# HYDROLOGY OF MOUNTAINOUS AREAS

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The mountainous regions are sources of water, forest, food, fiber and energy. Nearly 35% of the geographical area in the country is mountainous. Of these nearly 58% is accounted for by the mighty Himalayas extending from northwest to east. Besides, the Khasi and Jayantiya hills in the northeast, the Vindhyas and Satpura hills in central India, the western ghats running all along the west coast from Maharashtra to Kerala and the broken hill ranges of eastern ghats largely determine and guide the country's rainfall pattern during the summer monsoon as well as winter rainy season. Isolated hill ranges like the Aravalis in Rajasthan and Nilgiris in Tamilnadu also influence the rainfall occurrence locally. Fig. shows the mountain systems in the country.

## Distribution of Precipitation

Long before data from higher elevations became available the predominant influence of orography on precipitation was known more in a qualitative and subjective way. The precipitation distribution in mountainous areas is influenced not only by orography but also the fluctuations in the wind direction. Other controlling factors being constant, the gradient of precipitation is dependent not only on the wind speeds but also the orientation of the hill ranges with respect to the prevailing direction of winds which are carriers of the moist air.

Systematic studies on distribution of precipitation in mountainous areas have been undertaken only after the sixties when rain gauges were set up with the specific purpose of studying the distribution of precipitation with elevation. Such studies were limited mainly due to lack of proper instrumentation and other facilities to undertake such studies. Based on the information available from raingauges and snow gauge located at higher elevations some studies were conducted.

Superimposed on the regional and sub regional variations in precipitation in the mountains, there are important differences on a local scale for example between valley bottoms and exposed ridges. Very little work has been done in this respect. Results collected to date suggest lower precipitation amounts in valleys as compared to slopes and ridges. The lesser precipitation in the valleys has been ascribed to occurrence of persistently ascending mountain winds.

Some of the world's highest rainfall has been recorded near Cherrapunji and Mawsynram situated on the southern slopes of Meghalaya plateau when moist air from Bay of Bengal, is forced to ascend by 1200 m (Rao, 1981). At Shillong situated only

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Figure 1 Relief map of India

50 km north on the same plateau, annual rainfall decreased to about 2400 mm declining steadily to 1600-1800 mm as one descends into Assam valley. It rises again to 4000 mm on the lower Himalayan slopes of Arunachal Pradesh (Goswami, 1985). Not much is known about the behaviour of rainfall in the higher parts of the region.

The various longitudinal physiographic zones of the Himalayas, with their strong contrasts in elevation experience widely varying amounts of rainfall. Regionally, elevation and orientation towards moisture laden winds influence to a great extent the distribution of precipitation in Himalayas.

Heavy rainfall due to orographic effect is confined to the western ghats and the Khasi and Jayantiya hills of Assam and Meghalaya. Rainfall in 3 hour and 6 hour duration can be as much as 60 and 75% respectively of the 24 hour rainfall.

Dhar et al (1978) carried out a study of the heavy rainfall stations in India. For the purpose of the study stations having a mean annual rainfall of 500 cm or more were considered as heavy rainfall stations. In Table -1 stations receiving more than 500 cm annual rainfall together with their elevation and mean annual rainfall are presented. It may be seen from the table that ten out of the fourteen heavy rainfall stations lie in the western ghats and the rest are located in the hills of northeast India. There are, however, none from the Himalayan region.

**Table 1 : Heavy Rainfall Stations in India**

| Station | State | Elevation (m) | Mean Annual Rainfall(cm) | Period of Record |
|---|---|---|---|---|
| Agumbe | Karnataka | 659 | 847 | 1952-1970 |
| Amboli | Maharastra | - | 747 | 1934-1951 |
| Bhagamandal | Karnataka | 876 | 596 | 1907-1970 |
| Buxa | West Bengal | - | 532 | 1891-1968 |
| Cherrapunji | Meghalaya | 1313 | 1102 | 1902-1975 |
| Denning | Arun.Pradesh | 698 | 528 | 1929-1949 |
| Gaganbawda | Maharastra | 690 | 596 | 1901-1974 |
| Mahabaleswar | Maharastra | 1382 | 630 | 1891-1976 |
| Makut | Karnataka | - | 517 | 1933-1974 |
| Matheran | Maharastra | 695 | 534 | 1892-1974 |
| Mawsynram | Meghalaya | 1401 | 1221 | 1941-1969 |
| Neriamangalam | Kerala | - | 504 | 1940-1973 |
| Peermade | Kerala | - | 500 | 1901-1970 |
| Pulingoth | Karnataka | 919 | 588 | 1933-1967 |

***Source : Dhar et al (1978)***

During the onset of the southwest monsoon the moisture laden monsoon winds first approach the western ghats and the hills of north east India and precipitate most of the moisture over these regions. By the time they approach the Himalayan region much of the moisture is lost and this is the reason for the comparatively lesser rain in the Himalayan region.

In the case of highest one day rainfall, while Cherrapunji, Jowai and Mawsynram had 103.6, 101.9 and 99.0 cm respectively, Dharampur a plain station on the west coast in Gujarat received 98.7 cm.

## Variation of Precipitation with Elevation

Dhar and Bhattacharya (1976) made a study on the variation of precipitation with elevation in the central Himalayas. A relationship between precipitation and elevation was obtained for the central Himalayas using 15 to 20 years' data of more than 50 stations in this region of the Himalayas. Variation of rainfall with the elevation showed that there are two zones of maximum precipitation. One near the foot of the Himalayas and other at a elevation of 2.0 to 2.4 km. For higher elevations beyond 2.4 km the precipitation decreases sharply as one moves across the central Himalayas.

Statistically significant relationships between annual rainfall and elevation have been derived for some parts of the lesser Himalayas. (Katiyar and Strifler, 1984). It was, however, realised that such relationships have only local predictive value and hold for a certain range in altitude. Above a critical elevation (2500-3500 m) a reduction in precipitation was observed. North of the Greater Himalaya, precipitation decreases rapidly to less than 500 mm annually. Equally low amounts of precipitation have been reported for Tibetan Plateau. The annual precipitation at Lhasa was reported to be 350 mm (Majupuria and Majupuria, 1988). A similar overall pattern was observed by Dhar et al (1987) for the Kumaon and Garhwal Himalayas where annual precipitation of 2000 mm was reported.

