LOW FLOWS AND LOW FLOW DISTRIBUTIONS FOR IRELAND

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ABSTRACT

A brief overview of droughts and low flows and of related international and national literature is presented. Previous findings about the most prominent low flows of the past 30 years as reported by Mac Carthaigh (1996) are summarised. Commonly used measures of low flows are outlined and some approximate relationships between these variables and catchment area are presented. A selection of findings of some past and recent academic studies on low flows relating to statistical properties of low flow series and the forms of distributions most suitable for describing at-site and regional low flow distributions are presented. These find that EV1 and lognormal distributions are generally satisfactory for annual minimum flow series but there are a small number of exceptional catchments for which a three parameter distribution may be required.

INTRODUCTION

While the upper hydrological extreme, namely flooding, is very noticeable, dramatic and relatively short lived the lower extreme, namely low flow, is a much stealthier and longer lasting phenomenon. Both play major roles in the evolution of the natural ecology of rivers as well as bringing hardship, economic loss and even death to human populations. Demuth (2005) points out the little realised fact that economic loss caused by droughts (but not exclusively due to low flows) may be larger than that caused by extreme floods. For instance he points out that the damage, in monetary terms caused by droughts in 1988 and 1989 in USA was roughly double that caused by the great Mississippi floods of 1993.

LOW FLOWS AND DROUGHTS

Low river flows are just one consequence of drought, the primary cause of which is lack of rainfall over a “prolonged” period. What constitutes “prolonged” may vary from country to country. For instance 20 days without rain would be most unusual and could be considered extreme in humid mid-latitude climates like Ireland but would be in no way unusual in a semi-tropical or tropical country. Droughts of three types may be considered, but of course these tend to occur simultaneously.
These type sare:

- Meteorological, defined in terms of specified durations without rain or with less than a stated amount of rain.
- Agricultural, defined in terms of soil moisture deficit and crop wilting.
- Hydrological, defined in terms of low flows although there is no recognised low flow threshold below which hydrological drought is assumed to occur.

The World Meteorological Organisation (WMO) (1990) defines drought as the “prolonged absence or poor distribution of precipitation” or “a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance”. Neither of these specify a duration - this has to be tailored to local circumstances. For instance Met Eireann (Rohan, 1975) defines an absolute (meteorological) drought as a period of 15 or more consecutive days, on none of which 0.2 mm or more of rainfall occurs” and a partial drought as “a period of at least 29 consecutive days, the mean daily rainfall of which does not exceed 0.2 mm i.e. a maximum of 5.8 mm in 29 days. Met Eireann also defines a dry spell, ≤ 15mm rain in 15 days.
For hydrological purposes Mac Carthaigh (1996) found it useful to define what he terms a “period of insignificant rainfall” which in most circumstances may be longer than those used by Met Eireann.

They are longer because rainfall amounts of up to 6 mm in any day, which have no appreciable effect on the corresponding river hydrograph recession, are not considered to end the period of insignificant rainfall. MacCarthaigh determined the durations of “periods of insignificant rainfall” at 12 well spaced rainfall measuring sites in Ireland for each of the major low flow periods during the last 30 years and used them, in conjunction with the low flow values, to assess the severity and frequency of low flows in Ireland.

LOW FLOW PUBLICATIONS

There is a considerable literature available internationally on the subject of low flows. A comprehensive review, referring to c.400 worldwide publications has been given by Smakhtin (2001). The successive FRIEND projects have studied low, as well as high flows, in Europe and in many other international locations (e.g. Gustard 1989, FRIEND 1989; Gustard & Gross 1989; Demuth 2005; Kachroo et al. 1998) while UNESCO and WMO produced a joint report on hydrological aspects of droughts (Beran and Rodier, 1985). In the UK a major national Low Flow Studies Report was published by the Institute of Hydrology (Gustard et al., 1982), preceeded by Beran and Gustard (1977).

In Ireland much of the assessment of water resources and low flows has been carried out in the EPA and earlier by An Foras Forbartha, e.g. McCumiskey (1981), Mac Carthaigh (1992, 1996, 1999). Martin and Cunnane (1977) examined the frequency distributions of selected Irish low flow and volumes of deficit series while Kachroo (1992) generalised the latter. Dooge (1985) provides an account of drought years gleaned from historical sources as far back as the Annals of Clonmacnoise and extending to the 20th century. Other unpublished academic studies include those of Smyth (1984), King (1985) and Brogan (2005).

