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CHAPTER-5

DEVELOPMENT OF REGIONAL FLOW DURATION CURVES FOR UNGAUGED BASINS

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CHPATER-5

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5.0 INTRODUCTION

A flow-duration curve is simply the cumulative distribution function of daily streamflows at a site. Flow-duration curves were used widely during the first half of this century .Evidence of their widespread use is provided by Foster's (1934) description of flow-duration curves as one of the three most familiar graphical tools available to the hydrologist, the other two tools being the hydrograph and the mass curve. The first use of a flow-duration curve is attributed to Clemens Herschel in about 1880. Flow-duration curves have been advocated for use in hydrologic studies such as hydropower, water supply, and irrigation planning and design (Chow 1964). In perhaps the most complete manual on flow-duration curves ever written, Searcy (1959) describes additional applications to stream-pollution and water-quality management problems. Although most of the articles on flow-duration curves were written during the first half of this century , current textbooks still contain discussions pertaining to this important tool (Gupta 1989).

Complex interactions between precipitation inputs and landscape characteristics, such as geology, soil, topography and vegetation, have an influence on hydrological responses (McNamara *et al.*, 1998; Post & Jones, 2001). Indeed, one can view hydrological response as an indicator of how catchments transfer precipitation inputs into streamflow. Precipitation inputs, particularly rainfall and snow, are widely recognized as forcing factors that control hydrological responses. These important hydrometeorological descriptors are used as input variables in many hydrological models. However, techniques to identify and quantify those landscape descriptors that strongly influence hydrological response at the catchment scale are still lacking. To quantify the relationship between basin characteristics and hydrological descriptors, many investigators have developed single indices such as mean annual flow (Reimers, 1990), baseflow index (Nathan & McMahon, 1990; Lacey & Grayson, 1998), *Q*95 (Laaha & Blöschl, 2007), runoff ratio (Berger & Entekhabi, 2001), and baseflow recession curve characteristics (Zecharias & Brutsaert, 1988).

Prediction of continuous streamflow time series remains uncertain (Wagener & Wheater, 2006) although progress has been made for predicting indices like mean annual flow or extreme flow values. However, complete flow duration curves can provide more useful and detailed information than such indices. Flow duration curves (FDCs) incorporate the relationship between the frequency and magnitude of streamflow (Vogel & Fennessey, 1995). They also integrate the combined impacts of climate, geology, geomorphology, soils and vegetation, as well as flow regulation by dams and diversions; they are, therefore, useful in comparing runoff characteristics of different land-use areas at the catchment scale (Linsley *et al.*, 1949; Searcy 1959; Pearce, 1990; Sugiyama *et al.*, 2003). In general, FDCs sort out streamflow data by shifting high flows with high precipitation signals to one end of the curve, medium flows to the middle, and low flows (presumably with low precipitation signals) to the other end of the curve. According to

Fennessey & Vogel (1990), FDC applications should be limited to problems in which the sequential nature of streamflow is not important, thereby acknowledging FDC limitations for many reservoir operations issues. Castellarin *et al.* (2004) reviewed regionalization approaches to predict FDCs and classified these estimation procedures into statistical (Leboutillier & Waylen, 1993; Yu & Tang, 2000; Singh *et al.*, 2001; Yu *et al.*, 2002; Croker, *et al.*, 2003; Claps *et al.*, 2005), parametric (Quimpo *et al.*, 1983; Mimikou & Kaemaki, 1985) and graphical approaches (Smakhtin *et al.*, 1997). Since most locations where flow-duration curves are required are not coincident with stream gages, this lecture focuses on the development of flow-duration curves for ungauged sites.

5.1 FLOW-DURATION CURVES FOR WATER AVAILABILITY COMPUTATIONS

The flow duration curve is the most basic form of data presentation. It shows graphically the relationship between any given discharge and percentage of time that discharge is exceeded. The curve can be drawn from daily or monthly flow data or for any consecutive N day or month period. Thus the flow duration curve is simply the cumulative frequency distribution function of average stream flows occurring during a specified interval of time.