Upadhyay and Bahadur (1982) carried out a study of the variation of precipitation in Himalayas. The Himalayas Mountain system was conceived to be constituted of three parallel longitudinal ranges.

(i) the outer Himalayas or Shiwalik ranges with height from 1000 - 1300 m and width from 10 to 50 kms.

(ii) the lesser or middle Himalayas with height ranging from 2000 - 3300 and width between 60 to 80 kms.

(iii) the greater Himalayas with height of 6100 m and average width of about 200 km.

Data of rainfall from seven sub-regions in western Himalayas having homogeneous topographic aspects were considered for the study of the variation of precipitation with altitude. In Table-2 the annual precipitation in the different sub-zones is shown. It has been seen that the precipitation gradient decreases or even became negative when considerable increase of wind speed occurs with increasing elevation which partly explains the decrease of precipitation after a certain elevation in the Himalayas. This elevation was noticed to be generally around 2000 m.

**Table 2 : Variation of Precipitation with Altitude**

| Station | Latitude (N) | Longitude (E) | Height (m) | Annual precipitation (cms) |
|---|---|---|---|---|
| Kangra valley | | | | |
| Dehra | 31° 50' | 76°13' | 436 | 131.8 |
| Kangra | 32°06' | 76°15' | 733 | 196.6 |
| Palampur | 32°7' | 76°32' | 1250 | 263.7 |
| Dharamsala | 32°13' | 76°19' | 1387 | 300.9 |
| Doon Valley | | | | |
| Ambari | 30°30' | 77°49' | 489 | 183.7 |
| Dehradun | 30°19' | 78°02' | 679 | 207.5 |
| Raipur | 30°18' | 78°05' | 750 | 209.7 |
| Rajpur | 30°24' | 78°05' | 914 | 300.7 |
| Mussoorie | 30°27' | 78°05' | 2042 | 247.0 |
| Almora Hills | | | | |
| Almora | 29°36' | 79°40' | 1572 | 105.4 |
| Ranikhet | 29°38' | 79°26' | 1810 | 133.7 |
| Mukteshwar | 29°28' | 79°39' | 2311 | 132.5 |
| Nainital | | | | |
| Haldwani | 29°13' | 79°31' | 440 | 199.5 |
| Kathgodam | 29°17' | 79°32' | 513 | 209.2 |
| Nainital | 29°23' | 79°27' | 1934 | 253.9 |
| Joshimath | | | | |
| Karanoparyag | 30°16' | 79°15' | 769 | 142.3 |
| Ukhimath | 30°30' | 79°15' | 1220 | 201.1 |
| Birangkhal | 30°15' | 69°15' | 1520 | 122.8 |
| Joshimath | 30°33' | 79°35' | 1840 | 95.4 |
| Kulu & Lahaul Valley | | | | |
| Kulu | 31°57' | 77°7' | 1215 | 100.6 |
| Benjar | 31°38' | 77°20' | 1524 | 110.6 |
| Kathoi | 31°18' | 77°32' | 1608 | 101.2 |
| Keylong | 32°35' | 77°4' | 3166 | 61.4 |
| Shimla Hills | | | | |
| Kasauli | 30°53' | 76°58' | 1844 | 163.7 |
| Kotgarh | 31°18' | 77°29' | 1949 | 115.3 |
| Shimla | 31°06' | 77°10' | 2202 | 159.0 |

Based on the study, the authors concluded that the precipitation is influenced by increasing altitude in three ways.

(i) The quantity of precipitation increases with altitude upto a certain level and decreases thereafter. The level of maximum varies greatly from place to place depending on local topography. It was generally observed to be between altitudes of 1500 to 2500 m.

(ii) Average variability of precipitation generally increases with elevation.

(iii) At higher altitudes, the period of maximum precipitation is generally earlier than that on foot hills.

Surinder Kaur and Upadhyaya (1987) in connection with a study of network design for mountainous catchments presented a picture of the variation of precipitation with elevation in the Beas catchment and its variability which is given in Table

**Table 3 : Variation of Precipitation with Elevation in Beas Catchment**

| Station | Elevation (m) | Mean Annual Precipitation (cm) | Standard Deviation | Coeff. of variation % |
|---|---|---|---|---|
| Dharamsala | 1211 | 366 | 184 | 54 |
| Palampur | 1217 | 256 | 96 | 38 |
| Hamirpur | 786 | 142 | 55 | 40 |
| Kangra | 701 | 196 | 53 | 27 |
| Kulu | 1236 | 100 | 30 | 30 |
| Mandi | 752 | 157 | 25 | 16 |
| Jogindernagar | 1221 | 223 | 56 | 25 |
| Sundernagar | 1193 | 159 | 27 | 17 |
| Banjar | 1522 | 109 | 28 | 26 |

## Modelling of Orographic Rainfall

A dynamic model for orographic rainfall with particular reference to the Bombay - Poona region in the Western ghats was developed by Sarkar (1967). The model was based on steady state, two dimensional linearised equation and a saturated atmosphere with pseudo adiabatic lapse rate. Vertical velocities were computed analytically.

From a given characteristics of the air stream on the windward side, the terrain induced vertical velocity was computed from the equation

$$\frac{\delta W^2}{\delta x^2} + \frac{\delta W^2}{\delta z^2} + f(z)W = 0 \qquad ...(1)$$

by a quasi-numerical method. In the above equation f(z) is a function of wind speed, wind shear and stability of the undisturbed air stream.

The distribution of computed rainfall intensity showed reasonable agreement with the distribution of observed rainfall (Fig. 2). Other important conclusions of the study were:

(i) The model computed orographic rainfall increase from West Coast to inland along the slope of the ghats and reached a maximum before the crest of the mountain was reached after which it decreased sharply.

