107	26021	INNY	33	104.04	56.43	39.09	0.15	0.281	2.15	EV3	12.72	96.69	155.23	10.45	15.55	98.54	138.68	4.89	10.66
108	26004	ISLAND	5	20.21	11.44	8.04	0.05	0.423	1.26		3.86	17.98	35.75	7.52					
109	25020	KILLIMOR	41	48.15	29.04	21.38	0.38	−0.076	−0.65	EV1	14.32	39.89	105.76	11.35	13.28	39.41	112.55	12.68	−6.42
110	15001	KINGS	46	89.08	51.76	36.93	0.28	0.268	2.43	EV3	20.83	77.05	172.89	14.51	25.29	79.92	146.72	6.99	15.13
111	06026	LAGAN (GLYDE)	49	13.72	8.07	5.88	0.32	−0.113	−1.05	EV1	3.50	11.70	27.79	2.46	3.12	11.53	30.32	3.17	−9.12
112	22035	LAUNE	17	110.74	61.84	43.16	0.20	0.473	2.60		18.66	99.97	185.81	20.99					
113	39008	LOUGH GARTAN	36	28.21	16.21	11.59	0.26	0.103	0.82	EV1	6.09	24.69	52.71	4.81	6.64	24.99	49.33	3.42	6.41
114	23012	LEE (KERRY)	18	16.87	9.67	7.01	0.29	−0.312	−1.76		3.56	14.82	31.17	4.59					
115	22071	LOUGH LEANE	34	108.69	60.90	43.04	0.22	0.092	0.72	EV1	18.93	97.76	184.84	16.11	20.47	98.60	175.33	11.26	5.14
116	35071	LOUGH MELVIN	32	26.78	14.90	10.46	0.20	0.210	1.58	EV1	4.37	24.25	44.37	3.74	5.13	24.72	39.85	2.01	10.18
117	36071	LOUGH SCUR	21	6.34	3.45	2.40	0.15	0.138	0.84		0.80	5.87	9.57	0.82					
118	26014	LUNG	28	34.55	21.54	15.83	0.43	0.216	1.52	EV1	12.29	27.46	84.01	10.98	14.48	28.79	71.03	5.97	15.44
119	22003	MAINE	42	152.45	92.41	68.46	0.44	−0.152	−1.31	EV1	46.69	125.50	340.28	40.90	39.72	122.54	387.21	51.53	−13.79
120	07006	MOYNALTY	22	27.41	15.47	10.85	0.22	0.453	2.83		5.08	24.48	47.86	5.12					
121	08011	NANNY	28	32.68	18.61	13.08	0.24	0.507	3.58	EV3	6.57	28.89	59.09	5.91	8.79	30.71	46.35	0.87	21.57
122	25029	NENAGH	36	54.00	30.65	21.63	0.23	0.314	2.51	EV3	10.52	47.93	96.33	8.19	13.07	49.65	81.49	3.58	15.41
123	25002	NEWPORT	54	60.39	33.08	22.87	0.17	0.566	5.55	EV3	8.32	55.59	93.85	5.40	11.30	58.20	76.67		18.30
124	16013	NIRE	44	99.52	60.96	44.89	0.40	0.047	0.41	EV1	32.30	80.88	229.46	23.40	33.67	81.59	220.91	19.12	3.73
125	25027	OLLATRAM	47	23.72	13.75	9.83	0.02	0.194	1.77	EV3	5.45	20.58	45.64	3.80	6.33	21.11	40.38	2.15	11.54
126	11001	OWENAVORRAGH	36	49.70	28.81	20.82	0.33	−0.078	−0.62	EV1	11.42	43.11	95.65	10.60	10.57	42.72	101.20	10.86	-5.81
127	19001	OWENBOY	52	18.36	11.08	8.10	0.37	0.069	0.66	EV1	5.49	15.19	40.44	3.65	5.83	15.37	38.34	2.81	5.19
128	38001	OWENEA	36	68.97	37.56	26.14	0.17	0.155	1.24	EV1	8.86	63.86	104.62	7.66	10.04	64.53	97.53	4.37	6.78
129	34009	OWENGARVE	29	29.10	15.86	11.05	0.16	0.132	0.94	EV1	3.79	26.91	44.34	3.39	4.22	27.15	41.72	2.21	5.92

Table B2. Continued.

