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# Contents

## Summary

This paper reviews the estimation methods developed and used in India for low-flow, long-term mean flow and flood characteristics. The review is intended to provide a quick reference guide for such methods used for hydrological prediction in ungauged basins. As such it lists identified estimation formulae for various parts of India with necessary parameters. The paper also effectively gives a quick assessment of the status of hydrological predictions at ungauged sites in India. Few studies focusing on low-flow estimation at ungauged sites have been identified. Considerable work has been done to estimate flood characteristics and long-term mean annual flow using regression relationships with catchment parameters, but most of these methods were developed a long time ago and may need to be revisited. The practice of flow estimation at unagauged sites in India could benefit from improved access to already collected observed flow data.

## INTRODUCTION

The International Water Management Institute (IWMI) carries out a Research Project on re-assessment of the Indian National River Linking Project (NRLP). The project is funded by the CGIAR Challenge Program on Water and Food and has 10 components, which examine various aspects of India's water future relevant to the NRLP. The eco-hydrological component attempts to evaluate, amongst other things, the naturalized flow regimes at several ungauged sites in Indian rivers basins earmarked for water transfers. These naturalized flow time series may be used for the purpose of environmental flow analyses at selected sites and to compare natural regimes with those of the present day – to evaluate the degree of hydrological alterations in river basins.

There are many methods in modern-day hydrology that could be used to calculate hydrological characteristics at ungauged sites. The review in this paper focuses on methods which are based on hydrological regionalization and are developed by Indian and foreign hydrologists for use in Indian conditions Hydrological regionalization in this paper is understood as a range of techniques, which allow estimation of [ungauged] hydrological characteristics from climatic and physiographic catchment parameters to be made. The said parameters can be derived from maps, GIS, literature sources or observed climatic data (which are normally more readily available than flow data). The review focuses primarily on low-flow, long-term mean flow and flood characteristics. This review does not intend to develop new regionalization or estimation techniques and aims merely to identify the studies and actual recommended methods and formulae, which could be used directly for estimation in ungauged sites in India. By doing so, this review, however, attempts to give a quick assessment of the status of hydrological predictions at ungauged sites in India. The sections below deal with low-flow, mean flow and high flow estimation at ungauged sites separately.

## ESTIMATING LOW FLOWS AND DURATION CURVES AT UNGAUGED SITES

**Croker et al. (2001)** developed a set of techniques for estimating hydrological characteristics in the Himalayan part of Himachal Pradesh of India through the REFRESHA Project (Regional Flow Regimes Estimation for Small-scale Hydropower Assessment). Using data from 41 gauged catchments in the study area of 56,000 square kilometers (km$^2$), multi-variate regression techniques were used to relate observed flow statistics to pertinent catchment characteristics and to derive regional prediction models.

<u>Low-flow characteristics.</u> The main index used here was the flow corresponding to the 95$^{th}$ percentile of the flow duration curve (FDC) (Q95). A multivariate approach was used to relate groups of soil types with standardized Q95 data. The soil data was derived from 1:500,000 scale soil maps of Himachal Pradesh produced by the National Bureau of Soil Survey and Land Use Planning. The soils were classified into 17 soil groups according to their physical and hydrological properties. The amount of snow/ice cover in each catchment was also considered. Based on previous studies and the advice of local hydrologists, all areas above 4,500 meters (m) were assumed to have a permanent snow/ice cover, which were classified as a separate 'soil group'.

The digitized catchment boundaries were used to determine the proportional extent of each soils or geology group in the catchments. For the study area of Himachal Pradesh, with 18 soil groups, multivariate regression was applied, relating the soil types to the standardized value of the observed Q95. The first iteration gave high standard errors or negative parameter estimates for several soil types. This is normally an indication that these types are poorly represented in the sample dataset.

To overcome these problems it was necessary to regroup these soil types with others having similar hydrological properties. The reclassification was carried out by means of a simple step-wise regression approach, as follows:

- Conduct regression between standardized Q95 and the proportion of each soil "group" (in the first iteration there are as many groups as types);
- Identify the group with the highest standard error and include with another group of similar hydrological properties;
- Repeat the first two steps until all parameter estimates are within the observed range of observed Q95 and with standard errors indicate that the groupings are statistically representative in the regression;
- If several classes have similar hydrological characteristics and have similar parameter estimates and standard errors, group them together.

Using this procedure, nine groups of soil (G1: Deep, excessively drained and medium deep, excessively drained; G2: Deep, moderately drained and deep, well drained; G3: Medium deep, excessively drained and deep, excessively drained; G4: Medium deep, well drained; G5: Mountain and valley glaciers and rock outcrops; G6: Rock outcrops and shallow, excessively drained; G7: Shallow, somewhat excessively drained; G8: Shallow, well drained; G9: Permanent snow and ice) were defined in the final regression model for Himachal Pradesh. Based on this arrangement the Q95 for an ungauged catchment in the study area is calculated using the equation:

$$Q95 = [49.5 * G1] + [37.8 * G2] + [24.7 * G3] + [39.4 * G4] + [30.8 * G5] + [22.8 * G6] + [42.3 * G7] + [21 * G8] + [20.7 * G9] \tag{1}$$

The models were also assessed in terms of the bias, a measure of predicted Q95 ($Q95_{pred}$) versus observed ($Q95_{obs}$), which is expressed by the equation:

$$Bias = \frac{Q95_{pred} - Q95_{obs}}{Q95_{obs}} * 100 \tag{2}$$

For Himachal Pradesh, the mean bias was found to be 3% with a standard deviation of 19%.

<u>Regional flow duration curves.</u> Using the established spatial distribution of the Q95 above, the study further derived typical flow duration curves using the following procedure:

- The 'observed flow duration curves, standardized by the mean-flow for selected catchments were "pooled" into classes based on the value of Q95, ensuring a similar number of catchments in each class;
- For each class, the average curve (typical curve) was determined, resulting in a "family" of flow-duration curve types.
- The 'type' curves were smoothed in order to avoid problems of crossing curves.