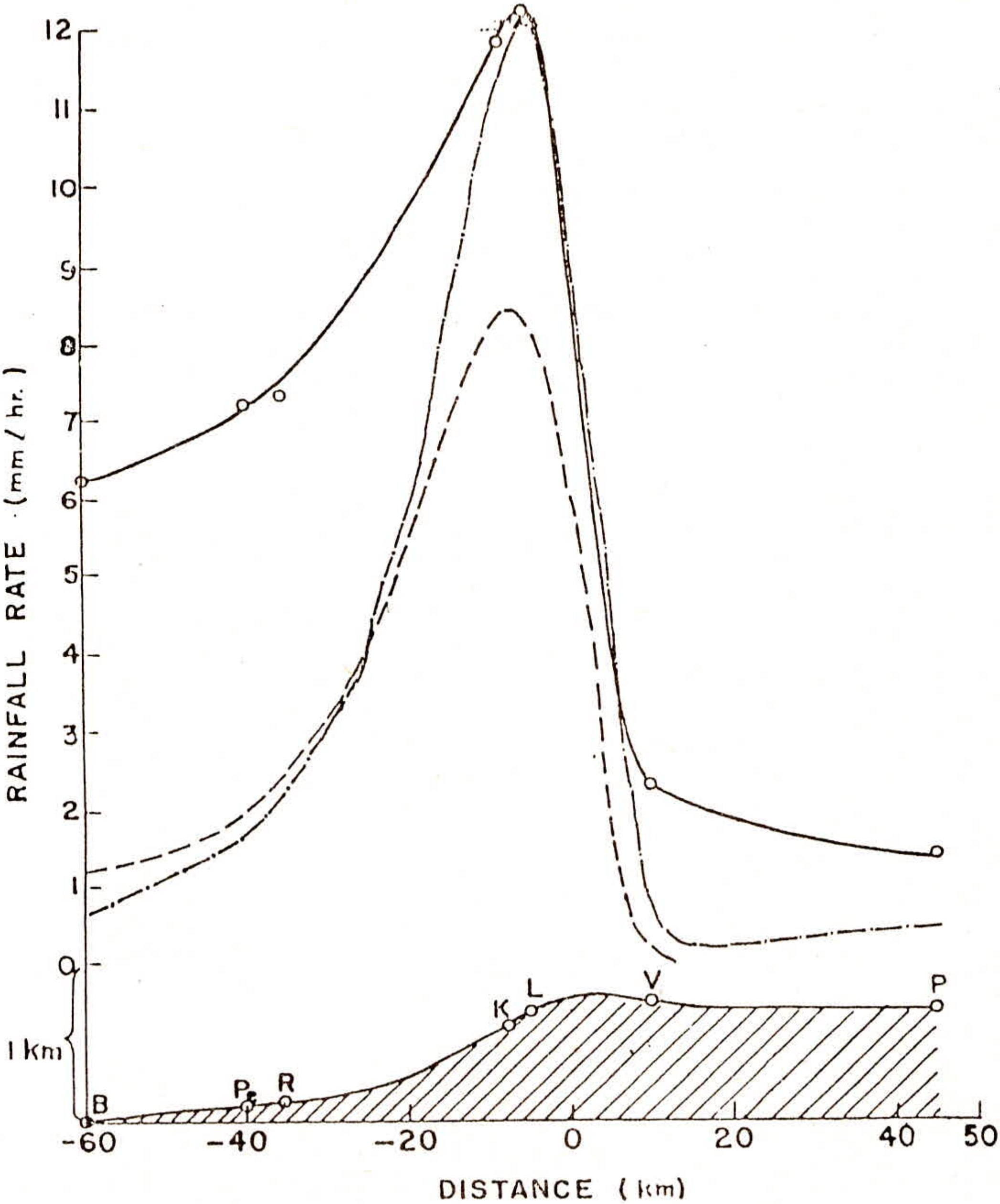



Fig. 2 Observed (upper solid curve), computed orographic from the approximate model (dashed curve) and computed orographic from the modified model (dashed-dotted curve) rainfall distribution for July 5, 1961 along the orographic profile (shaded) from the coast at Bombay (B) inland through Pen (Pe), Roha (R), Khandala (K), Lonavla (L), Vadgaon (V), and Poona (P). (Sarker, 1967).

(ii) The contribution of orography to coastal rainfall was only about 20% indirectly suggesting that the observed heavy rainfall along the coast is caused largely by synoptic scale convergence.

(iii) The observed maximum in rainfall close to the peak of the mountain was almost completely accounted for by the orographic model.

(iv) The rainfall on the windward side originates from levels below about 5 km but on the lee side from above that level.

Sinha Ray et al (1982) had studied the contribution of orography on the total rainfall in the western ghats and Khasi Jayantiya hills of Assam. An attempt was made to isolate the relative importance of the orographically induced vertical motion in terms of the flow characteristics like wind speed, direction, shear and stability of air and the role of the synoptic and convective factors also.

## Rainfall Extremes

In characterising a location climatically, it is important to consider not only the rainfall normals and seasonal distribution but also the extreme events such as heavy rain storms or prolonged dry spells.

In the Himalayan belt the eastern parts receive comparatively higher rainfall and intense rainstorms than in western Himalayas. Also, the rainfall intensities decrease as one goes from plains to mountains in the Himalayas. The highest daily rainfall ever observed in the Ganga basin was 823 mm recorded at Nagina in Bijnor in west UP in September 1880. The corresponding two day rainfall was 1042 mm (Sharma and Mathur, 1982). The highest one day total in northeastern hills was 1036 mm at Cherrapunji recorded in August 1841 (Holeman, 1968).

Sharma (1986) carried out probability analysis of 30 years of rainfall data at Barapani, Shillong for rainwater management in the northeastern hill region. The analysis indicated that the maximum six days rainfall of five year return period is 31.0 cm. The probability of occurrence of different amounts of rainfall was derived through the Weibull's formula.

Pandey et al (1984) reported relatively higher rainfall intensities in the foot hill zones than in the middle Himalayas.

Sreedharan and James (1988) used EV 1 distribution with the method of maximum likelihood for deriving intensity (depth) - duration- frequency relationships for Periyar basin in Kerala. Annual maximum rainfall depths of 1,2,3,7 and 10 days duration were analysed. The analysis was carried out for individual stations and later regional relationships were obtained based on station year concept. The regions were demarcated considering rainfall and topographical characteristics. Similar studies were done for the western ghats part of Kerala state (Sreedharan and James, 1990).

Dhar and his associates (Dhar et al 1980) prepared one day PMP estimates for different parts of the country based on the Hershfield's technique. The corresponding values for the western ghats exceed 45 cm.

## Variation of Temperature with Elevation

Air temperature is considered to be the best index of heat transfer processes associated with melting of snow. The temperature distribution with elevation in a snow covered basin is required for estimation of snowmelt. The observational network in mountainous areas being generally inadequate, information on the temperature distribution in various elevation zones has to be obtained on the basis of temperature observations at a few locations.

