Regional flow duration curve for a Himalayan river Chenab

Manohar Arora, N.K. Goel, Pratap Singh and R.D. Singh
National Institute of Hydrology, Jal Vigyan Bhawan, Roorkee – 247 667, Uttaranchal, India.
E-mail: *arora@nih.ernet.in*

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Abstract This study is carried out with the objective of examining the effect of altitude on water availability estimates for the various sub-basins of the Chenab river basin (mean elevation of the basin is 3600 m), which is a snow-fed Himalayan river basin located in the western Himalayas. This basin covers all three Himalayan ranges, i.e. outer, middle and greater Himalayas. For this study, the daily flow data of 11 gauging sites varying from 14 years to 23 years in the Chenab river basin are utilised. The other important information related to the physiography, hydrology and meteorology, etc, for the region are derived from the available literature and maps. The daily flow data of nine gauging sites are utilised for developing the regional relationships for water availability computations. These relationships are tested over the remaining two gauging sites. The regional relationships are 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 a whole of the selected probability distribution. The different methods are compared and discussed in detail. It is observed that the flow for a given dependability increases with catchment area and decreases with altitude. The flows of the catchments at higher altitudes exhibit larger variability in comparison to the catchments at lower altitudes. The regional relationships are recommended for the use of field engineers.

Keywords Dependability; digital elevation model; log-normal distribution; parameter regionalisation; physiographic characteristics

Introduction

The planning and development of water resources of a region requires a proper understanding of the hydrological behaviour of the river basins. The analysis of available historical information is necessary to decide about water availability at a site for an accurate estimation of the available water resource. Regionalisation techniques provide a mechanism to relate the hydrological behaviours of gauged catchments in a region. These techniques can be utilised to derive streamflow characteristics at ungauged catchments of the region.

Hydrologists have traditionally sought regional flow duration curves to estimate dependable flows at the sites where no gauge records exist or where gauge records are of very limited length. These flow duration curves help in the design of hydropower projects, water supply and irrigation planning. Other applications include water quality management, river and reservoir sedimentation studies, habitat suitability, low flow augmentation, rainfall–runoff model calibration and indicator of data quality (Vogel and Fennessey 1995; Yu and Yang 2000; Cole *et al.* 2003).

The contribution of several studies published by the National Environmental Research Council (NERC) revealed the paramount importance of regional relationships for low-flow estimation at ungauged sites and, consequently, led to the development of regional flow estimation procedures. Dingman (1978) used the area of the basin and mean elevation of the basin in regression equations to estimate the mean flow and 95% dependable flows. Many authors have used streamflow parameters of flow duration curves and flood frequency curves as criteria for hydrologic regionalisation (Quimpo *et al.* 1983; Cheng 1988; Fennessey and Vogel 1990). Some other flow properties have also been used for hydrologic regionalisation, such as monthly mean flow or peak flows along with their coefficients of variation (Mosley 1981; Tasker 1982; Gottschalk 1985; Bhasker and O'Connor 1989; Burn 1989). Mimikou and Kaemaki (1985) and Demuth (1993) parametrised monthly flow-duration characteristics in terms of mean annual areal precipitation, drainage area, hypsometric fall and length of the main river course from the divide of the basin to the site of interest. Fennessey and Vogel (1990) and Mosley and McKerchar (1993) developed a regional regression equation from information from gauged watersheds to estimate streamflows at ungauged sites. Vogel and Fennessey (1994) have introduced some new nonparametric methods for constructing and interpreting a flow duration curve and associated confidence intervals. Yu *et al.* (2002) investigated the approaches of the polynomial method and index method to uncertainty analysis of regional flow duration curves. Chiang *et al.* (2002) proposed a hydrologic regionalisation scheme for classification of watersheds at gauged sites and a time series model is applied for hydrologic regionalisation. Croker *et al.* (2003) have derived a regionalised model for predicting flow duration curves for ungauged catchments.

The problem of low flow estimation in Himalayan basins becomes more difficult as the rainfall–runoff process in the catchment is very complex and many climatic and physiographical parameters, varying with space and time, control this phenomenon. The snowmelt provides the major contribution to the runoff for the catchments located at high altitude whereas in the catchments at lower altitudes the rainfall significantly contributes to the runoff. Uplift of moisture-laden air currents striking against a mountain barrier provides good precipitation on the windward side. The gradients in the amount and intensity of the precipitation depend on several factors such as topography, strength of the moisture-bearing wind, its moisture content and orientation of mountain range with respect to the prevailing wind direction. Depending upon the relief of a mountain, there may be a continuous increase in precipitation with altitude, and it may begin to decrease above a particular altitude (Singh *et al.* 1995, 1997). Thus, orography plays an important role in precipitation distribution, which varies greatly in space and time within the range of mountains and also from one mountain range to another. Singh *et al.* (1995) studied the seasonal and annual distribution of rainfall and snowfall with elevation for the outer, middle and greater Himalayan ranges of the Chenab basin in the western Himalayas. The rainfall exhibited different trends of variation with elevation on the windward and leeward slopes of these three Himalayan ranges. Seasonal characteristics of rainfall have shown a spillover effect on the leeward side during winter, pre-monsoon and post-monsoon seasons in the outer Himalayas. The role of orography in the middle Himalayas was found to be more pronounced for rainfall in comparison to other ranges. In the greater Himalayan range, it was found that rainfall decreases exponentially with elevation and becomes negligible at elevations beyond 4000 m on the windward side of the greater Himalayan range.

