FLOOD FREQUENCY ANALYSIS OF IRISH RIVER FLOW DATA USING VARIANTS OF *L*-MOMENTS

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ABSTRACT:

The estimation of peak flow of a design return period is a standard requirement in many civil engineering projects such as design of bridge openings and culverts, drainage networks, flood relief/protection schemes and the determination of flood risk and 'finish-floor level' for both commercial and large-scale residential developments. A brief review of the methods traditionally and currently used in Ireland for estimating such peak flows is presented. This paper is focused mainly on the 'at-site method' of flood frequency analysis, involving the method of *L*-moments and the Generalized Extreme Value (GEV) distribution. Three variants of *L*-moments, namely, the simple *L*-moments, the higher *L*-moments (or *LH*-moments) and the partial *L*-moments (*PL*-moments), are applied for fitting the GEV distribution to the annual maximum series of a number of Irish rivers, and the results thus obtained are compared. Finally, a case is advanced for adopting the method of *LH*-moments and partial *L*-moments for flood frequency analysis of Irish flood data and for its inclusion in the 'Flood Studies Update Programme' about to be launched by the Irish Office of Public Works (OPW).

Key words: flood frequency analysis, *L*-moments, *LH*-moments, *PL*-moments, Irish river flow data

1. INTRODUCTION

The estimation of peak flow of a design return period is a necessary task in many civil engineering projects such as those involving design of bridge openings and culverts, drainage networks, flood relief/protection schemes, the assessment of flood risk and the determination of the 'finish-floor level' for both commercial and large-scale residential developments. The most commonly used procedure for estimating such a design flood in Ireland today is to follow the methods set out in the Flood Studies Report (FSR) (NERC, 1975), either analyzing the available flood record at a site or, in the case of ungauged catchments, using the catchment characteristics. In some instances, the FSR method for an ungauged catchment is utilized for estimating peak floods, without taking cognizance of the fact that a well-defined annual maximum series might be available either for a site further upstream/downstream on the same river/catchment or at a site in an adjacent catchment. According to the FSR, the mean annual flood estimated using the catchment's characteristics is hardly better than that based on a flood data series of just one year. Thus, the U.K. Flood Estimation Handbook (IoH, 1999) suggests that, while flood data at the subject site are of greatest value for estimating the peak flood, data transfers from a nearby site, or a similar catchment, are also very useful.

The main focus of this paper is on the at-site (subject site) method of flood frequency analysis involving the Generalized Extreme Value (GEV) distribution and the method of *L*-moments. Different variants of *L*-moments, namely the simple *L*-moments, the higher *L*-moments (or *LH*-moments) and the partial *L*-moments (*PL*-moments) are applied for fitting the GEV distribution to a number of Irish flood data series. Comparisons of the resulting averages of the 100-year return period floods are carried out on a catchment basis as well as on a hydrometric area basis.

2. BRIEF REVIEW OF FLOOD ESTIMATION METHODS IN IRELAND

A variety of empirical equations for various catchment regions (e.g. Benson, 1962; and Nash & Shaw, 1996) was in vogue in the U.K. prior to the publication of the FSR in 1975. The Irish Office of Public Works, prior to the introduction of the FSR equations, occasionally used empirical formulae, such as those given in the paper by Lynn (1971). Historically, the world-renowned Irish Hydraulic Engineer, Mulvany (1845), introduced the famous 'Rational Formula' for calculating the peak flood, which relates the peak flood to the catchment's 'time of concentration'.

Following the publication of the FSR (NERC, 1975), the traditional 'rational method' and its variations were almost entirely replaced by the FSR method of flood estimation.

The FSR is based on extensive research and analysis of what were then (in the early 1970s) the available hydrometric and rainfall records in Britain and Ireland. Some 5500 record years from 430 British gauging stations and 1700 record years from 112 Irish sites were used in the flood frequency studies and the FSR dealt with an investigation carried out during the period 1970 - 1975 at the Institute of Hydrology, Wallingford, and the Meteorological Office, Bracknell, in the U.K. The Irish Office of Public Works and the Meteorological Service participated actively in these studies and supplied data on floods and rainfall in Ireland for inclusion in the analyses. The results are accordingly applicable in the Irish context and provide much-improved bases for flood estimation (Cunnane & Lynn, 1975).

