LOW-FLOW PREDICTION FOR UNGAUGED RIVER CATCHMENTS IN IRELAND

Uzzal Mandal[1] and C. Cunnane[2]

[1] RPS Consulting Engineers, Galway
[2] Department of Engineering Hydrology, NUI Galway.

ABSTRACT

Reliable estimation/prediction of low-flows for rivers is vital for the proper planning and design of water resources projects. This paper explores the various low-flow measures/indices, their application and estimation techniques currently in use in Ireland and elsewhere in the world. A simple regression based generalised model for the flow-duration curves (FDC) for Irish rivers has been developed which can be used for predicting FDC for any ungauged catchment from the known catchment physiographic and climatological characteristics. Given the complex shape of the observed FDC and the higher variability in the high-flow sections of the FDCs, this study focuses on modelling of only the lower three-quarter section of FDC (25%ile to 99.99%ile). A two-parameter logarithmic type equation was found to fit well to this lower section of the FDCs at most of the 125 gauging sites in Ireland considered in this study. The parameters of the proposed model have been estimated from the easily measurable/obtainable catchment climatological characteristics, such as mean annual rainfall (SAAR), or mean annual potential evapotranspiration in addition to catchment area.

INTRODUCTION

Estimating streamflows for ungauged catchments is always a big challenge. Numerous studies have been carried out worldwide including Ireland to-date on high-flows (floods) estimations for ungauged catchments. However, only a limited number of studies have been carried out so far on the low-flow area of streamflows. One example of these studies is the UK Low-flow studies, carried out by the Institute of Hydrology in 1980, where a detailed methodology was developed for estimating various low-flow measures and indices for the gauged and ungauged British river catchments.

In the above context, this paper explores the various low-flow measures/indices, their application and estimation techniques currently in use in Ireland and elsewhere in the world. The paper has put forward a simple regression based generalised model for the flow-duration curves (FDC) for Irish rivers which can be used for predicting FDC for ungauged catchments from the known catchment climatological characteristics.

VARIOUS LOW-FLOW MEASURES AND INDICES CURRENTLY IN USE

The international glossary of hydrology (WMO, 1974) defines low-flow as 'flow of water in a stream during prolonged dry weather'. Low-flows are seasonal phenomena, and an integral component of a flow regime of any river. Low flows are normally derived from groundwater discharge or surface discharge from lakes, marshes, or melting glaciers. Lowest annual flow usually occurs in the same season each year. The arbitrary '**upper bound'** to low-flow hydrology may be given by the *long-term average mean daily flow*s or *long-term mean annual flow*. The lowest recorded daily discharge may be referred to as *Absolute Minimum Flow* Intermittent and ephemeral streams are characterised by natural extended periods of zero flow, which may generally be perceived as the '**lower bound**' of low-flow.

The term '**low-flow measures'** used here, refers to the different methods that have been developed for describing and/or expressing the low-flow regime of a river, often in graphic form, such as FDC. The term '**low-flow index'** is used predominantly to define particular values obtained from any low-flow measures such as 95%ile flow (Q_{95}).

Some of the commonly used low-flow indices are *annual minimum mean daily flow (mdf)*, *annual minimum m-day sustained low-flow (m-day SLF)*, *annual minimum m-day moving average flow (m-day MAF)* and *95%ile flow*. The most widely used low-flow indices (particularly in USA) are 7-day 10-year low flow (7Q10) and 7-day 2-year low flow (7Q2), which are defined as the lowest average flows that occur for a consecutive 7-day period at the recurrence intervals of 10 and 2-years, respectively. The average of the annual series of minimum 7-day average flows know as Dry Weather Flow (DWF) is used in the UK for water abstraction licensing. In Russia and Eastern Europe, the widely used indices are 1-day and 30-day summer and winter low-flows. *Baseflow* (sometime used as an important low-flow index) is an important genetic component of streamflow, which comes from groundwater storage or other delayed sources (shallow subsurface storage, lakes, melting glaciers, etc.). Another index called, *Baseflow Index (BFI)* is a non-dimensional ratio which is defined as the volume of baseflow divided by the volume of total streamflow. In catchments with high groundwater contribution to streamflow, BFI may be close to 1, but it is equal to zero for ephemeral streams. BFI was found to be a good indicator of the effects of geology on low-flows and for that reason is widely used in many regional low-flow studies (IH, 1980). An elaborate description for the above is given in Smakhtin (2001).

The most widely used low-flow indices in Ireland are *95%ile flow* (Q_{95}), *Dry Weather Flow (DWF)* which has been defined by the Environmental Protection Agency (EPA) as the minimum daily mean flow rate with a return period of 50 years, 7-day 15-year sustained low-flow. EPA uses *DWF & 7-day 15-year SLF* for stream water quality management purposes. Q_{95} is generally used to assess the stream waste-load assimilative capacity assessment. Under the Phosphorus Regulations and the Urban Wastewater Treatment Regulations, the 50%ile flow (Q_{50}) is used for phosphorus assimilative capacity assessment.

FLOW DURATION CURVE – ITS CONSTRUCTION, APPLICATIONS AND INTERPRETATIONS

A FDC is one of the most informative methods of displaying the complete range of river discharges from low-flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equalled or exceeded. Vogel (1990) described FDC as simply a non-parametric cumulative distribution function (cdf) of daily streamflows at a site.

A FDC may be constructed using different time resolutions of streamflow data: annual, monthly or daily. A FDC constructed on the basis of daily flow time series provide the most detailed way of examining the flow-duration characteristics of a river. Curves may also be constructed using some other time intervals, e.g. from m-day or m-month averaged flows from initially available daily or monthly data. FDCs may be calculated: (i) on the basis of the whole available record period (‘**period-of-record FDC’** Vogel and Fennessey, 1994), or (ii) ‘Long-term average annual FDC’ (FREND, 1989; Smakhtin et al,1997).

For gauged catchments, FDCs are constructed by reassembling the streamflow time series values in decreasing order of magnitude. All ranked flows are plotted against their ranks which are again expressed as a percentage of the total number of time steps. For ungauged catchments, FDCs can be constructed using various methods, such as **(i) Regional regression approach**, which generally involves developing regional mathematical models by relating low-flow indices or FDCs with catchment physiographic and climatic characteristics, **(ii) Regional prediction curve**, where FDCs for a number of gauged catchments of varying size in a homogeneous region can be converted to a similar scale, superimposed and averaged to develop a composite regional curve (e.g. FREND, 1989; Beran and Gustard, 1985). To make curves from different catchments comparable, all flows are standardised by catchment area, mean or median flow or other ‘index’ flow. A curve for ungauged site may then be constructed by multiplying back the ordinates of a regional curve by either catchment area or an estimate of the index low-flow depending on how the flows for the regional curve were standardised. The index flow is estimated either by means of regression equation or from regional map, **(iii) Regional**

mapping and other methods of spatial interpolation of low-flow characteristics-similarly to regression relationships. Flow maps can be constructed on the basis of flow characteristics estimated from the gauged data. For example, a normalised-Q_{95} map was prepared under the Water Framework Directives-River Basin District (WFD-RBD) Projects in Ireland and **(iv) Low-flow estimation from synthetic streamflow time series** - the alternative approach to low-flow estimate at ungauged sites is to utilise a time-series simulation method (stochastic and deterministic) to generate a satisfactorily long length of streamflow data and to calculate a set of low-flow indices and/or FDCs from the simulated series. A detailed description of these methods can be found in Smakhtin (2001).