Dhar *et al.* (2000) reviewed the precipitation studies carried out for high altitude regions of the Himalayas. In general, it was found that, near the foothills and adjoining plains of the Himalayas, precipitation is quite high. Precipitation starts decreasing thereafter as one proceeds northward across the Himalayas. It was reported to be a minimum at an elevation of 600–800 m. Thereafter, precipitation again starts increasing as one proceeds northward to higher elevations. The second maximum in the precipitation was reached at an elevation of about 2000–2400 m. The precipitation decreases as one proceeds towards the great Himalayan range in the north beyond this elevation. Thus the precipitation characteristics play an important role in the computation of the flow characteristics. As this characteristic varies with altitude, the effects of these may be indirectly considered, taking altitude as one of the physiographic characteristics in the regional analysis.

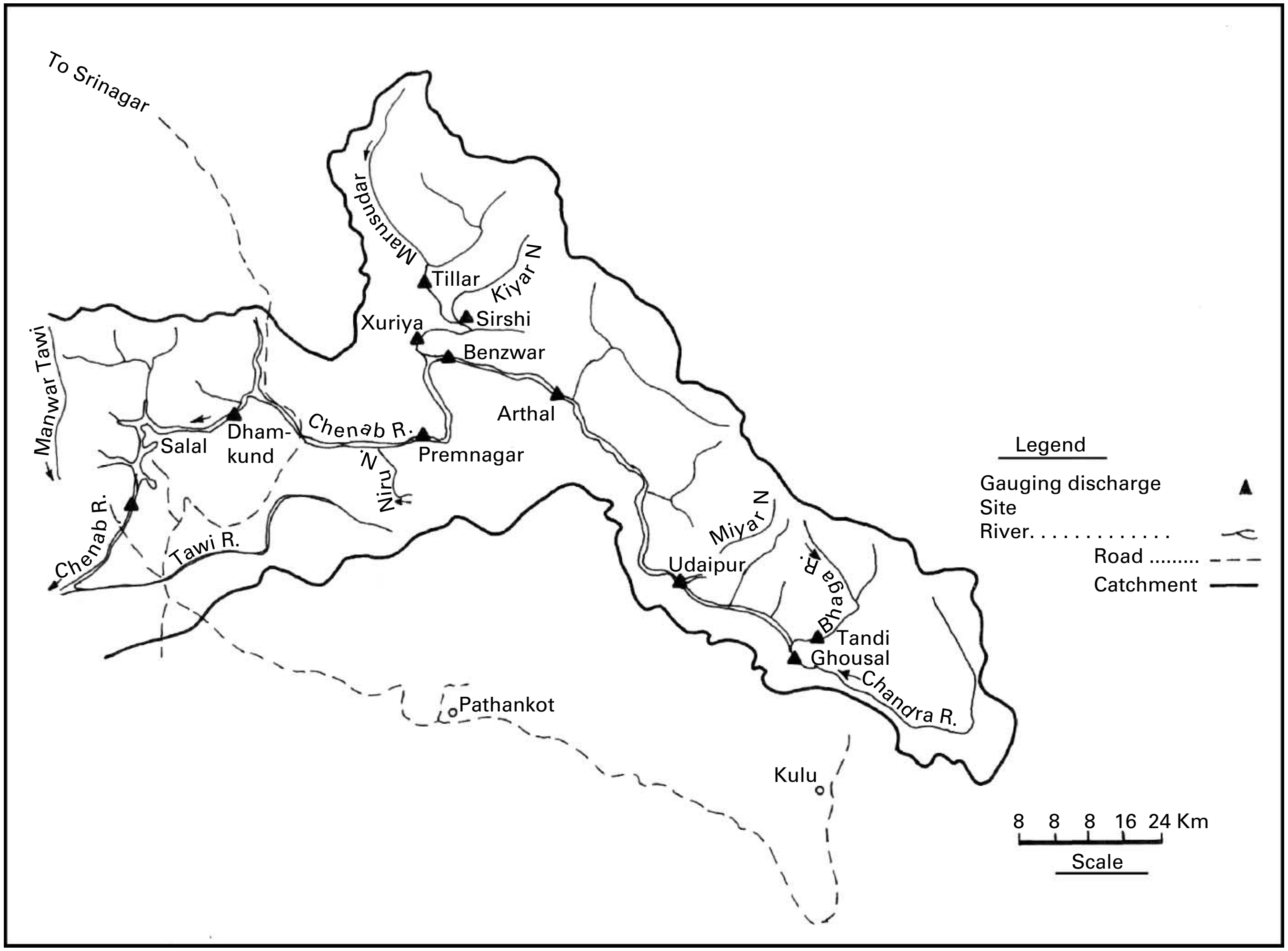

Figure 1 Chenab river basin with location of gauging sites

Besides the rugged topography and limited physical accessibility, the Himalayan basins are also faced with problem of limited data availability. AHEC (1997, 2000) completed a project to develop reliable and consistent methods for estimating the hydrological regime at ungauged sites in the Himalayan and sub-Himalayan regions of India and Nepal in order to assess the hydropower potential of such sites. Singh *et al.* (2001) developed simple regional flow-duration models for a large number of potential micro-hydropower project sites located in 13 states of the Himalayan region (India).

Few studies report on the effect of altitude on the streamflow characteristics of Himalayan rivers. Two examples are studies carried out by NIH (1998) and AHEC (1997, 2000) for the development of regional flow duration curves for the preparation of a zonal plan for small hydropower projects in Himalayan regions. Recently Chalise *et al.* (2003) has given a method for estimation of low flows for the Himalayan basins of Nepal. Regionalisation of the flow has been developed by applying multi-variate regression analysis of long-term hydrometeorological data and catchment characteristics. In this study an attempt has been made to collect and analyse the streamflow data at different altitudes to study the variation of streamflow characteristics with altitude, as well as catchment area, and to develop a regional formula for computation of dependable flows for any ungauged catchment in the Chenab river basin.