**Singh et al. (2001)** developed regional flow-duration models for ungauged sites located in 13 states of the Himalayan region, covering almost the complete width of the country from Jammu and Kashmir in the west to northeastern states in the east. The observed data of 10-daily flow from 108 catchments in 13 States of India (Jammu and Kashmir-7; Himachal Pradesh - 23; Uttar Pradesh - 20; Bihar - 22; West Bengal - 7; Sikkim - 0; Arunachal Pradesh - 12; Meghalaya - 7; Manipur - 3; Nagaland - 5; Mizoram - 2) were used to estimate the model parameters and regional flow-duration curves.

The flow-duration model for an ungauged site is developed using the concept of hydrological data (non-dimensional) transfer between the watersheds of the same hydro-meteorologically homogeneous region. Flows were made non-dimensional using mean flow and the resulting series was normalized using power transformation for estimating quantiles. Assuming that $Q$ and $q$, respectively, represent the original and non-dimensional flow series for a site:

$$q = \frac{Q}{Q_{mean}} \tag{3}$$

where: $Q_{\mathrm{mean}}$ = mean flow. The $q$-series obtained from the data transfer between the gauged watersheds is normalized using power transformation (Box and Cox 1964) as below:

$$W = \left(q^{\lambda} - 1\right)/\lambda, \text{ if } \lambda \neq 0 \tag{4}$$

or

$$W = \ln(q), \text{ if } \lambda = 0 \tag{5}$$

where: $W$ = power-transformed non-dimensional series; and $\lambda$ = model parameter determined by trial and error or by optimization using the normality conditions (coefficient of skewness = 0 and coefficient of kurtosis = 3) as the objective function. The statistical properties of the $W$-series, viz, mean $\mu_W$ and standard deviation $\sigma_W$, are estimated using the maximum likelihood method, and quantiles are estimated using the normal relation.

$$W_D = \mu_W + Z_D \sigma_W \tag{6}$$

where: $W_D$ = $W$-quantile of dependability $D$; and $Z_D$ = frequency factor of dependability $D$. Thus, for known $W_D$ and $\lambda$, the $q$-quantile of dependability $D$, $q_D$, can be derived from above equations using inverse transformation

$$q_D = \left[W_D \lambda + 1\right]^{1/\lambda}, \text{ if } \lambda \neq 0 \tag{7}$$

or

$$q_D = \exp\left[W_D\right], \text{ if } \lambda = 0 \tag{8}$$

To estimate the $Q$-quantile of dependability $D$, $Q_D$, using above equations, $Q_{\text{mean}}$ for an ungauged watershed is derived assuming the following regional power relation:

$$Q_{mean} = CA^m \qquad (9)$$

where: $A$ = watershed area; and $C$ and $m$ = coefficient and exponent, respectively, determined using regression . Thus, $Q_D$ for an ungauged watershed can be determined using:

$$Q_D = Q_{mean} q_D \qquad (10)$$

Using equation (9), regional models relating to a watershed area were developed for 9 regions/ zones (A to I) suggested by Central Water Commission (CWC 1983). These regions are shown in Figure 1 by different shades (Region A: Jammu and Kashmir (except Leh and Kargil) [7], Region B: Jammu and Kashmir (Leh and Kargil) [7], Region C: Himachal Pradesh [7], Region D: Uttar Pradesh [7], Region E: Bihar [1g, 3d], Region F: West Bengal [2a] and Sikkim [2a], Region G:

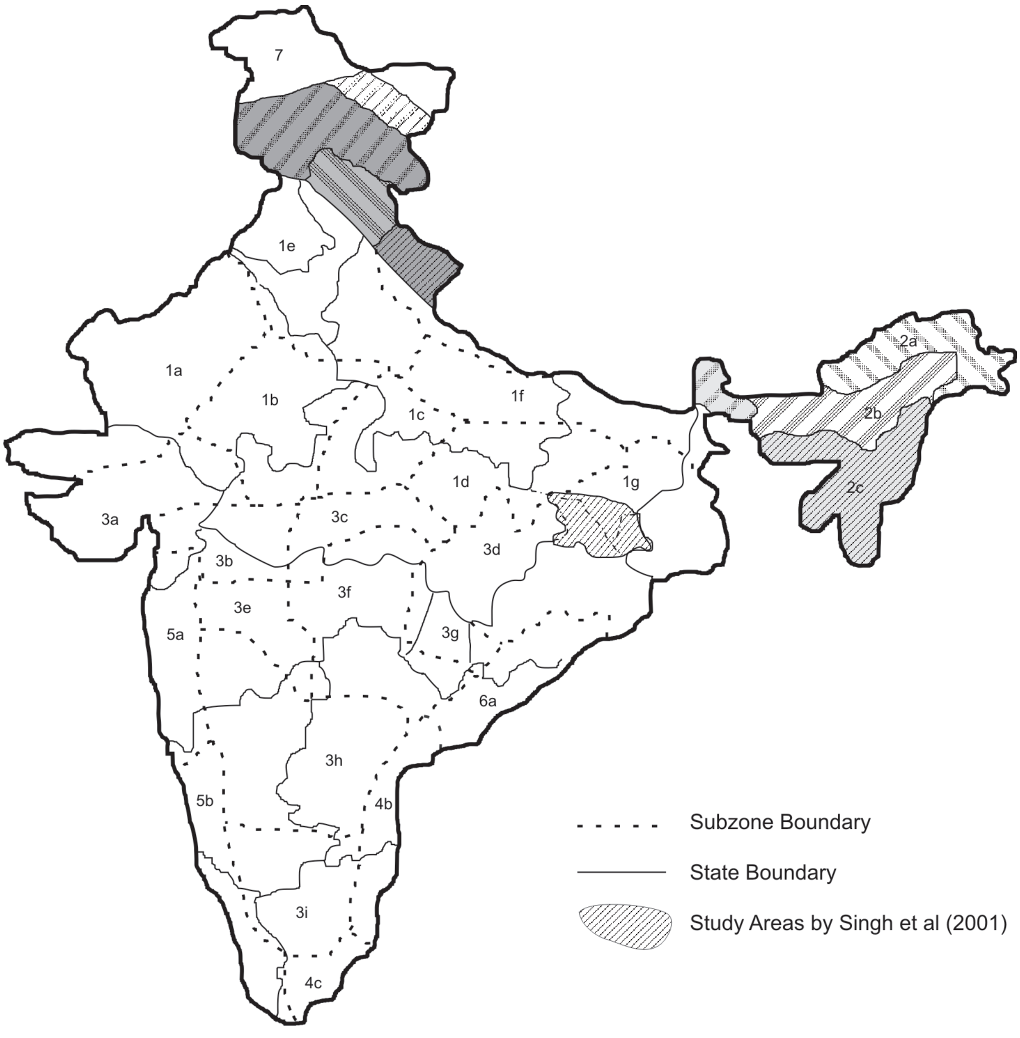


FIGURE 1. Hydrometeorologically homogeneous zones in India (CWC 1983) and study areas by Singh et al. (2001), shown in different shades

North Assam [2a] and Arunachal Pradesh [2a, 2b], Region H: South Assam [2b, 2c] and Meghalaya [2b, 2c], Region I: Manipur [2b], Nagaland [2b, 2c], Mizoram [2c] and Tripura [2c]). Using the above model, flows of the desired level of exceedence can be estimated for any ungauged catchment located in the said regions. The adequacy of the basic structure of the regional model was found to be fairly satisfactory with $r^2$ values ranging from 0.77 to 0.94 for the watersheds of the states of Himachal Pradesh, West Bengal, Sikkim, South Assam, Meghalaya, Manipur, Nagaland, Mizoram, and Tripura. However, for the watersheds of Jammu and Kashmir and Uttar Pradesh, the model exhibited less than satisfactory performance and it performed poorly on the watersheds of Bihar and North Assam with $r^2$ values ranging from 0.37 to 0.68.

**Pandey and Ramasastri (2003)** studied low flows in San and Barah rivers, tributaries of Indravati river system in Orissa using weekly flow data from two gauging sites. Streamflows in different weeks/months during lean season at various levels of the probability of exceedence, i.e., 50%, 75% and 90% were estimated. For hydrological studies dealing with water supply, especially during the lean flow season, many researchers have recommended 90% or 95% probability level for determining assured water supply. These levels of probability are considered safe if the lean season flows are essentially contributed by baseflow.

In this study, various sets of flow duration curves were also derived from daily/weekly/monthly discharge data for lean period (January-May) at each site using different combinations of daily, weekly and monthly flows. Dependable flows on a weekly basis were estimated for the 8 weeks during the 2 summer months (April and May) for which daily data was available.

The flow in both streams was found to decrease gradually from January to April and the flow touches the low level during the period between the second week of April and the second week of May. It is found that the availability lean season flow potential in San Nadi may meet the water demand for a proposed industrial plant (up to 36,000 $m^3$/day). However, the flows in Barah Nadi are not sufficient to meet the required demands. A comparison of results for weekly dependable flows obtained using extended database by deriving dimensionless values for weekly flow appear to be preferable than those obtained from other discussed methods.

**Rees et al. (2004)** developed a hydrological model for estimating dry season flows in ungauged catchments of Himachal Pradesh and Nepal, using recession curves. Ten-day average observed flows were fitted to a second order storage model to enable the average annual recession pattern to be examined. Regional models for three recession curve parameters (the storage constant; the initial recession flow and the start date of the recession) were developed using a dataset of 26 catchments. Relationships were identified between: the storage constant and catchment area; the initial recession flow and elevation (acting as a surrogate for rainfall); and the start date of the recession and geographic location (distance and mean elevation of 1 X 1 km elevation grid derived from the USGS GTOP030 dataset (USGS 1996)). Automated procedures identified recession periods from hydrographs using the following criteria: a recession was defined to begin at the third consecutively decreasing flow value and to end at the first increasing flow value; a minimum recession length of 100 days (ten 10-day flow values) was set to ensure that only the main, annual recession was identified. An independent dataset of 13 catchments was used to evaluate the robustness of the models. The regional models predicted the average volume of water in an annual recession period ($1^{st}$ of October to the $1^{st}$ of February) with an average error of 8%, while mid-January flows were predicted to within ±50% for 79% of the catchments in the dataset. The modeling equations developed for linear and non-linear storages are as follows:

$$q_{t+T} = \exp(-kT)q_t \tag{11}$$

$$q_{t+T} = \left[q_t^{-b} + a.b.T\right]^{-1/b} \tag{12}$$

where: q=q(t) is the outflow at time t, k is the recession constant, a=mk$^{1/m}$ and b=(m-1)/m, m is an exponential describing the form of storage (m=1 for a linear store, m=2 for quadratic store, etc.)

**Holmes et al. (2004)** examined the range of hydrological characteristics in Himalayan region of Nepal and Northern India. They developed a statistically based regional hydrological model for estimating average monthly dry-season flows in gauged and ungauged catchments for part of the region. The models are a significant advance over the regional hydrological models that have previously been developed, as they describe the temporal sequence of flows during the critical dry-season months. The models were incorporated in a prototype software package to demonstrate the potential for effective water management in the region and applied to two selected "pilot" basins in India and Nepal. The modeling equations are the same as described by Rees et al. (2004).