INTERPRETATION OF FDC:

A FDC provides a simple, yet comprehensive, graphical view of the overall historical variability associated with the streamflows in a river basin (Vogel and Fennessey, 1994). Vogel and Fennessey (1994) suggested a different interpretation of FDC. They considered FDCs for individual years and treat those annual FDCs in the way similar to a sequence of annual flow maxima or minima. Such curves represent the exceeding probability of flow in a typical year. This approach allows confidence intervals and return periods to be assigned to FDCs.

The shape and general interpretation of any FDC depend on the particular period of record on which it is based [Searcy (1959); Vogel and Fennessey (1994); Hughes and Smakhtin (1996); and Smakhtin et al.(1997)]. The period-of-record FDC represents variability and exceedance probability of flow over the available period (or selected period). If the record period is sufficiently long, this interpretation is appropriate, since the FDC approaches a ‘limiting’ cumulative flow distribution.

The shape of the FDC is an indication of hydrological conditions in the catchment. The entire low-flow section of the curve may be interpreted as an index of groundwater (and/or subsurface flow) contribution to streamflow. If the slope of the low-flow part of the FDC is small, groundwater/subsurface flow contribution is normally significant and low-flows are sustainable. A steep curve indicates small and/or variable baseflow contribution. A FDC is sometimes referred to as the ‘signature’ of a catchment, as it describes its behaviour and response. A flat FDC indicates little variability in the flow (slow response to rainfall), whereas a steep FDC indicates high variability in the flow magnitude (quick response to rainfall).

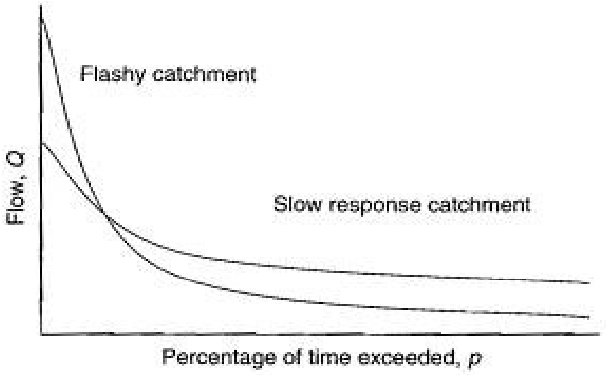

Figure 1: Shape of FDC represents catchment response behaviour

The ratio Q_{20}/Q_{90} may be interpreted as a measure of streamflow variability (Arihood and Glatfelter, 1991), the ratio Q_{50}/Q_{90} may represent the variability of low-flow discharges. The reverse ratio (Q_{90}/Q_{50}) may be interpreted as an index representing the proportion of streamflow originating from groundwater stores, excluding the effects of catchment area.

Applications of FDC:

FDCs have been advocated by many researchers and practitioners for use in hydrological studies such as hydropower, water supply, and irrigation planning (Vogel, 1994). Searcy (1959) described additional applications to waste-load allocation and other water quality management problems. FDC can be used to illustrate and evaluate the trade-offs among the variables involved in the selection of a wastewater treatment plant capacity (Male and Ogawa, 1994).The U.S. Bureau of Reclamation uses FDCs in river basin and reservoir sedimentation studies that examine the frequency of suspended sediment loads and determine the long-term average suspended sediment yield for a given site (Vogel, 1994). FDCs can be used for patching and extension of daily observed streamflow time series, for generation of low-flow time series at ungauged sites (Hughes and Smakhtin, 1996). The U.S. Fish and Wildlife Service use FDCs for determining the suitability of habitats to streamflow of different magnitudes and frequencies.

HISTORY OF LOW-FLOW STUDIES IN IRELAND

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 (1984, 1987, 1989, 1992, 1996, 1999, and 2002). 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. Other academic studies include those of Smyth (1984), King (1985), Carty and Cunnane (1986) and Brogan and Cunnane (2005). A brief description of some of the main studies is given below.

MacCarthaigh (2002) presented plots of EPA-Dry Weather Flow (DWF) versus catchment area and of Q_{95} versus catchment area for 371 sites where EPA-DWF is stated to be the low-flow of 50 year return period and Q_{95} is the period-of-record 95%ile flow. These plots show considerable scatter about an upward trend. A least squares line through the origin of each of these plots was described by the equations:

$$\text{EPA-DWF} = 0.0013A \text{ m}^3/\text{s} \qquad (1)$$

and

$$\text{EPA-}Q_{95} = 0.0026 \, A \text{ m}^3/\text{s} \qquad (2)$$

where A is catchment area in km^2

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 (Brogan and Cunnane, 2005).

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

$$q_{50} = 14.5 \, A^{1.6} \times 10^{-6} \text{ m}^3/\text{s} \qquad \text{where A is catchment Area in km}^2 \qquad (3)$$

This study was based on the data of 18 medium to large sized catchments ranging from 194-3401km^2. It has a very large factorial standard error (FSE) of 2.5, again indicating the imprecision of the relation as an estimating tool.

Smyth (1984) gave prediction equations for the location and scale parameters of both EV1 (Extreme value type 1) and LN2 (log-normal 2-parameter) distributions for annual minimum flows. These parameters were related to catchment area and a selection of catchment characteristics of lake-index, mean annual rainfall and 2-day 5-year return period rainfall. 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 (Eq. 3).

Brogan and Cunnane (2006) examined the suitability of various statistical distributions for the annual minimum mean daily flow series for Irish Rivers (28 stations). It was found that the EV1 distribution provides a good fit to annual minimum flow data at most stations while LN2 performs a little less well.

Studies were undertaken for the Water Framework Directive where FDCs were required in risk assessments and in preparation of a programme of measures. Initial screening used a national map of 95%ile flow per sq km. This was subsequently improved on the basis of a 'Region of Influence' approach to non-parametric FDC estimation using meteorological and topographical catchment descriptors, and also a set of soils, subsoils and aquifer descriptors developed by an expert group. The approach is a flexible system that has been applied and updated every two years by EPA and Local Authorities. A web-based version will be released by EPA.