According to the FSR method, the peak flood at a required location on a river can be estimated either from a statistical flood estimation method or by a rainfall-runoff method. In the case of the statistical flood estimation method, if the flood data are available at the subject site, then the peak flood (Q_T) for that site is estimated by using the Annual maximum Series (AMS) with the EV1 or GEV distribution. According to the FSR, satisfactory "at-site" estimates can be achieved for up to $T = 2 \times N$ years return period flood (N being the length of AMS in years), from an AMS set of length of N years. Where very short records are available, or where the required $T >> 2 \times N$, then it is recommended that a regional flood frequency analysis be carried out, using the index flood approach.

In the case where no flood data are available (i.e. for an ungauged catchment), the mean annual flow (popularly know as Q_{bar}) for that catchment is first estimated using certain catchment descriptors either in the 6-variable equation (page 341 of Vol. 1 of FSR (NERC, 1975)), or in the 3-variable equations (page 6.2 of FSSR No. 6 (NERC, 1978) and page 37 of IOH (1994) Report No. 124). The calculated Q_{bar} is then multiplied by an appropriate regional flood frequency growth factor (page 173-174, Vol. 1 of FSR) to yield a required return period flood estimate.

In the UK Flood Estimation Handbook (FEH) (IoH, 1999), four significant changes occur in the flood estimation procedure: (i) the median annual flood is used as the index flood instead of the mean annual flood; (ii) the region (now renamed as the pooling group) used is no longer a geographical one but one which pools data from catchments similar in area, rainfall and soil type; (iii) the required pooling group size varies with the return period; and (iv) the regional growth curve is obtained by L-moment fitting of the Generalised Logistic Distribution (Cunnane, 2000). As no Irish flood data was used in the FEH, the revised flood estimation method suggested by FEH is generally not used In Ireland. In this regard, the present author fully agrees with the lists of reasons put forward by Cunnane (2000) which make it imperative to prepare a revised Flood Study Report, similar to the UK – FEH but specifically for Republic of Ireland, and indeed understands that a 'Flood Studies Update Programme' is currently in the process of being initiated by the OPW.

3 *L*-MOMENTS AND ITS VARIANTS IN FLOOD FREQUENCY ANALYSIS

3.1 Flood Frequency Analysis Revisited

At any river site, it is usually assumed that nature provides a unique Q_T–T (Peak Discharge - Return Period) relationship and that Q_T is a monotonically increasing function of T. The main objective of flood frequency analysis of hydrological data is to determine such a Q_T-T relationship at any required site on a river so as to obtain a useful estimate of the quantile Q_T of the extreme event for a selected return period (T) (i.e. average time between occurrences), having scientific or practical relevance: this may be the design life of a structure or some legally mandated design period (Cunnane, 1996).

There are two broad categories of research in flood frequency analysis, namely, 'regionalization' and 'at-site'. Regionalization research investigates the relationship between flood frequency curves of catchments at different locations whereas at-site research investigates the relationship between peak flood discharge and its frequency of occurrence for a single catchment.

Before carrying out flood frequency analysis of a given flood data series, the hydrologist has to decide on the following three options:

I. Selection of a suitable flood frequency model (e.g. annual maxim series model, partial duration series or peak over threshold model, or time series model)

II. Selection of a suitable statistical distribution (e.g. Generalized Extreme Value Distribution, Exponential Distribution, General Logistic Distribution)

III. Selection of a parameter estimation method to fit the selected distribution to the given flood data, (e.g. the method of ordinary moments, probability weighted moments, *L*-moments etc.)