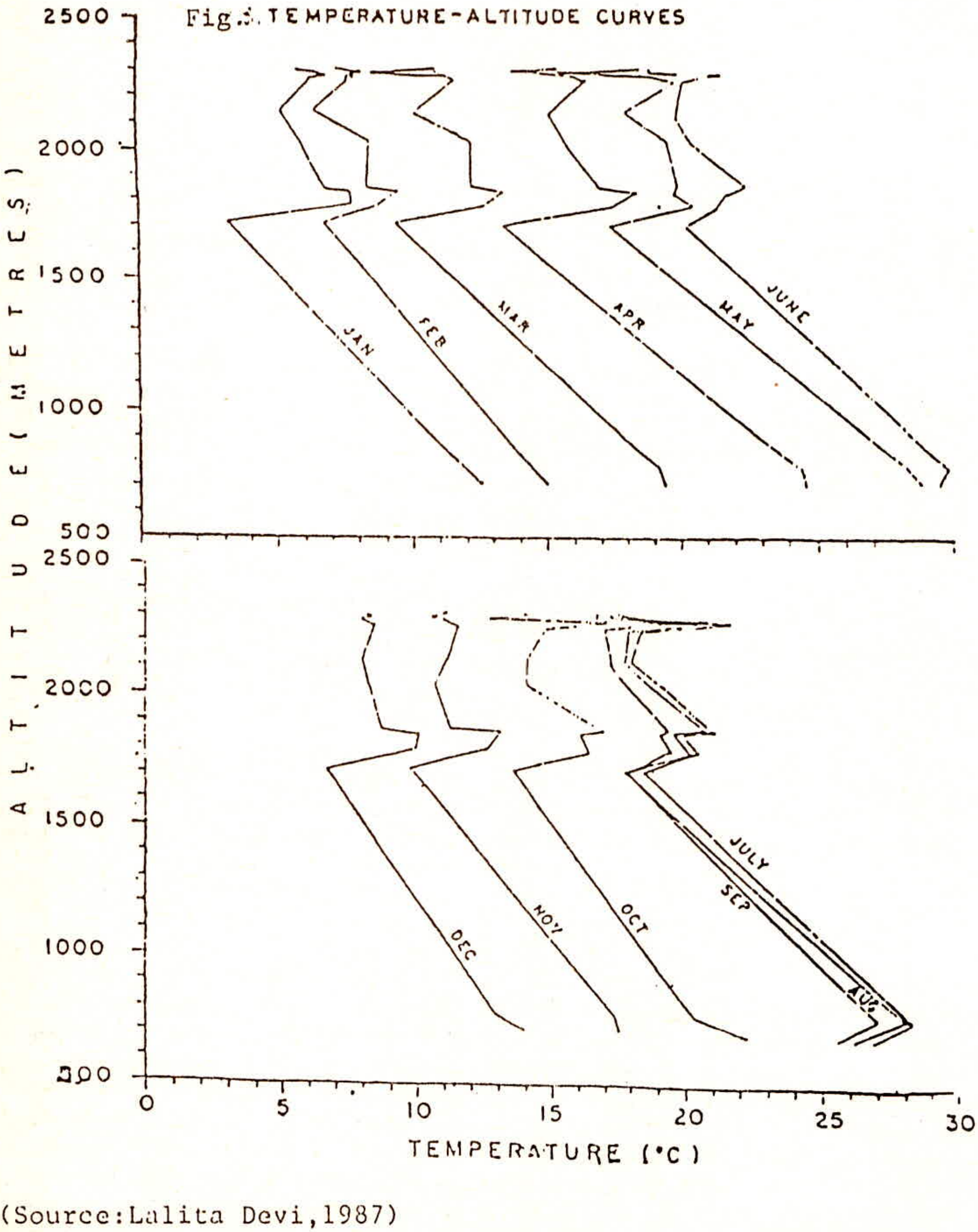
Very few studies have been reported on the distribution of temperature in the mountainous areas. A fixed value of temperature lapse rate (decrease of temperature with elevation) has been made use of by some authors (Thapa, 1980; Bagchi, 1981; Jeyram et al 1983 and Seth, 1983) for distribution of temperature in various elevation zones in a snow covered basin.

Devi (1987) has made an attempt to analyze the variation of temperature in the hills of western Uttar Pradesh. It was observed that lapse rate of temperature observed in both valley bottoms as well as along mountain slopes was less than 6.5 °C/km, the mean environmental lapse rate. It was found that both the diurnal and annual range of temperature decreases with ascent from plains upto a height of about 2400 m and thereafter it again increases attaining the highest value at higher elevations. The temperature altitude curves for different months are shown in figure 3.

Bhutiyani (1989) has reported a variation of temperature lapse rate ranging from 3.8 °C/km to 9.6 °C/km in the month of August on Chhota Shigri Glacier in Himachal Pradesh. Upadhyay et al (1989) have analysed the monthly normals of surface temperature for various stations situated at different altitudes in the Western Himalayas and reported that monthly lapse rates of temperature are fairly constant.

In the studies carried out by Devi (1987) and Upadhyay (1989) data from stations scattered over a wide range of mountainous part of Himalaya were considered. Presence of valleys and high crests between the stations considered for the studies would affect the conclusions regarding the temperature distribution with elevation. The results presented by Bhutiyani (1989) are based on data for a limited period, and therefore, cannot be generalised.

Singh (1991) studied the temperature lapse rate pattern in the Satluj catchment using data from three stations Rampur (1066 m), Kalpa (2439 m) and Rakcham (3130 m) located in a contiguous region. The mean daily maximum and minimum temperature data for a period of five years was used to compute the monthly mean values of temperature lapse rate. It was observed that mean monthly lapse rate varied between 6.7° C to 8.9° C/km for Rampur - Kalpa and between 3.0° to 5.3° C/km for Kalpa to Racham. The average values for the snowmelt season (March - June) for Rampur - Kalpa and Kalpa - Rakcham are 8.5° C/km and 4.05° C/km respectively. The conclusions of the study are not definitive due to the limited number of stations used in the study.