DEVELOPMENT OF A GENERALISED FDC MODEL FOR IRISH RIVERS

Introduction

This section of the paper presents a detailed methodology for the development of a simple regression based generalised model for the FDCs for Irish rivers. A generalised parametric model for FDC was developed from the observed low-flow records and the catchment physiographic and climatic characteristics. The developed model can be applied to obtain FDCs for ungauged catchments. The performance of the model is also assessed and discussed below

Methodology

Mathematically, a FDC has often been represented by a number of different forms, including power and exponential forms (Quimpo et al. 1983; Mimikou & Kaemaki 1985, Patel, 2007). Beard (1943) suggested constructing a FDC by fitting a 2-parameter lognormal cumulative distribution function (cdf).

FDCs are known to exhibit rather complex shapes, (Searcy 1959, Dingman 1978); three or more parameters are probably necessary to describe the location, shape, and scale of the probability density function. Vogel and Fennessey (1990) pointed out that a complex trade-off exists between the number of parameters required to describe the FDC and our ability to obtain regional regression models that relate those parameters to drainage basin characteristics.

In a study carried on 23 river basins in Massachusetts in USA, Vogel and Fennessey (1990) approximated the lower half of the daily FDCs using a two-parameter lognormal probability density function. Given the complex shape of the observed FDC and the higher variability in the high-flow sections of the FDCs, this study focuses on modelling of only the lower three-quarter section of FDC (25%ile to 99.99%ile). Furthermore, for the planning and design of water related schemes, knowledge of the FDC between the limits of 50 & 99.99%ile flows are adequate. Based on this we set our objective to develop a regional regression model for the lower three-quarter potion of FDC (Figure 2). This approach will also allow us to describe the model through a reduced number of parameters.

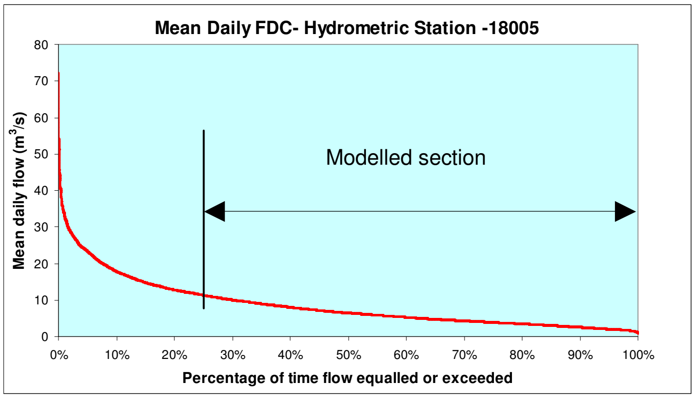

Figure 2: Modelled FDC section

Data Used

Mean daily flow data for 125 gauging sites were obtained from EPA (http://hydronet.epa.ie/conditions.htm) and OPW (www.opw.ie/hydro/index.asp) hydrometric database. FDCs for these gauging stations have also been obtained from EPA. Stations with the following attributes were selected:

1. Good rating curve
2. Rivers are perennial and all streamflows are greater than zero
3. No significant withdrawals, diversions, or artificial recharge areas are contained in the basins, hence we consider the streamflows to be essentially un-regulated.

The location of each station is illustrated in Figure 3. Table 1 provides a summary of the data used in this study. A wide range of catchments have been included in this study, representing catchments with a high variability in annual rainfalls and catchments that differ significantly in terms of their hydrogeology. The record lengths vary from a minimum of 5 years to a maximum of 57 years with a mean value of 25 years. Several other catchment physiographic and climatic characteristics were also obtained from EPA, OPW and Met Eireann. Climatic characteristics include long-term mean annual rainfall (SAAR) and mean annual potential evapotranspiration (PE). Physiographic characteristics used include catchment area (AREA), drainage density (DRAIND), stream frequency (STRMFRQ), geology as expressed by baseflow index (BFI) and main channel length (MSL).

Data Name	Notation	Median	Mean	Maximum	Minimum	Standard deviation
Catchment area (km^2)	AREA	122	261	2450	3	409
Mean annual rainfall (mm)	SAAR	1157	1226	2585	725	374
Mean Annual Flow (m^3/s)	MAF	2.87	5.72	39.90	0.09	7.43
Record Length (year)	L	26	25	57	5	12
50%tile Flow (m^3/s)	Q_{50}	1.77	3.75	27.80	0.05	5.12
95%tile Flow (m^3/s)	Q_{95}	0.29	0.65	5.90	0.01	0.94

Table 1: Data Summary

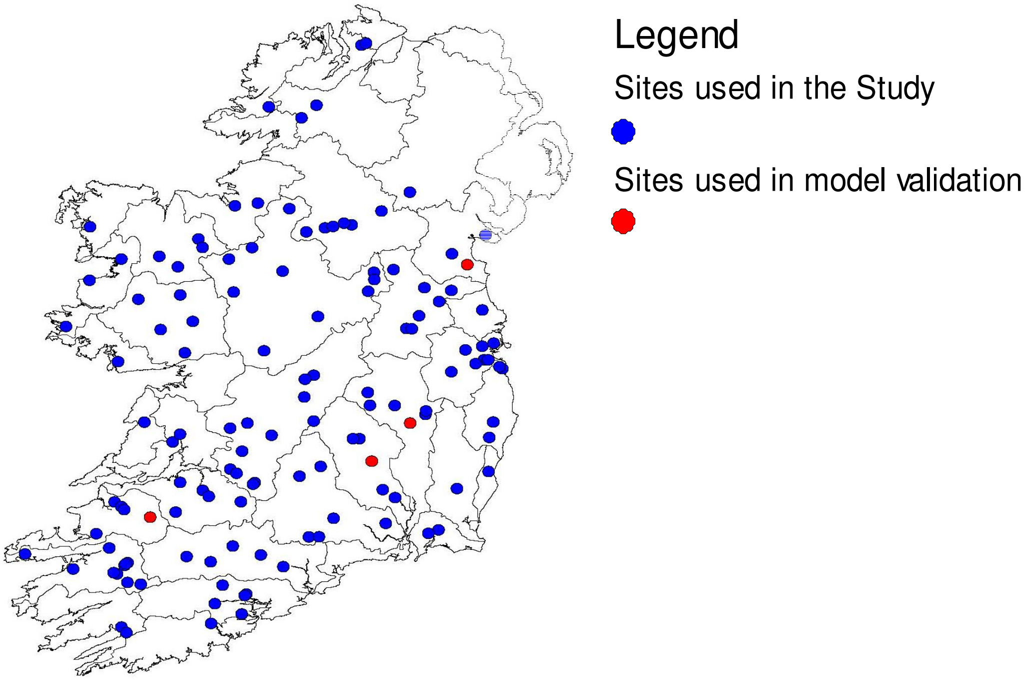

Figure 3: Spatial distribution of the gauging sites (125-sites)

Proposed Model

An empirical period-of-record FDC was developed for each gauging site. A best fit curve was fitted to the lower three-quarter section of each of the FDCs using MS Excel's data analysis tool. It was found that a 2-parameter logarithmic type model provides a good approximation to lower three-quarter part of the daily FDCs for almost all of the sites used in this study. The structure of such a model is:

$$Q_p = a + b \ln p \tag{4}$$

where Q_p represents the p%ile flow, '*a*' and '*b*' are two model parameters; p is the exceedance percentile for which flow is equalled or exceeded. Figure 4 shows a plot of the empirical FDC and the fitted logarithmic curve for a site at Killyon on the River Deel.