Description of study area and data used

The Chenab river is one of the main five tributaries of the great Indus River system. The major part of the Chenab River basin lies in India, while the lower part, including its outfall into the main Indus River, lies in Pakistan. The river passes through two Indian states, Himachal Pradesh and Jammu and Kashmir, where large contributions from snow and glaciers drain into it.

The river Chenab rises in two streams – Chandra and Bhaga – in the Himalayan canton of Lahaul in Himachal Pradesh. The shape of the Chenab basin is elongated. The elevation of the study area varies from about 305–7500 m. The mean elevation of the basin is 3600 m above sea level (asl). The catchment area of the Chenab River up to Akhnoor, the lowermost rain and gauge site in India, is 22 200 km^2. Singh *et al.* (1997) reported that an average snow and glacier melt contribution in the annual flow of the Chenab River at Akhnoor to be about 50%. On average about 70% of the total drainage area of the Chenab basin up to Akhnoor is covered by snow in the months of March–April and about 25% remains covered by snow and glaciers in the months of September–October. The study area along with the location of gauging sites is shown in Figure 1.

The topographical maps published by the survey of India topographical section are at two different scales, i.e. 1:50 000 and 1:250 000. The maps available in 1:250 000 scale have been used for this particular study.

Physiographic data

A contour map of 500 m intervals of the study area was prepared and digitised. Using ILWIS (Integrated Land and Water Information System) software a DEM (Digital Elevation Model) and classification map were prepared. The drainage network of the river system is also digitised and sub-basins were demarcated with the help of DEM. The area for each sub-basin is calculated from the prepared map. The physiographic characteristics such as catchment area (*Ca*), basin relief (*H*) and altitude (*A*) for the eleven gauging sites are given in Table 1. The catchment area varies from 1566–22 400 km^2 and the basin relief varies from 3000–5500 m. The entire catchment has been divided into 11 sub-basins. The sub-basin up to Ghousal, which is the smallest in size, and the sub-basin up to Akhnoor, which is the

Table 1 Physiographic characteristics for various sub-basins

Site no.	Name of sites	Catchment area (*Ca*) (km^2)	Relief (*H*) (m)	Altitude (*A*) (m)
1	Tandi	1566	3000	2850
2	Udaipur	5867	3000	2584
3	Tillar	2602	3000	2070
4	Arthal	9997	3070	1760
5	Shirshi	3383	3025	1680
6	Benzwar	15419	4500	1135
7	Kuriya	4575	4000	1110
8	Premnagar	17061	5000	896
9	Dhamkund	19688	5023	600
10	Ghoushal	2524	3000	2850
11	Akhnoor	22442	5500	310

largest in size, have been chosen as test catchments and the remaining nine sub-basins are considered for calibration purposes.

Discharge data

The daily discharge data observed at different sub-basins varying from 14–23 yr have been used for the analysis.

Methodology

The objective of the study is to develop regional flow duration curves using three different regionalisation methods and compare their relative performance over the eleven sub-basins of the Chenab river basin in order to choose the best method out of the three methods considered. These methods are briefly discussed now.

Regionalisation method I

In this method the relationships have been developed for the mean of flow values in log space as well as for the coefficient of variation of flow values in log space, correlating them with the important physiographic characteristics of the catchment such as catchment area (*Ca*), altitude (*A*) and Ca/A^2. The forms of the relationship developed are given below:

$$\bar{y} = a_1(X)^{b_1} \tag{1}$$

$$CV_y = a_2(X)^{b_2} \tag{2}$$

where $\bar{y}$ and CV_y represent the mean and coefficient of variation of the flow values in log space, respectively. a_1, b_1, a_2 and b_2 are the coefficients. X represents the physiographic characteristics. The computed value of $\bar{y}$ is multiplied by CV_y to get the standard deviation in the log domain for the selected catchment. The regional formula is derived in the appendix. The regional formula developed for the computation of dependable flow is

$$Q_D = K_1^{(X)^{b_1}} * K_2^{(X)^{c_1} Z_D} \tag{3}$$

where Z_D represents the normal reduced variate corresponding to the $D\%$ dependability and Q_D is the $D\%$ dependable flow.

Regionalisation method II

In this method of regionalisation different regional relationships have been developed for correlating the dependable flow with the physiographic characteristics. The form of the relationship is

$$Q_D = a_3(X)^{b_3} \tag{4}$$

where Q_D is dependable flows for given dependability, a_3 and b_3 are the constants and X represents the physiographic characteristics used.

Regionalisation method III

In this method the ratios of the observed daily flows to the at-site mean are computed in order to get the non-dimensional flow values at different gauging sites. These non-dimensional flow values for the nine gauging sites are pooled together to represent a population of the non-dimensional flows for the region. The two-parameter log normal distribution is fitted with the pooled data of non-dimensional flows. The form of the relationship developed is given as

$$\log \frac{Q_D}{\bar{Q}} = a_4 + b_4 Z_D \tag{5}$$

where Q_D represents the dependable flows corresponding to $D\%$ dependability and Z_D represents the corresponding normal reduced variate.

The mean flow ($\bar{Q}$) is correlated with the physiographic characteristics in the following form:

$$\bar{Q} = a_5(X)^{b_5} \tag{6}$$

where X represents physiographic characteristics and a_5 and b_5 are the constants.

For the comparison of the performance of the above regionalisation method, percentage absolute errors in dependable flows (PAEDF) are computed for each of the three methods using the relationship

$$PAEDF = \left| \frac{Q_D - \hat{Q}_D}{Q_D} \right| \times 100 \tag{7}$$

where Q_D represents the dependable flow corresponding to $D\%$ dependability computed from the historical daily flow data. $\hat{Q}_D$ represents the $D\%$ dependable flow computed using any one of the three regionalisation methods. The values of PAEDF are computed for each of the eleven sub-basins corresponding to each dependability considered.