(Source:Lalita Devi,1987)

Data of more stations representative of different elevation zones would be needed to arrive at representative values of the temperature lapse rates. It should also be ensured that the data is observed around the same time of the day at all the locations.

## Collection and Transmission of Hydrological Data

Reliable and accurate hydrological data are needed not only for water resources planning but also for flood forecasting and reservoir regulation for various uses like irrigation, power generation, domestic and industrial uses, navigation etc. Most hydrological data collection systems in the country were manual. Turbulent flows with high velocities, and boulders, inaccessible mountain terrain pose special problems for measurement of hydrometeorological and hydrological parameters for the mountain river systems.

The major features of a data collection system to be adopted are as follows:

(i) state of art instrumentation for observation of hydrological and meteorological data
(ii) compatible appropriate technology for measurement and computation
(iii) reliability and quality of collected data
(iv) communication of the data within allowable time limits and
(v) cost effectiveness of the system in comparison to the benefits derived out of it.

Ghanekar et al (1984) presented the sensors and their application which were used in UNDP assisted Yamuna flood forecasting system. Verdhan (1987) made a review of instrumentation and measurement techniques for flow measurements in mountainous areas.

The Snow and Avalanche Study Establishment (Kumar, 1989) has tested various sensors for use in the Automated Weather Stations. Snow pillows were found suitable for unattended measurement of snow water equivalent, monitoring build up and depletion of snow cover. SASE is now testing Automated weather stations and snow sensors fabricated indigenously.

The Central Water and Power Research Station (1986 and 1988) developed a digital water level recorder. The water level sensor works on battery and provides an electrical signal output. The recorder can be used for measuring water levels in reservoirs and river gauges.

Data transmission in mountain ranges is more often restricted by line of sight requirements. CWPRS (Gaikwad et al. 1984) has reported testing of the burst mode digital telemetry for hydrological data transmission. The burst mode digital telemetry was said to be a comparatively economical system for real time hydrological data collection and transmission system for watersheds, small river catchments.

Kundu (1989) reported the successful use of meteor burst communication for transfer of data from Pune to Delhi during September 1988. He mentioned that the system was more durable in the sense that the instruments even 10 years after installation were working without any trouble.

Apart from the Yamuna flood forecast system, the Damodar catchment also has a real time data collection and transmission system which is partly manual and is based on HF wireless communication system.

The Narmada development authority and Narmada control authority were together planning to establish a hydrometeorological data collection and transmission network for the entire Narmada basin for flood forecasting and integrated reservoir regulation of a number of reservoirs (Dikshit et.al., 1989).

**Forest Influences**

Forests influence the hydrological regime of an area through various processes such as evapotranspiration, infiltration, surface runoff and sediment yield. In India mountainous areas are also areas blessed with rich forests Estimates of forest land in the hill districts of Uttar Pradesh, Sub-Himalayan West Bengal and Sikkim suggest 30 to 40% of area as being under forest (Tejwani, 1985). In Meghalaya and Nagaland forests make up only 10% of the land area. It was reported that there was an over all loss of forest cover during the period 1951 to 1980 with deforestation exceeding plantation rate by 16%.

Information on various components of the water budget like evapotranspiration are not available. Puri et al (1982) gave figures of 1210 mm of streamflow against a total of 2235 mm of annual rainfall for the Bemunda watershed in Tehri Garhwal situated at an elevation of 800 m to 2200 m. This would imply an evapotranspiration figure of 1025 mm/yr for a largely forested catchment. This is probably due to the under estimation of flow and also not accounting for water stored in the sub soil.

Pandey et al (1984) observed the following rainfall intensities in different vegetation zones in the Kumaon Himalayas.

| Intensity Class (mm/30 min) | Sites (% of events) Sal Forest | Pine Forest | Mixed Oak Rain dominated Forest |
|---|---|---|---|
| 2 | 28.0 | 34.7 | 38.5 |
| 2-4 | 36.0 | 27.5 | 29.2 |
| 4.1-6 | 27.0 | 29.0 | 18.7 |
| 6.1-8 | 4.9 | 4.1 | 10.4 |
| 8.1-10 | 2.5 | 4.1 | 3.1 |
| 10 | 1.2 | 0.0 | 0.0 |
| Total number of events | 81 | 98 | 96 |

Source : Pandey et al (1984)

Studies on three catchments of average area of 1.5 sq.km by CWRDM indicated that the interception loss for an average storm was of the order of 10% from the forested catchment. In all seasons at all depths (upto 100 cm), soil moisture in the dense forest was the highest attaining a maximum value during the northeast monsoon. Average accumulation of sediment was 0.75, 4.00 and 4.73 $m^3/km^2$ for dense forest, partially exploited and fully exploited catchments respectively.

Pandey et al (1984) observed very low amounts of overland flow during consecutive rainy seasons in a range of forest types in Kumaon Himalayas. Subba Rao et al (1985) presented storm hydrographs for densely forested (but grazed) headwater catchment in the Shiwalik hills which suggests streamflow to be dominated by some sort of overland flow.

Pathak et al (1985) undertook studies of rainfall interception at six forest sites in Uttarakhand (Uttar Pradesh) during the monsoon seasons of 1981 and 1982. Five of these sites had a canopy cover in excess of 70% and only one as low as 38%. Throughfall rates ranged from 75 to 92% and canopy interception from 8 to 25%.

Apportionment of Rainfall in Central Himalayan Forests

| Forest | Canopy % | Rain-fall mm | Through-fall % | Stem-flow % | Inter-ception % | Litter Inter-ception % | Ground Vegetation Interception and Infiltration % | Over-land Flow % |
|---|---|---|---|---|---|---|---|---|
| Pine | 90 | 1234 | 74.7 | 0.3 | 25.0 | 7.2 | 58.9 | 0.8 |
| Pine +MB | 38 | 1179 | 91.5 | 0.4 | 8.0 | 7.2 | 83.5 | 1.3 |
| M.Oak/Pine | 78 | 915 | 82.8 | 0.4 | 16.8 | 8.9 | 73.8 | 0.6 |
| Mixed Oak | 81 | 1364 | 84.7 | 0.4 | 14.9 | 9.4 | 75.2 | 0.5 |
| Mixed Oak | 93 | 1240 | 80.8 | 0.9 | 18.3 | 9.2 | 72.3 | 0.2 |
| Sal | 89 | 1153 | 82.4 | 0.9 | 16.7 | 9.8 | 72.8 | 0.7 |

Source : Pathak et al (1985)

Rawat (1988) has shown that under identical geological and geomorphological character the agricultural land has the maximum capacity to generate suspended and dissolved load 24 times and 5.5 times respectively higher than from Oak mixed forest land.