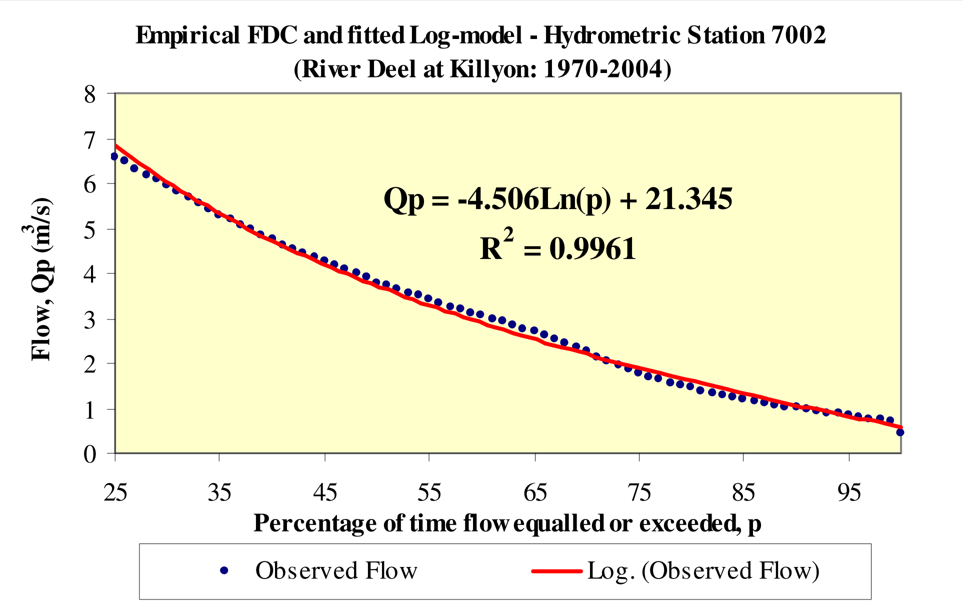

Figure 4: Fitted Log-model to an empirical FDC

Model Parametrisation

It was found that the derived model parameters obtained for the 125 study catchments are highly correlated and that the parameter '*a*' is approximately 4.6558 times of the parameter '*b*' (i.e. *b=4.6558a*). Figure 5 shows a plot of the parameter '*a*' against parameter '*b*'.

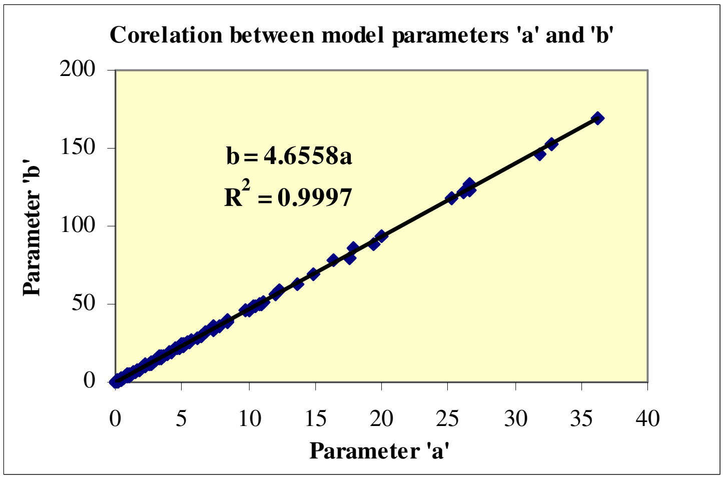

Figure 5: Correlation between parameters '*a*' & '*b*'

Thus the analytical FDC model can be approximated by a single parameter of '*a*' as follows:

$$Q_p = a(4.6558 - \ln p) \qquad (5)$$

It should be mentioned here that this approximation of parameter '*b*' is more reliable than an estimate of '*b*' obtained from a regression relationship between '*b*' and catchment physiographic and climatic characteristics.

The analytical FDC model represented by Eq.5 is extended for use at an ungauged site by developing a generalised regression equation for parameter '*a*'.

The shape of the FDC has been shown to have a strong dependence on catchment characteristics, particularly hydrogeology (Institute of Hydrology 1980, Gustard et al. 1992a; Vogel & Fennessey 1994). The UK low-flow studies Report (IH, 1980) has highlighted the need to index the hydrogeology of a catchment in order to predict low flows at ungauged locations. The low-flow studies Report recommended the use of BFI. Previous studies in the United States and elsewhere have developed multiple linear equations for estimating low-flow statistics and/or model parameters, by relating with the catchment physiographic, geologic, climatic and/or geomorphic parameters that are easily measured at ungauged sites (Male and Ogawa 1982; Tasker 1972; Vogel and Kroll 1990). The model derived by Vogel et.al. (1989) contains the independent basin parameters of catchment area, average basin slope and the basin relief.

In our study we attempted to describe the model parameter '*a*' using the catchment physiographic parameters: catchment area (AREA), catchment drainage density (DRAIND), stream frequency (STRMFRQ), Baseflow Index (BFI) and the climatic parameters of long-term average annual rainfall (SAAR) and Potential Evapotranspiration (PE). Multivariate regression procedures were employed to test a variety of combinations of model form and independent variables combinations. It was found that catchment area is the most significant, and the fit is improved when this is combined with just one climatological descriptor. Two alternative models were proposed for the model parameter '*a*', the details of which are discussed below.

AREA – SAAR Model:

It was found that the parameter '*a*' has a good correlation with the catchment area (AREA) and the long-term average annual rainfall (SAAR). The resulting regional regression for the parameter '*a*' is:

$$a = k_1 e^{k_2 (\ln AREA)(\ln SAAR)} \qquad (6)$$

where AREA is in km^2 and SAAR is in mm; ***k_1 and k_2*** *are two regression coefficients, the optimised values of these coefficients are* ***0.0229 & 0.1393*** *respectively.*

The large R^2- value (coefficient of determination) of **0.9428** in the above equation suggests high precision regression model. In other words, the catchment area and the long-term mean annual rainfall in the form of the above equation (Eq. 6 - exponential type) are good predictors of parameter '*a*'. Using '*a*' in Eq. 5 one may obtain a regression estimate of Q_p at an ungauged site.

