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Influences on Flood Frequency Distribution in Irish Catchments

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Abstract: *This study explores influences which result in shifts of generalized extreme value (GEV) flood frequency distributions in Irish rivers. Data from 139 gauging stations from 100 Irish rivers was analysed using the Hosking algorithm to determine whether Type I, II or III distributions are valid. Results indicate that hydrological data for 89 sites followed Type I distributions. Another 12 and 38 stations followed Type II and Type III distributions respectively. Type I distributions are spatially well represented throughout the country. The majority of Type III distributions appear in four clusters in geographical areas where attenuation influences from floodplains and lakes are influential. Type II distributions appear in a single cluster in a region in the west of the country characterised by a Karst landscape. Type II distributions in this area reflect the finite nature of Karst storage and the effects of saturation when storage is no longer available.*

Keywords: Flood frequency analyses, GEV distributions, statistical hydrology, floodplains, attenuation, karst landscape

1. INTRODUCTION

Flood studies regularly require the estimation of the peak discharge for a specified return period that is substantially longer than the available gauge record. Measured data for most catchments is typically available for periods significantly less than 100 years and is ideally suitable for the estimation of low to moderate floods. The estimation of higher design discharges therefore requires a degree of extrapolation that usually involves curve-fitting to the available data. The GEV (type I) / EV1 distribution is widely used to fit the measured annual maximum data to estimate the flood risk in many countries (Cunnane, 1989). The Flood Studies Report (NERC, 1975) and more recently, the Irish Flood Studies Update (FSU) (Reed and Martin, 2005) also recommend GEV (type I) distributions for flood frequency analysis in Ireland. However, floodplain effects, catchment characteristics and terrain together with and climate change can have considerable implications in flood frequency analyses. As a flood moves down the river it is subject to a series of influences that can alter the peak magnitude and travel time of a flood hydrograph. The actual behaviour is variable and is heavily influenced by the geometrical and resistance characteristics of the floodplain as well as the properties of the flood hydrograph. Floodplain effects can influence river flows in two ways. Firstly, floodplains can act as weak forms of storage reservoir, providing an area of extra water storage during flows just greater than bankfull level. Secondly, the increase in hydraulic resistance from the turbulent momentum exchange that occurs along the main channel and floodplain interface can also be significant. This initial storage and subsequent release of a portion of the total flood volume produces flood hydrographs that tend to be low and broad compared with those produced in similar watersheds where floodplain storage is not significant. These impacts are likely to be most pronounced for low volume, moderate-frequency (4 to 50-year recurrence interval) over bank floods (Diehl, 1990).

Flood flows in river channels in Ireland are commonly influenced by the effects of floodplain storage. This influence tends to be greater than that experienced in UK catchments and may, in part, explain why many growth curves in Ireland are mildly graded. The mild topographic gradient in much of Ireland promotes floodplain attenuation effects. When two hydrometric gauging stations are separated by a wide shallow floodplain without substantial intervening tributary inflows, the downstream flood frequency curve tends to be flatter than that observed upstream. Therefore, shape parameters of the assumed flood frequency distributions are likely to be different between upstream and downstream stations where frequent and extensive floodplain inundation occurs (Wolff and Burges, 1994;

McCartney and Naden, 1995). These shifts in distribution are reported in literature. Archer (1989) studied sites separated by floodplains on the River Tees in Darlington, UK, and by compensating for tributary inflows between these gauging stations (which were small in comparison to the flow entering the top of the reach) observed flood frequency shifts from GEV Type II to Type III distributions. A specific flood frequency distribution is valid only at a specified site. In general, distributions for multiple sites within a geographically homogeneous area can be assumed to have the same distribution and are pooled on this basis. However, the physical processes and hydraulic characteristics of floodplain flows can significantly influence flood frequency distributions (Haider, 1992; Wolff and Burges, 1994). Consequently, for catchments with active floodplains, assuming the same flood frequency distribution is likely to be erroneous. While this is the case, it is often inconvenient and impractical to separate sites influenced by floodplain storage from those that are not in situations where growth curves are based on pooled data in defined geographical regions,. This can potentially result in contaminated flood frequency relationships determined for these pooled sites.