## Geomorphological Studies

Since most of the catchments in the mountainous areas are either ungauged or do not have adequate data, study of the geomorphological characteristics of the catchments would help in deriving appropriate parameters suitable for developing rainfall runoff parameters, based on catchment characteristics.

Valdiya (1988) presented results of morphological studies in the Nainital region of Kumaon hills in west Uttar Pradesh. Besides the drainage pattern, the drainage density and drainage frequency in the region were studied.

Shandilya and Negi (1991) reported on geomorphological investigations in Garhwal Himalayas. Slope and drainage characteristics of the Srinagar area and channel characteristics of Alakananda river in the lesser Himalayas were studied.

Very few studies have been carried out on the study of geomorphological characteristics and their use for estimation of stream flows. Based on geomorphological studies in Ramganga catchment in U.P. Himalaya Rawat and Joshi (1983) concluded that stream discharge is a function of total stream length and silt delivery from a channel segment is a function of relief ratio.

National Institute of Hydrology (1988, Vijay Kumar, 1990) have carried out geomorphological studies for four sub-basins of Krishna in western ghats. The parameters estimated included linear aspects of channel system, areal aspects of the catchment and relief aspects of catchments and channel networks.

Panigrahi (1991) derived the Nash model parameters from the geomorphological instantaneous unit hydrograph for the Kolar sub-catchment in narmada basin.

**Rainfall-Runoff Relationships**

For planning and managing such systems quantitative information on water available at a particular site is essential. Often the observed streamflow records are too short to provide reliable estimates. When time scales are of longer duration such as ten days or a month, simple rainfall-runoff relationships are often adequate for representing the relation between rainfall and runoff without considering details of various influencing factors. The rainfall runoff relationships vary from simpler regression techniques to watershed models which simulate daily runoff.

James et al (1987) developed monthly rainfall-runoff relationships for sub-basin Chaliyar catchment in Kerala using a Quadratic equation.

$$Q_{p,t} = a_{t,o} + a_{t,1} P_{p,t} + a_{t2} P^2_{p,t}$$

coefficients in the equation were solved using multiple regression.

A Daily runoff simulation model was attempted using Tank model.

Ranganna et al (1990) developed a simple deterministic rainfall-runoff model based on monthly data for the monsoon period (June-Nov.) for the Sitanadi basin in Western ghats region. The model has been calibrated using data for a period of 14 years from 1973 to 1986. The model is of a nonlinear nature and can be applied to estimate streamflow from ungauged catchments which have hydrologically similar characteristics. The model has been tested for Gurpur river basin in the same region of westernghats.

Prasad et al (1990) developed a regional rainfall-runoff model for upper Narmada sub-basin using the coutagne's approach. The K value in the relation $R=KP^2$ (R=runoff and P=rainfall both in mm) has been determined by relating it to known catchment characteristics, streamslope of six catchments in the upper Narmada region. The model has been used to prepare runoff series for upper Narmada Project (CA: 1243 Sq.km.) for the period 1942- 43 to 1982-83.

Vasudeva Rao and Panakala Rao (1988) used the finite element method in space domain and finite difference method in time domain to formulate a mathematical model to estimate the surface runoff hydrograph from a given net rainfall hyetograph over small watersheds. The model was applied to a small catchment (area = 162.2 sq.km.) Pimpalgaon Joge in the western ghats in Maharashtra. The catchment was discretized into 15 overland elements and 7 stream segments with 8 nodes. The authors concluded that the peak of the computed hydrograph agreed reasonably well with the observed peak.

Sakthivadivel and others (1982) used the Chow-Kulaindaswamy model to model the rainfall runoff relationship in three mountainous catchments under different land use patterns namely Agricultural Watershed (Kateri, CA: 34.7 $km^2$, El: 1300-2200 m), forested watershed (Mukurthy CA: 44.0 $km^2$. El 1600-2150 m) in the high hills of Bhavani catchment, Tamilnadu.

Nath (1990) carried out a simulation study of rainfall- runoff relationships of the tropical hilly catchment of Vamsadhara river in the eastern ghats. Because of limited data availability synthetic unit hydrographs were used with rainfall runoff and topographical data.

Watershed Bounded network Model (WBNM) described by Piligrim and Cordery (1979) has been used by Anna University for developing rainfall runoff models for four watersheds in western ghats namely Malathy at Kalmane, Kamalavathy at Sedum, Maniknagarnala at Humnabad and Jayaanagali at Kyanenahalli (KERS, 1987).

The structure of the WBNM is similar to the Monash model. The main difference is that the WBNM has two different types of storage which correspond to the two different types of sub-area that comprise a catchment sub divided along watershed lines.

Also a multiple regression model for each one of the catchment predicts runoff as a function of the rainfall on the day the runoff is to be predicted, the rainfall of the previous day and the API. The API was worked out for a five day period with a coefficient of 0.9. The model was of the form

$$Y = a_1 x_1 + a_2 x_2 + a_3 x_3 + c$$

where

$Y$ = runoff depth in mm on any day
$x_1$ = rainfall depth in mm on same day
$x_2$ = rainfall depth in mm on previous day
$x_3$ = API in mm

$a_1$ . $a_2$ . $a_3$ = regression coefficients
C = intercept

## Floods in Mountainous Areas

Rivers in India are prone to seasonal floods due to excessive rainfall during the south west monsoon season. Flash floods are common in the entire belt of foot hills all along the Himalayas, southern slopes the Northeastern Hills and the eastern slopes of eastern ghats and the Nilgiris. During the last four decades there were several flash floods in the country. Flash floods in river Teesta in October 1968, Kalinadi in Sept 1975, Vamsadhara in October 1980, in the mountain streams of Andhra Pradesh in October 1983, Sutlej in September 1988, Amba valley in Western Ghats in July 1989 are but a few examples of such occurrences in several parts of the country. Floods are also caused by temporary blockade of rivers by landslips and subsequent sudden release of waters.