No.	Stn.	River	n	M_{100}	M_{110}	M_{120}	c	$\hat{k}$	Z	Dist	EV1				GEV				% Error
											$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	X_{100}
130	35001	OWENMORE	38	34.34	20.45	14.96	0.35	−0.057	−0.47	EV1	9.48	28.87	72.45	7.62	8.96	28.63	75.78	8.23	−4.60
131	26018	OWENURE	52	9.31	5.19	3.65	0.20	0.108	1.04	EV1	1.53	8.42	15.48	1.02	1.68	8.50	14.59	0.71	5.77
132	29001	RAFORD	45	14.67	8.21	5.80	0.21	0.076	0.68	EV1	2.52	13.22	24.80	1.81	2.69	13.31	23.74	1.36	4.26
133	26008	RINN	55	23.72	13.31	9.42	0.23	0.061	0.60	EV1	4.17	21.32	40.49	2.91	4.40	21.43	39.08	2.12	3.48
134	30005	ROBE	52	32.45	19.15	13.84	0.32	0.095	0.92	EV1	8.42	27.59	66.34	5.58	9.13	27.97	61.98	4.02	6.58
135	09001	RYEWATER	51	38.92	24.19	18.01	0.44	−0.030	−0.28	EV1	13.67	31.03	93.90	9.42	13.29	30.85	96.34	9.42	−2.60
136	25014	SILVER	57	17.51	9.87	7.00	0.22	0.081	0.81	EV1	3.21	15.66	30.44	2.05	3.44	15.78	29.01	1.52	4.69
137	14011	SLATE	29	11.90	6.81	4.84	0.25	0.235	1.69	EV3	2.49	10.47	21.90	2.19	2.96	10.76	19.09	1.13	12.84
138	14007	STRADBALLY	28	17.04	9.95	7.22	0.30	−0.065	−0.46	EV1	4.14	14.65	33.70	3.76	3.89	14.53	35.37	4.29	−4.95
139	39001	SWILLY	34	43.13	24.29	17.14	0.22	0.206	1.60	EV1	7.87	38.59	74.79	6.32	9.22	39.40	66.77	3.54	10.72
140	16012	TAR	45	50.99	28.18	19.70	0.18	0.243	2.17	EV3	7.74	46.52	82.15	5.47	9.27	47.48	73.14	2.78	10.96
141	36027	WOODFORD	18	24.99	13.25	9.05	0.11	0.563	3.18		2.19	23.73	33.79	2.56	2.97	24.41	29.29		13.32
142	36021	YELLOW	30	24.94	13.93	9.87	0.22	−0.057	−0.41	EV1	4.20	22.52	41.84	3.92	3.98	22.41	43.31	4.10	−3.50

Table B3. Summary of statistical analysis of EPA monitored gauges.