DROUGHT YEARS IN IRELAND

MacCarthaigh (1995) produced maps showing “periods of insignificant rainfall” at each of 12 well spaced climate stations for the six driest years over the last 30 years, namely 1975, 1976, 1989, 1990, 1991 and 1995. The mapped information for 1976, the driest of the 30 years, is reproduced in tabular form below, Table1. It can be seen that all areas except the North West experienced “insignificant” rainfall for a period of 8 weeks ending around 9th September.

Table 1. Durations of Periods of Insignificant Rainfall in 1976 (MacCarthaigh, 1995)

Location	Dates	No. days
Malin Head	15 Apr-30 Apr, 13 Aug-9 Sept.	16 and 28
Clones	16 Jul-9 Sept.	56
Mullingar	16 Jul -9 Sept	56
Dublin Airport	16 Jul – 9 Sept.	56
Casement	16 Jul – 9 Sept.	56
Birr	16 Jul – 9 Sept.	56
Kilkenny	16 Jul – 9 Sept., 11 Sept. – 18th Sept.	56 and 8
Moorepark	15 Jul – 18 Sept.	66
Killarney	21 Jul – 9 Sept	51
Shannon	16 Jul – 9 Sept.	56
Claremorris	16 Jul – 9 Sept.	56
Glencolumkille	11 Aug – 7 Sept.	27

The year 1975 had similarly long or slightly longer periods of “insignificant” rainfall between May and July and remarkably the southern part of the country had another 10 – 17 day dry spell ending in early September. However, the long dry period ending in July did not produce low flows as low as those that occurred in 1976 when the dry period ended in September. The other dry years mentioned above were not so severe in terms of duration but in the case of 1995, when drought again ended in September as in 1976, some river low flows dropped to the low levels experienced in 1976.

It should be noted that other dry years which occurred during the 20th century outside the period studied in detail by MacCarthaigh included 1934 (Dooge, 1985), 1949 (in the south east), 1955 and 1959 (MacCarthaigh, 2002). Met Eireann (www.met.ie/climate/rainfall.asp) notes that the longest known absolute drought in Ireland occurred in Limerick from 3rd April – 10th May, 1938 (38 days).

LOW FLOW DATA

Systematic flow measurements have been carried out by ESB, OPW and EPA in pursuit of their statutory obligations. Flow measurements have also been carried out by Dublin City Council and its predecessor. In the 1970's OPW installed Crump weirs at a number of flow gauging stations in order to improve the quality of low flow measurement. The Water Resources Division (WRD) of An Foras Forbartha (later subsumed into EPA) installed a wide network of gauges in order to assist Local Authorities fulfil their role laid down in the Local Government (Water Pollution) Act 1977. The WRD also undertook a very extensive programme of low flow current meter measurements during the dry summers of 1975 and 1976, and its successor, EPA, continues this practice during prolonged dry periods. The "Register of Hydrometric Stations in Ireland" and a file entitled "dwf and 95 percentile_July_05.xls" can be downloaded from www.epa.ie/Public Authority Services/Hydrometric Programme surfacewaters while data from the OPW archives can be viewed at www.opw.ie/hydro/index.asp.

MEASURES OF LOW FLOW

Daily mean flows are a convenient starting point for the definition of low flow magnitudes – finer refinement on the time scale is unnecessary and indeed a coarser time scale may indeed be adequate.

There are three standard statistically defined low flow categories:

(i) annual minimum m-day moving average flows with m = 1, 7, 10 and 15 days
. being the most commonly used . The case m = 1 corresponds to the annual minimum mean daily flow series, i.e. the flow series published by EPA and OPW.

(ii) annual minimum m-day sustained low flows with m = 1,3, 7, 10 or 15 days. The case m = 1 provides the annual minimum daily mean flow series as in (i).

(iii) the series of annual flow duration curve (FDC) q_{95} values, i.e. q_{95} values obtained separately from successive sets of 365 (or 366) mean daily flows.