A typical flow duration curve wherein the daily discharge values (Q) are plotted against the percent time (P) or probability of exceedance on arithmetic scale graph paper. However, semi-log or log-log paper may also be used depending upon the range of data and use of the plot. The ordinate Q_p at any percentage probability P represents the flow magnitude in an average year that can be expected to be equalled or exceeded P per cent of time and is termed as P% dependable flow. For a perennial river Q_{100} = 100% dependable flow is a finite value. On the other hand in an intermittent or ephemeral river the streamflow is zero for a finite part of an year and as such Q_{100} is equal to zero.

Methodology for the development of flow duration curve depends upon the availability of streamflow data at the site under consideration. In case the adequate records of streamflow are available at the site, the flow duration curves may be easily developed analysing those records. However, for the ungauged sites or sites having inadequate stream flow data the regional flow duration curves are developed and utilized for the estimation of available water resources.

5.1.1 Data Requirements for Development of Flow Duration Curves

The length of data required for the development of flow duration curves depend upon the type of scheme, type of development and variability of inputs. General guidelines regarding the minimum length of data required for some of the projects are given below:

The above guidelines are only illustrative and not exhaustive. Sometime the rainfall records are available for along period, however, the runoff records are available for short period. In such a situation the rainfall-runoff relationships may be developed based on the available rainfall-runoff records for the concurrent period. Then these relationships are used to generate the long term runoff records corresponding to the available long term rainfall records. Many a time, all such data are not generally available and it becomes necessary to use data of nearby site(s) also. Considering these aspects, the data requirements for major water resources projects may be summarised as:

Table 5.1 The minimum length of data required for some of the projects

	Type of Project	Minimum length of data
(i)	Diversion project	10 yrs.
(ii)	Within the year storage projects	25 yrs.
(iii)	Over the year storage projects	40 yrs.
(iv)	Complex system involving combination of above	Depending upon the predominant element

(a) Streamflow data of the desired specific duration (daily, 10-daily, or monthly, etc.) at the proposed site for at least 40 to 50 years, or

(b) Rainfall data of specific duration for at least 40 to 50 years for raingauge stations influencing the catchment of the proposed site as well as streamflow data of specific duration at the proposed site for the last 5 to 10 years, or

(c) Rainfall data of specific duration for the catchment of the proposed site for the last 40 to 50 years and flow data of the specific duration and concurrent rainfall data of the existing work located at upstream or downstream of the proposed site for the last 5 to 10 years or more; or

(d) Rainfall data of specific duration for the catchment for the last 40 to 50 years for the proposed site and flow data and concurrent rainfall data of specific duration at existing works on a nearby river for 5 to 10 years or more, provided orograhic conditions of the catchment at the works are similar to that of the proposed site.

In case the flow data are not virgin because of construction of water resources projects upstream of the gauging site, the operational data such as reservoir regulation which include the outflows from spillway and releases for various uses, etc. is required. If the flow data time series consists of the records for the period prior as well as after the construction of the structure, the flow series is considered to be non-homogeneous. Necessary modifications have to be made to the records in order to make them homogeneous.

For the development of flow duration curve and computation of dependable flows for ungauged catchments some important catchment and climatic characteristics are required. The catchment characteristics are derived from the toposheet covering the drainage area of the catchment. The basic statistics such as mean, standard deviation, etc. of the rainfall data represent the climatological characteristics.