Analysis and discussion of results

The physiographic characteristics, given in Table 1, are correlated among each other. The cross-correlation has been computed among various physiographic characteristic considering nine catchments. The cross-correlation between relief (H) and altitude (A) is -0.87. It indicates a high correlation between the altitude and relief. Furthermore the cross-correlation between the catchment area (Ca) and altitude is -0.79 whereas it is 0.91 between the catchment area and relief. It indicates that the catchment area is highly correlated with relief in comparison to the altitude. In view of this the catchment area and altitude are considered for the regional analysis. A non-dimensional measure Ca/A^2 is computed for each of the sub-basins. This non-dimensional measure is considered as an independent variable for regression. The values of Ca/A^2 vary from 193 to 54 688. The basic statistics such as mean, standard deviation, coefficient of variation and coefficient of skewness computed from the available historical flow data at respective gauging sites in real space as well as in log space are given in Table 2. The mean and standard deviation of daily flow data vary from 54 cumec to 870 cumec and from 65 cumec to 900 cumec, respectively. The coefficient of variation represents the non-dimensional measure of spread whereas the coefficient of skewness represents the non-dimensional measure of symmetry. The values of the coefficient of variation and coefficient of skewness, computed from the daily flow data at different gauging sites, vary from 0.97–1.17 and 1.27–5.45, respectively. Since the values of the coefficient of skewness are very high, the normal distribution may not be used for water availability analysis. The sample statistics such as mean, standard deviation, coefficient of variation and coefficient of skewness are computed from the log transformed values of the daily flow (log base to e) for each gauging site. The values of mean and standard deviation in log domain vary from 3.3–6.3 and 1.0–1.2, respectively. The values of the coefficient of variation and coefficient of skewness in log domain vary from 0.15–0.34 and 0.15–0.52, respectively. Figure 2 shows the probability plots for four catchments (catchment No. 1, 3, 9 and 11). In this figure the log of the daily flow is considered on the Y axis and the normal reduced variate on the X axis. The daily flow data exhibited high skewness. When this series was transformed to a log transformed series the skewness was reduced and it is observed that the daily flow data are clustered around a straight line on log normal probability plots. Similar plots were prepared for the remaining five catchments (not presented here) and it is found that the daily flow data of those catchments also follow a log normal distribution.

Analysis using regionalisation method I

In this method the following relationships have been developed between the mean of flow values in log space with the important physiographic characteristics of the catchment such as catchment area (Ca), altitude (A) and Ca/A^2:

$$\bar{Y} = 45.604(A)^{-0.31} \quad (r = -0.83) \tag{8}$$

$$\bar{Y} = 0.8352(Ca)^{0.20} \quad (r = 0.95) \tag{9}$$

$$\bar{Y} = 2.2255(Ca/A^2)^{0.10} \quad (r = 0.94) \tag{10}$$

The relationships have also been developed between the coefficient of variation (CV_y) computed in log space and physiographic characteristics such as catchment area (Ca),

Table 2 Basic statistics of daily mean flow data in real and log domain

Site no.	Name of sites	In real space				In log space			
		Mean (cumec)	S.D. (cumec)	*Cv*	Skew	Mean (cumec)	S.D. (cumec)	*Cv*	Skew
1	Tandi	54.0	65.1	1.2	1.76	3.3	1.1	0.34	0.52
2	Udaipur	221.7	271.7	1.23	5.45	4.8	1.1	0.23	0.45
3	Tillar	108.9	113.6	1.04	1.7	4.2	1.0	0.24	0.31
4	Arthal	372.5	424.0	1.14	1.32	5.2	1.2	0.23	0.36
5	Shirshi	163.1	174.8	1.07	1.45	4.5	1.1	0.23	0.36
6	Benzwar	411.9	480.0	1.17	1.56	5.4	1.1	0.21	0.44
7	Kuriya	202.7	195.8	0.97	1.27	4.8	1.0	0.21	0.17
8	Premnagar	664.2	706.5	1.06	1.46	5.9	1.1	0.18	0.32
9	Dhamkund	823.2	809.0	0.98	1.42	6.2	1.0	0.16	0.15
10	Ghoushal	104.0	120.3	1.16	1.45	4.0	1.1	0.29	0.42
11	Akhnoor	869.6	900.4	1.04	2.85	6.3	1.0	0.15	0.25

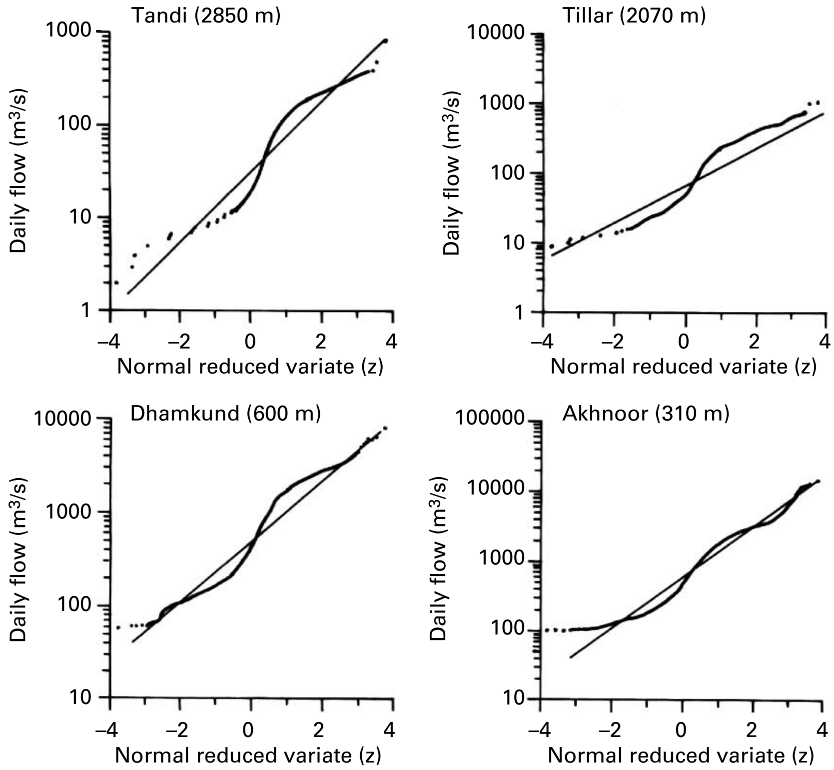

Figure 2 Plots of daily flows with normal reduced variates for four different catchments