Table 2. Selected ordinates of FDCs shown in Figure 1

	5%	15%	30%	50%	70%	80%	90%	95%
Highest	76.8	54.8	41.0	26.7	15.0	12.8	11.7	10.1
2nd Highest	74.4	54.3	38.8	26.4	14.6	9.1	6.3	5.9
Full Record	61.9	43.4	28.6	14.5	7.4	5.4	4.0	**3.3**
2nd Lowest	44.6	32.5	17.8	7.4	4.5	**3.4**	2.7	2.4
Lowest	34.9	17.8	10.9	6.7	4.1	**3.4**	2.3	2.0

For a particular gauging station some q_{95} values are larger than and some are smaller than the q_{95} value obtained from the full record flow duration curve. Thus use of the full record q_{95} as a project design flow e.g. dilution capability of a river, would provide less protection than might be expected. In a typical dry year, flow could be lower than the full record q_{95} for between 5 and 10 weeks and not 5% of the year or 18 days. This can be seen on **Figure 1** and the related **Table 2**. **Figure 1** shows the FDC's for the two wettest and two driest years of a 28 year record of flows as well as the full record FDC. The full record FDC q_{95} value is 3.3 m^3/s which **Table 2** shows corresponds (approximately) to q_{80} in the two driest years, meaning that flow could be less than full record q_{95} in 20% of days or 73 days during these driest years.

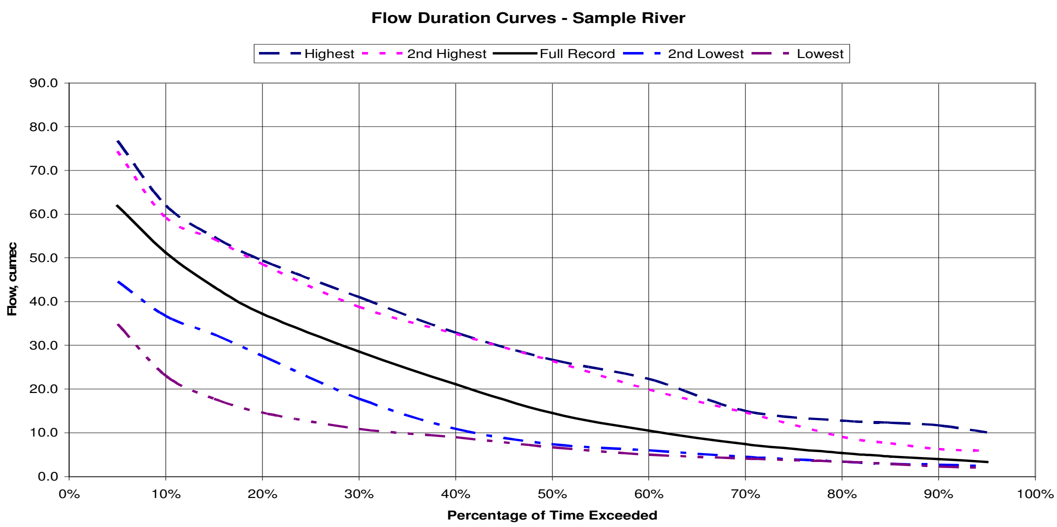


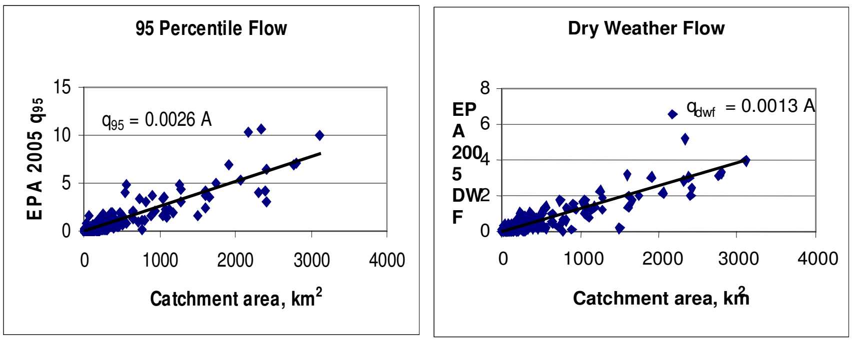
Figure 1 Flow duration curves for 2 wettest years and 2 driest years and full record FDC

