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Effect of orography on precipitation in the western Himalayan region

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Abstract

The present study deals with precipitation distribution with altitude for the Satluj and Beas basins in the western Himalayas. Rainfall increases linearly with elevation for both basins in the outer Himalayan range. The middle Himalayan range of the Beas basin has exceptionally heavy rainfall on the windward side and much less rain (less than half) on the leeward side. Rainfall gradients are 106 mm per 100 m to windward and 13 mm per 100 m to leeward of this range. Different trends of rainfall variation with elevation are observed in different seasons in the middle Himalayan range with a linear increase in annual rainfall. Rainfall follows an exponential decreasing trend with altitude in the greater Himalayan range. Average annual rainfall decreases from the outer Himalayas to the greater Himalayas in the Satluj basin. In the greater Himalayas, it is about one-sixth of outer Himalayas rainfall. Maximum rainfall is in the middle Himalayan range in the Beas basin. Monsoon rainfall contributes the largest part of the annual rainfall for all the Himalayan ranges. Spatial correlation is higher in the outer Himalayas range than in the other ranges.

Snowfall increases linearly with elevation in the greater Himalayas. Snowfall gradients for the Spiti and Baspa sub-basins are 43 mm per 100 m and 10 mm per 100 m, respectively. The ratio of snowfall to annual precipitation varies linearly with altitude. All stations recorded more than 60% snow contribution to annual precipitation. Extrapolation of the relationship indicates that snow and rain contribute equally at about 2000 m, and all the precipitation occurs as snow above 5000 m.

1. Introduction

In large mountainous basins weather systems interact with topography and result in highly non-uniform precipitation. Uplift of moisture-laden air currents striking against a

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mountain barrier provides good rainfall on the windward side. Gradients in amount and intensity of precipitation depend upon several factors such as topography, strength of moisture-bearing wind, its moisture content and orientation of the mountain range with respect to the prevailing wind direction. Depending upon the relief of a mountain, there may not be continuous increase in precipitation with altitude: above a particular altitude, it may begin to decrease. Information on precipitation distribution helps to provide realistic assessment of water resources, estimation of probable maximum precipitation and hydrological modelling for mountainous areas. A summary of important precipitation distribution studies carried out in different parts of the world is given in Table 1.

A significant part of northern India is covered by the Himalayas, where a number of major Indian rivers originate. Detailed studies to assess the orographic effect of the Himalayas on precipitation have hitherto been lacking. Lack of a good network of precipitation stations especially at higher elevations is one of the reasons for limited studies. The Satluj and Beas basins (Fig. 1) of the present study have a reasonably good network at high elevations. Precipitation data for the elevation range 400–4079 m have been used in the present study. This has helped in understanding the nature of precipitation distribution in the western Himalayas.

2. Seasons and weather systems in the study area

Seasonal and annual precipitation distribution in the Satluj and Beas basins are studied for each Himalayan range separately. For this study, a year has been divided into four quarters: October–December, January–March, April–June and July–September, which form post-monsoon, winter, pre-monsoon and monsoon seasons, respectively. Precipitation during winter is caused by extratropical weather systems of mid-latitude regions, originating over the Caspian Sea. These winter weather systems are known as western disturbances and approach India from the west. Precipitation during winter is generally in the form of snow in the greater Himalayas, snow and rain in the middle Himalayas, and light to moderate rain over the outer Himalayas and the adjoining north Indian plains. The higher precipitation in the western Himalayas during winter is the combined effect of nearly east–west configuration of the Himalayas and eastward movement of the winter weather systems. Winter is followed by the pre-monsoon season, which is considered as the transition period between winter and summer. Most of the precipitation falls as rain in the summer all over the ranges because of rising temperature in the Himalayan region. Light to moderate rains are caused by convective storms in the pre-monsoon season.

During the monsoon season, precipitation over the Himalayas normally is caused by moist air currents from the Bay of Bengal. After striking Burma and the eastern Himalayas, these air currents are deflected westwards and travel along the Himalayas. Rainfall decreases westward because of increasing distance from the source of moisture. In general, the monsoon starts withdrawing from this region towards the end of September. At the time of crossing the greater Himalayan ranges and approaching trans-Himalayan regions, these currents become practically dry, as most of the moisture content they initially carried is precipitated during their passage over the plains and mountain ranges of the Himalayas, resulting in insignificant rainfall in the trans-Himalayan region. Clear autumn weather sets in during the post-monsoon season and there is generally little rainfall.

3. Study areas

3.1. Satluj basin

The Satluj river rises in the lakes of Mansarover and Rakastal in the Tibetan Plateau at an elevation of about 4572 m and forms one of the main tributaries of the Indus river. Most of the Tibetan plateau and some areas downstream are without rainfall and have a cold desert climate. The Satluj is joined by its principal Himalayan tributary, the Spiti, just after entering India. Bhakra dam (Govind Sagar) has been built downstream in the outer Himalayas on this river. The catchment area of the Satluj basin up to Bhakra is about 57 000 km^2, of which a major part lies in Tibet. In the present study, precipitation distribution has been studied for the Indian part of the Satluj basin up to Bhakra (Fig. 1(b)). This part of the basin covers the outer, middle and greater Himalayan ranges. However, the shape and location of this basin is such that the major part of the basin area lies in the greater Himalayas, where heavy snowfall is experienced during winter. Owing to large differences in seasonal temperature and great range of elevation in the catchment, the snowline is highly variable, descending to an elevation of about 2000 m during winter. The permanent snowline in this portion of Himalayan range is at about 5400 m (BBMB, 1988).

3.2. Beas basin

The Beas river is the principal tributary to the Satluj river in the Indus river system. It has its origin at Beas Kund, a small spring near the Rohtang pass in the Himachal Pradesh at an elevation of about 4085 m. Before reaching Pandoh dam it is joined by its principal tributaries from the north-eastern part of the upper basin. Another dam, Pong dam, exists downstream on this river. The Beas basin up to Pong dam is considered in the present study (Fig. 1(c)). The total area of the Beas basin up to Pong dam is about 12 500 km^2. Like the Satluj basin, this basin also includes areas of the outer, middle and greater Himalayan ranges. This basin has a permanent snowbound area of about 775 km^2 which lies above 5500 m (BBMB, 1988).

Both the Satluj and Beas rivers flow through areas with varying climatic and topographic features and have similar streamflow characteristics. In the annual flows a substantial contribution is provided by snow and glacier melt runoff. During winter, snowmelt is less than rainfall runoff because the conditions are not suitable for melting. After March, snowmelt exceeds rainfall, which leads to a significant rise in streamflow. The snowmelt contribution increases continuously as the snowmelt season advances. Peak values of the discharge in July and August are essentially due to monsoon rains in the lower part of the catchment. Glaciers at high altitudes continue melting during this season.