Climatic and catchment specific influences play an important role in flood generation in Ireland. Ireland experiences marked difference in climate across the country where the west and north-west of the country experiences significantly more rainfall than areas on the eastern seaboard (Reed and Martin, 2005). The nature of the terrain in Irish catchments is also important. Large areas of the country are underlain with karst. The hydrology and geomorphology in these terrains is intimately and genetically linked to greater level than with other rock types (Drew, 1990). The surface-subsurface interaction in karstic environments tends to be less significant in upland plateau karsts where surface water is a rarity, but is of great importance in lowland karst regions where rivers and lakes may co-exist with a subterranean drainage system. The main characteristic of karst aquifers is the existence of irregular networks of pores, fissures, fractures and conduits of various size and forms. Such structure, with its significant physical and geometrical heterogeneity, causes complex hydraulic conditions and contributes to spatial and temporal variability of hydraulic parameters (Denic-Jukic and Jukic, 2002). Karst and river interactions can modify flood waves significantly but because of the complexity, cannot be readily represented analytically (Bailly-Comte, 2008).

Although the use of Generalised Extreme Value (GEV) Type I distributions are recommended for flood frequency analysis throughout Ireland, karstic and floodplain attenuation effects have the capacity to produce shifts in these distributions. This study systematically explores whether catchment influences produce shifts in GEV flood frequency distributions. A total of 139 gauging stations in 100 Irish rivers were analysed. Where they occur, the paper attempts to identify the underlying reasons for these changes in flood frequency distribution.

2. METHODOLOGY

GEV Type 1 distributions are defined in terms of only two parameters (scale (α) and location (u)) and such distributions do not provide the flexibility to accommodate the variations in distribution that can arise from karst and floodplain influences. These influences may be better represented in a three-parameter GEV distribution. Application of the EV1 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, 1955 and 1969).

This paper explores primarily the hydraulic and hydro-geological influences in flood frequency distributions in Irish river catchments. The study presents the findings of a systematic investigation of annual maximum (AM) data series from 139 gauging stations of 100 rivers (with records in excess of 25 years) in Ireland in which the GEV statistical distributions that best fit the hydrological data are identified. Appropriate distributions were identified by an application of the Hosking *et al* (1985) algorithm.

The cumulative distribution function (CDF) of a GEV distribution can be written:

$$F(x) = \exp\left\{-\left[1-\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}}\right\} \qquad (1a)$$

$$F(x) = \exp\left\{-\exp\left[-\frac{1}{\alpha}(x-u)\right]\right\} \quad k = 0 \qquad (2a)$$

where α is a scale parameter, *u* is a dimensionless location parameter, and *k* is the shape parameter. The inverse of Eqn. 1a and Eqn. 2a are given in Eqn. 1b and Eqn. 2b.

$$X_T = u + \frac{\alpha}{k}\left(1 - \left(-\ln\left(1 - \frac{1}{T}\right)\right)^k\right) \quad (1b) \qquad X_T = u - \alpha \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right) \quad (2b)$$

where X_T is the flood quantile for a given return period, *T*. The shape parameter determines which of the three extreme value distributions in the GEV family of distributions is appropriate. 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 specified; and with $k > 0$, the Weibull or GEV Type III (EV3) distribution is appropriate.

The equations involved in GEV parameter estimation are not immediately soluble but Hosking *et al* (1985) provide a simple algorithm that involves determining the shape parameter from a limited sample, $\hat{k}$, (sample size greater than 25) using:

$$\hat{k} = 7.8590c + 2.9554c^2 \quad (3)$$

where:

$$c = \frac{2M_{110} - M_{100}}{3M_{120} - M_{100}} - \frac{\log 2}{\log 3} \quad (4)$$

in which M_{100}, M_{110} and M_{120} are probability weighted moments (PWMs).

