Training Course

On

Hydrological Processes in an Ungauged Catchment

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CHAPTER-6

Development of Regional Flow Duration Curves for Ungauged Basins

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CHPATER-6

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6.0 INTRODUCTION

A flow-duration curve (FDC) is simply the cumulative distribution function of daily streamflows at a site. Flow-duration curves were used widely used all over, and 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 are given in Chow (1964) and Institute of Hydrology (1980). 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). 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 (Fennessey and Vogel, 1990).

Complex interactions between precipitation inputs and landscape characteristics, such as geology, soil, topography and vegetation, have an influence on hydrological responses (Sefton and Howarth, 1998). 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 hydro-meteorological descriptors are used as input variables in many hydrological models. To quantify the relationship between basin characteristics and hydrological descriptors, many investigators have developed single indices such as mean annual flow, baseflow index, *Q*95, runoff ratio, and baseflow recession curve characteristics.

Prediction of continuous streamflow time series remains uncertain, 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 as it incorporate the relationship between the frequency and magnitude of streamflow (Vogel & Fennessey, 1994). 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.*, 1975). 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 Vogel & Fennessey (1994), 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. 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.

6.1 FLOW-DURATION CURVES FOR WATER AVAILABILITY COMPUTATIONS

The flow duration curve shows graphically the relationship between any given discharge and percentage of time that discharge is exceeded. This 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* i.e. generally denoted as partially or semi gauged sites, the regional flow duration curves are developed to apply this curve within a hydro-homogeneous region.

6.1.1 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 in Table 6.1. The guidelines are only illustrative and not exhaustive, as sometime the rainfall – runoff records at a given project site does not match for concurrent period or may be qualitatively in coherent. In such a situation the rainfall-runoff relationships may be developed based on the available rainfall-runoff records for the

Table 6.1 The minimum length of data required for some of the projects

Case	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

concurrent period, and 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 follows:

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,

b) or 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 stream flow 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 cases where 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. are required. If the flow data time series consists of the records for the period prior as well 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.

6.1.2 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:

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

2) Assign each day's discharge to its appropriate class interval;

3) Count the total number of days in each class interval.

4) Cumulate the number of days in each class interval to get the number of days above the lower limit of each class interval.

5) Compute the probabilities of exceedance dividing the quantities obtained from step (iv) by the total number of days in the record e.g. 365 if one year record is considered for the construction of flow duration curve.

6) Multiply the probabilities of exceedance obtained from step (5) by 100 to get percentage exceedance.

7) 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 using monthly flow data or any other duration larger than daily may be developed in the following steps:

1) Arrange the flow data in descending order;

2) Assign the probability of exceedances to each data item obtained from step (1) using the Weibull plotting position formula:

$$P = \frac{m}{N+1} x\, 100 \qquad (6.1)$$

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:

$$P = \frac{m - 0.375}{N + 0.250} x\, 100 \qquad (6.2)$$

3) Plot the ranked flow values against the probabilities of exceedences computed using eq. 6.1) 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. 6.2 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 6.1.1 under data requirement, the steps involved in development of flow duration curves are as follows:

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

2) Compute the long term flow data of the specific duration using the developed relationship at step (1) and long term available rainfall data.

3) 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 6.1.1 under data requirement, the following steps may be followed for the development of the flow duration curve.

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

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

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

4) Multiply the flow values obtained from step (3) by the catchment area of the proposed site for which the flow duration curve is required to be developed.

6.2 REGIONAL FLOW DURATION CURVES

The development of a flow duration curve for sites having adequate flow data can directly developed as discussed in the last section. However, flow duration derivation is somewhat different as the last one for ungauged or partially gauged sites. For such cases, the *regional flow duration curve* is to be developed for a region as a whole. This is because 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. This approach has been applied considering twelve hundred small catchments in Himalayan regions, where the data circumstances in the catchments were either partial or ungauged (Singh et al., 2001).

In India, the present practice is to estimate water availability on an individual cases basis if there is a case with absence of any historical data and nearby gauging stations. In such cases, developers carry out a programme of occasional *adhoc* flow measurements over a relatively short period of about 2 to 5 years, and the data collected are assumed to be representative of flow conditions at the site. A procedure for developing the regional flow duration model is described hereunder.

1) 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}).

2) 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:

   $$W = (Q^{\lambda} - 1)/\lambda \qquad \text{when } \lambda \neq 0 \qquad (6.3)$$

   and $$W = \ln(Q) \qquad \text{when } \lambda = 0 \qquad (6.4)$$

   here, λ is an exponent which may either be obtained by trial and error procedure or any other suitable optimization technique so as to give a normalized 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.