Table 1
A summary of some important world-wide precipitation distribution studies

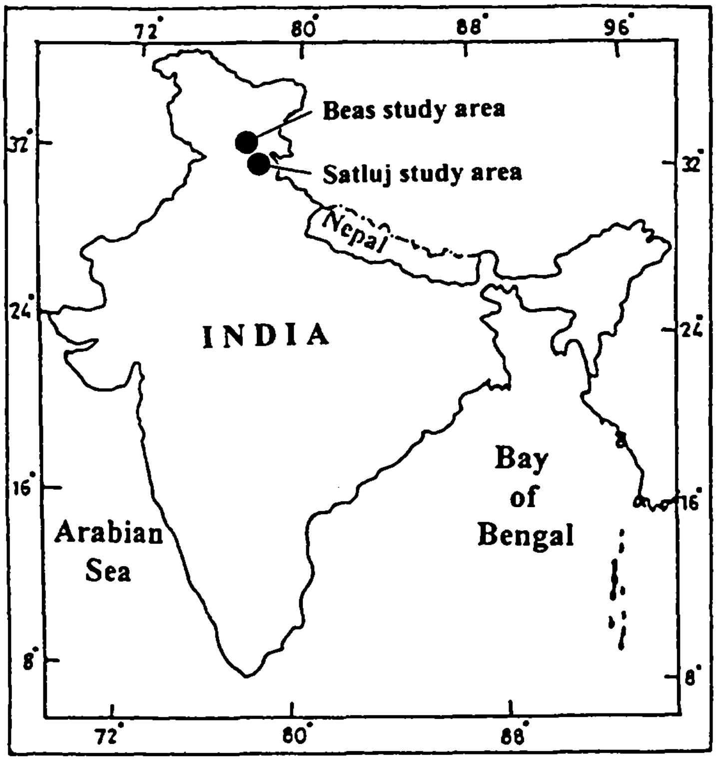
Reference	Study area or basin	Type of precipitation	Relationship with altitude or gradients	Other specific conclusions
Rumley (1965)	Andes in Ecuador	Rain	–	Two zones of maximum rainfall observed: along western slope at 1000 m and along eastern slope at 1400 m
Golding (1968)	Rocky Mountains	Snow	87 mm per 100 m	Linearly increases with altitude
Engman and Hershfield (1969)	NE Vermont, USA	Rain, snow	–	Average number of precipitation days and hours increases with altitude
Hamon (1971)	SW Idaho	Snow	–	Winter precipitation at 2100 m was four times higher than at 1200 m
Duckstein et al. (1972)	Santa Catalina Mountains near Tucson	Rain	Quadratic polynomial	–
Storr and Ferguson (1972)	Rocky Mountains	Precipitation	64 mm per 100 m for annual precipitation and 10 mm per 100 m for summer rain	–
Caine (1975)	San Jaun Mountains near Colorado	Snow	65 mm per 100 m	Linearly increases with altitude
Sugden (1977)	Antarctica and north Greenland	Snow	–	Increases to about 1500–1600 m and thereafter decreases
	South-east Greenland	Snow	–	Maximum snow occurs at about 700 m
Hendrick et al. (1978)	Mansfield, Vermont, USA	Precipitation	–	A threefold increase in the hours of precipitation between 400 m and 1200 m
Dhar and Rakhecha (1981)	Central Himalayas (Nepal Himalayas)	Rainfall	Polynomial of fourth degree	Maximum rainfall occurs at 2000–2400 m
Higuchi et al. (1982)	Nepal Himalayas	Rainfall	–	Rainfall decreases with altitude in the range from 2800 to 4500 m
Witmer et al. (1986)	Alps	Snow	80 mm per 100 m on SE slopes, and 730 mm per 100 m on northern slopes	–

Table 1 Continued

Reference	Study area or basin	Type of precipitation	Relationship with altitude or gradients	Other specific conclusions
Niemczynowicz (1989)	Jamtland area, Swedish mountains	Rain	9.5% per 100 m	Highest rainfall observed behind the crest of mountains on leeward side
Ohmura (1991)	Western Greenland	Snow		Maximum precipitation zone around 2500 m at 69°N, and descending northward to about 1500 m at 76°N
Barry (1992)	Alps	Precipitation	–	Precipitation increases with altitude to the highest level of 3000–3500 m
Singh et al. (1994), Singh et al. (1995)	Chenab basin, Western Himalayas	Rain, snow	Second-order polynomial for annual rainfall on windward of outer Himalayas, windward and leeward of middle Himalayas; linear increase on leeward of outer Himalayas and exponential decrease in the greater Himalayas; linear increase in snow with altitude	Spill-over effect noticed in the outer Himalayas; maximum rainfall in the outer Himalayas
Loukas and Quick (1993), Loukas and Quick (1996)	British Columbia	Rain, snow		Increases up to mid elevation of basin, then decreases and/or levels off or may increase; hourly rainfall intensity decreases with altitude

4. Data used

To study the distribution of rainfall in the Satluj basin, daily rainfall for nine stations located at different elevations are used. Study of snow distribution used daily snowfall data of 11 stations in the greater Himalayan range. For both rain and snow, 10 year average values were used for the analysis. Rainfall data were available from 1983–1984 to 1992–1993, whereas snow data covered from 1984–1985 to 1993–1994. For one station (Rakchham), data were available only for 9 years. There were only a few stations which had both rain and snowfall data. Contribution of snow to total precipitation was



(a)

Fig. 1. (a) Location map of the study basins. (b) Topographical features of the Satluj basin (Indian part) up to Bhakra dam with location of stations. All the elevation contours are in metres. (c) Topographical features of the Beas basin up to Pong dam with location of stations. All the elevation contours are in metres.

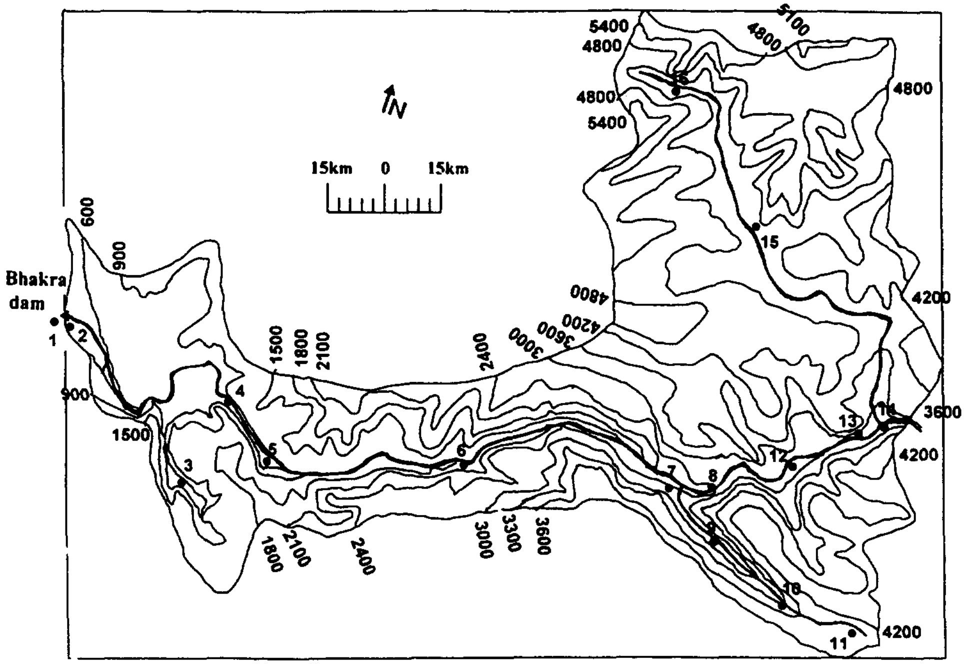
determined using data of these stations. Location and altitude of all stations of Satluj basin are given in Fig. 1(b).

For the Beas basin, daily rainfall data for 12 stations located in different ranges of the Himalayas were used. Average seasonal and annual values of 10 years of rainfall (from 1983–1984 to 1992–1993) for each station were considered in the analysis. Location of these stations is given in Fig. 1(c). Snowfall data were not available for the Beas basin.

Mean seasonal and annual values of precipitation were computed from daily data. Similarly, mean annual rainy days and snow days were determined and used to compute mean seasonal and annual rainfall and snowfall intensities. A period from October to September is considered in terms of annual analysis so that the complete snow cycle is covered. Generally, snowfall starts in or after October at higher reaches in these basins.