5.1.2 Development of Flow Duration Curves

(a) **Case 1:**

For gauged catchments if the data available corresponds to the situation (a), as discussed in section above, the flow duration curves from daily flow data may be developed in the following steps:

(i) Choose a constant width class interval (ci) such that about 25 to 30 classes are formed;

(ii) Assign each day's discharge to its appropriate class interval;
(iii) Count the total number of days in each class interval.
(iv) Cumulate the number of days in each class interval to get the number of days above the lower limit of each class interval.
(v) Compute the probabilities of exceedance dividing the quantities obtained from step (iv) by the total number of days in the record (for example 365 if one year record is considered for the construction of flow duration curve).
(vi) Multiply the probabilities of exceedance obtained from step (v) by 100 to get percentage exceedance.
(vii) Plot the probabilities of exceedance in percentage against the corresponding lower bound of class interval on linear graph paper. Sometimes the flow duration curve better approximates to a straight line if log normal probability paper is used in place of linear graph paper.

(b) **Case 2:**

In case the data items are not sufficient enough to define the class intervals, the flow duration curves (from monthly flow data or any other duration larger than daily) may be developed in the following steps:
(i) Arrange the flow data in descending order;
(ii) Assign the probability of exceedances to each data item obtained from step (i) using the Weibull plotting position formula:

$$P = \frac{m}{N+1} x\ 100 \tag{20}$$

where m = 1 for the highest flow values and N is the number of data items (or variate).

Note: If the flow duration curve is required to be linearized on normal probability paper or log normal probability paper, the probability of exceedences may be assigned using the Blom's Plotting position formula:

$$P = \frac{m - 0.375}{N + 0.250} x\ 100 \tag{21}$$

(iii) Plot the ranked flow values against the probabilities of exceedences (computed using eq. 1) on linear graph paper to get the flow duration curve.

Note: Use normal probability paper, if the required dependable flow (or probability of exceedance) is to be extrapolated. Try to fit either normal distribution or log normal distribution in order to linearized the flow duration curve. Here the probabilities of exceedance may be computed using Eq. 20 for the purpose of plotting. Fitting of other theoretical frequency distribution may also be tried.

(c) **Case 3:**

If the data situation corresponds to (b), as discussed in section on data requirement, the steps involved in development of flow duration curves are as follows:

(i) Develop the rainfall runoff relationship for the specific duration utilising the available data for the concurrent period;

(ii) Compute the long term flow data of the specific duration using the developed relationship at step (i) and long term available rainfall data.

(iii) Develop the flow duration curve either using the procedure stated for Case 1 or for Case 2.

(d) **Case 4:**

If the data availability situation corresponds to either (c) or (d), as discussed in Section on data requirement, the following steps may be followed for the development of the flow duration curve.

(i) Develop the rainfall-runoff relationship for the existing site for the specific duration analysing the available rainfall-runoff records for the concurrent period;

(ii) Develop the flow duration curve using the procedure described either for Case 1 or Case 2.

(iii) Divide the flow values of flow duration curve by the catchment area of the existing project site.

(iv) Multiply the flow values obtained from step (iii) by the catchment area of the proposed site for which the flow duration curve is required to be developed.

5.2 REGIONAL FLOW DURATION CURVES

An accurate assessment of river flow regime is essential for estimating the hydropower potential of a proposed site. The flow duration curve is a graphical tool which gives an idea about temporal variability of water flow in a very simplistic manner. The flow duration curves for those sites for which adequate flow data are available can be directly developed. For ungauged catchments estimation of dependable flow may be accomplished by using the regional flow duration curve which is intended to be developed for a region as a whole. The regional model is evolved on the basis of data available for a few gauged sites in the same region or transposed from similar region in its vicinity. The regional model is then employed for developing the flow duration curve for any ungauged location of interest within the region. There is an extensive literature available on low flow processes, in particular the surface or groundwater interaction and description of the low flow regime of individual basins. However, relatively little work has been reported on techniques for estimating low flow measures at ungauged sites. Synthesis of flow-duration curves for ungauged locations on unregulated streams in New Hampshire, Northern New England was presented by Dingman S. L. (1978). Low Flow Study report of Institute of Hydrology, UK (NERC, 1975) summarizes the main conclusions of low flow estimation procedures for United Kingdom rivers. The revision of these estimation procedures for ungauged sites has been published as Low Flow Estimation in the United Kingdom, Institute of Hydrology Report No. 108 (1990). The principal advance in the development of the estimation procedures in the revised report has been the application of the provisional Hydrology of Soil Types (HOST) response classification.This classification related the physical properties of soil and geology mapping units to the low flow response of gauged catchments.