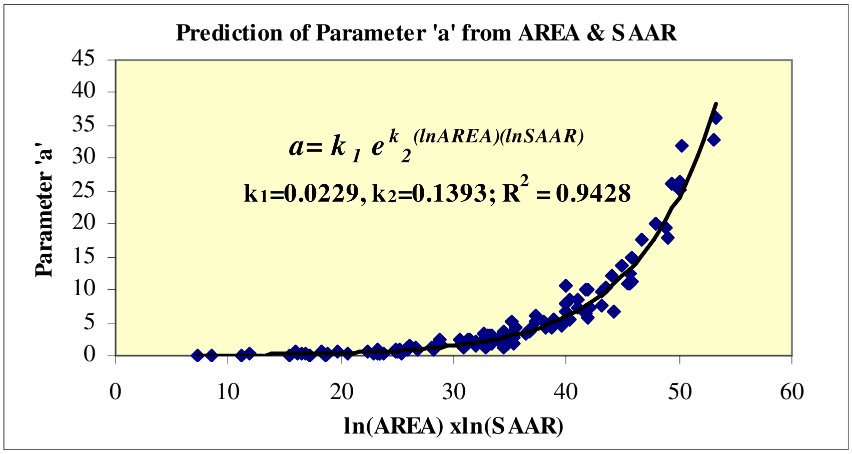

Figure 6: **Regression of parameter 'a' on AREA & SAAR**

Mean Flow Model (MF-Model):
An alternative attempt was made to have a generalised estimate for parameter 'a' from the observed long-term mean annual flow (MF) and mean annual potential evapotranspiration (PE) data for each of the catchments. A regression on the MF with parameter '*a*' showed that MF is a good predictor of parameter '*a*' and the resulting regression is:

$$a = k(MF) \tag{7}$$

where MF is in m^3/s, k is the regression coefficient, the optimised value of which is 0.9301

Conceptually MF could be linked with the catchment area (AREA) and the mean net annual rainfall (NAR) in the following way:

i.e MF = AREA x NAR

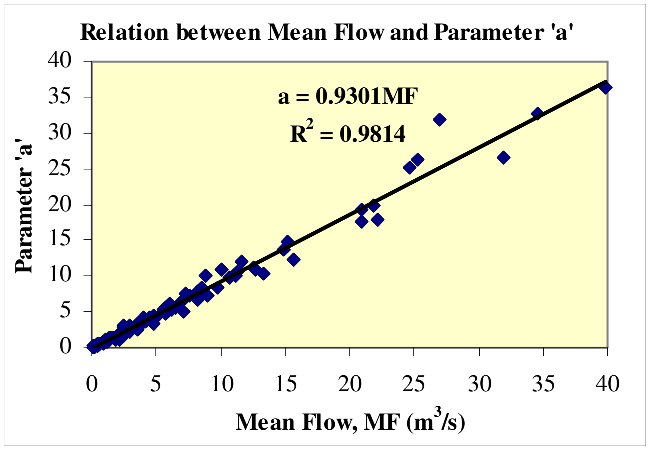

Figure 7: Regression of Parameter 'a' on MF

From the known mean annual PE, the NAR at each of the sites was estimated by subtracting it from the observed long-term mean annual rainfall. Mean annual PE for a total of 14 synoptic stations in Ireland were obtained from Met Eireann. Using the MapInfo GIS technique PE values on a 20km x 20km spatial grid resolution have been calculated by linear interpolation. A contoured map with a 50mm resolution was prepared (Figure 8). PE values for any unguaged site can be read from this map. By knowing PE and long-term mean annual rainfall, MF at any ungauged site can be calculated as follows:

$$MF = AREA(SAAR - AE)/(365 * 24 * 60 * 60) \text{ x } 10^3 \text{ m}^3/\text{s} \qquad (8)$$

where AREA is in km^2 *and PE is in mm*

A scatter plot of the observed and estimated MFs shown in Figure 9 indicates a reasonably good performance of the above estimate of MF for an ungauged site. Using Eq. 8 'MF' and inserting this in Eq. 7 gives an estimate of parameter 'a, which can then be used in Eq. 5 to provide an estimate of Q_p for an ungauged site.

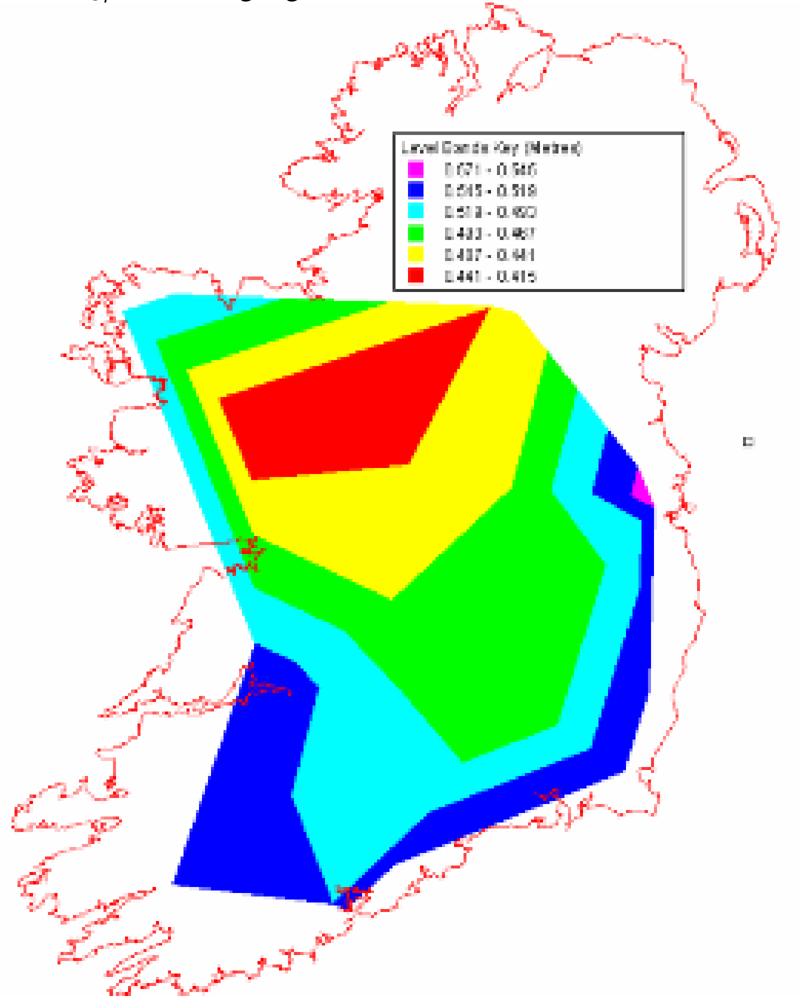

Figure 8: Potential Evapotranspiration Map (PE-Map) for Ireland.