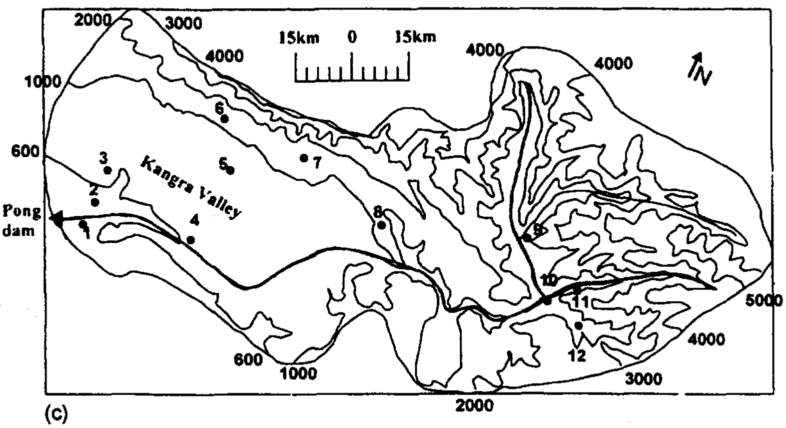
5. Results and discussion

The results of seasonal and annual rainfall and snowfall distributions with altitude are presented and discussed separately for each basin in the following sections.



(b)

1. Nangal (NG) (400m)
2. Bhakra (BH) (518m)
3. Kahu ((KH) 649m)
4. Kasol (KS) (661 m)
5. Suni (SU) (625m)
6. Rampur (RM) (1066m)
7. Kilba (KI) (2030m)
8. Kalpa (KL) (2439m)
9. Sangla (SN) (2439m)
10. Rakchham (RK) (3130m)
11. Chitkul (CH) (3841m)
12. Moorang (MO) (2744m)
13. Pooh (PO) (2896m)
14. Namgia (NM) (2910m)
15. Kaza (KZ) (3639m)
16. Lossar (LO) (4079m)



(c)

1. Ghamrur (GH) (436 m)
2. Harsur (HR) (697m)
3. Shahpur (SH) (755m)
4. Dehra Gopipur (DG) (576m)
5. Kangra (KG) (803m)
6. Dharamshala (DS) (1381m)
7. Palampur (PL) (1198m)
8. Jogingra Nagar (JO) (1219m)
9. Bhuntar (BU) (1080m)
10. Larji (LR) (995m)
11. Sainj (SJ) (1348m)
12. Banjar (BJ) (1536m)

Fig. 1. Continued.

6. Variation in rainfall with altitude in the Satluj basin

6.1. Outer Himalayas

Only five stations provide information on the rainfall distribution over the outer Himalayan range of the Satluj basin: two are on the windward side and three on the leeward side of the range. There is not much variation in the amount of rainfall, rainy days and rainfall intensity observed between the two windward stations, possibly because there is only a small difference in elevation and the stations are too close. In the post-monsoon, pre-monsoon and monsoon seasons, rainfall linearly increases with altitude on the leeward side of the outer Himalayan range in this basin (Fig. 2). The orographic effect is dominant during the monsoon period. Most of the monsoon rain is convective, with orography triggering convective uplift which continues downwind of the orographic barrier. Magnitude and trend of annual rainfall distribution are governed by the monsoon rainfall. Only in winter does rainfall decrease with altitude. Both a higher number of rainy days and higher rainfall intensity are responsible for the increase in rainfall with altitude (Fig. 3).

Rainfall is less variable from year to year in the monsoon season as compared with other seasons. This may be because of strong and well-established weather systems in this season. There is no significant change in the standard errors of the mean rainfall with altitude for all the seasons on either side of this range.

6.2. Middle Himalayas

Rainfall distribution in the middle Himalayan range could not be studied because there is only one station available in this range. Average seasonal and annual rainfall and other related information for this station are given in Table 2.

6.3. Greater Himalayas

Rainfall data were available for three stations on the leeward side of this range, but there were no data for the windward side. There is very little rain in this range because most of the moisture is precipitated over the outer and middle Himalayan ranges. The leeward trends of rainfall variation with altitude for different seasons are shown in Fig. 4. Rainfall decreases as altitude increases for all the seasons, except for the monsoon season. Rainfall in the monsoon shows no specific trend with altitude, largely owing to the data for Namgia (2910 m). Rainfall at this station is usually low during the monsoon. One reason for such low rainfall may be the location in a very narrow valley. Rainfall exponentially decreases with elevation in the pre-monsoon and post-monsoon seasons. During winter, rainfall linearly decreases with elevation to negligible levels above 3000 m. The annual distribution follows an approximate exponentially decreasing trend. Similar trends of change in rainfall in the greater Himalayan range of another basin were found by Singh et al. (1995).

A striking feature in this range is an increase in rain intensity and a decrease in average annual rainy days with altitude (Fig. 5). The decrease in annual rainfall with altitude is primarily due to the smaller number of rainy days at higher altitude. In general, the magnitude of standard error of the mean rainfall decreases with altitude in this range.

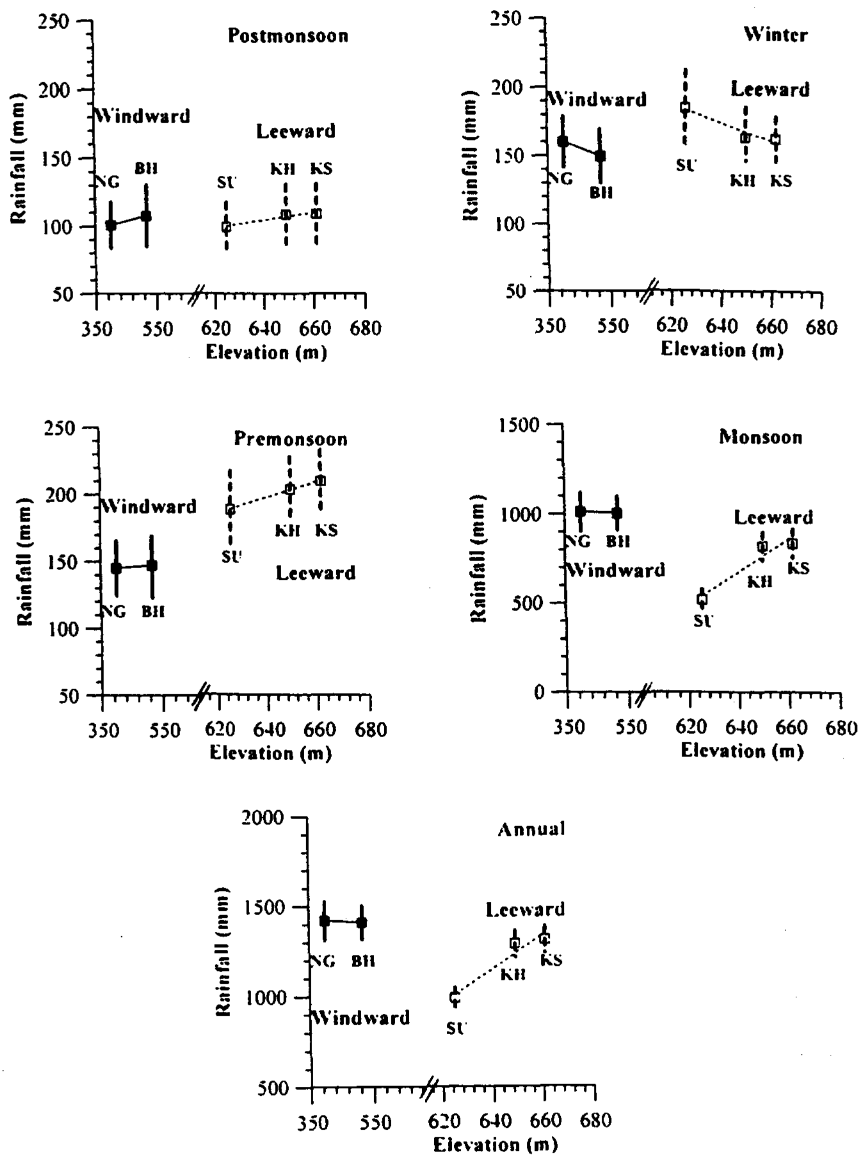


Fig. 2. Variation in seasonal and annual rainfall with elevation in the outer Himalayan range of the Satluj basin. Plotted error limits are one standard error of the mean in this and subsequent figures.