APPROXIMATE MAGNITUDES OF LOW FLOW QUANTITIES AND RELATIONSHIPS BETWEEN THEM

MacCarthaigh (2002) presented plots of EPA DWF versus catchment area and of EPA q_{95} versus catchment area where EPA DWF is stated to be the low flow of 50 year return period and EPA q_{95} is the full record flow duration curve 95 percentile value. These plots show considerable scatter about an upward trend. A least squares line through the origin of each of these plots, shown here as a subset of 371 of the EPA stations in Figures 2 (a) and (b), are described by the equations

EPA DWF $= 0.0013\ A$ m^3/s where A is in km^2 (1)

and EPA q_{95} $= 0.0026\ A$ m^3/s (2)



Figures 2(a) and (b) Relations between Full Record q95 and EPA DWF and catchment area. Data selected from EPA website file "dwf and 95 percentile_July_05.xls"

It is clear from the diagrams that these equations are largely guided by the values plotted for the larger catchments, that the percentage scatter among values for small catchment is very large and ***that these equations cannot be used reliably for low flow estimation*** but they give an indication of the relative magnitudes of DWF and q_{95}. It might be noted that 0.0013A is of the same order of magnitude as that provided by an old rule of thumb (P.N. Corish, Personal Communication) which gave "one tenth of a cusec per square mile" as a typical low flow on Irish catchments, equivalent to = 0.0011 m^3/s per km^2.

Earlier Martin and Cunnane (1977) gave an expression for q_{50} (equivalent in meaning to EPA DWF) as :

$$q_{50} = 14.5\,A^{1.6} \times 10^{-6}\ m^3/s \qquad (3)$$

This was based on the data of 18 medium to large sized catchments, 194 $km^2 \leq A \leq$ 3401 km^2. It has a very large factorial standard error (FSE) of 2.5, again indicating the imprecision of the relation as an estimating tool. The same data set of 18 catchments also yield the expression q_{50} = 0.0013A , as in **eq (1)**. Further analysis of Smyth's (1984) data gave a result similar to **eq (3)**.

Smyth (1984, Chapter 5) gave prediction equations for the location and scale parameters of both EV1 and LN2 distributions for annual minimum flow. These parameters were related to catchment area and a selection of catchment characteristics from lake index, mean annual rainfall and 2 day R_5. When q_{50} was estimated from such an approach it was shown to have FSE of about 1.5, a considerable improvement on using area alone, as in **eq (3)** above.

Martin and Cunnane (1977) also gave a lower bound for q_{50} in terms of mean annual flow, $\overline{F}$, as

$$q_{50} = > 2\%\ \overline{F}\text{, when } A < 800\ km^2 \qquad (4a)$$

$$[2\% + 0.5\,(A - 800) / 100\%]\ \overline{F} \text{ when } A > 800\ km^2 \qquad (4b)$$

but on almost half the catchments studied q_{50} was substantially greater than this lower bound, and 2 catchments had much lower values.

Equations (1) and (2) show that, in general, EPA q_{95} (full record value) = 2 EPA DWF. Individual year q_{95} values exceed the annual minimum flow of the same year by varying amounts ranging from 10% to 30%. Using data, published earlier by OPW, for 1603 Suir at Rathkennan, we see, **Figure 3** based on 28 years of data, that $q_{95} \approx 1.3q$, where now q_{95} is the individual year FDC value and q is the corresponding annual minimum flow. This shows a 30% difference between q_{95} and q but for other stations a different percentage may apply.

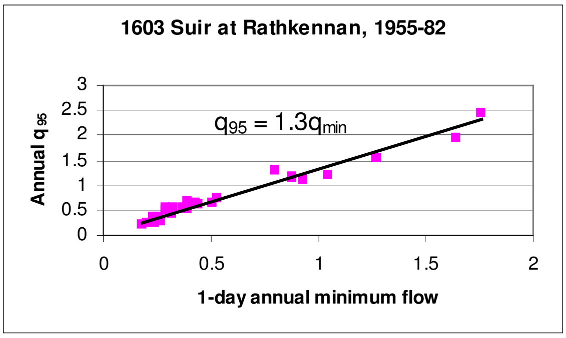


Figure 3 Relationship between individual year q_{95} and corresponding annual minimum flow for station 1603 Suir at Rathkennan derived from data published in 1985.