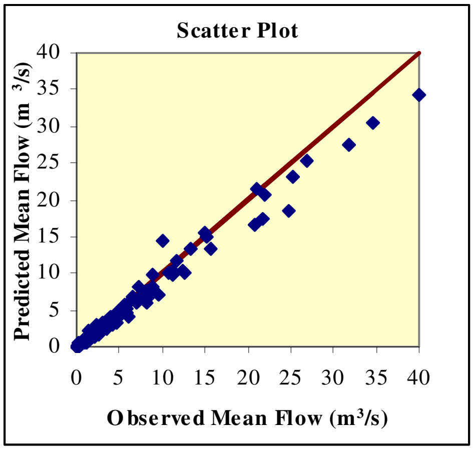

Figure 9: Relationship between the predicted and observed Mean Flows

Model Performance

Performance of the generalised FDC model was assessed through both graphical and analytical approaches. Scatter plotting techniques for a number of low-flow indices of Q_{25}, Q_{50}, Q_{75} & Q_{95}) were used under the graphical approach where the predicted versus observed flows were plotted. Figures 10 & 11 show scatter plots for the above low-flow indices estimated from AREA-SAAR and MF parameter estimation models respectively. In general these plots show good agreement between the observed and predicted values. The MF-Model performs slightly better than the AREA-SAAR Model. A slightly better correlation was observed for the Q_{25}, Q_{50} and Q_{75} flows than for the 95%ile flow in both parameter estimation models. A considerable spread of data is observed around the 45^0 line for the Q_{95} flow, particularly for higher flow values.

In the analytical approach, two performance indicator statistics, average bias (BIAS) and root mean sum of squares error (RSME) were used. Table 2 presents the estimated BIAS and RSME statistics for the proposed FDC models and the parameter estimation methods. In general, the agreement between the observed and predicted FDCs is reasonably good. The AREA-SAAR Model under-estimates Q_{95} flows by 7.60% while the MF-Model under-estimates Q_{95} by 12.12%.

Model	BIAS*				RMSE			
	Q25	Q50	Q75	Q95	Q25	Q50	Q75	Q95
AREA-SAAR Model	-1.20%	-7.50%	-10.10%	+7.60%	34.0%	31.0%	35.0%	43%
MF-Model	+9.8%	+1.6%	-2.6%	+12.12%	24%	27%	38%	48%