No.	Stn.	River	*n*	M_{100}	M_{110}	M_{120}	*c*	$\hat{k}$	*Z*	Dist	EV1				GEV				% Error
											$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	$\hat{\alpha}$	$\hat{u}$	X_{100}	Se(X_{100})	X_{100}
143	20006	ARGIDEEN	30	24.30	13.30	9.31	0.00	0.029	0.21	EV1	3.32	22.39	37.64	2.88	3.40	22.43	37.09	2.50	1.45
144	10028	AUGHRIM	21	79.83	50.82	38.88	−0.04	−0.296	−1.81		31.47	61.67	206.44	35.65					
145	10002	AVONMORE	52	98.76	62.40	47.29	−0.03	−0.210	−2.02	EV2	37.57	77.08	249.89	29.63	29.69	73.93	303.94	44.25	−21.63
146	07044	BALLIVOR	16	2.19	1.31	0.95	0.02	0.166	0.89		0.62	1.83	4.69	0.72					
147	06030	BIG	29	12.26	7.95	6.01	0.00	0.004	0.03	EV1	5.26	9.22	33.42	4.65	5.28	9.23	33.31	4.35	0.34
148	18016	BLACKWATER	26	83.62	47.05	33.02	0.05	0.383	2.60	EV3	15.13	74.89	144.49	13.91	19.39	77.96	119.93	4.96	17.00
149	12016	BORO	27	43.99	27.35	20.40	−0.01	−0.066	−0.46	EV1	15.45	35.07	106.14	15.36	14.47	34.62	112.50	16.37	−5.99
150	25124	BROSNA	12	13.54	8.11	5.79	0.07	0.589	2.72		3.88	11.30	29.14	5.52					
151	25040	BUNOW	23	4.16	2.39	1.72	−0.02	−0.126	−0.81		0.89	3.64	7.74	0.91					
152	32011	BUNOWEN	27	80.35	45.97	32.76	0.02	0.123	0.85	EV1	16.72	70.70	147.61	15.10	18.50	71.69	136.72	10.31	7.38
153	31002	CASHLA	30	13.24	7.43	5.28	−0.01	−0.066	−0.48	EV1	2.34	11.90	22.64	2.06	2.19	11.83	23.59	2.34	−4.20
154	21002	COOMHOLA	34	149.08	86.13	61.53	0.02	0.174	1.35	EV1	33.43	129.79	283.58	27.65	38.34	132.66	254.10	16.23	10.39
155	13002	COROCK	17	9.23	5.04	3.50	0.03	0.273	1.50		1.23	8.52	14.16	1.48					
156	30020	DALGAN	20	4.25	2.43	1.73	0.01	0.078	0.46		0.88	3.74	7.79	0.94					
157	24030	DEEL	27	48.62	25.34	17.14	0.11	0.866	6.00	EV3	2.97	46.91	60.58	2.94	4.16	48.39	53.10		12.35
158	15021	DELOUR	31	23.44	13.33	9.55	−0.01	−0.083	−0.62	EV1	4.65	20.75	42.16	4.30	4.28	20.59	44.60	4.85	−5.78
159	23006	FEALE	19	246.11	145.16	105.56	0.00	−0.036	−0.21		63.77	209.30	502.68	70.53					
160	26059	INNY	26	11.12	5.98	4.12	0.05	0.435	2.957	EV3	1.22	10.42	16.01	1.13	1.59	10.70	13.86	0.32	13.42
161	25044	KILMASTULLA	37	23.27	13.74	10.04	−0.02	−0.137	−1.11	EV1	6.06	19.78	47.64	5.04	5.24	19.43	53.08	6.81	−11.41
162	25034	L. ENNELL TRIB	28	1.50	0.89	0.65	0.02	0.154	1.088	EV1	0.41	1.26	3.17	0.38	0.47	1.29	2.84	0.23	10.43
163	24022	MAHORE	24	8.01	4.59	3.25	0.04	0.308	2.012		1.69	7.03	14.80	1.65					
164	32012	NEWPORT	26	16.91	10.27	7.33	0.09	0.690	4.685	EV3	5.24	13.88	38.00	5.01					
165	13003	OWENDUFF	18	17.80	9.96	6.92	0.09	0.691	3.904		3.04	16.05	30.05	3.66					
166	34024	POLLAGH	29	20.83	11.23	7.77	0.02	0.189	1.358	EV1	2.35	19.47	30.26	2.12	2.72	19.69	28.04	1.19	7.35
167	30021	ROBE	28	24.27	13.65	9.63	0.03	0.207	1.461	EV1	4.38	21.74	41.88	4.09	5.13	22.20	37.41	2.17	10.68
168	26029	SHANNON	35	93.76	54.28	39.62	−0.04	−0.319	−2.52	EV2	21.36	81.43	179.70	19.74	14.35	78.94	229.29	42.63	−27.60
169	09011	SLANG	23	4.56	3.26	2.64	−0.05	−0.354	−2.26		2.84	2.92	15.99	3.11					
170	23017	SMEARLAGH	28	127.99	75.70	55.13	−0.01	−0.040	−0.28	EV1	33.76	108.50	263.82	31.42	32.50	107.90	271.98	32.39	−3.09
171	14031	TULLY	10	0.52	0.32	0.23	0.04	0.347	1.463		0.18	0.42	1.23	0.25					