**Arora et al. (2005)** examined the effect of altitude on water availability for the various sub-basins of the Chenab River Basin – a snow-fed river in the Indus Basin in Western Himalayas. The objective of the study was to develop regional flow duration curves using three different regionalization methods and compare their relative performance over the eleven sub-basins of the Chenab River system. Three different approaches are; (i) parameter regionalization for individual gauge sites of selected probability distribution, (ii) regionalization of flows of different exceedence levels, and (iii) parameter regionalization for the region as a whole of the selected probability distribution. It is observed that flow for a given exceedence increases with catchment area and decreases with altitude. The catchment area under study ranges from 1566-22,400 km$^2$. The performance of the regionalization method given in Case 3 below was better than the other two:

Case 1: $\bar{y} = a_1(X)^{b_1}, \quad CV_y = a_2(X)^{b_2}$ and $Q_D = K_1^{(X)^{b_1}} * K_2^{(X)^{c_1 Z_D}}$ (13)

Case 2: $Q_D = a_3(X)^{b_3}$ (14)

Case 3: $\log\dfrac{Q_D}{Q} = a_4 + b_4 Z_D. \qquad Q_D = a_5(X)^{b_5}$ (15)

where: $\bar{y}$ and $CV_y$ represent the mean and coefficient of variation of the flow values in log space, relatively, $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, $b_1$, $b_2$, $b_3$, $b_4$ and $b_5$ are the coefficients, X represents the physiographic characteristics (catchment area, basin relief and altitude), $Z_D$ represents the normal reduced variate corresponding to the D% exceedence and $Q_D$ is the D% exceeded flow.

In the third 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 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:

$$\log \frac{Q_D}{Q} = -0.5782 + 1.0408 Z_D \quad (r = 0.96) \tag{16}$$

In order to compute the mean flow, $Q_{mean}$ , the following relationship is developed correlating the mean flow with $Ca/A^2$:

$$Q_{mean} = 6.5143 \left( \frac{C_a}{A^2} \right)^{0.455} \quad (r = 0.94) \tag{17}$$

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

$$Q_{mean} = 0.06117 (C_a)^{0.947} \quad (r = 0.98) \tag{18}$$

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

## MEAN FLOW ESTIMATION

**Kothyari (1984)** used the available data from several Indian catchments (Mahanadi, Tapi, Sabarmati, Tawa, Chambal, Pennar, Betwa, Yamuna, Ghataprabha, Damodar, Narmada, etc.) to verify the existing relationship for annual runoff given by Khosla (1949), Panchang (1954), and Sehgal and Gulati (1969). These equations were found to give unsatisfactory results and therefore a new analysis of data from 26 catchments spread over various parts of India has been carried out. For identification of significant factors affecting annual runoff and for establishing the relationships for annual runoff and the mean annual runoff, the multiple regression technique has been used. The relationship obtained for annual runoff R using multiple regression analysis is:

$$R_m = \frac{0.1146 (P_m - 0.5 T_m)^{1.55} F_v^{0.47}}{T^{0.31}} \tag{20}$$

where: $R_m$ is the mean annual runoff in cm, $P_m$ = the average annual rainfall over the catchment in cm, $T_m$ = the average annual temperature over the catchment in $^oC$, and $F_v$ = the vegetal cover factor.

The correlation coefficient between $\log(R_m / F_v^{0.49})$ and $\log(P_m - 0.5T_m)$ is found to be 0.93 and the standard deviation of residual is 0.031 (this study was further applied by Kothyari in 1991 and 1995).

**Kothyari and Garde (1991)** used the data from 55 non-snow-fed catchments in the Indian subcontinent, with areas greater than 347 km², to study the influence of selected climatic, topographic and land-use variables on mean annual runoff. The mean annual rainfall, mean annual temperature, and vegetal (forest) cover factor were found to be the most important variables influencing the mean annual runoff. The vegetal cover is positively correlated with mean annual runoff from large catchments.

$$R_m = \frac{F_v^{0.49}\left(P_m - 0.5T_m\right)^{1.59}}{26.5} \quad (21)$$

where: $R_m$ is the mean annual runoff in cm, $P_m$ = the average annual rainfall over the catchment in cm, $T_m$ = the average annual temperature over the catchment in °C, and $F_v$ = the vegetal cover factor:

$$F_v = \frac{\left(a_1F_F + a_2F_G + a_3F_A + a_4F_W\right)}{A} * 100 \quad (22)$$

$a_i$ = the weighting factor (i = 1-4), A= the total catchment area in km$^2$, and $F_F$, $F_G$, $F_A$, $F_W$ are percentage of forest, grass and scrub, arable and wastelands, respectively. A close study of the partial correlation coefficient reveals that, in explaining the variation in log $R_m$, contribution of the log transforms of L, $D_d$, and S is negligible. The regression equation that uses the least number of variables but still describes a sufficient percentage of variation in $R_m$ is as follows:

$$R_m = C\left(P_m - 1.4T_m\right)^{0.90} F_v^{0.20} A^{0.04} T_m^{-0.95} \quad (23)$$

where: C = 5.55. The coefficient of multiple regression of equation (22) is 0.87. The model has been applied in many river basins of India (Ghataprabha with a CV = 0.21, Manjira above Nizam Sagar with a CV of annual flows of 0.56, Bhawani above Kodivery with a CV = 0.35) and used to generate the annual runoff of a catchment whose other characteristics are known. The mean standard error of estimates is 0.12. Relationship for the coefficient of variation of annual runoff has also been proposed.

**Kothyari (1995)** used data from 31 non-snow fed catchments in India with areas less than 1,515 km$^2$ in the Indian states of Uttar Pradesh, Madhya Pradesh, Bihar, Rajasthan, West Bengal and Tamil Nadu - to develop a simple method for the estimation of monthly runoff for the monsoon months of June to October in the following form:

$$R(I) = K(I)\left[1 + K(I)^{n(I)-1}\{1 - K(I-1)\}P(I-1)/P(I)\right]P(I) \quad (24)$$

where: R(I) = monthly runoff during the I$^{th}$ month, P(I) = monthly areal rainfall during the I$^{th}$ month, K(I) and n(I) are parameters for the I$^{th}$ month with K(I)<1.0 and n(I)>1.0. The values of the exponent n(I) were found to vary significantly in Damodar (Bihar), Barakar (Bihar), Mayurakshi (West Bengal), Chambal (Madhya Pradesh), Lower Bhawani (Tamil Nadu) and Ram Ganga River (Uttar Pradesh) during any one month and the coefficient K was found to be related to T, $F_A$ and A according to equation given below as it represents the loss from the total rainfall.

$$K = 260.9T^{-2.02} F_A^{-0.05} A^{0.05} \quad (25)$$

where: T is temperature in °C, A is the catchment area in km$^2$ and $F_A$ is the percentage of forest area. The values computed by the model were then compared with the corresponding observed values of runoff. This comparison revealed that the proposed method produces results with an error less than 25% for 90% of the data points. However, an error of less than 50% resulted for the arid catchments from the Chambal Basin (Madhya Pradesh).