Flood frequency models

For the annual maximum series (AMS) model, the hydrograph for each year is represented solely by the value of its largest flood and the series thus formed is called the Annual Maximum Series (AMS). The series Q_1, Q_2, … Q_n, where Q_i is the maximum flow occurring in the i^{th} year, is assumed to be a random sample from some underlying population. In contrast, in the Peaks over a Threshold (POT) model, the continuous hydrograph of flows is replaced by a series of randomly spaced peak flow values (over a selected threshold value) on the time axis. The POT model is perceived as providing a more accurate estimate of the Q_T–T relationship when only short records of discharge are available (NERC, 1975). In this study, the AMS model is used.

Statistical distributions

The statistical analysis does not give the Q_T-T relation directly but rather the relation between Q_T and probability of occurrence expressed by a distribution function $F(x) = PR(Q \leq x)$ for the series. Its complement, 1-F(x), is called the exceedance probability. The return period T is the reciprocal of the exceedence of probability, i.e., $T = 1/(1-F(x))$ (Cunnane and Lynn, 1975). It was found during the preparation of the FSR that the General Extreme Value (GEV) distribution is best suited to Irish flood data, and hence the GEV distribution is used in this study.

Methods for parameter estimation

In flood frequency studies, various methods are used to fit the selected statistical distribution to the given flood series. The most commonly used methods include ordinary moments, probability weighted-moments, maximum likelihood estimators, *L*-moments, etc. In almost all moment methods, the sample moments are first calculated which are substituted in the given relationship between the parameters of the selected distribution and the moments.

This paper focuses mainly on the use of the method *L*-moments and their variants, namely, simple *L*-moments, the higher order *L*-moments (or *LH*-moments) and the partial *L*-moments (or *PL*-moments), in the analysis of Irish river flow data.

3.2 *L*-moments and their variants

Hosking (1990) defined *L*-moments as the expected value of the linear combination of the element of an ordered sample multiplied by some scalar constant which contains information about the location, scale and shape of the distributions from which the sample was drawn. The '*L*' in *L*-moments is to emphasise the construction of *L*-moments from the linear combination of order statistics. The first, second, third and fourth *L*-moments of order statistics are denoted by the symbols λ_1, λ_2, λ_3, and λ_4. The ratio of second *L*-moment to first *L*-moment, i.e., $\tau = \lambda_2 / \lambda_1$, is analogous to the ordinary coefficient of variation C_v and called *L*-C_v, which is defined as the coefficient of *L*-variation. Similarly, the quantity $\tau_3 = \lambda_3 / \lambda_1$ is called *L*-skewness and $\tau_4 = \lambda_4 / \lambda_1$ is called *L*-kurtosis which are analogous to ordinary skewness and kurtosis respectively.

Hosking (1990) showed that, compared with conventional moments, *L*-moments are less subject to bias in estimation, and yield more accurate estimates of the parameters of a fitted distribution, and that parameter estimates obtained from *L*-moments tend to be more accurate in small samples than are the maximum-likelihood estimates. Hence, *L*-moments have the advantage of providing parameter estimates that are nearly unbiased, highly efficient and less influenced by outliers (extreme observations) than ordinary statistical moments, where the data are squared, cubed, etc. (Stedinger et al., 1993). For these reasons, the method of *L*-moments has found widespread application in both regional and at-site flood frequency analyses.

Wang (1996) derived expressions for direct sample estimation of *L*-moments. Previously, sample *L*-moments had been calculated not directly from the sample, but from the probability weighted moments. Using Wang's (1996) method of direct sample estimation of *L*-moments, Bhattarai (1997) showed that the method of *L*-moments is superior to both the method of conventional (ordinary) moments and the method of (biased) probability weighted moments for estimating the parameters of the GEV distributions.

With the objective of reducing the undesirable influence that small sample events may have on the estimation of large return period events, Wang (1997) introduced the method of *LH*-moments (i.e. higher-order *L*-moments). The letter 'H' in *LH*-moments is to denote higher order *L*-moments, e.g., *L1*-moment denoting 1st higher order, *L2*-moments denoting 2nd higher order, *L3*-moments denoting 3rd higher order and *L4*-moments denoting 4th higher order *LH*-moments. The zero order *LH*-moments or *L0*-moments are equivalent to simple *L*-moments.