Hosking *et al* (1985) also provide a simple test based on PWMs for testing whether the shape parameter, $\hat{k}$, is zero in the GEV distribution. This test enables the user to examine the EV1 hypothesis with other GEV distributions as alternatives. On the null hypothesis H_0: $\hat{k} = 0$, the PWMs estimate of $\hat{k}$ is taken to be asymptotically distributed as:

$$N[0, 0.5635/n] \quad (5)$$

where *n* is the record length of the annual maximum data at each gauging station. The test consists of comparing the standardised normal variate, Z, given by:

$$Z = \hat{k}(n/0.5635)^{1/2} \quad (6)$$

with the critical values of the standardized Normal distribution. Significant positive values of Z imply rejection of H_0 in favour of the alternative $\hat{k} > 0$, and significant negative values of Z imply rejection in favor of $\hat{k} < 0$. Hosking *et al* (1985) noted that for sufficient discriminating power, the test sample size (*n*) should be greater than 25.

Given $\hat{k}$ ($\neq 0$) the scale ($\hat{\alpha}$) and location ($\hat{u}$) parameters can be estimated from Eqn. 7 and Eqn. 8:

$$\hat{\alpha} = \frac{(2M_{110} - M_{100})\hat{k}}{\Gamma\left(1 + \hat{k}\right)\left(1 - 2^{-\hat{k}}\right)} \quad (7) \qquad \hat{u} = M_{100} + \hat{\alpha}\left\{\Gamma\left(1 + \hat{k}\right) - 1\right\} \Big/ \hat{k} \quad (8)$$

Given $\hat{k}$ $(=0)$,the GEV distribution reduces to a Type I (EV1) distribution and the scale and location parameters of the distribution can be estimated from Eqn. 9 and Eqn. 10:.

$$\hat{\alpha} = \frac{(2M_{110} - M_{100})}{\ln 2} \qquad (9) \qquad\qquad \hat{u} = M_{100} - \varepsilon.\hat{\alpha} \qquad (10)$$

Following GEV identification, the flood quantile (Q_{100}) for the 100-year recurrence interval was determined for the 139 stations analysed assuming both an EV1 and a GEV distribution. Comparison of these estimates enables the potential errors produced from an incorrect assumption of EV1 distributions to be determined.

3. RESULTS

The Hosking *et al* (1985) algorithm was applied to AM data from 139 Irish gauging stations, each with record lengths that exceed 25 years. Numbers of GEV Type I, II and III distributions are shown in Figure 1.

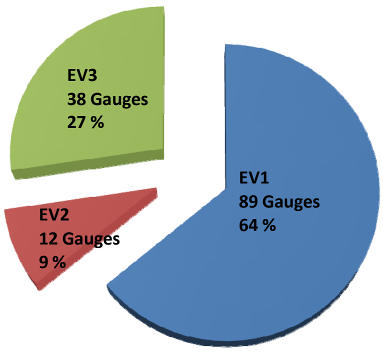

Figure 1 GEV distributions of gauging station

Results indicated that 64% of data sets from these stations AM data follow a Type I distribution and 9% and 27 % follow Type II and Type III distributions respectively. The assumption therefore of a 'universally' applied EV1 distribution is incorrect and can produce errors in estimates of specified flood quantiles. When data at a particular gauge follows an EV2 distribution, the assumption of a Type I distribution will result in underestimated flood quantiles. Correspondingly, when Type III distributions are appropriate, overestimates will occur.

More notably, Seven Irish rivers (Rivers Boyne, Clare, Deel, Maigue, Nore, Suck and Suir) show shifts in GEV distribution with increases in downstream distance (Table 1).

The variation of flood frequency distribution and the shift from Type I to Type III distributions (and vice versa) for these rivers with the exception of the River Clare, are likely to be promoted by extensive floodplain storage. These rivers are characterised by floodplains that extend laterally a significant distance from the main channel and are known to become inundated at frequent intervals. Increasing storage on the floodplain and associated delays due to frictional resistance will contribute to the suppression of the flood growth at the downstream station.

To further assess these influences, data was incorporated into an ArcGIS platform and combined with layers that show Flood Attenuation Indicators (FAIs) and the geographic distribution of karst features in Ireland (Figures 2 and 3). FAIs represent flood polygons of the lateral extent of flooding at a depth of 1m above surrounding bankfull river levels and give an indication of the and extent of floodplain inundation. These polygons were developed as part of the Irish FSU programme.