altitude (A) and Ca/A^2 using linear regression in log domain. These relationships are given below along with their correlation coefficients:

$$CV_y = 1.246(Ca)^{-0.20} \quad (r = -0.85) \tag{11}$$

$$CV_y = 0.0157(A)^{0.36} \quad (r = 0.89) \tag{12}$$

$$CV_y = 0.5168(Ca/A^2)^{-0.11} \quad (r = -0.92). \tag{13}$$

The variation of CV_y with physiographic characteristics Ca, A and Ca/A^2 are shown in Figure 3.

The coefficient of correlation between the mean of the log flows ($\bar{y}$) and catchment area (Ca) and the mean of the log flows and Ca/A^2 in log domain are 0.95 and 0.94, respectively. As the correlation coefficient for Eq. (10) is not significantly different from that of Eq. (9), therefore the relationship between $\bar{y}$ and Ca/A^2 is used as the regional relationship for computing the $\bar{y}$ for ungauged catchments of the region. Another advantage of using Ca/A^2 is that it provides the combined effects of Ca and A on $\bar{y}$. The correlation coefficient between the CV_y and Ca/A^2 is -0.92, which is statistically significant. It is observed from Figure 3 that the CV_y decreases with an increase in catchment area whereas it increases with an increase in the altitude Thus the flows of the catchments at higher altitudes exhibit larger variability in comparison to the catchments at lower altitudes. The CV_y shows a decreasing trend with increase in Ca/A^2. It also indicates the larger variability in the flows of the catchments at higher altitude as compared to the same size catchment at lower altitudes. Thus Eq. (13) is used to compute the values of CV_y corresponding to the known values of Ca/A^2 for the catchments of the region. For a catchment whose catchment area and altitude are known Eqs. (8) and (9) may be used to compute the mean flow in log domain. It may be

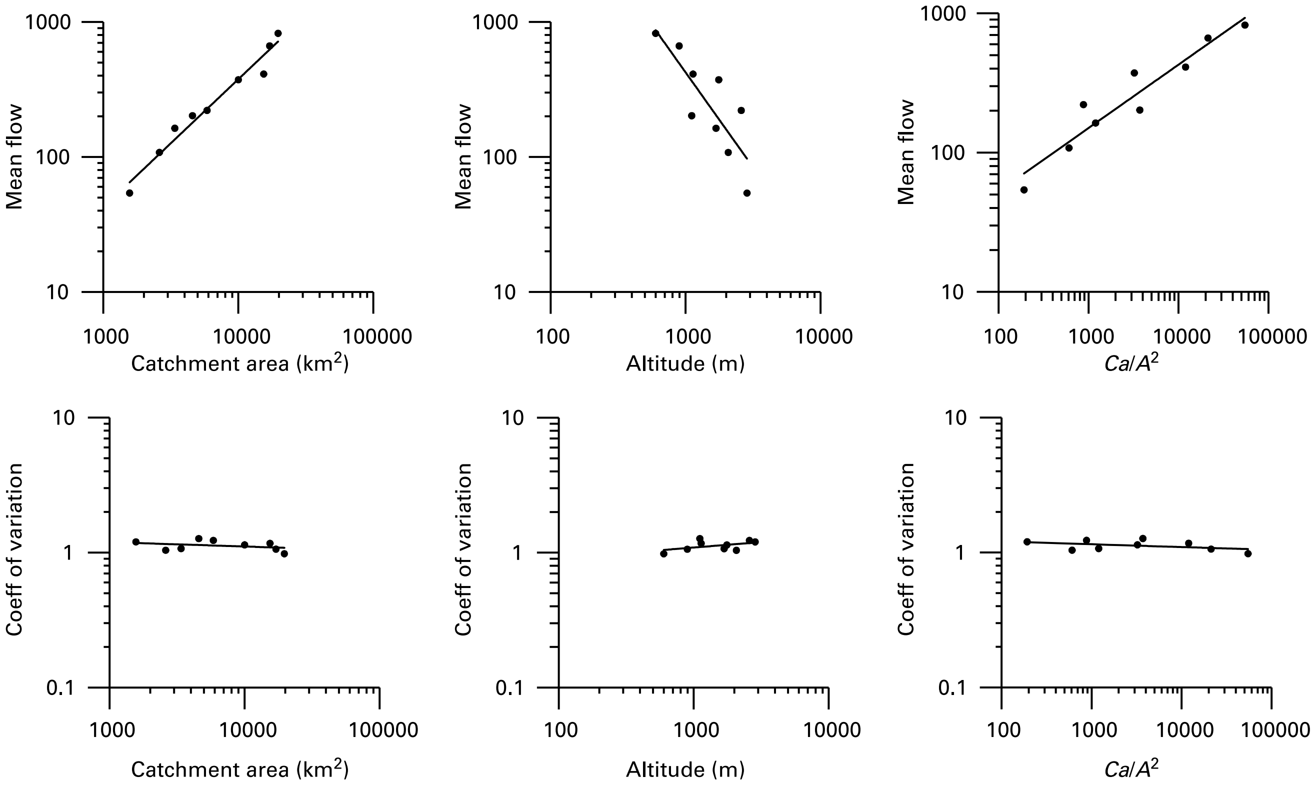

Figure 3 Variation of mean flows and coefficient of variation with catchment area, altitude and *Ca/A* ^{2} in log–log space