Partial *L*-moments (or *PL*-moments) are a modified version of *L*-moments, which are used to analyse censored flood samples. Bhattarai (2004) showed that, both *PL*-moment and *LH*-moments have similar sampling properties, and both are useful for estimating the quantiles for higher return periods.

To estimate the parameters of the GEV distribution in the present study, the relations given by Hosking (1990) for the case of simple *L*-moments, by Wang (1997) for the case of *LH*-moments, and those given by Bhattarai (2004) for the case of *PL*-moments were used.

4. DATA USED AND ANALYSIS METHODOLOGY

All 98 annual maximum series (AMS) available in the official website of Office of Public Works (http://www.opw.ie/hydro/home.asp) that are longer than 20 years were used in the study. These AMSs are for river catchments located in 26 hydrometric areas in Ireland (see Table 2). The size of catchment varies from 23 km^2 (the Yellow River in hydrometric area 36) to 7989 km^2 (River Shannon in hydrometric area 25). The size of AMS series used varies from 21 years to 61 years.

Flood frequency analyses were carried out using the GEV distribution and the methods of simple *L*-moments, *LH*-moments (*L1*-moments, *L2*-moments, *L3*-moments and *L*-moments) and *PL*-moments with censoring of the flood data at the 10%, 20% and 30% levels, from below. The eight flood frequency curves (plots of Q_T - T relations) thus obtained using simple *L*-, *LH*- and *PL*-moments were plotted for each of the AMSs, and only the best-fit Q_T - T relations, on the basis of visual comparison, were considered for further comparison purposes.

5. DISCUSSION ON RESULTS

From the comparison of the eight frequency curves (Q_T - T relations) obtained from the method of simple *L*-, *LH*- and *PL*-moments for the 98 AMSs, it was found that the method of simple *L*-moments produced the best-fit frequency curves in the case of 49 AMSs. This means there was no improvement in flood peak estimation by *LH/PL* moments for the case of 50% of the AMSs. For the remaining 49 catchments, various degrees of improvement in the frequency curves (based on visual comparison) were obtained by *LH*-moments in the case of 38 of the AMSs (39% of the total group of AMSs) and by *PL* moments in the case of 11 AMSs (11% of the total). The results also showed that the use of *LH/PL*-moments reasonably improved the flood estimates in almost 25% of total number of AMSs.

It was generally observed in the fitted frequency curves that, for the annual maximum series showing only one segment on the probability plots, all three variants of *L*-moments produced virtually the same curve, indicating that, in such cases, the application of simple *L*-moments seems to be quite adequate. However, for those annual maximum series showing two or more segments on a probability plot (see Fig. 1(a) and (c)), both the methods of *PL*- and *LH*-moments produced a better fit to the larger flow values than that of the simple *L*-moments. The method of *PL*-moments was unstable (i.e. produced a very unrealistic fit) for some short AMSs, indicating that, for shorter flood samples, the method of *PL*-moments might be unstable in some cases. A similar instability problem was encountered by Wang (personal communication, 18th December 2002) in the case of partial probability weighted moments. However, the method of *LH*-moments did not exhibit such behaviour.

The 100-year return period flood for each AMS, obtained from the best-fit frequency curve, was divided by the catchment areas of the corresponding gauging station from which the AMS was taken, to obtain the specific Q_{100} flood (i.e. the Q_{100} flood per square kilometre). Such specific Q_{100} floods were grouped catchment-wise (Table 1) and also hydrometric area-wise (Table 2), and the average specific Q_{100} was calculated for each case. It was observed that the specific Q_{100} for some of the stations were exceptionally high or low, in comparison to the other stations of the same catchment or hydrometric area, and hence these were not incorporated for group averaging.