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

4) 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 μ_W and σ_W respectively by using the transformation:

   $$W_D = \mu_W + Z_D \sigma_W \qquad (6.5)$$

5) Since, the estimates of flow in terms of mean flow at step (4) are in the transformed domain they are brought to the original domain by using the inverse transformation as:

$$\left(\frac{Q}{Q_{mean}}\right)_D = [W_D \lambda + 1]^{\frac{1}{\lambda}} \qquad \text{when } \lambda \neq 0 \qquad (6.6)$$

and

$$\left(\frac{Q}{Q_{mean}}\right)_D = \exp\,[W_D] \qquad \text{when } \lambda = 0 \qquad (6.7)$$

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

$$Q_{mean} = C_1 A^2 + C_2 A \qquad (6.8)$$

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

7) Now, Q_{mean} for any ungauged catchment in the region may be obtained by the regional relationship established at step (6). Value of Q_{mean} when multiplied by the factor $(Q/Q_{mean})_D$ obtained at step (5) gives the required D% dependable flow (Q_D) for that ungauged catchment.

8) The steps from (5) - (7) 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.

Example 6.1

Average monthly flow data for the month of June of a river catchment is available for 10-years. Deduce the flow duration curve for this month.

Table 6.2 Monthly flow data for 10-years in column-1

Flow vol. (TCM)	Probability of exceedance (P)	
	$P = \frac{m}{N+1} x\ 100$ using Weibull plotting position	$P = \frac{m - 0.375}{N + 0.250} x\ 100$ using Blom's plotting position
314.45	9.09	6.10
257.62	18.18	15.85
222.62	27.27	25.61
142.52	36.36	35.37
131.49	45.45	45.12
130.16	54.55	54.88
130.03	63.64	64.63
127.50	72.73	74.39
113.04	81.82	84.15
109.58	90.91	93.90

Example 6.2

Annual average l flow data for the 10 years are available for a catchment. The volumetric rainfall-runoff relationship for the catchment is given as $Q= 0.472\ (P - 600)^{1.043}$, where P is the annual average rainfall. Deduce the flow duration curve.

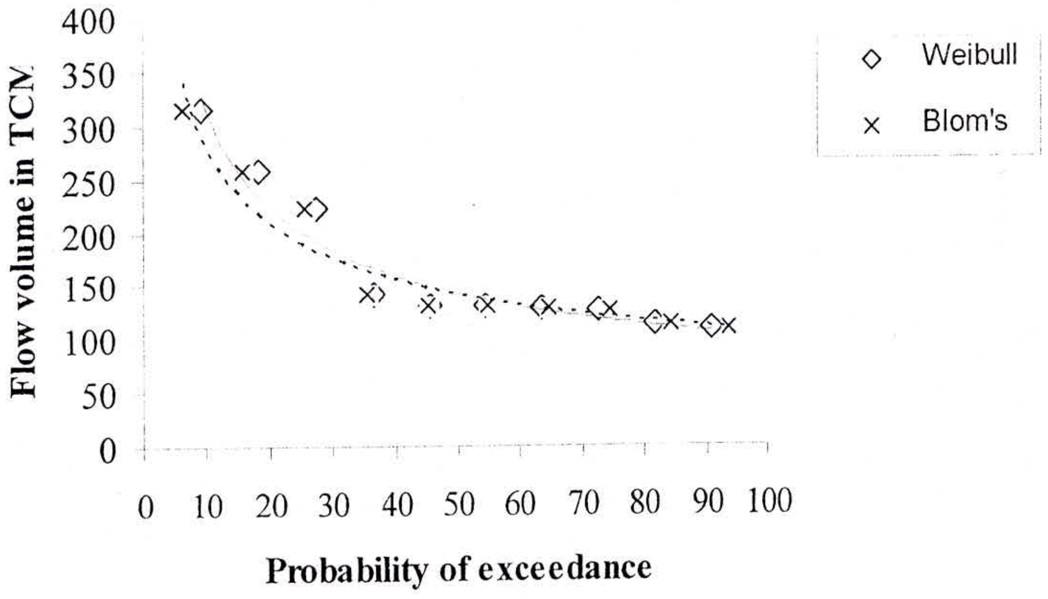

Fig. 6.1 Flow Duration Curve for Example 6.1

Table 6.3 Annual average flow data for the 10 years in column-1

Flow (TCM)	Rainfall (mm)	Probability of exceedance (P)	
		$P = \frac{m}{N+1} x\, 100$ using Weibull plotting position	$P = \frac{m - 0.375}{N + 0.250} x\, 100$ using Blom's plotting position
111.34	-	6.67	4.10
106	-	13.33	10.66
97.43	-	20.00	17.21
81.56	-	26.67	23.77
81.16	-	33.33	30.33
79.1	-	40.00	36.89
78.32	-	46.67	43.44
73.42	-	53.33	50.00
73.12	-	60.00	56.56
70.42	-	66.67	63.11
65.06248	*123*	73.33	69.67
59.17295	*121*	80.00	76.23
50.38459	*118*	86.67	82.79
30.1454	*111*	93.33	89.34