172	06033	WHITE (DEE)	35	21.27	13.41	9.92	0.02	0.177	1.398	EV1	8.00	16.66	53.45	6.59	9.19	17.36	46.27	3.80	13.43
143	20006	ARGIDEEN	30	24.30	13.30	9.31	0.00	0.029	0.21	EV1	3.32	22.39	37.64	2.88	3.40	22.43	37.09	2.50	1.45
144	10028	AUGHRIM	21	79.83	50.82	38.88	−0.04	−0.296	−1.81		31.47	61.67	206.44	35.65					
145	10002	AVONMORE	52	98.76	62.40	47.29	−0.03	−0.210	−2.02	EV2	37.57	77.08	249.89	29.63	29.69	73.93	303.94	44.25	−21.63
146	07044	BALLIVOR	16	2.19	1.31	0.95	0.02	0.166	0.89		0.62	1.83	4.69	0.72					
147	06030	BIG	29	12.26	7.95	6.01	0.00	0.004	0.03	EV1	5.26	9.22	33.42	4.65	5.28	9.23	33.31	4.35	0.34
148	18016	BLACKWATER	26	83.62	47.05	33.02	0.05	0.383	2.60	EV3	15.13	74.89	144.49	13.91	19.39	77.96	119.93	4.96	17.00
149	12016	BORO	27	43.99	27.35	20.40	−0.01	−0.066	−0.46	EV1	15.45	35.07	106.14	15.36	14.47	34.62	112.50	16.37	−5.99
150	25124	BROSNA	12	13.54	8.11	5.79	0.07	0.589	2.72		3.88	11.30	29.14	5.52					
151	25040	BUNOW	23	4.16	2.39	1.72	−0.02	−0.126	−0.81		0.89	3.64	7.74	0.91					
152	32011	BUNOWEN	27	80.35	45.97	32.76	0.02	0.123	0.85	EV1	16.72	70.70	147.61	15.10	18.50	71.69	136.72	10.31	7.38
153	31002	CASHLA	30	13.24	7.43	5.28	−0.01	−0.066	−0.48	EV1	2.34	11.90	22.64	2.06	2.19	11.83	23.59	2.34	−4.20
154	21002	COOMHOLA	34	149.08	86.13	61.53	0.02	0.174	1.35	EV1	33.43	129.79	283.58	27.65	38.34	132.66	254.10	16.23	10.39
155	13002	COROCK	17	9.23	5.04	3.50	0.03	0.273	1.50		1.23	8.52	14.16	1.48					
156	30020	DALGAN	20	4.25	2.43	1.73	0.01	0.078	0.46		0.88	3.74	7.79	0.94					
157	24030	DEEL	27	48.62	25.34	17.14	0.11	0.866	6.00	EV3	2.97	46.91	60.58	2.94	4.16	48.39	53.10		12.35
158	15021	DELOUR	31	23.44	13.33	9.55	−0.01	−0.083	−0.62	EV1	4.65	20.75	42.16	4.30	4.28	20.59	44.60	4.85	−5.78
159	23006	FEALE	19	246.11	145.16	105.56	0.00	−0.036	−0.21		63.77	209.30	502.68	70.53					
160	26059	INNY	26	11.12	5.98	4.12	0.05	0.435	2.957	EV3	1.22	10.42	16.01	1.13	1.59	10.70	13.86	0.32	13.42
161	25044	KILMASTULLA	37	23.27	13.74	10.04	−0.02	−0.137	−1.11	EV1	6.06	19.78	47.64	5.04	5.24	19.43	53.08	6.81	−11.41
162	25034	L. ENNELL TRIB	28	1.50	0.89	0.65	0.02	0.154	1.088	EV1	0.41	1.26	3.17	0.38	0.47	1.29	2.84	0.23	10.43
163	24022	MAHORE	24	8.01	4.59	3.25	0.04	0.308	2.012		1.69	7.03	14.80	1.65					
164	32012	NEWPORT	26	16.91	10.27	7.33	0.09	0.690	4.685	EV3	5.24	13.88	38.00	5.01					
165	13003	OWENDUFF	18	17.80	9.96	6.92	0.09	0.691	3.904		3.04	16.05	30.05	3.66					
166	34024	POLLAGH	29	20.83	11.23	7.77	0.02	0.189	1.358	EV1	2.35	19.47	30.26	2.12	2.72	19.69	28.04	1.19	7.35
167	30021	ROBE	28	24.27	13.65	9.63	0.03	0.207	1.461	EV1	4.38	21.74	41.88	4.09	5.13	22.20	37.41	2.17	10.68
168	26029	SHANNON	35	93.76	54.28	39.62	−0.04	−0.319	−2.52	EV2	21.36	81.43	179.70	19.74	14.35	78.94	229.29	42.63	−27.60
169	09011	SLANG	23	4.56	3.26	2.64	−0.05	−0.354	−2.26		2.84	2.92	15.99	3.11					
170	23017	SMEARLAGH	28	127.99	75.70	55.13	−0.01	−0.040	−0.28	EV1	33.76	108.50	263.82	31.42	32.50	107.90	271.98	32.39	−3.09
171	14031	TULLY	10	0.52	0.32	0.23	0.04	0.347	1.463		0.18	0.42	1.23	0.25					
172	06033	WHITE (DEE)	35	21.27	13.41	9.92	0.02	0.177	1.398	EV1	8.00	16.66	53.45	6.59	9.19	17.36	46.27	3.80	13.43