It is also observed from Table 1 that, out of the 98 AMSs considered in the present study, 91 of them produced specific Q_{100} values smaller than 1.0 m^3/s/km^2. Two rivers, namely the Yellow River (hydrometric area 36) and the Nire River (hydrometric area 16) produced exceptionally high specific Q_{100} values, which were larger than 2.0 m^3/s/km^2. Five rivers, namely, the River Ownea (hydrometric area 38), the River Swilly (hydrometric area 39), the River Inagh (hydrometric area 28), the River Galey (hydrometric area 23) and the River Maine (hydrometric area 22) produced specific Q_{100} values larger than 1.0 m^3/s/km^2 but smaller than 2.0 m^3/s/km^2.

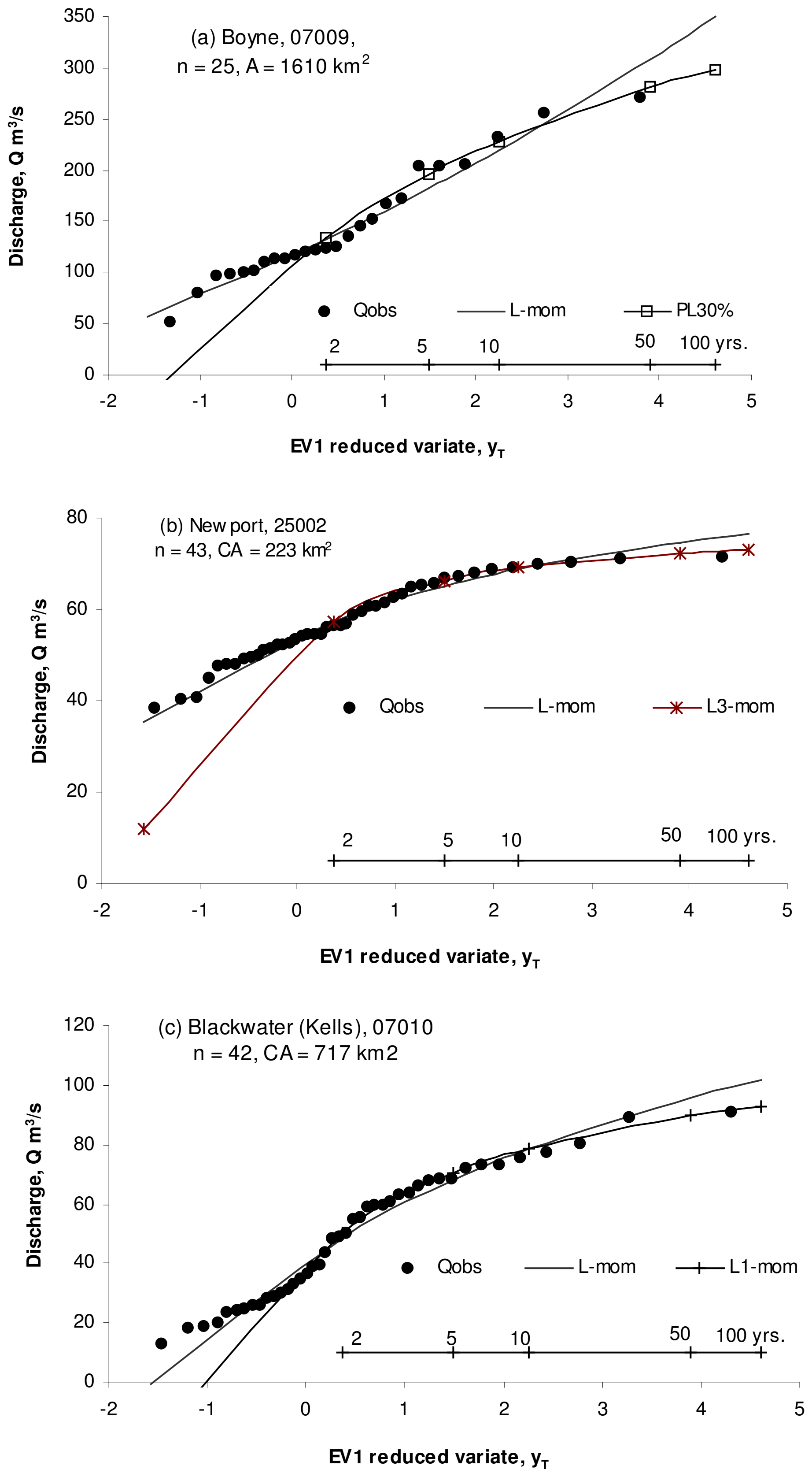

Figure 1. Fit of the GEV distribution using the methods of variants of *L*-moments to the AMS of (a) River Boyne (b) River Newport and (c) River Blackwater (Kells)