noted that the relationship between $\bar{y}$ and Ca/A^2 may be considered for the computation of $\bar{y}$ values as it consists of Ca as well as A in the relationship. The computed value of $\bar{y}$ may be multiplied by the CV_y value to get the standard deviation in the log domain for the selected catchment. Combining the regional relationship for $\bar{y}$ as well as for CV_y the following regional formula has been developed for the computation of dependable flow:

$$Q_D = 9.253483^{(Ca/A^2)^{0.12}} * 3.152198^{(Ca/A^2)^{0.01} Z_D} \tag{14}$$

where Z_D represents the normal reduced variate corresponding to the $T\%$ dependability and Q_D is the $T\%$ dependable flows. Eq. (14) has been used to compute the dependable flows for different dependabilities for the nine catchments (No. 1 to No. 9) considered for calibration and two test catchments (No. 10 and No. 11) considered for validation. The test catchment No. 10 has the smallest size whereas the size of catchment No. 11 is the largest among the catchments considered for the study. Thus it provides an opportunity to test the regional formula in the extrapolation range (according to the catchment size) for both the extremes. The PAEDF has been computed for each of the sites using regionalisation method I.

Analysis using regionalisation method II

In this method of regionalisation different regional relationships have been developed for correlating the dependable flow with the physiographic characteristics. The form of the developed relationships are tabulated below:

Dependability	Relationship using *Ca*	Relationship using *A*	Relationship using *Ca/A* ^{2}
40%	$Q_{40} = 0.04328(Ca)^{0.95}$ $r = 0.97$	$Q_{40} = 8121294(A)^{-1.47}$ $r = 0.85$	$Q_{40} = 4.349235(Ca/A^2)^{0.47}$ $r = 0.96$
50%	$Q_{50} = 0.03439(Ca)^{0.95}$ $r = 0.96$	$Q_{50} = 6649153(A)^{-1.48}$ $r = 0.86$	$Q_{50} = 3.320117(Ca/A^2)^{0.47}$ $r = 0.96$
60%	$Q_{60} = 0.02843(Ca)^{0.95}$ $r = 0.96$	$Q_{60} = 5780496(A)^{-1.49}$ $r = 0.86$	$Q_{60} = 2.691234(Ca/A^2)^{0.47}$ $r = 0.96$
70%	$Q_{70} = 0.02192(Ca)^{0.94}$ $r = 0.96$	$Q_{70} = 4592798(A)^{-1.50}$ $r = 0.87$	$Q_{70} = 1.993716(Ca/A^2)^{0.47}$ $r = 0.96$
80%	$Q_{80} = 0.01673(Ca)^{0.94}$ $r = 0.95$	$Q_{80} = 4501855(A)^{-1.51}$ $r = 0.87$	$Q_{80} = 1.01005(Ca/A^2)^{0.47}$ $r = 0.96$
90%	$Q_{90} = 0.011914(Ca)^{0.94}$ $r = 0.95$	$Q_{90} = 2813669(A)^{-1.52}$ $r = 0.88$	$Q_{90} = 1.01005(Ca/A^2)^{0.47}$ $r = 0.96$

The relationship developed using Ca/A^2 have almost similar correlation coefficients as those relationships developed using Ca for each dependabilty. The relationships developed using altitude (A) show poor correlation coefficients as compared to the relationships with Ca/A^2. These relationships are used to compute respective dependable flows for nine catchments for calibration and two test catchments. The PAEDF has been computed for each of the site using regionalisation method II.

Analysis using regionalisation method III

In regionalisation method III, the ratios of the observed daily flows to the at-site mean are computed in order to get the non-dimensional flow values at different gauging sites. These non-dimensional flow values for the nine gauging sites are pooled together to represent a population of non-dimensional flows for the region. The two-parameter log normal distribution is fitted with the pooled data of non-dimensional flow and the following relationship is developed for the region:

$$\log\frac{Q_D}{\bar{Q}} = -0.5782 + 1.0408Z_D \quad (r = 0.96) \tag{15}$$

In order to compute the mean flow, $\bar{Q}$, the following relationship is developed correlating the mean flow ($\bar{Q}$) with Ca/A^2:

$$\bar{Q} = 6.5143\left(\frac{Ca}{A^2}\right)^{0.455} \quad (r = 0.94) \tag{16}$$

The regional formula for the computation of dependable flows is developed combining Eq. (15) and Eq. (16) in the following form:

$$Q_D = 3.653917e^{1.0408Z_D}\left(\frac{Ca}{A^2}\right)^{0.455} \tag{17}$$

Equation (17) is used to compute the dependable flows for nine catchments considered for calibration and two catchments considered for validation.

The relationships have also been developed for mean flow ($\bar{Q}$) correlating it with catchment area (Ca) and altitude (A), respectively, in the following forms:

$$\bar{Q} = 0.06117(Ca)^{0.947} \quad (r = 0.98) \tag{18}$$

$$\bar{Q} = 69184334(A)^{-1.404} \quad (r = 0.80) \tag{19}$$

From Eqs. (16), (18) and (19), it is observed that the mean of the observed flows increases with increase in Ca/A^2 and Ca and decreases with increase in A. In order to examine the effect of catchment area and altitude, the relationship between mean flow and Ca/A^2 is considered for the regionalisation of the mean flow. The correlation coefficient for this relationship is 0.94.