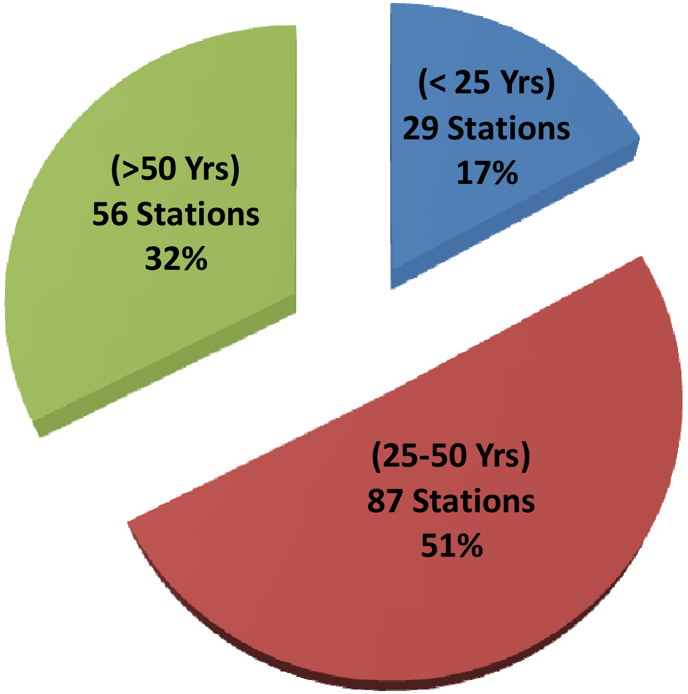


Fig. 1. Numbers of gauging stations with hydrometric records for **(a)** less than 25 yr; **(b)** between 25 and 50 yr and **(c)** greater than 50 yr.