LOW FLOW DISTRIBUTIONS FOR ANNUAL MINIMUM 1 DAY FLOWS

Annual minimum flows series for Irish rivers are generally positively skewed and therefore, perhaps somewhat surprisingly, may be described by distributions which are already widely used in flood hydrology such as Extreme Value Type 1 (EV1) and lognormal with two or three parameters (LN2, LN3).

Smyth (1984), based on examination of probability plots and Chi Square and Kolmogorov goodness of fit tests, concluded that both EV1 and LN2 distributions provided satisfactory description of a little more than half of the 45 series examined by him while the LN3 was satisfactory in almost three quarters of cases. His series were mostly of length ≤5 years with a few much shorter and a few much longer than this and an average length of 18 years. He concluded that use of a 3 parameter distribution might not be justified with such short records even though LN3 provided a very good fit.

King (1985), examined sustained low flows (SLFs) of several durations from 1 day to 30 days from 71 gauging stations in Ireland. Hydrometric record length varied from 10 to 42 years with an average of 19.5 years. He found for 1 day flows that these records had average Cv = 0.583 and average skewness $\overline{g}$ = 1.084 (= 1.557 if adjusted by Hazen's correction factor of 1 + 8.5/N, with N = 19.5 years). Noting that the EV1 distribution has a fixed skewness of 1.14 it is seen that the corrected average value of skewness exceeds this value. King did not examine the goodness of fit of any distribution at individual sites but rather examined the goodness of fit of distributions to the regionally pooled dimensionless data. He concluded that EV1/GEV distributions performed this task better than either the Weibull or Wakeby distributions. However, he also concluded that none of the available distributions (note the lognormal distributions were not considered) were satisfactorily able to describe the lower tail of the data where low flow quantile estimates are required and he developed distribution free estimates of $q_T / \overline{q}$ instead. Table 3 gives his estimates of $q_{50} / \overline{q}$ for SLFs of various durations, $\overline{q}$ being the mean SLF value of the relevant duration.

Table 3 Sustained low flow $q_{50} / \overline{q}$ for various durations, from King (1985, Table 6.9).

Duration	1 day	3 day	7 day	15 day	30 day
$q_{50} / \overline{q}$	0.075	0.100	0.100	0.125	0.120

Brogan (2005) examined the suitability of EV1 and lognormal distributions for annual minimum flow series at 28 Irish gauging stations, with record lengths varying from 31 to 47 years and an average of 39 years, double the average length available to King (1984). Cv had an average value of 0.57, being smaller on large catchments and larger, but very variable, on small catchments (< 250 km^2). Individual skewness values ranged from 0.15 to 1.76 with average of 1.06. When Hazen's correction factor is applied these figures change to 0.177, 2.34 and 1.30 respectively. The null hypothesis that skewness is zero in the log series was rejected at the 95% level in only 5 out of the 28 series.

Probability plots of q on EV1 base and log q on Normal base were prepared for each station. From visual inspection it was concluded that the data could be described by a straight line in 22 of the 28 cases in the EV1 case and in 17 of the 28 cases in the log Normal case. Some examples of good and bad fits are shown on Figures 5 a, b, c, d. It should be noted that the practice of plotting low flow data in decreasing order of magnitude on an EV1 base, as in Martin and Cunnane (1976), never leads to a good straight line fit but of course use of decreasing order has no effect on Normal base plots, because of the symmetry involved.

CONCLUSION

The dry year 1976 produced the lowest flows recorded in Ireland over the past 30 years and most likely the lowest for perhaps the past 60 or 70 years. Annual minimum flow of 50 year return period among larger catchments is approximately 0.0013 $m^3/s/km^2$ while 95 percentile flow, q_{95}, in the full record flow duration curve is approximately two times as large, 0.0026 $m^3/s/km^2$. It was shown that full record q_{95} is not necessarily a reliable guide for dry year conditions as flow could be less that full record q_{95} for up to 70 days during a very dry year.