Table 1 Classified distributions based on the Hosking *et al.* (1985) statistical test and Q_{100} estimates

STN.	RIVER	n	M_{100}	M_{110}	M_{120}	c	$\hat{k}$	Z	Distr	EV1				GEV				% Error
										$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	$\hat{\alpha}$	$\hat{u}$	X_{100}	$Se(X_{100})$	X_{100}
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

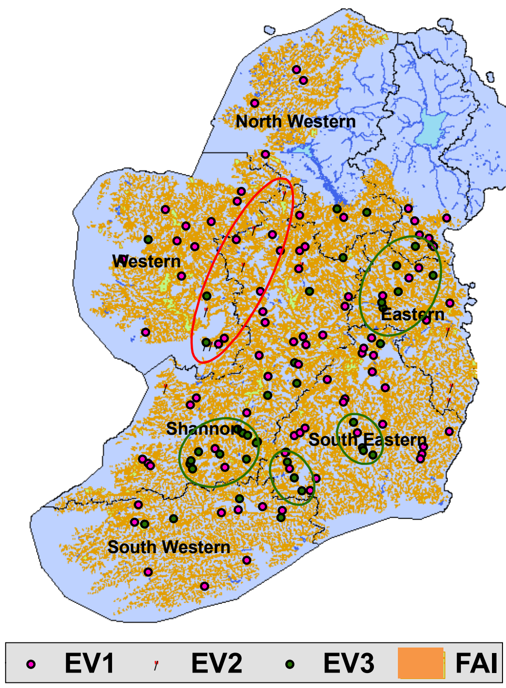

Figure 2 Identified GEV distributions with Flood Attenuation Indicator (FAI)

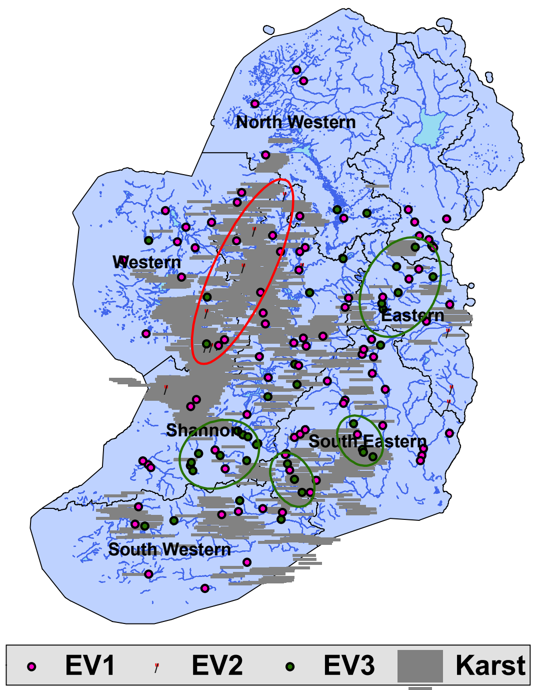

Figure 3 Identified GEV distributions with karst features

Figure 2 indicates that four clusters of GEV (type III) distributions were observed in the Shannon, Eastern and South Eastern river basins where floodplain and lake storage is likely to be significant. Although not clear at the scale shown, higher resolution inspection of Figure 2 indicates that the density of FAIs in these regions is significantly higher than in, for example, Type II regions. This provides some support to the assertion that floodplain storage is a strong influence on the increased frequency of Type III distributions in these regions. The findings, based on this assertion, are consistent with those from previous studies where similar shifts in distribution from floodplain influences were observed (see for example Mason *et al*, 1988; Archer, 1989; Wolf and Burges, 1994; McCartney and Naden, 1995)

The single cluster of GEV Type II distributions appeared in the Western river basin which is underlain by pure carboniferous limestone with relatively thin quaternary deposits which overlie the bedrock (Figure 3). In many areas, large areas of rock outcrops remain exposed. The Western river basin receives comparatively high rainfall totals than in other parts of the country and high volume hydrographs in rivers in this region are common. For karst floods the volume of the hydrograph is much more important than in cases of non-karst floods. For low and moderate volume floods, a significant proportion of river flow penetrates into the karst where it fills voids, fractures and other karst features. As a result, the remaining overland flow tends to be low. In the context of large volume floods, the capacity of these voids is not significant and rapid rises in groundwater levels can occur. In these situations, the system of karst conduits becomes pressurised, activating further flow paths and producing springs that can contribute significantly to surface 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 clustering of Type II distributions observed in the north-south direction in Figure 3.