6.4. Contribution of seasons to annual rainfall over different Himalayan ranges

To compare average seasonal rainfall and their contribution to the annual rainfall on both sides of all Himalayan ranges, an average rainfall is computed by taking an average of all stations on each side of the mountains. The values of seasonal and annual rainfall and their contribution to annual rainfall are given in Table 2. It is evident that monsoon rainfall

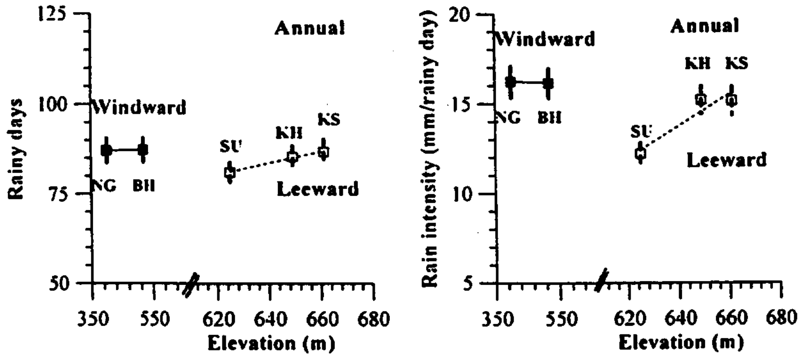


Fig. 3. Variation in annual rainy days and rain intensity with elevation in the outer Himalayan range of the Satluj basin.

contributes the largest part (45–71%) of the annual rainfall throughout the ranges of Himalayas in the Satluj basin. Contribution of pre-monsoon rainfall to annual rainfall increases from the outer Himalayas to the greater Himalayas and becomes significant in the greater Himalayan range. Minimum rainfall is experienced in the post-monsoon season in the outer and middle Himalayas, whereas in the greater Himalayan range the minimum occurs in the winter. This is because most of the precipitation occurs in the form of snow in the greater Himalayan range during winter.

Average annual rainfall is drastically reduced from the outer Himalayan range to the greater Himalayan range (Table 2). In the greater Himalayas, it is about one-sixth of rainfall in the outer Himalayas. Higher annual rainfall, more rainy days and higher rainfall intensity in the outer Himalayas are expected because of its location with respect to the monsoon currents.

7. Variation in snow with altitude in the Satluj basin

Snow distribution with altitude has been studied only for the greater Himalayan range of the Satluj basin because of the lack of data for other ranges. The major part of the study

Table 2
Seasonal distribution of average rainfall in different ranges of the Himalayas in the Satluj basin

Himalayan range	Side	Rainfall (mm)				
		Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Outer	Windward	155 (10.9%)	146 (10.3%)	1010 (71.3%)	105 (7.4%)	1416
	Leeward	172 (14.3%)	201 (16.7%)	725 (60.3%)	106 (8.8%)	1203
	Average	164 (12.5%)	174 (13.3%)	868 (66.2%)	106 (8.0%)	1312
Middle	Leeward	209 (28.0%)	128 (17.2%)	336 (45.0%)	73 (9.8%)	746
Greater	Leeward	6 (3.0%)	75 (37.5%)	105 (52.5%)	14 (7.0%)	200

Each season's contribution to the annual rainfall is also indicated, as a percentage. In the middle Himalayan range, values are based on only one station.

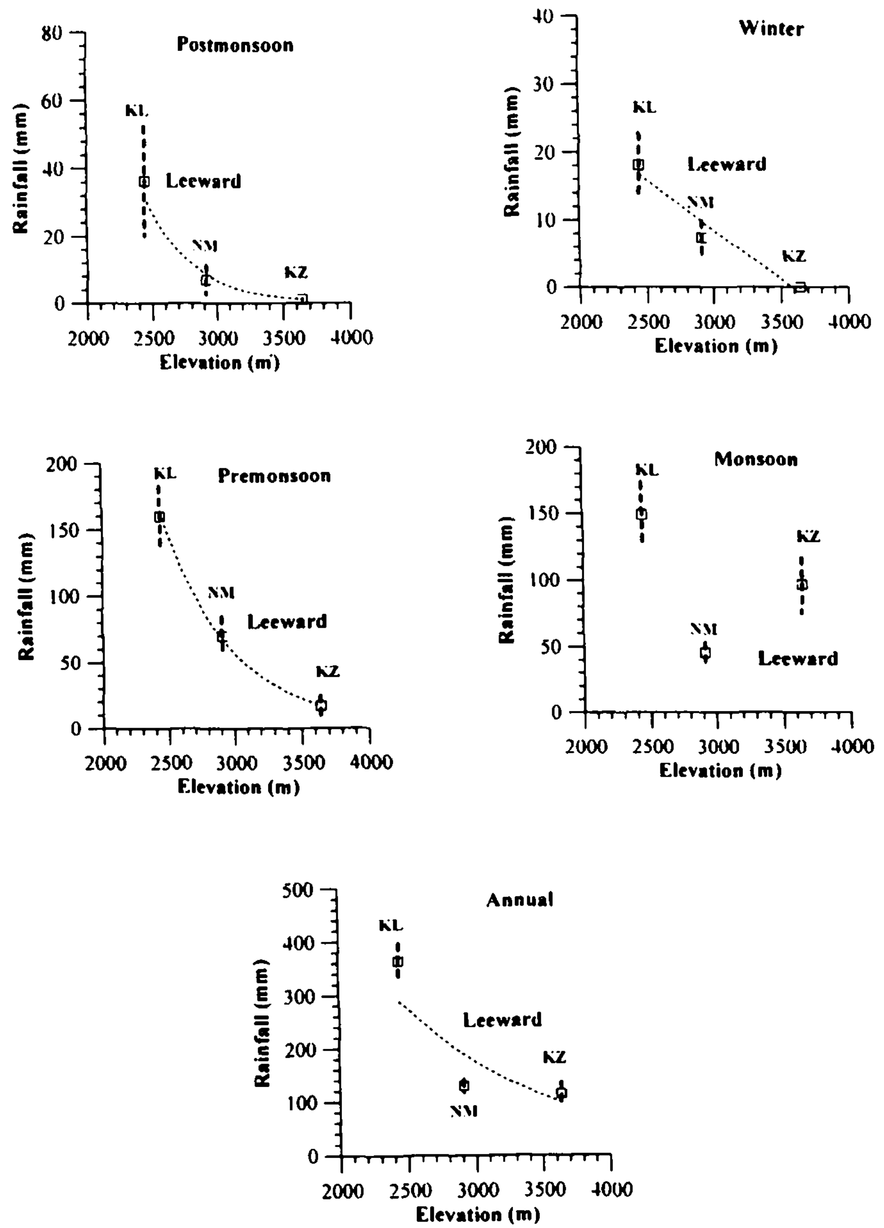


Fig. 4. Variation in seasonal and annual rainfall with elevation in the greater Himalayan range of the Satluj basin.

area is covered by the greater Himalayan range and can broadly be divided into three sub-basins, namely, Spiti sub-basin, Baspa sub-basin and upper Satluj sub-basin. All these sub-basins are located on the leeward side of the greater Himalayan range. These basins have different orientations and relief. Therefore, snow distribution analysis has been carried out

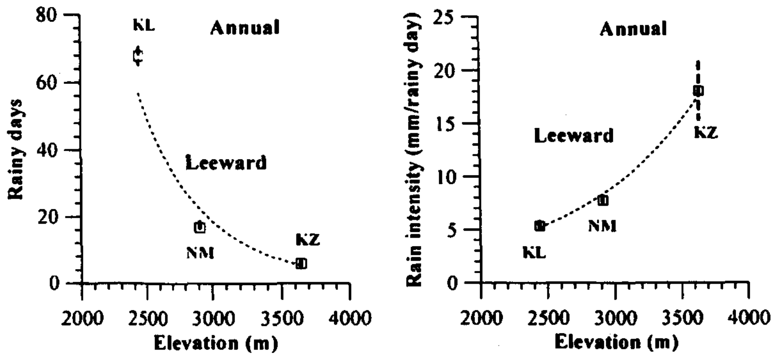


Fig. 5. Variation in annual rainy days and rain intensity with elevation in the greater Himalayan range of the Satluj basin.

separately for each sub-basin. Most of the stations are located at different elevations along the valleys.