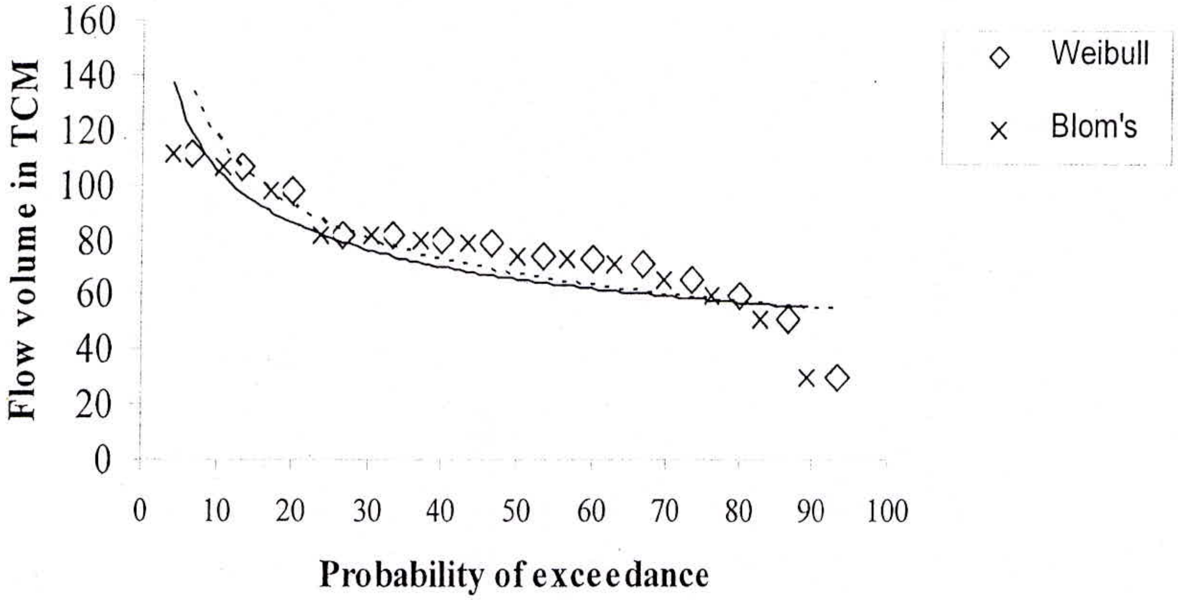

Fig. 6.2 Flow Duration Curve for Example 6.2

EXAMPLE 6.3

Mean monthly flows along with catchment area, and length of stream for 5 catchments in a homogeneous region are given in Table-6.4. Derive a flow duration curve and compute the 75 % dependable flow in an ungauged catchment in the region having a catchment area of 1000 Sq. km and stream length equal to 60 km.

Table 6.4 Mean monthly flows in cumecs

Catchment-1	Catchment-2	Catchment-3	Catchment-4	Catchment-5
24	17	9	21	11
14	22	17	29	22
18	23	23	33	32
35	37	54	65	41
37	23	68	132	33
46	56	143	156	76
67	69	243	123	78
100	112	116	98	198
57	58	98	78	76
32	44	56	45	44
22	13	23	33	34
12	10	17	11	10

	Catchment-1	Catchment-2	Catchment-3	Catchment-4	Catchment-5
A (km^2)	450	520	1034	546	475
L(km.)	50	53	65	57	43
Q_{mean}(m^3/s)	38.66	40.3	72.35	68.7	54.58

The Q_{mean}-value is given at the end of the table. The parameters of the normal distribution of Q/Q_{mean} is; $\mu = 1$, $\sigma = 0.78$. The standard variates of normal distribution for different probability-values given in Table-6.5 (Singh, 1988). Using Eq.(6.5):

$$Q/Q_{mean} = \mu + Z\,\sigma$$

Table 6.5 Standard variates of normal distribution for different Probability exceedance

p	X	p	X
0.1	1.7	0.6	1.31
0.2	1.62	0.7	1.23
0.3	1.55	0.8	1.16
0.4	1.47	0.9	1.08
0.5	1.39		

To get the flow duration curve for the ungauged catchment, the X-p values of Table-6.5 are used along with the regional curve obtained using a multiple regression of A, L an Q_{mean} given in the Table 6.4.

$Q_{mean} = 1.72\ A^{0.5}\ L^{0.07},\ R^2 = 0.6$

Q_{mean} for the ungauged catchment = 72.5 m^3/s. Multiplying Q_{mean} obtained above to values of X in Table-2 gives the dependable flows for various probabilities (Table-6.6).

Table 6.6 Standard dependable flows for various probabilities

P	X (m^3/s)	P	X (m^3/s)
0.1	123.225	0.6	94.9888
0.2	117.578	0.7	89.3416
0.3	111.93	0.8	83.6944
0.4	106.283	0.9	78.0472
0.5	100.636		

6.3 USE OF FLOW DURATION CURVES

According to the current practice, the irrigation projects are planned using 75% dependable flow. Hydropower and drinking water projects are planned with 90% and 100% dependable flows respectively. The 90% value is also used as a measure of ground water contribution to stream flow. This same value can also be used as a measure of the run-of-the river hydropower potential. Other important uses of flow duration curves are:

(i) In evaluating various dependable flows in the planning of water resources engineering projects.
(ii) In evaluating the characteristics of the hydro-power potential of a river.
(iii) In the design of drainage systems.
(iv) In flood control studies.
(v) In computing the sediment load and dissolved solids load of a stream, and
(vi) In comparing the adjacent catchments with a view to extend the stream flow data.

6.4 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 hydro-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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