Low flow distributions are positively skewed, with average skewness in excess of 1.0. The EV1 distribution provides a good fit to annual minimum flow data at most stations while LN2 performs a little less well. This conclusion was strengthened when the longer records of almost 40 years were examined. However the LN3 distribution performed well for the shorter samples and for the small number of longer records which were unable to be described by EV1 or LN2 the LN3 distribution is necessary.

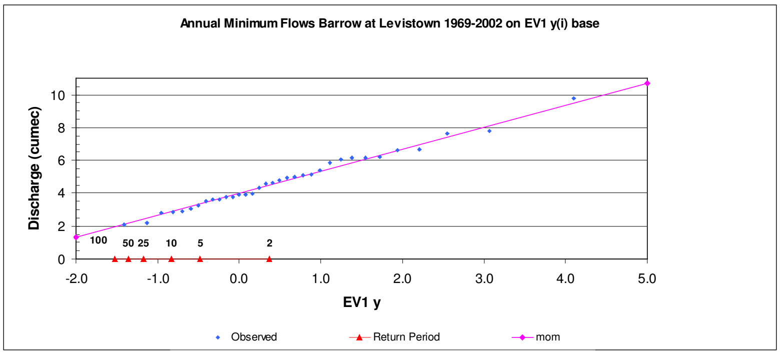


Figure 4(a) Example of very good fit of EV1

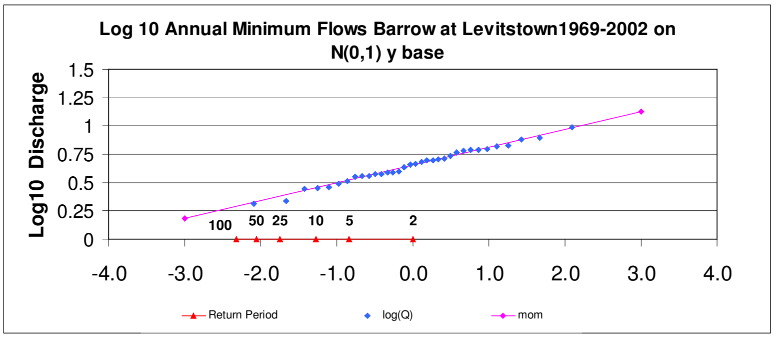


Figure 4(b) Example of very good fit of Lognormal

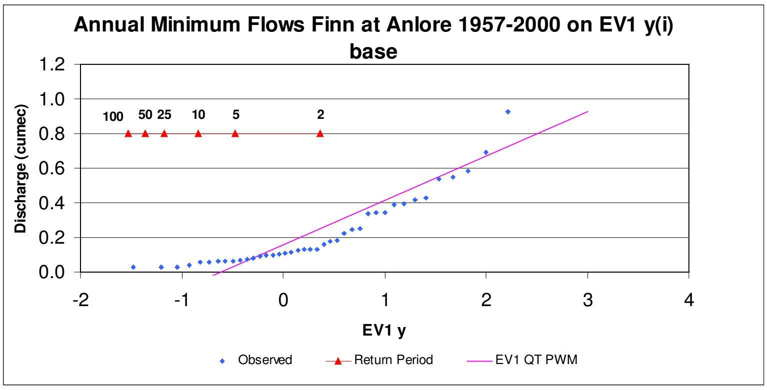


Figure 4(c) Example of very poor fit by EV1

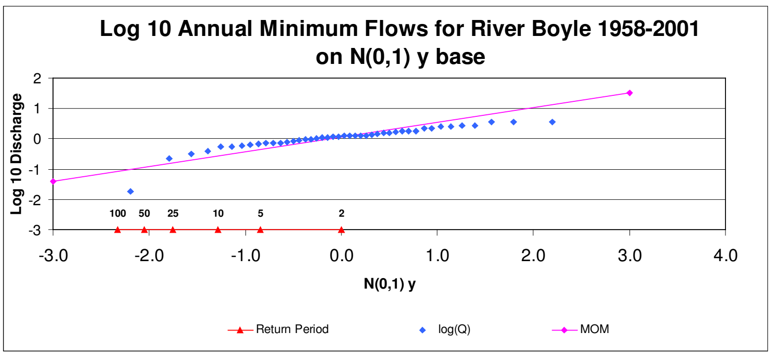


Figure 4(d) Example of poor fit by Lognormal

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