**Croker et al. (2001)** using the data from 41 gauged catchments of Himachal Pradesh with a catchment area of 56,000 $km^2$ developed regression for mean flow expressed as an average annual runoff depth (in millimeters (mm)) (AARD). In Himachal Pradesh, catchment average values of annual precipitation derived from a 1:2,000,000 scale map were so inconsistent with the observed runoff that they had to be discarded. In the absence of adequate climatic data for the study area, the runoff was calculated from the following simple relationship, where the mean catchment elevation (ELEV, in meters) was calculated from the USGS GTOPO30 dataset:

$$AARD = (0.5997 * ELEV) - 319.692 \qquad R^2 = 0.73;\ \text{standard error} = 306\ \text{mm} \tag{26}$$

**Goel and Chander (2002)** discussed various regional relationships used in India for peak flow, mean flow, regional flood frequency analysis, and soil erosion estimation. Some of the most important studies reviewed in this report, are briefly summarized below:

<u>Binnie's percentages (1872) (taken from Hydrology Part III 1978)</u> Sir Alexander Binnie measured the runoff from a small catchment (16 $km^2$) near Nagpur during 1869 and 1872, developed curves of cumulative runoff against cumulative rainfall (for annual rainfall of 500 to 800 mm) and established percentages of runoff from rainfall. These percentages have been used in the Madhya Pradesh and Vidarbha regions of Maharashtra for the estimation of mean annual flow.

<u>Barlow's tables (1915) (taken from Varshney 1979).</u> Barlow carried out studies (during 1915) of catchments under 30 $km^2$ and expressed runoff R as $R = K_b P$ where $K_b$ is runoff coefficient which depends upon the type of catchment (catchment condition factor) and the nature monsoon rainfall (e.g., continuous downpour or light rain – Monsoon factor). This approach was recommended for use in Uttar Pradesh State.

<u>Inglis and de Souza (1946)</u> used data from 53 stream gauging sites in Western India and developed regional formulae between annual runoff (R) in cm and annual rainfall (P) in cm.

For Western Ghats region in Western India

$$R = 0.85P - 30.5 \tag{27}$$

For Deccan Plateau in central part of India

$$R = \frac{1}{254} P(P - 17.8) \tag{28}$$

<u>Khosla</u> (1949), developed a relationship for monthly runoff:

$$\begin{aligned} R_m &= (P_m - L_m) \\ L_m &= 0.48Tm \ \text{ for } Tm > 4.5^\circ C \end{aligned} \tag{29}$$

where: $R_m$ = Monthly runoff in cm and $R_m \geq 0$, $P_m$ = Monthly rainfall in centimeters (cm), $L_m$ = Monthly losses in centimeters, $T_m$ = Mean monthly temperature of the catchment in °C. He supplied provisional values of losses for different temperatures. Annual runoff can be estimated as a sum of monthly values. Khosla's formula is indirectly based on the water-balance concept and the mean monthly temperature is used to reflect the losses due to evapotranspiration. The formula has been used on a number of catchments in India and is found to give fairly good results for the annual yield for use in preliminary studies.

Lacey's (1957) formula. Lacey developed an empirical generalized formula for mean runoff calculation (R) of different catchments of India. The formula uses Barlow's catchment condition factors (S) and Monsoon duration factor (F) together with annual rain (P). The values of F/S factors were tabulated for five classes of catchments.

$$R = \frac{P}{1 + \frac{304.8}{P}\left(\frac{F}{S}\right)} \qquad (30)$$

Dhir et al. (1958) relationships. The equations derived by them (converted to metric units) for different basin outlets in India were:

| | | |
|---|---|---|
| Gerina River Basin (6,200 km$^2$, Andhra Pradesh) | $R = (13150P - 133000)$ | (31) |
| Machkund River Basin (2,220 km$^2$ Andhra Pradesh) | $R = (13.18P + 86.5)$ | (32) |
| Chambal River Basin (22,500 km$^2$, Rajasthan) | $R = (120P - 4945)$ | (33) |
| Tawa River Basin (5,950 km$^2$, Madhya Pradesh) | $R = (34.6P - 1510)$ | (34) |
| Manjra River Basin (21,700 km$^2$, Andhra Pradesh) | $R = (90.5P - 4800)$ | (35) |
| Maniari River Basin (805 km$^2$, Chattisgarh) | $R = (4270P - 254000)$ | (36) |
| Tapti River Basin (64,400 km$^2$, Gujarat) | $R = (435P - 17200)$ | (37) |
| Damodar River Basin (19,900 km$^2$, West Bengal) | $R = (13400P - 5.75 * 10^5)$ | (38) |
| Ghataprabha River Basin (248 km$^2$, Karnataka) | $R = (3330P - 383000)$ | (39) |
| Kangsabati River Basin (5,850 km$^2$, West Bengal) | $R = (9000P - 284000)$ | (40) |

In these relationships R and P represent annual precipitation in centimeters and annual runoff in million cubic meters (MCM), respectively.