Comparison of different regionalisation methods

The dependable flows, obtained from analysing the available historical flow records at different sites, are compared with those obtained from regionalisation method I, method II and method III. The PAEDF values obtained from different regionalisation methods are plotted in Figures 4 and 5. It is observed from the figures that the PAEDF values for regionalisation method II and regionalisation method I are higher for most of the catchments. Thus out of the three methods considered for regionalisation, regionalisation method III performs better for most of the catchments considered for the study.

However, the performance of this method is not so good when it is used for the catchments having Ca/A^2 in the extrapolation range (according to size). Even in the extrapolation range the performance of regionalisation method III is better than the other two methods. It suggests that regionalisation method III may be used for the computation of dependable flows for the ungauged catchment of the region. However, as far as possible, the computation of dependable flows for those catchments whose Ca/A^2 lie in the extrapolation range may be avoided.

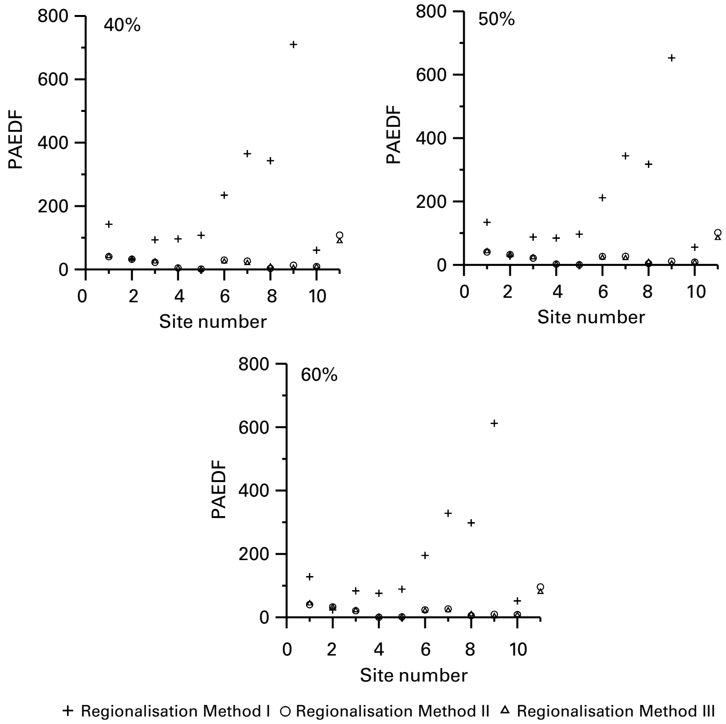

Figure 4 A plot of PAEDF values of different regionalisation methods for 40%, 50% and 60% dependability

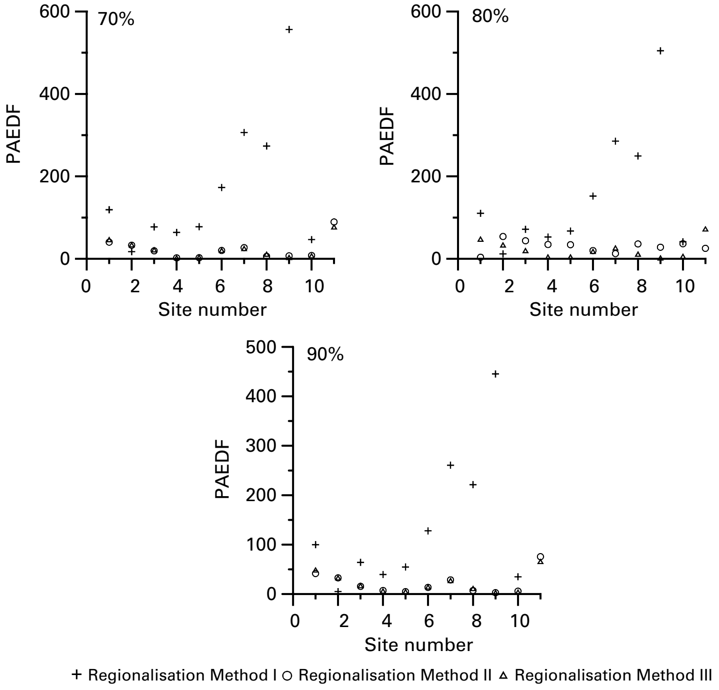

Figure 5 A plot of PAEDF values of different regionalisation methods for 70%, 80% and 90% dependability

Conclusions

The regional flow duration curves have been developed for the Chenab river basin. Three different regionalisation methods were used. In regionalisation method I parameters were regionalised for individual gauged sites of log normal distribution, in regionalisation method II regionalisation of dependable flows was performed and in regionalisation method III parameter regionalisation for the region as a whole of log normal distribution was done. These methods were used for computing the dependable flows in the 11 sub-basins in the study area. Out of these sub-basins two were selected as test catchments. The selection of test catchments was done in such a way that one was a high altitude sub-basin and the other was a low altitude sub-basin.

The effect of altitude was studied and it was found that the flow for a given dependability increases with catchment area and decreases with altitude. The flows of the catchments at higher altitudes exhibit larger variability in comparison to the catchments at lower altitudes.

The performance of different methods were compared and it was found that, for all the sub-basins, the performance of regionalisation method III was better than the other two methods considered in this study. However, the performance of regionalisation method III was not so good for the sub-basin having the physiographic characteristics in the extrapolation range. It is therefore recommended that regionalisation method III may be used for the computation of dependable flows for the ungauged catchments in the Chenab River basins provided that the physiographic characteristics of those catchments are not in the extrapolation range.

References

AHEC (1997, 2000). *REFRESHA*, Regional flow regimes estimation for small-scale hydropower assessment. AHEC, India.

Bhaskar, N.R. and O'Connor, C.A. (1989). Comparison of method of residuals and cluster analysis for flood regionalisation. *J. Wat. Res. Plann. Mngmnt.*, **115**(6), 793–808.