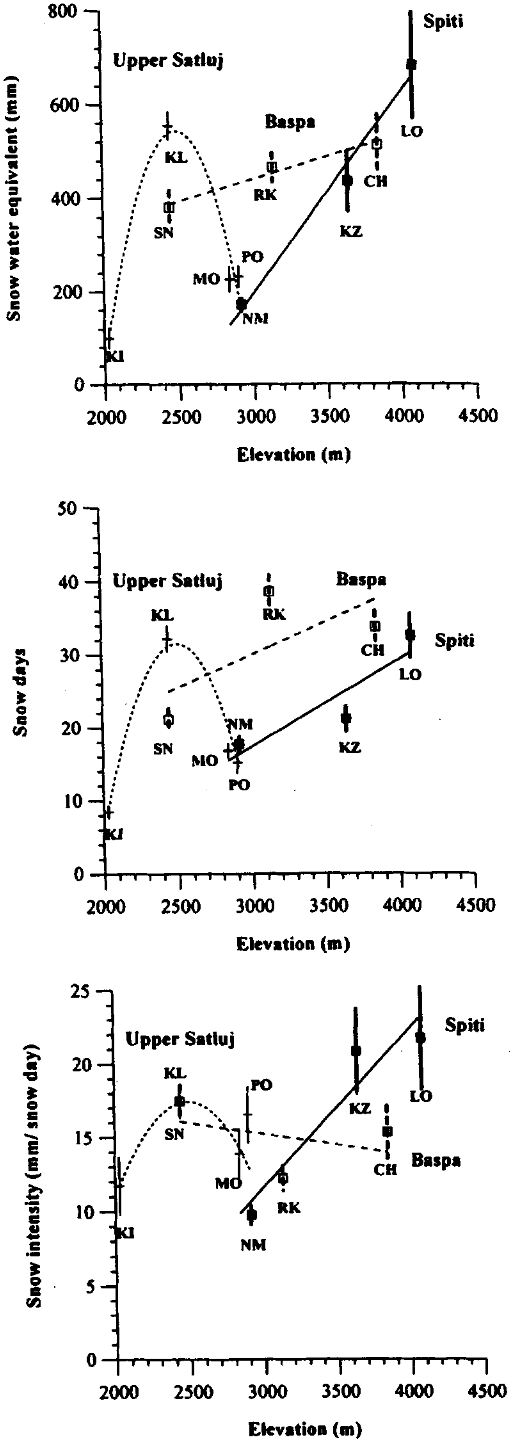
7.1. Spiti sub-basin

The Spiti sub-basin has SE orientation, and covers a major portion of the Satluj catchment. This sub-basin experiences heavy snowfall, and consequently substantial runoff is derived from snowmelt through the Spiti river into the Satluj river. Snow water equivalent (SWE) increases linearly with altitude in the Spiti (Fig. 6). Based on available data, snow gradient in this sub-basin is estimated to be about 43 mm per 100 m. Analysis of snow days and snow intensity also indicates a linear trend of increase with elevation in the Spiti. Higher number of snow days and higher intensity provide an increase in SWE at higher elevations. Standard errors of mean SWE, snow days and snow intensity increase with altitude in this sub-basin.

7.2. Baspa sub-basin

The NW-facing Baspa sub-basin is south of the Spiti. Its trend of snow variation with altitude is similar to that of the Spiti, i.e. it linearly increases with elevation (Fig. 6). However, the snow gradient is about 10 mm per 100 m, significantly lower than that in the Spiti basin. The distribution of snow days and snow intensity shows an approximately linear change with altitude. However, the data are not sufficient to determine the role of snow days and snow intensity in increasing the snow at higher altitude. The results indicate that higher number of snow days plays a major role in providing higher snow at high altitude. Like the Spiti sub-basin, standard errors of mean SWE, snow days and snow intensity increase with altitude.

Fig. 6. Variation in annual snow water equivalent, snow days and snow intensity in the Spiti, Baspa and upper Satluj sub-basins in the greater Himalayan range of the Satluj basin.


Snow water equivalent (mm)
Elevation (m)
Upper Satluj
Baspa
Spiti
KI
KL
SN
MO
PO
NM
RK
KZ
CH
LO
Snow days
Elevation (m)
Upper Satluj
Baspa
Spiti
Snow intensity (mm/ snow day)
Elevation (m)
Upper Satluj
Spiti
Baspa

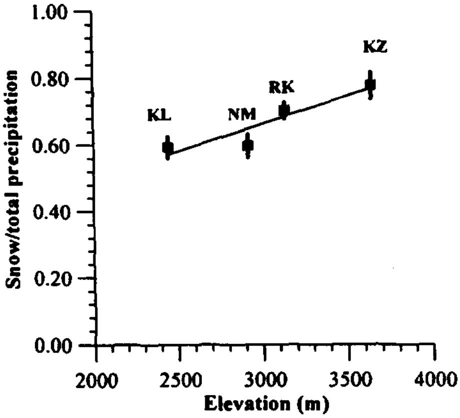


Fig. 7. Variation in snow contribution to total precipitation with altitude in the greater Himalayan range of the Satluj basin.

7.3. Upper Satluj sub-basin

The upper Satluj sub-basin has an east–west orientation. The eastern part of this sub-basin meets the Spiti valley and the western part is joined by the Baspa valley. The relief of this sub-basin is less than in the Spiti and Baspa. It can be noticed from Fig. 6 that the trend of snow distribution is strongly influenced by the snowfall at Kalpa (2439 m). This station has very heavy snowfall even though it is not at a very high altitude. The reason for this heavy snowfall may be the location of the station at a bend in the valley. Additionally, sudden increase in relief near Kalpa behaves as a barrier and most of the moisture is precipitated on this relief. In this situation, this station experiences more snow days, and higher intensity, as compared with other stations. A linear increase in snow water equivalent with elevation is observed if Kalpa is excluded. In that case, snow gradient in this sub-basin is like that of the Baspa sub-basin. No significant change in standard errors of the mean SWE, snow days and snow intensity with altitude is noticed for this sub-basin.

The above snow gradients for different sub-basins are estimated based on the data available at valley stations. All these sub-basins have very high relief, and higher snow gradients are expected at higher elevations, providing heavy snowfalls at high altitudes. There are glaciers at high altitude because of this heavy snowfall. Data collection at higher elevations is required for further investigation in this regard.

7.4. Snowfall and annual precipitation

Data available at four stations located at different elevations in the greater Himalayas indicate that the ratio of annual snowfall to annual precipitation varies linearly with altitude (Fig. 7). All the stations recorded more than 60% snow contribution to annual precipitation. The elevation where all the precipitation falls in the form of solid precipitation could not be determined because both rainfall and snowfall data beyond 3639 m were not available. However, based on extrapolation of this linear relationship, one can expect that about at 2000 m altitude snow and rain equally contribute to annual precipitation, and above 5000 m elevation all the precipitation occurs as snow.