Table 1. Catchment-wise average specific Q_{100} (in $m^3/s/km^2$)

Catchment	No. of AMS	Hydrometric Area / Gauging Station No.	Avg. Q_{100}/A	Avg Q_{100}/Q_{bar}
Erne	3	36	0.0889	1.509
Little Brosna	2	25	0.1225	1.453
Dee	2	6	0.1409	1.453
Brosna	5	25	0.1422	1.774
Boyne	5	7	0.1470	1.879
Glyde	3	6	0.1475	1.740
Barrow	8	14	0.1711	1.825
Dunkellin	2	29	0.1747	1.869
Owenmore	2	35	0.1944	1.776
Suck	4	26	0.2100	1.910
Moy	3	34	0.2385	1.566
Corrib	3	30	0.2525	1.899
Suir	8	16	0.2612	1.583
Blackwater (Munster)	5	18	0.2737	1.623
Mulkear	5	25	0.2943	1.298
Nore	5	15	0.2952	1.716
Maigue	3	24	0.3506	1.819
Deel	2	24	0.3726	1.432
Bandon	1	20001	0.6502	1.849
Owenboy	1	19001	0.5024	1.426
Camlin	1	26019	0.1545	1.809
Inny	1	26021	0.1272	1.328
Fallan	1	26022	0.1928	1.755
Killimore	1	25020	0.3902	1.724
Clarin Bridge	1	29004	0.1197	1.550
Rinn	1	26008	0.1452	1.828
Black	1	26009	0.2036	1.465
Boyle	1	26012	0.1276	1.783
Owenure	1	26018	0.1247	1.611
Slaney	1	12001	0.3772	2.312
Owenavorragh	1	11001	0.8462	2.534
Flesk (Laune)	1	22006	0.8812	1.718
Shannon	1	25017	0.0742	1.446
Fergus	1	27002	0.1095	1.794
Fane	1	06012	0.1748	1.895
Nenagh	1	25029	0.2572	1.432
Nanny	1	08011	0.2592	1.465
Ryewater	1	09001	0.3888	2.247
Leannan	1	39008	0.6165	1.680
Owenea	1	38001	1.0279	1.567
Swilly	1	39001	1.3061	1.425
Inagh	1	28001	1.1310	3.351
Galey	1	23001	1.2528	2.192
Maine	1	2203	1.5926	2.802
Yellow	1	36021	2.0130	1.837
Nire	1	16013	2.3896	2.214

It is also observed from Table 1 that, the Erne catchment (hydrometric area 36) produced the lowest specific Q_{100} (100-year flood per unit catchment area), which is equal to 0.0889 m^3/s. The second lowest specific Q_{100} value of 0.1225 $m^3/s/km^2$ was produced by the Little Brosna catchment (hydrometric area 25). On a catchment basis (consisting of two or more AMSs), the highest average specific Q_{100} value was produced by the Deel catchment (hydrometric area 24), the value of which is 0.3726 $m^3/s/km^2$.

The ratio of the 100-year flood to the mean annual flood (i.e., Q_{100}/Q_{bar}), computed for each AMS, are also shown in Table 1. This value (Q_{100}/Q_{bar}) varies from 1.18 to 3.35, the average value being 1.73, with a standard variation of 0.366. From the regional analysis of 56 reliable OPW stations, Cawley & Cunnane (2003) found the value of Q_{100}/Q_{bar} for Ireland as 1.84. According to the Flood Study Report (FSR), the typical regional value for Irish rivers is 1.96. Therefore, the average value of Q_{100}/Q_{bar} of 1.73, obtained from this study using 'at-site' analysis is quite comparable to that of Cawley & Cunnane (2003) based on regional analysis.