UP Irrigation Research Institute (1960) formulae:

Uttar Pradesh Irrigation Research Institute, Roorkee, has developed the following relationships between runoff and precipitation:

A. Himalayan rivers

| | | |
|---|---|---|
| Ganga Basin at Hardwar (23,400 km$^2$) | $R = 5.45P^{0.60}$ | (41) |
| Yamuna Basin at Tajewala (11,150 km$^2$) | $R = 0.354P^{0.11}$ | (42) |
| Sharda Basin at Banbassa (14,960 sq.km) | $R = 2.7P^{0.80}$ | (43) |

B. Bundelkhand area rivers (in Uttar Pradesh State)

| | | |
|---|---|---|
| Garai Basin at Husainpur (290 km$^2$) | $R = 0.58P - 2.8$ | (44) |
| Ghori Basin at Ghori (36 km$^2$) | $R = P - 62.3$ | (45) |
| Ghaghar Basin at Dhandraul (285 km$^2$) | $R = 0.38P$ | (46) |

Sukhra Basin at Sukhra (15 km$^2$) $R = 0.47P - 2.8$ (47)

Karamnasa Basin at Silhat (518 km$^2$) $R = 0.49P$ (48)

where: R is runoff in centimeters and P is rainfall in centimeters.

UPID's formula. The Uttar Pradesh Irrigation Department (UPID) developed the following correlation between rainfall and runoff for Rihand River:

$$R = \left(P - 1.17P^{0.86}\right) \tag{49}$$

where: R and P are = runoff and rainfall in centimeters.

Indian Council of Agricultural Research's formulae for small watersheds. Runoff and rainfall from 17 sub-watersheds in the Nilgiri Hills, gauged by the Government of Tamil Nadu have been analyzed by the Central Soil and Water Conservation Research and Training Institute, Dehradun. The regression equation developed for annual flow:

$$Q = \frac{1.511P^{1.44}}{T_m^{1.34} A^{0.0613}} \tag{50}$$

where: Q = annual runoff (cm), P = annual rainfall (cm), A = Watershed area (km$^2$), $T_M$ = Mean annual temperature ($^0$C)

## UNIT HYDROGRAPH METHODS FOR FLOW ESTIMATION

A significant effort over the years went into determining design floods at ungauged locations. The Central Water Commission (CWC) (1983) under the long-term hydrological plan for water resources development and management, divided the country into already mentioned 26 hydro-meteorologically homogeneous zones (Figure 1; Table 1) and carried out analysis of selected concurrent rainfall and flood data for the gauged catchments to derive unit hydrographs of mostly 1-hour duration on the basis of rainfall data, gauge and discharge data collected during the monsoon season. Representative unit hydrographs are obtained for each of the gauged catchments. The characteristics of the catchments and their unit hydrographs, prepared for several catchments in a sub-zone, are correlated by regression analysis and the equations for synthetic unit hydrograph for the sub-zone are derived for estimating design flood for ungauged catchments. Studies are also carried out by the CWC to arrive at suitable recommendations for estimating loss rate and baseflow for ungauged catchments.

**Bhunya et al. (2003)** introduced a simplified version of the existing two-parameter gamma distribution to derive accurate synthetic hydrographs. Empirical relationships have been developed for the estimation of â and ë (factors governing the shape of the dimensionless unit hydrograph) from the Nash parameter *n* (= number of reservoirs).

**Bhaskar et al. (1997)** derived the Geomorphological Instantaneous Unit Hydrograph (GIUH) from watershed geomorphological characteristics and then related it to the parameters of the Nash instantaneous unit hydrograph (IUH) model for deriving its complete shape. The parameters of the

TABLE 1. List of hydro-meteorologically homogeneous sub-divisions in India.

| Code | Homogeneous zone | Sub-zone | River basins in the sub-zone |
|---|---|---|---|
| 1(a) | Luni Basin and thar (Luni and other rivers of Rajasthan Kutch) | Lupi | Luni river. Thar (Luni and other rivers of Rajasthan and Kutch and Banas River) |
| 1(b) | Chambal Basin | Chambal | Chambal River |
| 1(c) | Betwa Basin and other tributaries | Betwa | Sind, Betwa and Ken rivers and other South Tributaries of Yamuna |
| 1(d) | Sone Basin and right bank tributaries | Sona | Sone and Tons. Rivers and other South Bank Tributaries of Ganga |
| 1(e) | Punjab Plains including parts of Indus, Yamuna, Ganga and Ramganga basins | Upper Indo-Ganga Plains | Lower portion of Indus Ghaggar Sahibi Yamuna, Ganga and Upper portion of Sirsa, Ramganga, Gomti and Sai rivers |
| 1(f) | Ganga Plains including Gomti, Ghagra, Gandak, Kosi and other | Middle Ganga Plains | Middle Portion of Ganga, Lower portion of Gomti, Ghagra, Gandak, Kosi and middle portion of Mahanadi |
| 1(g) | Lower Ganga Plains including Subarnarekha and other east-flowing rivers between Ganga and Baitarani | Lower Ganga Plains | Lower portion of Ganga, Hoogli river system and Subarnarekha |
| 2(a) | North Brahmaputra Basin | North Brahmaputra | North Bank Tributaries of Brahmaputra River and Balason River |
| 2(b) | South Brahmaputra Basin | South Brahmaputra | South Bank Tributaries of Brahmaputra River |
| 2(c) | Barak and other Barak | Barak | Barak, Kalden and Manipur Rivers |
| 3(a) | Mahi, including the dhadhar, Sabarmati and rivers of Saurashtra | Mahi and Sabarmati | Mahi and Sabarmati including Rupen and Meehha Bandar, Ozat Shetaranji rivers of Kathiawad Peninsula |
| 3(b) | Lower Narmada and Tapi Basin | Lower Narmada and Tapi | Lower portion of Narmada, Tapi and Dhadhar rivers |
| 3(c) | Upper Narmada and Tapi Basin | Upper Narmada and Tapi | Upper portion of Narmada and Tapi rivers |
| 3(d) | Mahanadi Basin including Brahmani and Baitarani rivers | Mahanadi | Mahanadi, Baitarani and Brahmani rivers |
| 3(e) | Upper Godavari Basin | Upper Godavari | Upper portion of Godavari Basin |
| 3(f) | Lower Godavari Basin except coastal region | Lower Godavari | Lower portion of Godavari Basin |
| 3(g) | Indravati Basin | Indravati | Indravati river |
| 3(h) | Krishna sub-zone including Pennar Basin except coastal region | Krishna | Krishna and Pennar rivers except coastal region |
| 3(i) | Kaveri and East flowing rivers except coastal region | Kaveri | Kaveri, Palar and Ponnaiyar rivers (except coastal region) |
| 4(a) | Circars including east flowing rivers between Mahanadi and Godavari | Upper Eastern Coast | East flowing coastal rivers between Deltas of Mahanadi and Godavari rivers |
| 4(b) | Coromandal Coast including east flowing rivers between Godavari and Kaveri | Lower Eastern Coast | East flowing coastal rivers, Manimukta, South Pennar, Cheyyar, Palar, North Pennar, Munneru, Palleru, Cundalakama and Krishna Delta |
| 4(c) | Sandy Coroman Belt (east flowing rivers between Cauvery and Kanyakumari) | South Eastern Coast | East flowing coastal rivers, Manimuther, Vaigani, Arjuna, Tamraparni |
| 5(a) | Konkan coast (west flowing river between Tapi and Panaji) | Konkan Coast | West flowing coastal rivers between Tapi and Maudavi rivers |
| 5(b) | Malabar Coast (west flowing rivers between Kanyakumari and Panaji) | Malabar Coast | West flowing coastal rivers between Mandavi and Kanyakumari |
| 6. | Andaman and Nicobar | Andaman and Nicobar | |
| 7. | J and K Kumaen Hills (Indus Basin) | Western Himalayas | Jhelum, Upper portion of Indus, Ravi and Beas rivers |