Present practice, in India, is to estimate water availability on an individual cases basis. In absence of any historical data and nearby gauging stations, developers carry out a programme of occasional adhoc flow measurements over a relatively short period of about 2 to 5 years. The data collected are assumed to be representative of flow conditions at the site and are used as the basis of the hydropower potential calculations. Carrying out these investigations significantly delays implementation of a project. A procedure for developing the regional flow duration model is described hereunder.

5.3 Development of the Regional Flow Duration Model

(i) Non-dimensionalise the average ten daily flow data series (Q_i) for each catchment by dividing each data value in the series by its respective long term average (Q_{mean}) to get the flow series in terms of mean flow (Q_i/Q_{mean}).

(ii) Pool up the non-dimensionalised flow data series of all the gauged catchments into one series and evaluate the basic characteristics of this series to see if the series is normally distributed. In case the series is not normally distributed, transform the pooled up series using power transformation into another series which has the characteristics of normally distributed series. This is done as explained below:

Let Q and W imply the corresponding elements of original and the transformed series respectively. Power transformation is achieved using the transformation formula given by:

$$W = (Q^{\lambda} - 1)/\lambda \qquad \text{when } \lambda \neq 0 \tag{5}$$

and

$$W = \ln(Q) \qquad \text{when } \lambda = 0 \tag{6}$$

here, λ is an exponent which may either be obtained by trial and error procedure or any other suitable optimisation technique so as to give a normalised W series. The W series is considered to be a near normalized series for that value of λ which reduces the coefficient of skewness of W series to nearly zero and maintains the coefficient of kurtosis as 3. Thus, for a region the value of parameter λ is obtained.

(iii) The statistics like mean (μ_W) and standard deviation (σ_W) of the transformed series W are estimated using maximum likelihood method.

(iv) Using the normal probability distribution, estimates of the flows in transformed domain (W_D) for any desired level of dependability D are made. For this purpose, first the standardized flow (Z_D) corresponding to any probability level (D) may be obtained by using widely available table for frequency factors for standard normal distribution (μ=0, σ=1). This standard flow is converted for the case of a series having mean and standard deviation as $\square_W$ and σ_W respectively by using the transformation:

$$W_D = \mu_W + Z_D \sigma_W \tag{7}$$

(v) Since, the estimates of flow (in terms of mean flow) at step (iv) are in the transformed domain they are brought to the original domain by using the inverse transformation as:

$$\left(\frac{Q}{Q_{mean}}\right)_D = [W_D \lambda + 1]^{\frac{1}{\lambda}} \qquad \text{when } \lambda \neq 0 \tag{8}$$

and

$$\left(\frac{Q}{Q_{mean}}\right)_D = \exp[W_D] \qquad \text{when } \lambda = 0 \tag{9}$$

(vi) A relationship between catchment area (A) and the corresponding long term average flow (Q_{mean}) is established in the form:

$$Q_{mean} = C_1 A^2 + C_2 A \tag{10}$$

Here, C_1 and C_2 are the coefficients which are obtained by regression analysis.

(vii) Now, Q_{mean} for any ungauged catchment in the region may be obtained by the regional relationship established at step (vi). Value of Q_{mean} when multiplied by the factor $(Q/Q_{mean})_D$ obtained at step (v) gives the required D% dependable flow (Q_D) for that ungauged catchment.

(viii) The steps from (v) to (vii) may be repeated to obtain the flow corresponding to any desired level of dependability for any ungauged catchment within the region.

Thus, the regional model may be evolved for any region of interest and then subsequently employed for estimation of the flows for desired levels of dependability for any ungauged catchment located within the region. It is expected that this kind of regional flow duration model would be very useful in reducing the gestation period for individual projects. While, the regional model is primarily concerned with hydropower development, it is also a key requirement for water resource planning and estimating the water available for public water supplies, irrigation and dilution of industrial and domestic effluent. The above methodology has been used for development of regional flow duration curves for evaluation of hydropower potential in the Himalayan region.