Burn, D.H. (1989). Evaluation of regional flood frequency analysis with a region of influence approach. *Wat. Res. Res.*, **26**(10), 2257–2265.

Chalise, R.S., Kansakar, R.S., Rees, G., Croker, K. and Zaidman, M. (2003). Management of water resources and low flow estimation for the Himalayan basins of Nepal. *J. Hydrol.*, **282**, 25–35.

Cheng, C.C. (1988). Hydrologic regionalisation based on flow duration curve. PhD dissertation, Syracuse University, NY, Unpublished.

Chiang, S.M., Ting-Kuei, T. and Stephan, J.N. (2002). Hydrologic regionalisation of watersheds I: Methodology development. *J. Wat. Res. Plann. Mngmnt.*, **128**(1), 3–11.

Cole, R.A.J., Johnston, H.T. and Robinson, D.J. (2003). The use of flow duration curve as a data quality tool. *Hydrol. Sci. J.*, **48**(6), 939–951.

Croker, M.K., Young, R.A., Zaidman, D.M. and Rees, H.G. (2003). Flow duration curve estimation in ephemeral catchments in Portugal. *Hydrol. Sci. J.*, **48**(3), 427–439.

Demuth, S. (1993). Untersuchungen zum Niedrigwasser in West-Europa (Low flow studies in West Europe). *Freiburger Schriften zur Hydrlogie*, Bd. I. Freiburg I, Br, Germany (in German).

Dhar, O.N., Mandal, B.N. and Kulkarni, A.K. (2000). Review of precipitation studies carried out for High Himalaya in recent years. In *High Altitudes of the Himalaya II. Biodiversity, Ecology and Environment*, Y.P.S. Pangtey (ed.), Gyanodaya Prakashan, Nainital, India, vol 2, pp. 509–521.

Dingman, S.L. (1978). Synthesis of flow-duration curves for unregulated streams in New Hampshire. *Wat. Res. Bull.*, **14**(6), 1481–1502.

Fennessey, N. and Vogel, R.M. (1990). Regional flow-duration curves for ungauged sites in Massachusetts. *J. Wat. Res. Plann. Mngmnt.*, **116**(4), 530–549.

Gottschalk, L. (1985). Hydrologic regionalisation of Sweden. *Hydrol. Sci. J.*, **30**(1), 65–83.

Mimikou, M. and Kaemaki, S. (1985). Regionalization of flow duration characteristics. *J. Hydrol.*, **82**, 77–91.

Mosley, M.P. (1981). Delimitation of New Zealand hydrologic regions. *J. Hydrol.*, **49**, 173–192.

Mosley, M.P. and McKerchar, A. (1993). In *Streamflow. Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill, New York.

NIH (1998). Regional water availability study for Himalayan region for GEF UNDP project. NIH in collaboration with AHEC.

Quimpo, R.G., Alejandrino, A.A. and McNally, T.A. (1983). Regionalized flow duration for Philippines. *J. Wat. Res. Plann. Mngmnt.*, **109**(4), 320–330.

Singh, P., Jain, S.K. and Kumar, N. (1997). Estimation of snow and glacier melt contribution to the Chenab river, Western Himalayas. *Mountain Res. Develop.*, **17**(1), 49–56.

Singh, P., Ramasastri, K.S. and Kumar, N. (1995). Topographical influence on precipitation distribution in different ranges of western Himalayas. *Nord. Hydrol.*, **26**, 259–284.

Singh, R.D., Mishra, S.K. and Chowdhary, H. (2001). Regional flow-duration models for large number of ungauged Himalayan catchments for planning microhydro projects. *J. Hydrol. Engng.*, **6**(4), 310–316.

Tasker, G.D. (1982). Comparing methods of hydrologic regionalisation. *Wat. Res. Bull.*, **18**(6), 965–970.

Vogel, R.M. and Fennessey, N.M. (1994). Flow duration curves. I: New interpretation and confidence intervals. *J. Wat. Res. Plann. Mngmnt.*, **120**(4), 485–505.

Vogel, R.M. and Fennessey, N.M. (1995). Flow duration curves. II: A review of applications in water resources planning. *Wat. Res. Bull.*, **31**(6), 1029–1039.

Yu, P.S. and Yang, T.C. (2000). Using synthetic flow duration curves for rainfall-runoff model calibration at ungauged sites. *Hydrol. Proc.*, **14**, 117–133.

Yu, P.S., Yang, T.C. and Wang, Y.C. (2002). Uncertainity analysis of regional flow duration curves. *J. Wat. Res. Plann. Mngmnt.*, **128**(6), 424–430.

Appendix

For log normal distribution the relationship between dependable flows and mean flow is

$$\ln Q_D = \bar{y} + \sigma_y Z_D$$

where Z_D is the normal reduced variate and σ_y is the standard deviation in log space.

$$\ln Q_D = \bar{y} + \bar{y} CV_y Z_D$$

where CV_y is the coefficient of variation in log space.

$$Q_D = e^{\bar{y}(1+CV_y Z_D)}$$

Since $\bar{y} = a_1(X)^{b_1}$ and $CV_y = a_2(X)^{b_2}$

$$Q_D = \mathrm{e}^{a_1(X)^{b_1}(1+a_2(X)^{b_2} Z_D)}$$

$$Q_D = (\mathrm{e}^{a_1})^{(x)^{b_1}} \mathrm{e}^{a_1 a_2 (X)^{b_1+b_2} Z_D}$$

$$Q_D = (K_1)^{(X)^{b_1}} (K_2)^{(X)^{C_1} Z_D}$$

where $K_1 = \mathrm{e}^{a_1}$, $K_2 = \mathrm{e}^{a_1 a_2}$ and $c_1 = b_1 + b_2$.