**Note: +ve BIAS: under-estimaton, -ve BIAS: over-estimation*

Table 2: Summary of Results

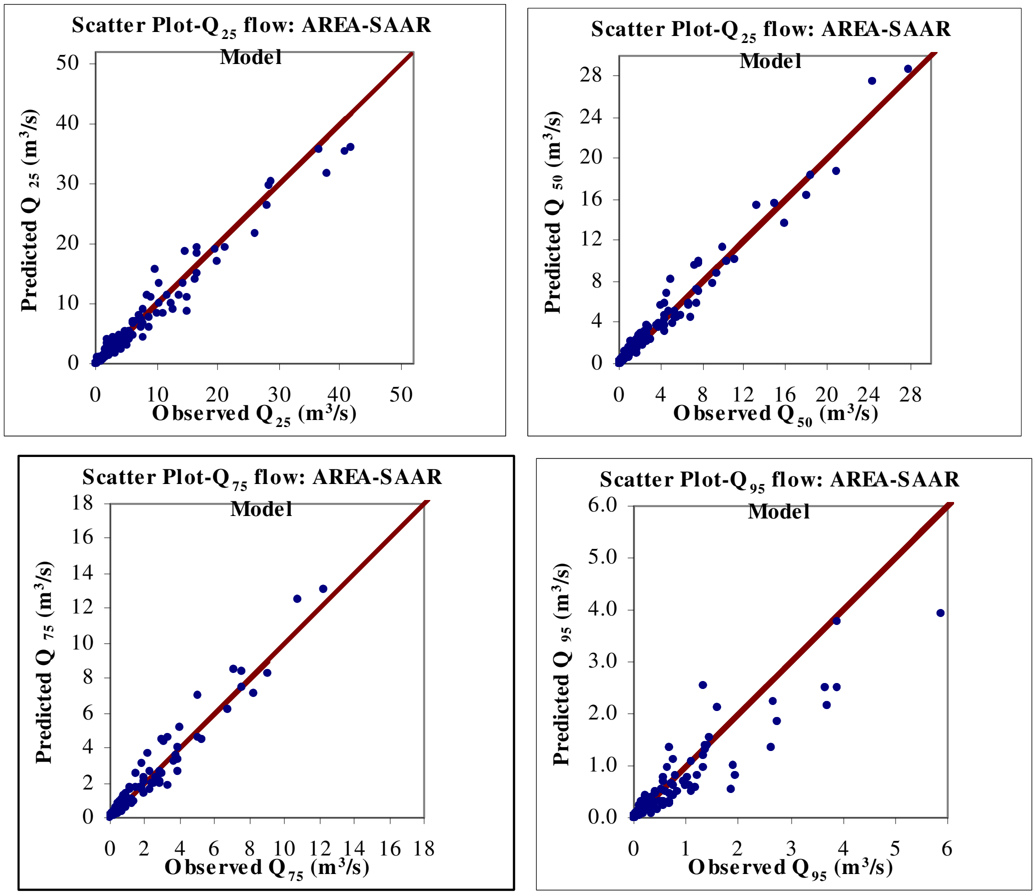

Figure 10: Scatter Plots – AREA-SAAR Model

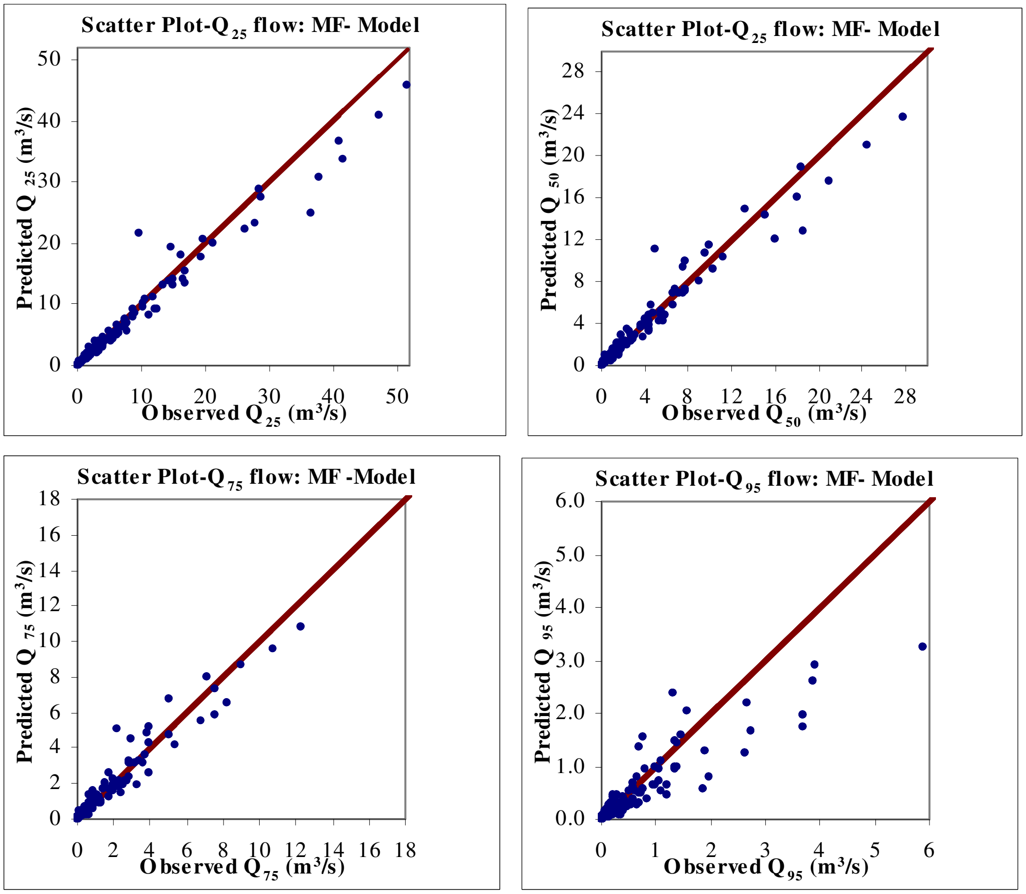

Figure 11: Scatter Plots Mean Flow Model

Model validation

Model validation was carried out on four independent river catchments which were not used in the calibration of the above models. Record lengths, other associated physiographic and climatic characteristics for these stations are summarised in Table 3. These validation sites are located in different river basins; hence they cover a wide geographic region. Figure 12 depicts the agreement between the observed and the predicted/estimated FDCs. The MF-Model performs better than the AREA-SAAR Model. Overall, the agreement between the observed and the estimated FDCs for the MF model is very good in all four cases. At three sites Q_p estimates with AREA-SAAR model are consistently greater than Q_p observed, particularly at high-flow end of the FDCs. However, both models predict a slightly better estimate at the low-flow end of the curves.

Data Name	Notation	Hyd. Stn. 14019	Hyd. Stn. 23005	Hyd. Stn. 6013	Hyd. Stn. 15003
Catchment area (km^2)	AREA	1690	62	308	298
Mean annual rainfall (mm)	SAAR	862	1253	873	933
Mean Annual Flow (m^3/s)	MAF	20.20	1.93	4.25	6.16
Record Length (year)	L	26	24	29	33
50%tile Flow (m^3/s)	Q_{50}	15.0	0.998	2.73	3.27
95%tile Flow (m^3/s)	Q_{95}	4.12	0.135	0.43	0.43

Table 3: Catchment characteristics for the selected Validation Sites

The regional regression estimator Q_p contains substantial variability due to the inevitable errors associated with the regression models; the sampling errors that arise from fitting the models to short, cross-correlated (in space) and uncorrelated (in time) streamflow sequences; and finally, to the unavoidable errors associated with all streamflow measurements.

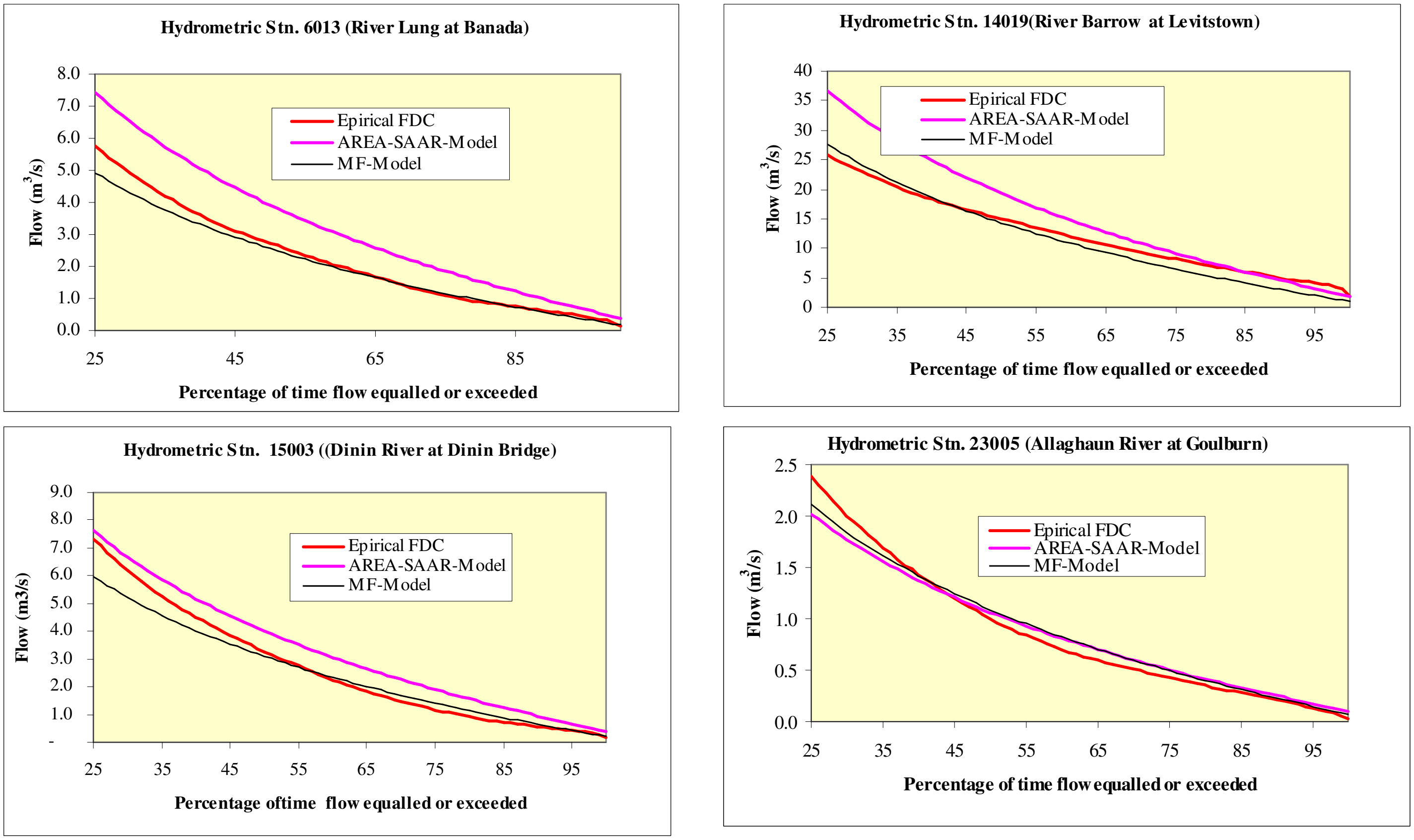

Figure 12: Observed and predicted FDCs

CONCLUSIONS AND RECOMENDATIOS

Conclusions

1. Given the complex shape of the observed FDC and the higher variability in the high-flow sections of the FDCs, this study focused on modelling of only the lower three-quarter section of FDC (25%ile to 99.99%ile).