5.3.1 Some Case Studies:

Many models have been developed for simulating flow records in recent years, e.g. HSPF , SWRRB but most are unsuited to general use on ungauged catchments unless the purpose of the application has large economic consequences, since they have large input data demands and the resources required to assemble the necessary data may be more than can be committed for the whole design or planning exercise. Examples of such exercises would be the development of a mini-hydropower scheme, design of a drought protection irrigation scheme for a few farms, or development of a surface water supply for household use in a small village. For such projects only a few person-days of effort can be devoted to design. Use of models such as HSPF would require far more time just to assemble the input data.

A few simple models have also been developed for estimating runoff volumes on ungauged catchments. Those authors built their models for specific purposes, with assumptions (and limitations) to suit the specific needs. Some of those models are used for small catchments or urban areas, some of them need laboratory and field experiments to support the input data, some use many parameters needing an optimization technique to determine the model parameters, and some are based only on statistical relationships. In spite of contrary claims for some models, all models need recalibration when applied in regions other than those for which they were developed. Experience has shown that runoff production is dependent on such a large range of climatic and geomorphological factors that it has not yet been possible to develop runoff or hydrograph models that are so capable of mimicking the real process that they do not need local calibration or verification.

A simple rainfall-runoff model (Ibrahim & Cordery, 1995) was developed to predict runoff volumes from ungauged catchments is presented. The parameters of the model are determined from easily measured catchment characteristics and other generally available data. The model was calibrated and tested using a wide range of catchments in New South Wales.

A hydrological model was calibrated by Mwakalila (2003) to 19 semi-arid catchments of the Great Ruaha basin in south-western Tanzania to obtain a set of parameters that efficiently characterise the hydrological response of a catchment. Physical catchment properties indexing topography, geology, climate and land use were collated using Geographical Information System and linked to the calibrated parameter values. The resulting quantitative relationships were assessed with respect to their value for estimating the parameter values of the model and the streamflow. The relationships indicated to be robust enough to reproduce hydrological response of the catchment. Hydrological model parameters were satisfactorily estimated for four validation catchments within the region using physical catchment properties. The results indicated that the technique is likely to offer a viable method for estimating flows of ungauged semi-arid catchments and the impact of land use and climate change on water resources.

Arora et al (2005) predicted the flows at ungauged sites of a Himalayan basin. For this study, the daily flow data of 11 gauging sites varying from 14 years to 23 years in the Chenab river basin were utilised. The other important information related to the physiography, hydrology and meteorology etc for the region were derived from the available literature and maps. The daily flow data of nine gauging sites were utilised for developing the regional relationships for water availability computations. These relationships were tested over the remaining two gauging sites. The regional relationships were developed using three different approaches. These approaches include (i) parameter regionalisation for individual gauged sites of selected probability distribution, (ii) regionalisation of dependable flows and (iii) parameter regionalisation for the region as whole of selected probability distribution.

5.4 REMARKS

Flow duration curve is a simple graphical depiction of variability of water flow at a location without any reference to the sequence in which this flow would be available. Flow duration curve for the site for which adequate flow data is available can be directly developed. Flow for various levels of dependability for gauged site may be estimated from this curve. It is quite obvious that most of the prospective sites for hyrdo-power projects are likely to be ungauged. For such potential sites, there are either insignificant data or no flow data available for such analyses.

To derive a flow duration curve for a location on a stream for which adequate flow data are not available, Regional flow duration curve may be used. Regional flow models are developed on the basis of data available for a few other gauged catchments in the same region or transposed from similar nearby region. Such models are employed to compute flow duration curves for ungauged catchments in that region. Availability of such regional flow duration models is of paramount significance in estimating the flows at ungauged sites.

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