8. Variation of rainfall with altitude in the Beas basin

8.1. Outer Himalayas

The rainfall distribution with altitude for the Beas basin could be studied only for the leeward side of the outer Himalayas. The results show that rainfall increases linearly with elevation on this side for all seasons (Fig. 8). A similar trend is followed by annual rainfall. Average annual rainy days linearly decrease with altitude, whereas rain intensity increases linearly (Fig. 9). Higher rainfall at higher elevations to the leeward of the outer Himalayas occurs because of higher intensity of rain on this side. Standard errors of mean rainfall, rainy days and rain intensity did not change much with altitude. Great variation was observed at the highest station on this side. The gradient in annual rainfall over this range is estimated to be 30 mm per 100 m.

A comparison of rainfall on leeward sides of the outer Himalayan range for the Beas and Satluj basins indicates that average annual rainfall is higher in the Beas basin (1395 mm) than the Satluj (1203 mm) in this range. It is noted that this difference is caused mainly by variation in monsoon rainfall in these basins. For the Satluj, average monsoon rainfall over this range is 725 mm, whereas for the Beas it is 985 mm. The lower mountain barrier for the Beas watershed permits more of the monsoon moisture to reach the leeward side of the mountains, to give higher precipitation in the Beas basin.

8.2. Middle Himalayas

Rainfall distribution with altitude for the middle Himalayan range of the Beas basin has been studied for both windward and leeward sides. Different types of rainfall distribution are observed in the different seasons on both sides (Fig. 10). Rainfall linearly increases with altitude in the monsoon and post-monsoon seasons. Annual rainfall distribution also shows a similar distribution on both sides. Singh et al. (1995) found different rainfall distribution for these seasons for the middle Himalayan range of another Himalayan basin. A very wide valley known as the 'Kangra valley' exists between the outer and middle Himalayan ranges of this basin and significantly affects rainfall distribution with altitude. The sudden rise in relief, from about 900 m in the valley to over 3700 m in the middle Himalayas (Singh, 1989), results in heavy rainfall at all the stations on the windward side of the middle Himalayan range of this basin. Gradients in annual rainfall on the windward and leeward sides are estimated to be 106 mm per 100 m and 13 mm per 100 m, respectively. This significant difference is caused by the typical topography in the range of the basin. Dharamshala experiences exceptionally heavy average rainfall during the monsoon (1972 mm), owing to an immediate increase in relief near this station and the presence of abundant moisture in the atmosphere in this season.

In the winter and pre-monsoon seasons, rainfall increases with elevation up to a certain altitude and thereafter decreases. A second-order polynomial describes approximately the

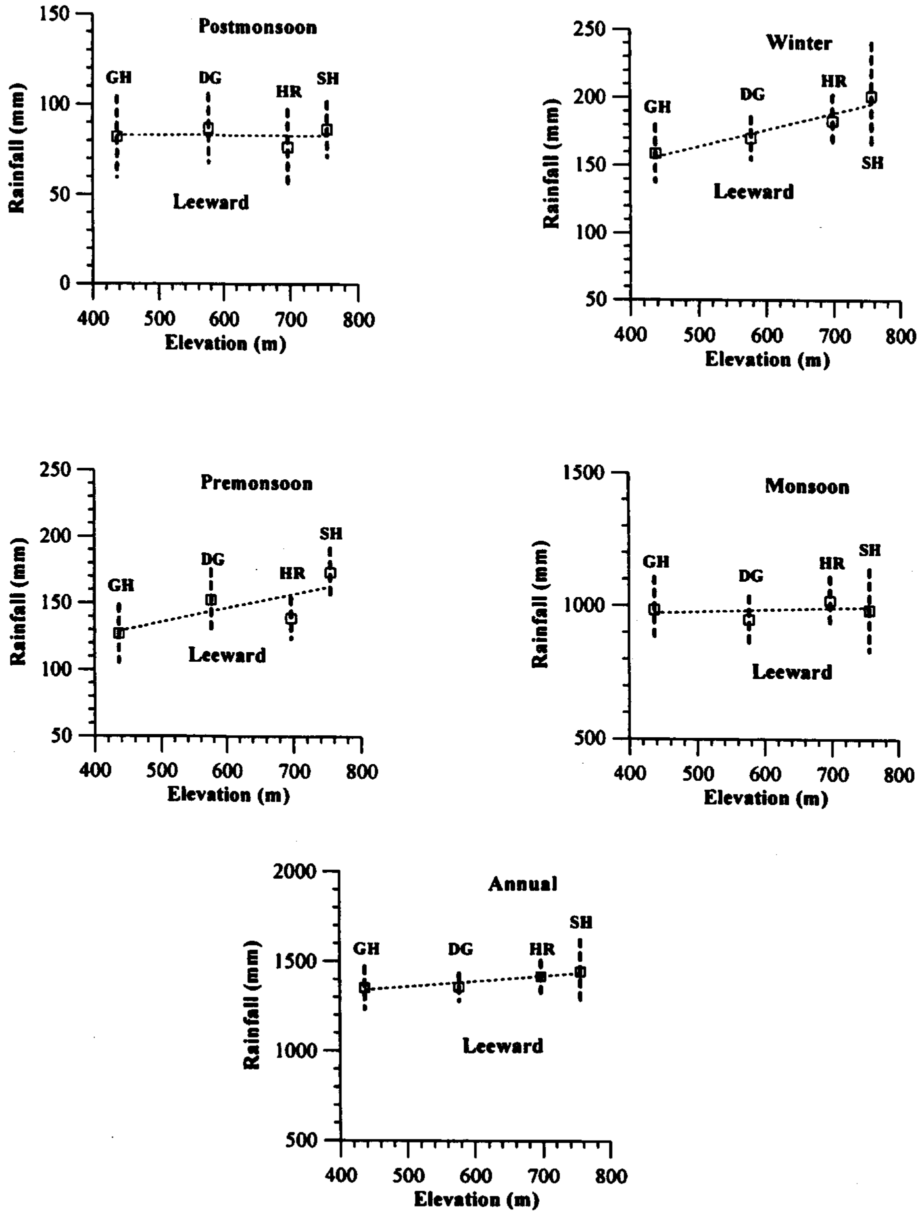


Fig. 8. Variation in seasonal and annual rainfall with elevation in the outer Himalayan range of the Beas basin.

behaviour of rainfall variation for these two seasons. A higher number of rainy days contributes more to increase rainfall with altitude on the windward side, whereas higher intensity at higher elevation is more responsible for increasing rainfall on the leeward side (Fig. 11). The standard errors of mean rainfall, rainy days and rain intensity are higher on the windward side. One station on the windward side (Joginder Nagar) has maximum

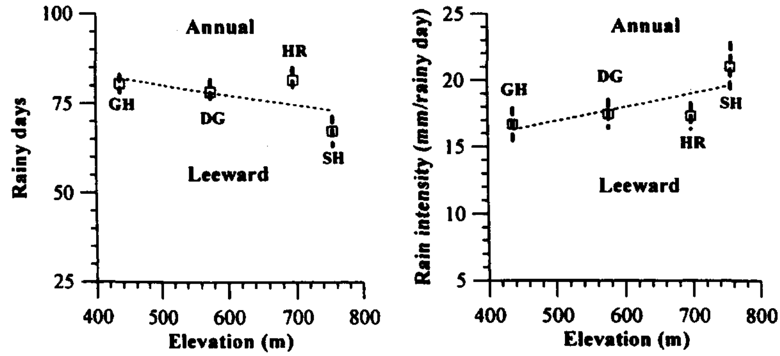


Fig. 9. Variation in annual rainy days and rain intensity with elevation in the outer Himalayan range of the Beas basin.

variation. Its location between two close mountains may be the reason for such high variation in rainfall, rainy days and rain intensity as compared with all other nearby stations on the same side.

Snowfall distribution for the Beas basin could not be studied because of lack of snow data for any range of this basin.