2. It was found that a 2-parameter logarithmic type model provides a good approximation to lower three-quarter part of the daily FDCs for almost all of the sites used in this study.

3. The parameters of the proposed model have been estimated from the easily measurable/obtainable catchment physiographic and climatic characteristics, such as catchment areas (AREA), mean annual rainfall (SAAR) and mean annual potential evapotranspiration. Two alternative regression based model were proposed for parameter ‘a’ such as AREA-SAAR Model and MF-Model.

4. The MF-Model performs slightly better than the AREA-SAAR Model. The AREA-SAAR Model under-estimates Q_{95} flows by 7.6% while the MF-Model under-estimates Q_{95} by 12.12%. The both models perform reasonably well for 25%, 50% and 75%ile flow estimations but less well for the 95%ile flow estimation.

4. The proposed models provide a reasonably satisfactory basis for the estimation of low-flows for ungauged catchments in Ireland.

Recommendations

1. Further improvement of the model performance can be obtained by incorporating more gauging sites and additional catchment characteristics in estimating model parameters.

2. In the view of growing attention to climate variability/change, additional research is required regarding the specific inputs of climate change on low-flows.

3. It is recommended to use a range of flow estimation methods to arrive at a reliable design low-flow for an ungauged catchment.

4. It is recommended that 2km x 2km grid maps of ‘Potential Evapotraspiration (PE)’ and Net Annual Rainfall (NAR) be prepared for Ireland to assist in estimating the model parameters.

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REFERENCES

An Foras Forbartha & Electricity Supply Board. Small-Scale Hydro-Electric Potential of Ireland”. Department of Energy. October 1985.

Beran, M. and Gustard, A.(1985). A study into the low flow characteristics of British rivers, J. Hydrol., 35, 147-157.

Beran, M. and Rodier, J.A., (1985). Hydrological aspects of drought, UNESCO-WMO Studies and Reports in Hydrology, vol. 39, 149 p.

Brogan, L., Cunnane, C. (2006). Low flows and low flow distributions for Ireland. Irish National Hydrology Seminar (2006) pp. 85-92.

Carty, G. and Cunnane, C. (1986). An evaluation of some methods of determining storage yield relationships for impounding reservoirs.

Castellarin A, Camorani G, Brath A.Predicting annual and long-term flow-duration curves in ungauged basins.. Advances in Water Resources 30(2007) 937-953.

Castellarin A, Galeati G, Brandimarte L, Montanari A, Brath A.(2004). Regional flow-duration curves: reliability for ungauged basins. Advances in Water Resources 27(2004) 953-965.

Dooge, J.C.I. (1985) Droughts in Irish history. In de Buitléar, É., (Ed.) Irish Rivers, Country House Press, Dublin, pp26-28.

Fennessey, N.M, Vogel, R.M. Regional Flow-Duration Curves for Ungagued Sites in Massachusetts, Journal of Water Resources Planning and Management, ASCE 1990:116(4):530-549.

FREND (1989). Flow regimes from experimental and network data I: Hydrological studies, II: Hydrological data, Wallingford, UK.

Gustard, A. and GROSS. R (Eds) (1989). Low flow regimes of northern and western Europe.

FRIENDs in Hydrology, IAHS publ. no. 187, 205-212.

Hughes D.A., Smakhtin, V.U. (1996). Daily flow time series patching or extension: a spatial interpolation approach based on flow duration curves. Hydrological Science Journal, 41(6) 851-871.
Kachroo, R.K. (1992). Storage required to augment low flows: a regional study. Hydrol. Sc. J., 37, 247-261.

King, M.C. (1985). A low flow frequency analysis for Irish rivers, M.Eng.Sc. Thesis, University College, Galway. 213 p.

Mac Cárthaigh M. “Parameters of low flow and data on low flows in selected Irish rivers,” National Hydrology Seminar 2002;64-70.

Mac Cárthaigh, M. "A Statistical Analysis of River Flows - The Southern Water Resource Region”. An Foras Forbartha. December 1987.

Mac Cárthaigh, M. "Surface Water Resources in Ireland”. Institution of Engineers of Ireland.Module 1, Water Course. Presented 24 March 1999.

MacCarthaigh (1999). Surface water resources in Ireland, paper presented to Inst. Eng. Irl. Water Course, EPA, Dublin, 18 p.

MacCarthaigh, M. (1992). Assessment and forecasting of drought flow conditions in Irish rivers. Paper pres. to Water and Env. Eng. Section, Inst. Eng. Ire. , Nov. 1992, 33p.

Martin, J.V. and Cunnane, C. (1977). Analysis and prediction of low flow and drought volumes for selected Irish rivers. Trans. Inst. Eng. Ire. 101, 1976-77, 21-28.

McCummiskey, L.M. (1981). A review of Ireland’s water resources. Irish J. Env.Sc., 1(2).

Male, J.W., and Ogawa, H. (1982). Low flows of Massachusetts streams. Publication No. 125, Water Resources Res. Centre, Univ. of Massachusetts, Amherst, Mass.

Male, J.W., and Ogawa, H. (1984). Tradeoffs in water quality management. J. Water Resources Planning and Management, ASCE, 110(4) 434 – 444.

Mimikou, M., and Kaemaki, S. (1985). Regionalization of flow duration characteristics. J. Hydrology, 82, 77-91.

Quimpo, R.G., Alejandrino, A.A., and McNally, T.A. (1983). Regionalised flow duration curves for Philippines. J. water Res. Plng. Mgmt., ASCE, 109(4), 320-330.

Natural Environment Research Council/ Institute of Hydrology (1980). Low flow studies report, Wallingford, U.K.

Patel, J.A.(2007). Evaluation of low flow estimation techniques for ungauged catchments. Water and Environment Journal, 21(2007) 41-46.

Smahtkin, V.U. (2001). Low flow hydrology: a review. J.Hydrol., 240, 147-186.

Smyth, A.J. (1984) An analysis of low flow data. M.Eng.Sc. Thesis. University College Galway. 171 p + x Annexes.

Searcy, J.K. (1959). Flow-duration curves. Water Supply Paper 1542-A, U.S. Geological Survey, reston Virginia.

Vogel, R.M., Fennessey, N.M(1994). Flow-duration curves. I: new interpretation and confidence intervals. Journal of Water Resources Planning and Management, ASCE 1994:120(4):485-504.
Vogel R.M., Fennessey N.M(1995). Flow-Duration Curves. II: A review of Applications in water resources planning. Water Resources Bulletin 1995:31(6):1029-39.