CASE STUDY

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PRECIPITATION DISTRIBUTION IN THE SUTLEJ AND BEAS BASINS

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Preface

Accurate estimation of precipitation and its distribution in the mountainous are needed for streamflow forecasting, design flood and snowmelt contribution in the rivers in the snowfed rivers etc. Precipitation phenomenon differ greatly from place in the mountainous area because of highly rugged topography. It is important, therefore, to study the distribution of precipitation in the different parts of the Himalayas for both phases of precipitation namely snowfall and rainfall. The results are very important for analysis and simulation of runoff from a basin and to prepare the precipitation maps of the basin/region.

In India, about 35% of the geographical area is mountainous and 58% of this is accounted for by the mighty Himalaya with mountain zone of perpetual snow has given rise to a number of rivers, but very limited studies to assess the orography effect on precipitation in the Himalayan region are carried out. Lack of a good network of observing stations especially at higher elevations because of inaccessibility and other difficulties, is considered one of the reasons for limited studies over Himalayas. However, at present (snowfall and rainfall) data base for few basins has improved. The Satluj and Beas basins which are taken up for the present study have a very good network even at high elevations. This has helped in undertaking a systematic scientific study to understand the nature of precipitation distribution in the western Himalayas.

This study concentrates on the examination of pattern of rainfall and snowfall distribution with altitudes for Satluj and Beas basins. Depending upon the availability of precipitation data, studies are extended for outer, middle and greater Himalayan ranges. It is found that rainfall and snowfall both follow a definable trend of variation with altitude and different types of trend are found for different Himalayan ranges of a basin. A comparison of rainfall distribution for both basins is also presented in this report. This study has been carried out in the Mountain Hydrology Division of this Institute. Dr Pratap Singh, Scientist C, Shri Naresh Kumar, Senior Research Assistant, Shri S K Dhariwal, Research Assistant were involved in carrying out this study.

(S M Seth)
Director

PRECIPITATION DISTRIBUTION IN THE SATLUJ AND BEAS BASINS

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Abstract

Rainfall distribution with altitude has been studied for Satluj and Beas basins both located in the western Himalayas. Depending upon the availability of precipitation data, studies are extended for outer, middle and greater Himalayan ranges. Snowfall distribution was studied only for Satluj basin because snowfall data were not available for Beas basin. It is found that rainfall and snowfall both follow a definable trend of variation with altitude. The rainfall distribution with altitude in the outer Himalayas has shown that for all the seasons rainfall increases linearly with elevation for both Satluj and Beas basins. Based on limited rainfall stations on the windward side of the outer Himalayas in the Satluj basin, it could be concluded that rainfall on the windward side is higher than that of on the leeward side of this range.

A very significant role of topography has been found in the middle Himalayan range of the Beas basin. In this basin, middle Himalayan range starts just after the Kangra valley and immediately gain very high altitude. This sudden rise in altitude behaves as a giant mountain barrier and imposes a remarkable impact on rainfall distribution resulting in heavy rainfall on the windward of this side and very less rain on the leeward side. The second order polynomial is well fitted to explain the behaviour of rainfall variation for all the seasons on both sides in this range. Annual rainfall also follows similar distribution. No distribution study was carried out for middle Himalayan range of Satluj basin because of non-availability of data. As such very little area of basin is covered by the middle Himalayan range of the Satluj basin.

Availability of rainfall data restricted study to the leeward side of greater Himalayan of Satluj basin. Rainfall decreases exponentially with elevation in the postmonsoon, premonsoon seasons. The annual distribution also followed this exponentially decreasing trend with altitude. Rainfall distribution in the monsoon season has shown no specific decreasing trend with altitude in this basin. The winter season rainfall decreases linearly with elevation in this range as such there no rainfall observed above 3000 m elevation. The reduction in rainfall at higher elevation caused by lesser number of rainydays at those elevations in this range. As such very little

rain is observed in this range of Himalayas because most of the moisture of monsoon currents is precipitated over outer and middle Himalayan ranges.

Average annual rainfall decreases considerably from outer Himalayan range to middle Himalayan range in the Satluj basin while reverse is found true for Beas basin because of its typical topography. Annual rainfall is further drastically reduced in the greater Himalayan range in the Satluj basin and same is expected for this range of Beas basin. Contribution of seasonal rainfall into annual rainfall has shown that that over all the ranges of Himalayas in the Satluj and Beas basins, monsoon rainfall contributed maximum in the annual rainfall.