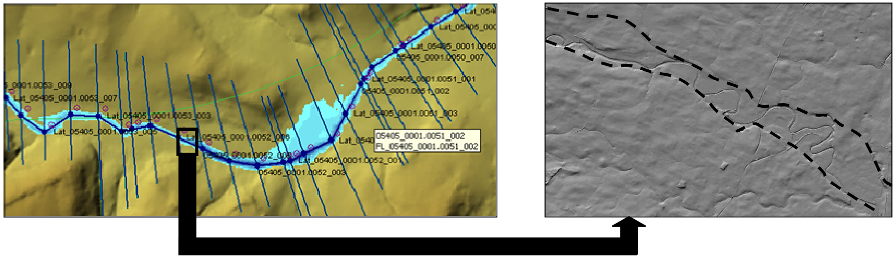
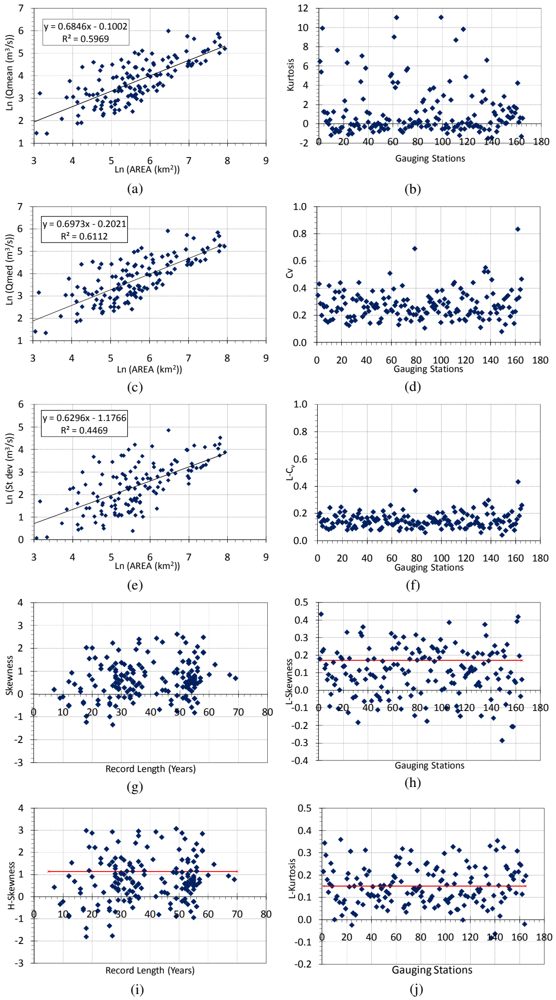
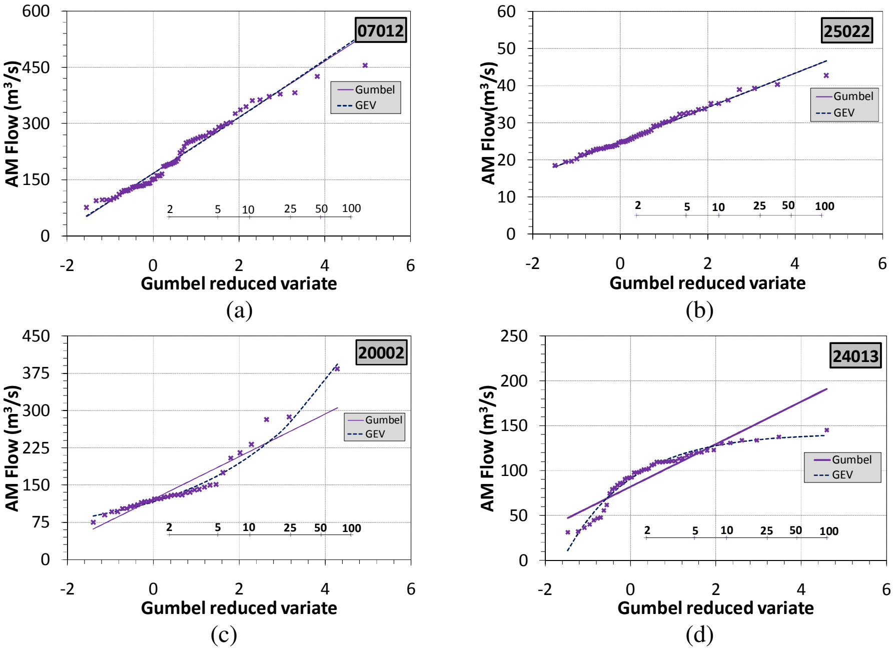


Fig. 2. DTM with FAI as developed for Irish catchments from normal depth modelling in FSU.