Table 2. Hydrometric area-wise average of the specific Q_{100}

Hydrometric area	Number of AMS	Q_{100}/A $m^3/s/km^2$	Rivers/catchments in the hydrometric area
36	3	0.089	Erne
27	1	0.109	Fergus
7	5	0.1470	Boyne
6	6	0.150	Dee, Glyde, Fane
29	2	0.156	Dunkellin, Lavally
14	8	0.171	Barrow
26	11	0.174	Suck, Camlin, Inny, Fallan, Rinn, Black, Boyle, Owenur
35	2	0.194	Owenmore
25	14	0.220	Little Brosna, Brosna, Mulkear, Killeen, Nenagh
34	3	0.238	Moy
30	3	0.2525	Corrib
8	1	0.259	Nanny
16	8	0.2612	Suir
18	5	0.274	Blackwater (Munster)
15	5	0.295	Nore
24	5	0.359	Maigue, Deel
12	1	0.377	Slaney
9	1	0.389	Liffey
19	1	0.502	Lee (Owenboy)
20	1	0.650	Bandon
11	1	0.846	Owenavorragh
39	2	0.9613	Swilly, Leannan
38	1	1.028	Owenea
28	1	1.131	Inagh
22	2	1.237	Maine, Laune
23	1	1.253	Galey
Exceptionally hig or low values			
16	1	2.390	Nire (stn. 16013)
25	1	0.074	Shannon (stn. 25017)
36	1	2.013	Yello (stn. 36021)

On a hydrometric area basis, it is observed from Table 2 that, the catchments in hydrometric area 23 produced the highest specific Q_{100}, the value of which is 1.253 $m^3/s/km^2$, whereas those in hydrometric area 36 produced the lowest specific Q_{100} value of 0.089 $m^3/s/km^2$. The catchments in hydrometric areas 6, 7, 14, 26, 27, 29 and 35 produced specific Q_{100} between 0.1 to 0.2 $m^3/s/km^2$ and those in hydrometric areas 8, 15, 16, 18, 25, 30 and 34 produced specific Q_{100} between 0.2 to 0.3 $m^3/s/km^2$. Similarly, the catchments in hydrometric areas 9, 12 and 24 produced specific Q_{100} between 0.3 to 0.4

$m^3/s/km^2$ and those in hydrometric areas 11, 19, 20 and 39 produced specific Q_{100} between 0.5 and 1.0 $m^3/s/km^2$. Catchments in four hydrometric areas, namely, 22, 23, 28 and 38 produced the specific Q_{100} value of higher than 1.0 $m^3/s/km^2$.

The exceptions to the above average values were the River Shannon (hydrometric area 25), which produced very low specific Q_{100} value. Two other individual rivers, namely the River Nire (hydrometric area 16) and the River Yellow (hydrometric area 36) produced exceptionally high specific Q_{100} values than the average value of the corresponding hydrometric areas.

6. SUMMARY AND CONCLUSIONS

At-site flood frequency analyses were carried out using 98 annual maximum series (AMS) of Irish rivers/catchments, the AMSs ranging in length from 21 years to 61 years. Out of a total of 98 AMS, the method of simple *L*-moments produce the best fit for 49 AMS, the method of *LH*-moments produced best fit in the case of 38 AMS, and the *PL*-moments produced best fit in the case of 11 AMS. The method of *LH/PH* moments reasonably improved the fitting of the frequency curve in the case of almost 25% of the total AMSs. The results of the present study show that the use of variants of *L*-moments, particularly the *LH*-moments, can significantly improve the peak flood estimates in almost 25% of cases.

The 100-year return period flood estimates for each AMS, produced by the best-fit frequency curve (Q_T - T relation), was divided by the corresponding catchment area to get specific Q_{100} floods. These specific floods were averaged on a catchment basis as well as on a hydrometric area basis, to produce average specific Q_{100} values for each catchment and for each hydrometric area.