Figure 2 also indicates that several other Irish catchments (as reflected in Type III distributions) exhibit characteristics that suggest floodplain storage has suppressed flood growth and produced beaks in slope of the flood frequency curve around the bankfull stage. It should also be noted that, as reported by Archer (1989), the real effects of floodplain storage on flood frequency distributions may be obscured in less ideal reaches where there is a larger lateral inflow contributions.

Figure 4 shows the 100-year flood quantiles estimated from both the EV1 and GEV distributions for the 139 gauging stations analysed in this study.

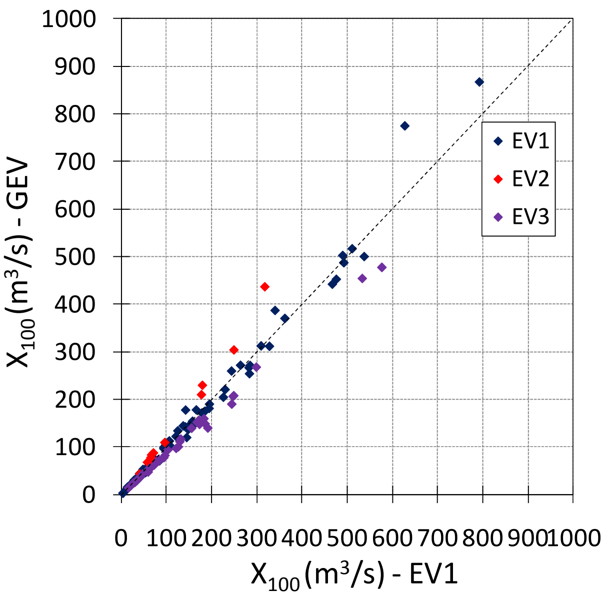

Figure 4 Estimated X_{100} from EV1 and GEV distributions for the stations analysed

Figure 4 shows that there is a reasonable agreement between estimated X_{100} flow magnitudes from both EV1 and GEV distributions for most of the gauging stations. However, some notable exceptions exist. In the most extreme cases, assuming an EV1 distribution when a sample comes from a Type II distribution can produce underestimates in Q_{100} of approximately 35%. Similarly, assuming an EV1 distribution at a station where a sample comes from a Type III distribution can produce overestimates of the 100-year flood quantile that are in the order of 25%.

4. CONCLUSIONS

Data from 139 gauging stations from 100 Irish rivers was analysed using the Hosking *et al* (1985) algorithm to determine whether Type I, II or III distributions are valid. The majority (64%) of Irish gauging station flow records follow EV1 distribution and these are evenly distributed throughout the country. A cluster of GEV (type 2) distributions appeared straddles the Shannon and Western river basins in an area that is characterised by karst terrain. Four clusters of GEV (Type III) distributions were observed in the Shannon, Eastern and South-Eastern river basins where floodplain and lake storage are likely to be of influence. At gauging stations downstream of major floodplains or lakes, or in areas where karst features are hydrologically influential, the fitting of the recommended (Type 1 distributions for Ireland) statistical distributions to the flow records can lead to serious errors in predicted flood quantiles at high return periods. This study shown that for Irish catchments, incorrectly assuming that a Type I distribution is valid when in fact the sample comes from Type II or Type III distributions can result in underestimates and overestimates of the 100-year flood quantile of around 35% and 25% respectively. Results also have potentially significant implications in regional flood frequency estimation approaches where a single regional parent frequency distribution is scaled to give at-site distributions.

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