The weather systems responsible for floods in mountain rivers in India are listed by Ramasastri (1989). They are

i. the occurrence of severe thunderstorms including those described as cloud bursts

ii. the movement of depressions and cyclonic storms

iii. shift of axis of the monsoon trough close to foot hills during the monsoon period

iv. the movement of low pressure systems

Heavy rainfall due to orographic effect is confined to the western ghats and the hills in the north east.

## Flood Forecasting

Flood forecasting in Indian rivers is mostly based on coaxial graphical techniques based on gauge to gauge correlation of present upstream condition with future downstream condition.

Parashar and Agarwal (1984) used the coaxial correlation technique for preparing forecasts of river stage at Elgin bridge at the confluence of Ghagra and Sarada rivers both originating from Nepal. The forecasts were said to be within ± 15 cm in case of 90 to 95% of forecasts.

Meijerink (1974) claimed to have obtained good results with the rational formula for computing flood magnitudes for catchments upto 20 $Km^2$ in homogeneous Shiwalik areas around Dehradun. However, when catchments situated outside Shiwaliks were considered the results were not satisfactory due, probably, to variation in rainfall intensities.

Goyal and Adhikari (1982) presented a nomogram for two small sub-catchments in the sub-mountainous Bihar - Orissa region. The nomogram could be used to determine the peak flood discharge in cumecs for a given rainfall (mm) for a given duration. Though the use of such nomograms is limited to the area for which they have been developed, they are useful for determining peak flood discharges from rainfall data alone.

Adhikary (1987) described a model for forecasting hourly flood stages in small catchments. The model uses the physiographic characteristics of the catchment such as longitudinal section of the river, elevation of several points, land use and soil type. The study area was a small sub-catchment (area 136 $km^2$ ) of Mahanadi basin. The catchment is at an elevation of 500 m. The runoff was estimated using the curve number technique originally developed in USA and modified as for Indian conditions. The model forecasted the peak stage well though the total hydrograph could not be reproduced properly.

Using a unit hydrograph based approach, Gosain and Chander (1984) attempted real time flood forecasting on river Yamuna. The performance of the model was tested using both the graphical and numerical techniques recommended by WMO. The model was said to provide reasonably good forecasts upto a lead time between 9 and 12 hours.

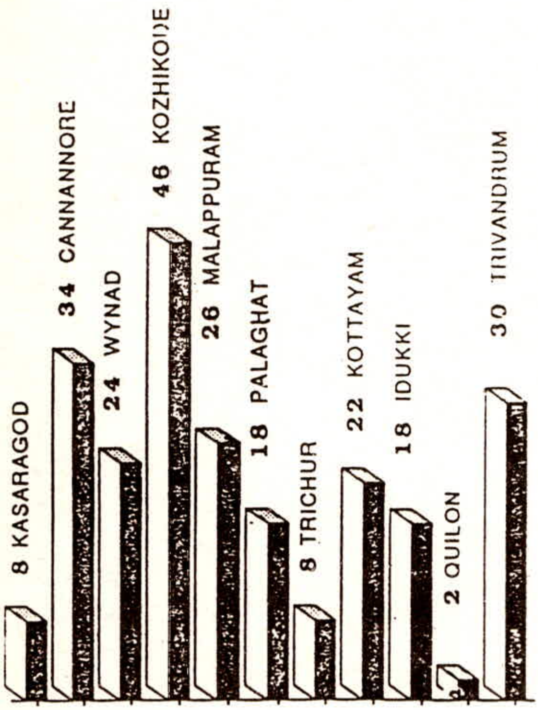
Goswami (1984) reviewed the available methods of flood forecasting on river Brahmaputra (at Dibrugarh) and its tributaries, Buridehing (at Chanimari) and Subansiri (at Badatighat). A discrete linear time variant mathematical model has been developed for forecast of floods in river Brahmaputra at Dibrugarh on the basis of difference of gauge at Base stations of three major tributaries namely Dehang, Debang and Luhit. Three hourly water level of flood period have been taken for all the stations and an average travel time of 12 hours has been assumed from all base stations to Dibrugarh.

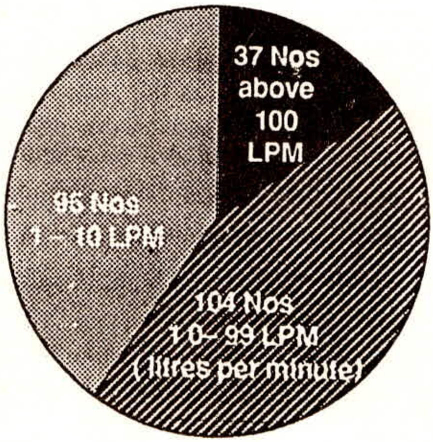
The forecast efficiency of the mathematical model was compared with the coaxial graphical method. This indicated that the results of forecast by the graphical method were much better than those given by mathematical method. Coaxial graphical methods were also used to forecast the river gauges at Chanimari and Badatighat.

Singh and Singh (1984) used the Sacramento model for flood forecasting in the catchment of Burhi Gandak (Catch Area 12180 $km^2$ ) upto its confluence with Ganga. 2130 $km^2$ area of the catchment lies in the hilly region. Unlike the Clark's the Unit hydrograph developed by the authors was said to take care of the interflow delay through soil moisture accounting.

Sinha (1984) applied the SSARR model for flood forecasting in river north Koel a tributary of river Sone in Bihar. The river originates at an elevation of 700 m in the hills of Chhota Nagpur Plateau in Bihar. The catchment (area : 10800 $km^2$) was divided into three subbasins for the purpose of modelling. The forecast efficiency of the calibrated model for forecasting flood peaks was said to be 62 to 64%.

In 1980, the Central Water Commission formulated a pilot project to establish a modern operational flood forecasting system for the Yamuna upto Delhi with UNDP assistance. The upstream parts of Yamuna catchment are mountainous with



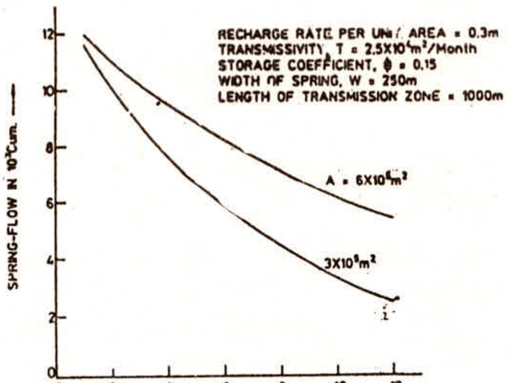




FIG. EFFECT OF URBANISATION ON SPRINGFLOW elevations ranging from 2000 m to 5000 m. Even before the monitoring network and Telemetry system became operational in 1986, a number of hydrological models with forecasting capability have been calibrated and tested for the Yamuna system. These included HEC I (Chopra, 1984), SSARR (Mukhopadhyay, 1984) and NWSRFS (Gosain and Subhash Chander, 1984).