GIUH and the Nash IUH model are derived using two different approaches. In the first approach (referred to as GIUH-I) the rainfall intensity during each time interval is allowed to vary, whereas in the second approach (referred to as GIUH-II) rainfall intensity is averaged over the entire storm period. This methodology has been applied to the Jira River subcatchment in eastern India to simulate floods from 12 storm events. Results from both the GIUH approaches and those obtained by using Nash IUH are comparable with observed events.

**Jain et al. (2000)** applied the unit hydrograph derived using the GIUH approach for the simulation of flood events and estimation of design flood for the ungauged catchments at Gambhiri Dam of Chambal Catchment in Rajasthan.

**Kumar et al. (2004)** derived the GIUH from geomorphological characteristics of a basin and it is related to the parameters of Clark's instantaneous unit hydrograph (IUH) model as well as the Nash IUH model for deriving its complete shape. The developed GIUH based on Clark and Nash models were applied for simulation of direct surface runoff hydrographs for ten rainfall-runoff events of Ajay Basin in eastern India.

**Sahoo et al. (2006)** developed and applied geomorphologic instantaneous unit hydrograph (GIUH) based on models by Clark in 1945 and Nash in 1957 to the Ajay River Basin at Jamtara in northern India for flood estimation from ungauged basins.

## FLOOD ESTIMATION

**Garde and Kothyari (1990)** analyzed data from 93 catchments in India and suggested the following relationships for the estimation of mean annual flood (with return period of 2.33 year) and the coefficient of variation of annual flood peak series:

$$Q_{2.33} = CP^{1.103} A^{0.74} S^{0.36} F_V^{-0.30} \tag{51}$$

where: A is the catchment area in km$^2$, S is the catchment slope, C = 0.185, $Q_{2.33}$ is mean annual flood in m$^3$/s, $F_v$ = the vegetal cover factor $= \frac{(a_1F_F + a_2F_G + a_3F_A + a_4F_W)}{A} * 100$, $a_i$ = the weighting factor, P = 2 yr, 45 min rainfall in mm if A/S ≤ 300; P = 2 yr, 3 h rainfall in mm if 300 < A/S ≤ 3000; P = 2 yr, 6 h rainfall in mm if 3000 < A/S ≤ $6*10^4$, and P = 2 yr, 24 h rainfall in mm if < A/S $6*10^4$.

**Swamee et al. (1995)** developed and described a dimensional analysis approach to regional annual flood peak estimation in India. Dimensional variables were formed using the mean annual flood, the average rainfall, the rainfall duration, the return period, the drainage area, the catchment slope, the fraction forested, and the gravitational acceleration. The utility of the approach is demonstrated by fitting it to a sample of 93 river basins ranging in size from 14.5 km$^2$ to 935,000 km$^2$, and with record lengths of 10 to 84 years. Most (90%) of the model predictions fall within ±50% of the observed mean annual flood. During the calibration of the model, average rainfall of different durations varying from 0.75 h to 12 h and return period varying from 2 to 25 years were used. The validity of this model was further investigated using the average rainfall of 24 h duration and 2 yr recurrence interval. Although the model was validated with only a 2-yr-return-period 24-h-duration rainfall data, it was found that 85% of the model predictions fell within ±50% of the observed mean annual flood. The equations used are as follows:

$$Q = 1.724 \frac{A^{0.8925} p^{0.92}}{D^{0.24} T^{0.17}} \left( \frac{S_o + 0.012}{C_f + 0.049} \right)^{0.55} \tag{52}$$

$$Q = 0.2 A^{0.8925} p^{0.92} \left( \frac{S_o + 0.012}{C_f + 0.049} \right)^{0.55} \tag{53}$$

Where: A is the catchment area in $km^2$, D in min, T in years, Q in $m^3/s$, S is land slope, p is precipitation in mm, $C_f$ is forest cover factor.