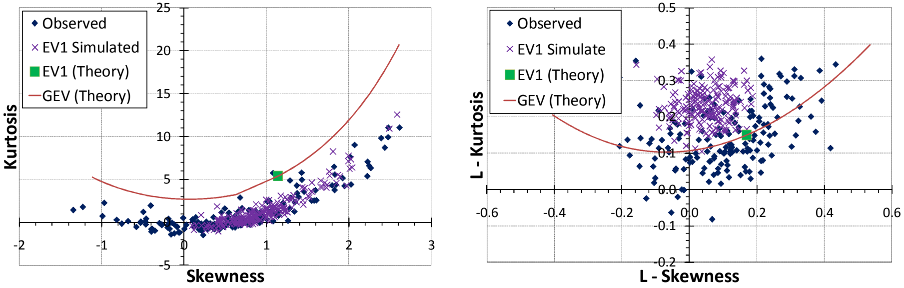
(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Fig. 3. Descriptive statistics of the 172 Irish Gauging Stations analysed.



(a) (b) (c) (d)

Fig. 4. Probability plots of AM flow ($m^3\,s^{-1}$) against Gumbel reduced variates for **(a)** Station 07012; **(b)** Station 25022; **(c)** Station 20002 and **(d)** Station 24013.



(a) (b)

Fig. 5. Moment **(a)** and *L*-moment **(b)** ratio diagrams for the 172 stations analysed. The 200 simulated GEV type I samples are also shown.

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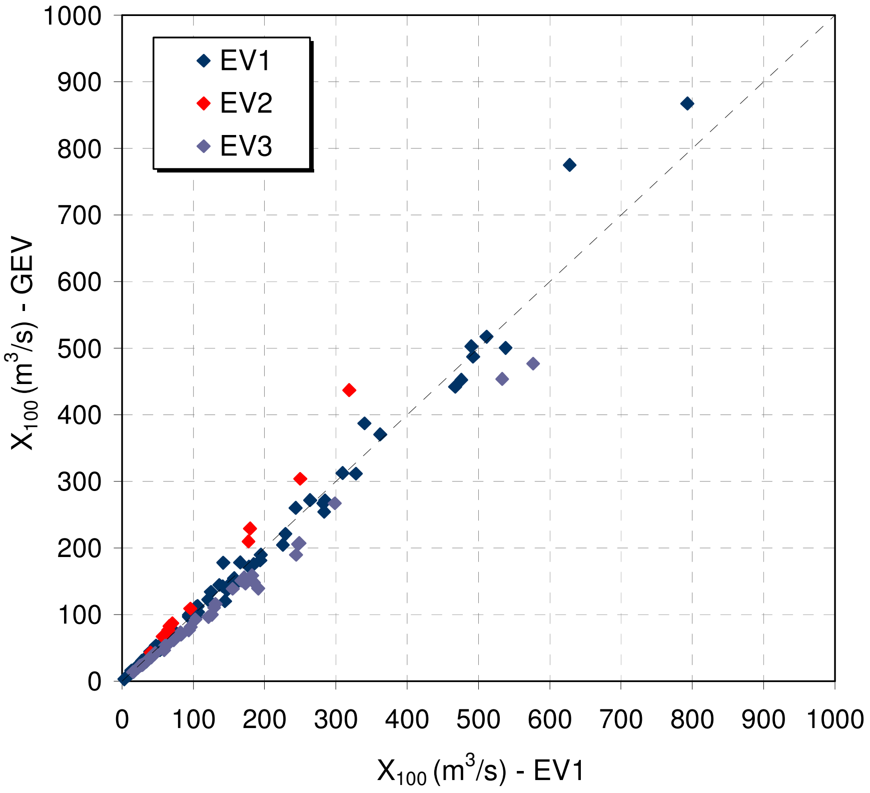

Fig. 6. Comparison of 100-yr flood quantiles X_{100} estimated from GEV type I distributions with those determined for GEV distributions for the 143 Irish gauging stations analysed.