8.3. Contribution of seasons to annual rainfall over different Himalayan ranges

For the Beas basin, monsoon rainfall contributes the most (39–71%) and post-monsoon rainfall contributes the least (6–10%) to annual rainfall over both the outer and middle Himalayan ranges (Table 3). The role of winter rainfall becomes significant in the annual rainfall on the leeward side of the middle Himalayas. Maximum average annual rainfall (2549 mm) is observed on the windward side of the middle Himalayan range. On the leeward side it is less than half that on the windward side.

9. Spatial correlation function for the Satluj and Beas basins

Spatial correlation for annual rainfall and snowfall was studied for both the Satluj and Beas basins. The correlation coefficient (r) for rainfall and snowfall series was determined for different ranges. Correlation matrices for the Satluj and Beas basins for rain and snow are given in Table 4 and Table 5. Spatial correlation functions were developed using correlation coefficients and the following equation:

$$r(d) = r(0)\exp(-d/d_0) \qquad (1)$$

where $r(d)$ is the spatial correlation coefficient, d is the distance between two stations, d_0 is the correlation radius (the distance at which the correlation reduces e times) and $r(0)$ is the correlation function at zero distance). Spatial correlation functions obtained for different ranges and type of precipitation, and distance for which spatial correlation coefficient is greater than 0.75, are given in Table 6. For other regions, either data were not sufficient to develop the spatial correlation coefficient or the spatial correlation was very poor.

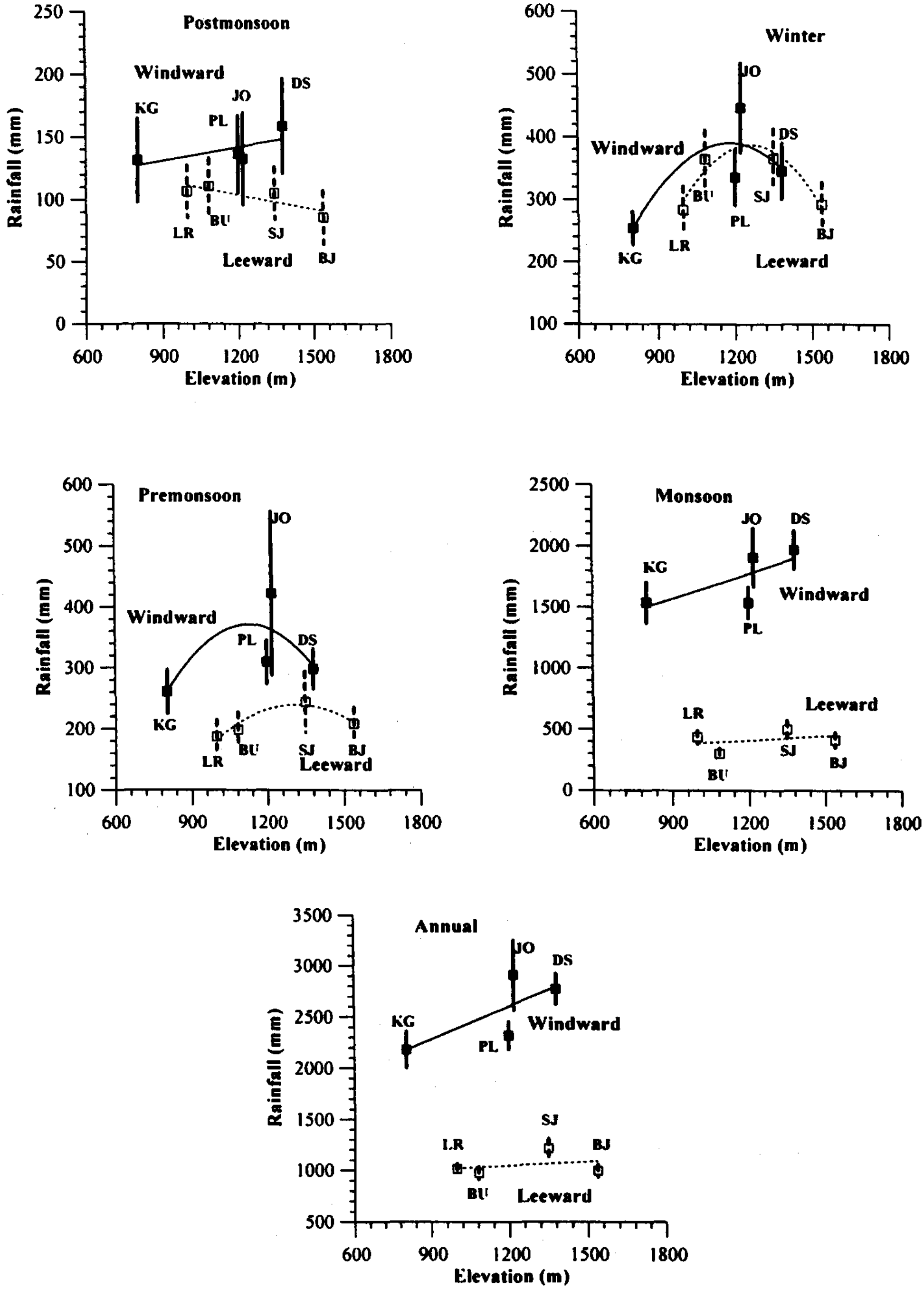


Fig. 10. Variation in seasonal and annual rainfall with elevation in the middle Himalayan range of the Beas basin.

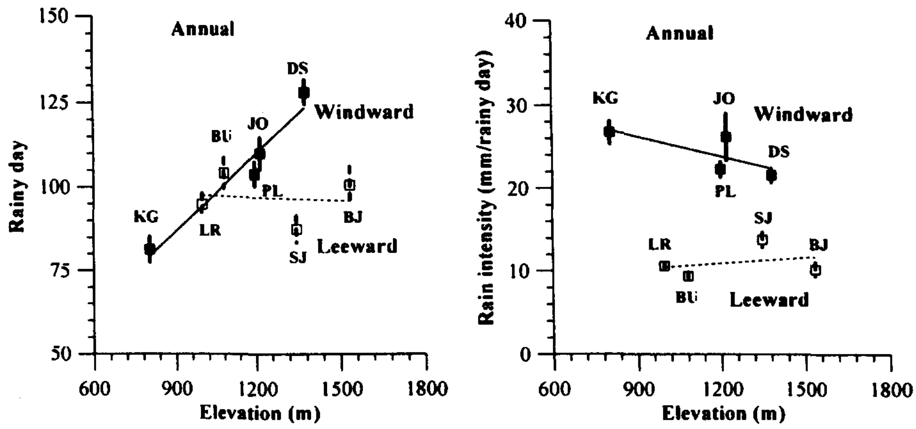


Fig. 11. Variation in annual rainy days and rain intensity with elevation in the middle Himalayan range of the Beas basin.

Table 3
Seasonal distribution of average rainfall in different ranges of the Himalayas in the Beas basin

Himalayan range	Side	Rainfall (mm)				
		Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Outer	Leeward	179 (12.8%)	148 (10.6%)	985 (70.6%)	83 (5.9%)	1395
Middle	Windward	346 (13.6%)	323 (12.7%)	1740 (68.3%)	140 (5.5%)	2549
	Leeward	327 (31.1%)	210 (19.9%)	413 (39.2%)	102 (9.7%)	1052
	Average	337 (18.7%)	267 (14.8%)	1077 (59.8%)	121 (6.7%)	1801

Each season's contribution to the annual rainfall is also indicated, as a percentage.

Spatial correlation of rainfall appears to be higher in the outer Himalayas than in other ranges. This may be because of lower relief in the outer Himalayan range as compared with the middle and greater Himalayan range. Spatial correlation of rainfall is better on the leeward than the windward side in the middle Himalayan range. Recently, Loukas and Quick (1996) made similar studies of storm precipitation in southwestern British Columbia, Canada. They reported that all types of storms indicated correlation coefficients larger than 0.75 for distances smaller than 32 km. Rainfall spatial correlation over the British Columbia mountain watershed matches that on the leeward side of the middle Himalayan range of the Beas basin.