## Springs

In a comprehensive planning of the water resources of the country springs as a water resource are an important component. Springs are natural source of fresh water like rivers, lakes and wells. Very often, the water emanating from the springs was found to be of good quality. A number of springs are located in the Himalayas, western ghats, eastern ghats and other mountainous areas of the country. But we do not have proper documented information on their location, potential, potability, present use pattern and the hydrological and hydrogeological features associated with them.

CWRDM, Kerala has carried out field investigations to identify springs in Kerala state and to assess their potential. 236 springs could be identified out of which 60 are recorded in the available GTS maps. All the springs identified were found to be perennial. The district wise distribution of springs in the Kerala state is shown in figure 4 and the summer discharge in figure 5. The water quality of 95% of the springs was found to be of good quality.

Bhar (1989 and 1991) discussed the problem of the effect of development of land resources on the discharge from springs and presented a methodology. The methodology was applied to Parda spring in Nainital district of Uttar Pradesh. Figure 6 shows the estimated spring flow for 12 months after the recharge for no reduction and 50% reduction in recharge area due to man made activities like urbanisation.

Various parameters depicting recharge, aquifer characteristics and aquifer geometry used are shown in the figure 6. The plots in the figure provide a reasonably fair idea of the extent of decrease of spring flow due to reduction in the recharge area. It was said that a 50% reduction of recharge area will lead to 35% reduction of the spring flow on the 6th month and 50% reduction of spring flow on the 12th month.

## Sedimentation

Sedimentation is a major problem in the mountainous areas owing to the steep slopes and high intensity rains. The problem further becomes serious in areas where large scale deforestation has occurred. Due to the transportation of the sediment year after year the live capacity of reservoirs and lakes gets eroded gradually.

The sediment transport from the Himalayan rivers is comparatively higher than from the peninsular rivers as may be seen from figure 7 Dhruva Narayana (1987) estimated the sediment yield from catchment of Tehri as 1940 t/km$^2$ /yr. Das (1987) sampled the sediment loads of the Bhagirathi and Bilangana rivers above Tehri high dam in Garhwal. Between July and October, these rivers carry a silt load of the order of 2 kg/m$^3$ and 44 kg/m$^3$ respectively.

The Centre for Water Resources Development and Management (CWRDM) Kerala has studied the reservoir sedimentation for two reservoirs Mangalam (Bharathapuzha river) and Peruvannamuzhi (Kuttiyadi river) in western ghats. Different factors of the universal soil loss equation have been estimated with specific reference to the two catchments and the average annual soil loss was computed. The soil loss from the catchments of Mangalam and Peruvannamuzhi has been estimated as 23 t/ha/yr. and 66 t/ha/yr respectively. Significant depositional trends were observed at higher elevations mainly at the forest bed. (James et al, 1990).

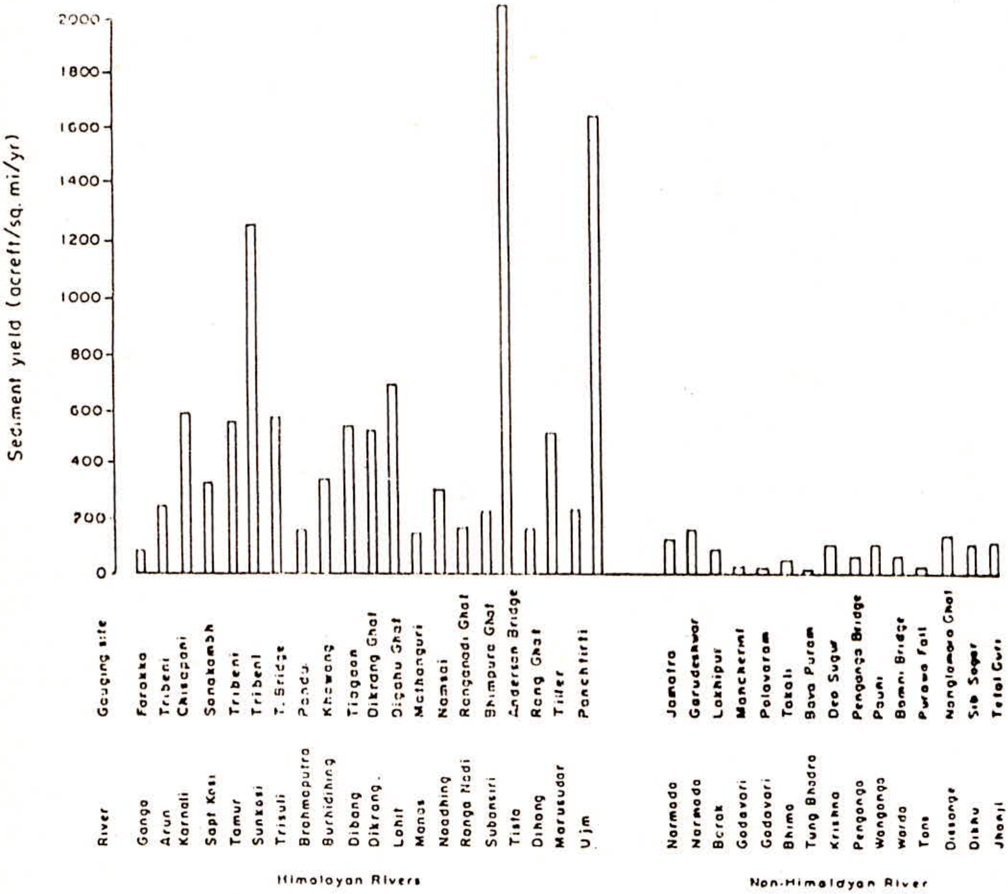



Figure Sediment yields for Himalayan and Peninsular rivers in India (after Gupta (1975) in Tejwani, 1985).

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