Results of the present study showed that the catchments in hydrometric area 23 produced the highest specific Q_{100} value, whereas those in hydrometric area 36 produced the lowest specific Q_{100} value. The catchments in hydrometric areas 6, 7, 8, 14, 15, 16, 18, 25, 26, 27, 29, 30, 34 and 35 produced specific Q_{100} values between 0.1 to 0.3 $m^3/s/km^2$ and those in hydrometric areas 9, 12, 19 and 24 produced specific Q_{100} values between 0.3 to 0.6 $m^3/s/km^2$. Similarly, the catchments in hydrometric area 11, 20 and 39 produced specific Q_{100} value between 0.6 and 1.0 $m^3/s/km^2$ and those in hydrometric area 22, 23, 28 and 38 produced specific Q_{100} values higher than 1.0 $m^3/s/km^2$. The exceptions to the above groups were the River Shannon (hydrometric area 25), which produced very low specific Q_{100} value and two other individual rivers, namely the River Nire (hydrometric area 16) and the River Yellow (hydrometric area 36) produced exceptionally high specific Q_{100} values.

The average specific Q_{100} value obtained in the present study could be used as an indicative value, for checking the Q_{100} values obtained for ungauged catchments using catchment characteristics.

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REFERENCES

Benson M.A. (1962). Factors influencing the occurrence of floods in a humid region of diverse terrain. USGS Water Supply Paper, 1580-B.

Bhattarai, K. P. (1997) Use of L-moments in flood frequency analysis. MSc Thesis, National University of Ireland, Galway.Bhattarai, K.P. (2004). Partial L-moments for the analysis of censored flood samples. Journal of Hydrological Sciences, Vol. 49 (5), 855-868.

Cawley, A.M. and C. Cunnane (2003) Comment on Estimation of Greenfield Runoff Rates. In National Hydrology Seminar, Tullamore, Ireland, 2003, pp 29-43.

Cunnane, C. & M.A. Lynn (1975) Flood Estimation following the Flood Studies Report. Presented at a meeting of the Civil Division of IEI on 9th February 1975 in the Engineering School UCD.

Cunnane, C. (1996) Applied Hydrology II. Unpublished lecture note. Department of Engineering Hydrology, National University of Ireland, Galway.

Cunnane, C (2000) Flood Estimation Procedures – a review in the context of the new UK Flood Estimation Handbook. Presented to the Institution of Engineers of Ireland at 22 Clyde Road on Monday 17th April & at NUI, Galway on Wed. 19th April 2000.

Hosking, J. R. M. (1990) L-moments: analysis and estimation of distributions using linear combinations of order statistics. J. Roy. Statist. Soc. 52(2), 105–124.

Institute of Hydrology (1994), Flood estimation for small catchments. IOH Report No. 124, Wallingford, UK.

Institute of Hydrology (1999), Flood Estimation Handbook, Wallingford, UK.

Lynn M.A. (1971). Flood Estimation for Ungauged Catchments. IEI presentation and transactions, March 1971, Dublin.

Mulvany, W.T. (1845). Observations on regulating weirs. *Trans. Inst. Civ. Eng.* Ireland. Vol. I: 83-93.

Nash, J.E. and Shaw, B.L. (1966). Flood Frequency as a function of catchment characteristics. In *River Flood Hydrology* (Proc. 1965 Symp.), Inst. Civil Engineers, London, 115-136, 1966.

Natural Environmental Research Council (NERC) (1975). Flood Studies Report. Vol 1 to 5, London.

Natural Environmental Research Council (NRC) (1978). Flood Studies Supplementary Report No. 6 – Flood prediction for small catchments. London, UK.

Stedinger, J. R., Vogel R. M. & Foufoula-Georgiou, E. (1993) Frequency analysis of extreme events. Chapter 18 in Handbook of Hydrology (ed. by D. R. Maidment). McGraw-Hill, New York, USA.

Wang, Q. J. (1996) Direct sample estimators of L-moments. Water Resour. Res. 32(12), 3617–3619.

Wang, Q. J. (1997) LH-moments for statistical analysis of extreme events. Water Resour. Res. 33(12), 2841–2848.