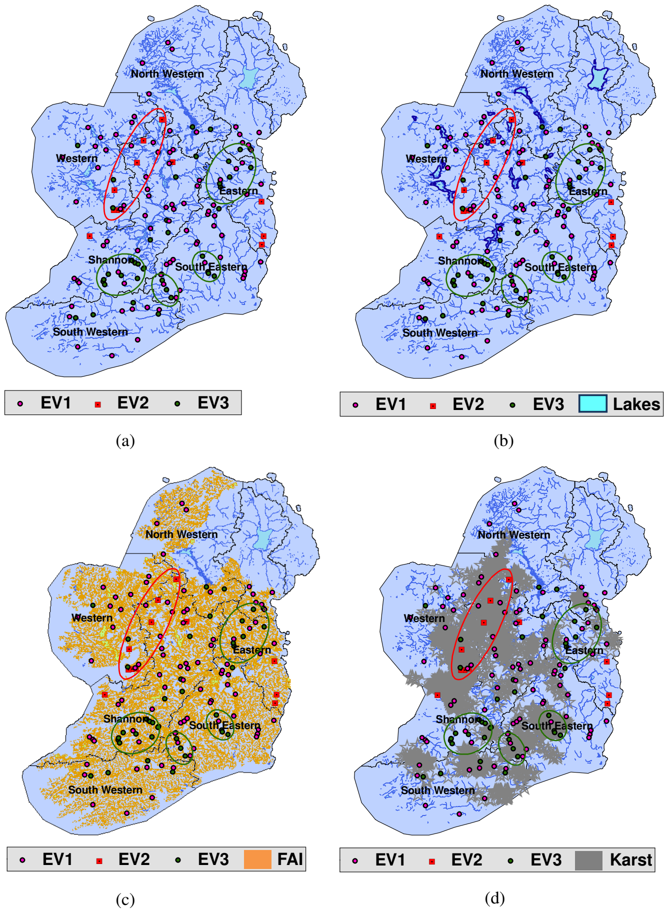

Fig. 7. Spatial variation of GEV distributions in Irish river catchments for **(a)** different river basins; **(b)** catchments with strong lake storage influences; **(c)** flood attenuation indicators in Irish rivers and **(d)** karst terrains.

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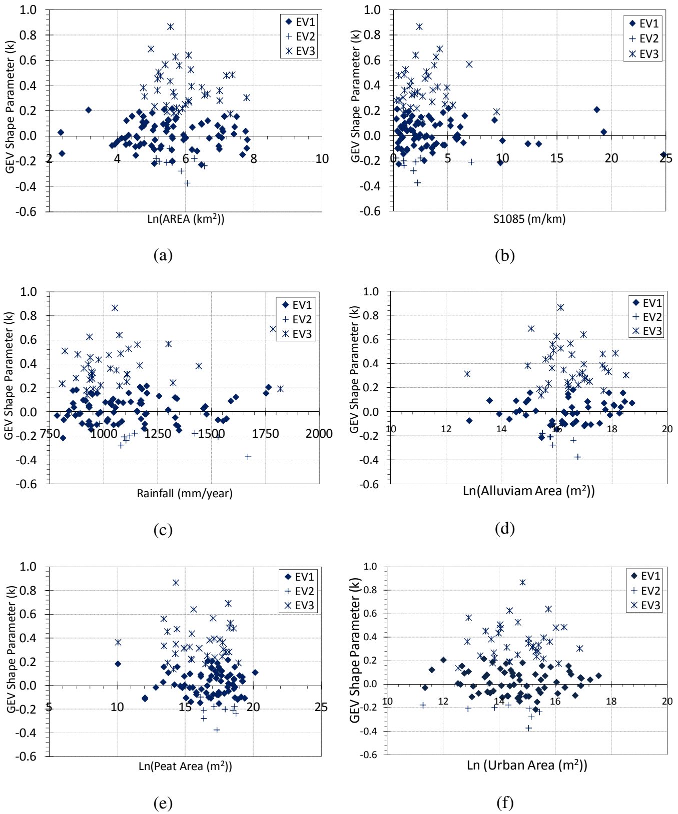

Fig. 8. Variation of GEV distribution shape parameter (k) with catchment properties for: **(a)** catchment area, **(b)** longitudinal slope (S1085), **(c)** annual rainfall, **(d)** catchment area covered by alluvium deposits, **(e)** peat and **(f)** urbanised area in catchment.