10. Conclusions

Mountains have a strong impact on precipitation distribution. Knowledge of precipitation distribution is a basic and important requirement for planning and managing water resources, simulation of runoff and to prepare precipitation maps of the basin or region.

Table 4

Correlation matrices for annual rainfall and snowfall at various stations in the different Himalayan ranges of the Satluj basin

Himalayan range	Type of precipitation	Station				
			Nangal	Bhakra		
Outer (windward)	Rain	Nangal	1.00			
		Bhakra	0.92	1.00		
			Suni	Kahu	Kasol	
Outer (leeward)	Rain	Suni	1.00			
		Kahu	0.84	1.00		
		Kasol	0.88	0.98	1.00	
			Kalpa	Namgia	Kaza	
Greater (leeward)	Rain	Kalpa	1.00			
		Namgia	0.54	1.00		
		Kaza	− 0.04	− 0.28	1.00	
			Namgia	Kaza	Lossar	
Greater (leeward) Spiti sub-basin	Snow	Namgia	1.00			
		Kaza	0.14	1.00		
		Lossar	− 0.27	0.61	1.00	
			Sangla	Rakchham	Chitkul	
Greater (leeward) Baspa sub-basin	Snow	Sangla	1.00			
		Rakchham	0.69	1.00		
		Chitkul	0.44	0.72	1.00	
			Kilba	Kalpa	Moorang	Pooh
Greater (leeward) Upper Satluj sub-basin	Snow	Kilba	1.00			
		Kalpa	0.01	1.00		
		Moorang	− 0.82	− 0.24	1.00	
		Pooh	− 0.26	0.54	0.15	1.00

Precipitation distribution for the Himalayas is poorly known as compared with many other mountains of the world. In the present study, seasonal and annual precipitation distributions for the Satluj and Beas basins are studied. Depending upon the availability of precipitation data, the study includes the outer, middle and greater Himalayan ranges. The following conclusions are drawn from this study.

10.1. Rainfall distribution

1. On the leeward side of the outer Himalayas, for all seasons, rainfall increases linearly with elevation for both the Satluj and Beas basins. Both more rainy days and higher

Table 5
Correlation matrices for annual rainfall at various stations in the different Himalayan ranges of the Beas basin

Himalayan range	Type of precipitation	Station				
			Ghamrur	D. Gopipur	Harsur	Shahpur
Outer (leeward)	Rain	Ghamrur	1.00			
		D. Gopipur	0.90	1.00		
		Harsur	0.77	0.82	1.00	
		Shahpur	0.81	0.75	0.72	1.00
			Kangra	Palampur	J. Nagar	Dharamshala
Middle (windward)	Rain	Kangra	1.00			
		Palampur	0.53	1.00		
		J. Nagar	0.21	0.27	1.00	
		Dharamshala	0.54	0.88	0.08	1.00
			Larji	Bhuntar	Sainj	Banjar
Middle (leeward)	Rain	Larji	1.00			
		Bhuntar	0.83	1.00		
		Sainj	0.74	0.93	1.00	
		Banjar	0.87	0.77	0.55	1.00

Table 6
Spatial correlation function for different Himalayan ranges of the Satluj and Beas basins

Basin	Himalayan range	Type of precipitation	Spatial correlation function ($r(d)$)	Distance for $r = 0.75$ (km)
Satluj	Outer (leeward)	Rain	$0.984\exp(-0.0038d)$	71
Spiti sub-basin	Greater (leeward)	Snow	$1.200\exp(-0.0277d)$	17
Baspa sub-basin	Greater (leeward)	Snow	$1.039\exp(-0.0280d)$	12
Beas	Outer (leeward)	Rain	$0.877\exp(-0.0035d)$	43
	Middle (windward)	Rain	$1.231\exp(-0.0441d)$	5
	Middle (leeward)	Rain	$0.851\exp(-0.0037d)$	34

rainfall intensity are responsible for increasing rainfall with altitude in the outer Himalayan range, in the Satluj basin. In the Beas basin, rainfall intensity plays a major role in increasing rainfall with elevation. Rainfall on the windward side is higher than that on the leeward side in the outer Himalayan range of the Satluj basin.

2. Rainfall varies linearly with altitude for the post-monsoon and monsoon seasons in the middle Himalayan range. Annual rainfall follows a similar distribution. However, for

winter and pre-monsoon seasons, rainfall first increases and then decreases above a certain elevation. The rainfall distribution was fitted reasonably well by a second-order polynomial for these two seasons. A sudden rise in altitude of the middle Himalayan range in the Beas basin behaves as a giant mountain barrier and increases rainfall very significantly on the windward side of this range. Owing to this orographic effect, average annual rainfall on the leeward side is less than half that on the windward side. Gradients in annual rainfall on the windward and leeward sides are about 106 mm per 100 m and 13 mm per 100 m, respectively. More rainy days contribute to increasing rainfall on the windward side, whereas intensity is higher on the leeward side. Dharamshala experiences exceptionally heavy rainfall (average 1972 mm) during the monsoon season. Standard errors of the mean rainfall are always higher on the windward side.

3. There is little rain in the greater Himalayan range of the Satluj basin. Most of the moisture is precipitated over the outer and middle Himalayan ranges. Rainfall decreases approximately exponentially with elevation in the post-monsoon and pre-monsoon seasons. However, rainfall in the monsoon season has no trend. The annual rainfall distribution also follows an exponentially decreasing trend with altitude. Winter rainfall decreases linearly with elevation in this range. Negligible rainfall is observed above 3000 m elevation in winter. The reduction in rainfall at higher elevation is due to fewer rainy days at those elevations. Standard errors of the mean rainfall decrease with altitude in the greater Himalayas.
4. The orographic effect on rainfall has led to maximum rainfall in the middle Himalayan range in the Beas basin and in the outer Himalayan range in the Satluj basin. Average annual rainfall decreases considerably from the outer Himalayas to the greater Himalayas in the Satluj basin. Average annual rainfall in the greater Himalayas is about one-sixth of the outer Himalayas rainfall.
5. Monsoon rainfall contributed most to the annual rainfall—45%–71% in the Satluj basin and 39%–71% in the Beas basin—over all Himalayan ranges. Minimum rainfall occurs in the post-monsoon season in the outer and middle Himalayas because of the lower moisture content in this season. However, in the greater Himalayan range, minimum rainfall occurs in winter because most of precipitation falls as snow over this range. The contribution of pre-monsoon rainfall to annual rainfall increases from the outer Himalayas to the greater Himalayas, and becomes significant in annual rainfall in the greater Himalayan range. Winter rainfall is also significant in the middle Himalayan range for both basins.
6. There is a higher spatial correlation of rainfall in the outer Himalayan range; this may be because of lower relief in the outer Himalayan range than in the other ranges.

10.2. Snowfall distribution

1. Snow increases linearly with elevation in the Spiti and Baspa sub-basins. In the upper Satluj sub-basin, it first increases and then decreases. The trend of snowfall variation in the upper Satluj sub-basin is significantly influenced by the magnitude of snowfall at

one station; otherwise, it also suggests a linear increase with altitude. Snow gradient in the Spiti sub-basin (43 mm per 100 m) is found to be more than four times than in the Baspa sub-basin (10 mm per 100 m). Standard errors of the mean snow water equivalent increase with altitude in both the Spiti and Baspa sub-basins, with a higher variability in the Spiti sub-basin.
2. The ratio of snowfall to annual precipitation varies linearly with altitude. All the stations recorded more than 60% snow contribution to annual precipitation. An extrapolation of this linear relationship suggests an equal contribution of rainfall and snowfall to annual precipitation at about 2000 m. Moreover, above 5000 m altitude all the precipitation falls as snow.

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