**Goel (1998)** presented the details of flood estimation procedures for Indian catchments in general and for mountainous watersheds in particular. The flood peak data of 11 small and medium catchments ranging from 6 $km^2$ to 2,072 $km^2$ in and around the sub-Himalayan Region (Zone 7, Table 1) have been analyzed and flood frequency analysis for these streams has been carried out using methods based on L-moments. The results indicate the versatility of L-moments as parameter estimator, as homogeneity measure and as goodness of fit measure. Finally, the regional flood formula for the sub-Himalayan region has been developed as:

$$\overline{Q} = 4.57 A^{0.76239} \text{; r=0.870} \tag{54}$$

where: $\overline{Q}$ = mean annual flood in $m^3/s$ and A = catchment area in $km^2$

**Goel and Chander (2002)** list some other prediction methods for floods.

<u>UPIRI (1960) formula</u> The Irrigation Research Institute, Roorkee, Uttar Pradesh has carried out frequency studies on Himalayan rivers and suggested the following relationship to compute Dicken's constant 'C' for the desired return period:

$$C = 2.342 \log(0.6T) * \log(1185/p) + 4 \tag{55}$$

where: $P = \left( \frac{a+6}{A+a} \right) 100$, a = Perpetual snow are in $km^2$, A+a =Total catchment area ($km^2$). After computing the value of 'C' for desired return period 'T' the peak flood for the corresponding return period may be obtained using Dicken's formula.

### *Envelope curves*

The maximum flood per square kilometer experienced in one basin is quite likely to be experienced in a nearby basin in the same region and possessing similar hydro-meteorological characteristics. A smooth curve enveloping the plotted points on log-log paper against the drainage area provides the most concise description. The curves are not associated with frequencies, but within the region to which they apply. They give the magnitude of flow that has occurred. Kanwar Sain and Karpov (as reported in the CWC (1983)) collected data of Indian rivers and developed two enveloping curves, one to suit the basin of South India and the other for those of Northern and Central lndia. Generalized curves of this nature may be useful as a rule-of-thumb estimate of potential flood risk. They are not definitive enough to justify their use in specific engineering applications.

**Kumar et al. (2003)** have carried out the regional flood analysis for estimation of floods of various return periods for gauged and ungauged catchments of the North Brahmaputra River system. Screening of data has been carried out by employing discordancy measure, in terms of L-moments. Homogeneity of the region has been tested using the L-moment based heterogeneity measure by carrying out 500 simulations using four parameter Kappa distribution. Regional flood formula has been developed for estimation floods of various return periods for gauged and ungauged catchments of the North Brahmaputra River system. The catchment area and mean annual peak flood data were used to compute peak floods of different return periods. The relationship between mean annual peak flood and catchment area was found to explain 89.8% of initial variance ($r^2$= 0.898) and the standard error of the estimates was 0.535. Kumar et al. (2004) and Kumar and Chatterjee (2005) carried out similar studies in the Sona sub-zone and Brahmaputra basin (extended area).

**Parida et al. (2004)** carried out a regional flood frequency analysis using the index flood procedure and the L-moments with the objective of investigating the hydrological homogeneity of India's hydro-meteorological sub-zone 3-a and identification of a suitable frequency distribution for it. Based on analysis of flood data at 12 gauged sites, the Mahi-Sabarmati Basin is shown to be hydrologically homogeneous and follows the generalized normal distribution. Regional curve developed based on the analysis has been recommended for carrying out flood frequency analysis at both gauged and ungauged sites in this region.

**Parida (2004)** carried out clustering of the flood sites of central India between latitudes 13$^o$7' -24$^o$57' N and longitudes 69$^o$8'- 87$^o$2' E, extending over 104,1679 km$^2$ area which approximately covers a third of the total area of the country. The main rivers flowing across the study area are: The Baitarani, Brahmani, Mahanadi, Mahi, Sabarmati, Saraswati, Narmada, Tapi, Godavari, Krishna and the Pennar. Attributes such as maximum rainfall in design duration, catchment area, basin slope, length of main stream, etc., have been considered responsible for flood generation and to determine mean annual peak flood data. Relationships between mean annual peak flood and above basin characteristics have been developed for each homogeneous region of the Central Water Commission (CWC 1983).

**Kothyari (2004)** described a technique of Artificial Neural Networks (ANN) and a concept is introduced on the use of ANN for estimation of hydrological parameters from ungauged catchments. A regression-based model was coupled with the ANN by Kothyari (2004) for the estimation of the mean annual flood. The model was first derived for the estimation of Q by making use of the independent variables. The output of such an auxiliary model, along with the other variables, was considered as input to the ANN model that was termed as the substantive model. ANN based modeling for annual mean flood was preformed for two scenarios: (i) Input: rainfall, catchment area, catchment slope and vegetal cover characteristics, Output: mean annual flood; (ii) Input: hydro-climatic and physiographic characteristics after simple regression in auxiliary model, Output: mean annual flood. The values of $r^2$, MES and percentage of data points estimated with error less than 20%.

**Raghuvanshi et al. (2006)** used ANN, to predict both runoff and sediment yield on a daily and weekly basis, for a small agricultural watershed. Regression models for predicting daily and weekly runoff and sediment yield were also developed using the above training datasets, whereas these models were tested using the testing datasets. In all cases, the ANN models performed better than the linear regression based models.

## CONCLUSIONS

The review covered techniques and studies produced and published by Indian hydrologists on the topic of ungauged basins over the past decades. Few studies focusing on low-flow estimation at ungauged sites have been identified. Relevant work focused on the Himalayan region of India and Nepal to assess the water availability during lean period for the establishment of hydropower stations. Therefore, there is a need to test existing methods developed elsewhere - for estimation of low-flow characteristics like Q95, 7Q10, etc., flow duration curves and other low-flow relevant hydrological measures and indices in different hydrologically homogeneous regions of India.

Considerable work has been done in India to estimate the long-term mean annual flow of various river basins of India using regression relationships with catchment parameters. However, most of these methods appear to have been developed a long time back.

Extensive work has been done in the field of flood estimation characteristics using various techniques. Summaries of these are available in relevant CWC Reports (some cited in this paper). More recent studies attempt to apply new statistical approaches (like ANN) in flood studies, following the world trends.

Indian science and practice of flow estimation at unagauged sites would benefit significantly from opening the already collected observed hydrological data time series for wider use in water research and from participating in international hydrological research initiatives like Flow Regimes from International Experimental and Network Data (FRIEND).

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