Snow distribution with altitude has been studied for the greater Himalayan range of Satluj basin. It is observed that snow increases linearly with elevation in this Spiti and Baspa basins, whereas for the upper Satluj sub-basin it first increases and then decreases. Maximum and second to maximum snow is observed in the month of March and February, respectively in all the valleys in the greater Himalayan range of the Satluj basin. The ratio of snowfall to the annual precipitation varied linearly with altitude and all the stations recorded more than 60% snow contribution in the annual precipitation. An extrapolation of this linear relationship indicates that above 6000 m elevation, whatever precipitation occurs may be falling as snow only.

1.0 Introduction

Precipitation varies greatly in space and time from one mountain range to another and hydrological processes can not be properly represented unless distribution of precipitation with elevation is known. The mountainous environment in comparison to the plain areas has strong impact on precipitation distribution. The gradients in amount and intensity of precipitation depend upon several factors such as topography,strength of moisture bearing winds, its moisture content and orientation of the mountain range with respect to the prevailing wind direction. The ambient temperature determines types of precipitation namely rain, snow or both types of precipitation. Either a deficiency of water vapour or the non-occurrence of weather systems, or both, are mainly responsible for lower precipitation in some years.

In the mountainous regions orography provides necessary uplift to the moisture laden currents striking against a mountain or chain of mountains which results in good rainfall on the windward side of the mountains. If basin relief is very high, there may not be continuous rise; beyond a particular altitude the precipitation may actually decrease with height. The variation in precipitation with altitude is limited by mean height of clouds and decrease of water vapour with altitude. Thus, precipitation in mountains can decrease with altitude above certain level. Information on variation of precipitation with elevation for a particular watershed would be very much useful in determining the net increase or decrease in precipitation due to elevation. Such studies will assist in the realistic assessment of the water resources of these regions so that optimum utilization of the available water resources is can be made. Such information are also very essential for estimation of PMP for mountainous areas.

In India, about 35% of the geographical area is mountainous and 58% of this is accounted for by the mighty Himalaya with mountain zone of perpetual snow. The Himalayas are source for a number of major rivers, but detailed studies to assess the orography effect on precipitation in the Himalayan region are not carried out.Lack of a good network of observing stations especially at higher elevations because of inaccessibility and other difficulties, is one of the reason for limited studies over Himalayas. However,in recent years snowfall and rainfall data base for few basins has improved.The Satluj and Beas basins which are taken up for present study has a reasonably good network at high elevations. This has helped in undertaking a systematic scientific study to understand the nature of precipitation distribution in the western Himalayas.

2.0 Review of Orographic Effect on Precipitation Distribution

The influence of mountain barriers on precipitation distribution has been attracting the attention of scientists since long. Several studies were carried out on distribution of rainfall, snowfall and total precipitation with elevation in different parts of the world. Because all these have shown different patterns of variation with elevation, therefore, a brief review on the important rainfall, snowfall and total precipitation distribution studies has been presented in the following section.

2.1 Rainfall distribution

The distribution of rainfall with elevation in the Sierra Nevada mountains showed that rainfall increases up to a height of 1500m in these mountains (Linsley et al., 1949). Engman and Hershfield (1969) reported that average number of days and hours with precipitation increases with elevation in both summer and winter in north-eastern Vermount, USA. A study on elevation effects on rainfall using an event based stochastic model of thunderstorm rainfall and empirical data was carried out by Duckstein et al (1972). The model was verified using data from cloud seeding experiments designed to investigate the possibility of increasing thunderstorm rainfall in the Santa Catalina Mountains near Tucson.It was noted that the mean total seasonal rainfall could be described by a quadratic polynomial in relation with elevation. In the Andes mountains in the Ecuador two zones of maximum rainfall along the western and eastern slopes at elevation of 1000m and 1400m, respectively, were found (Rumley, 1965). Recently, Loukas and Quick (1993) has shown that rainfall depth per event increased up to mid elevation of a mountainous watershed in the British Columbia, and then decreased at upper elevations. Hourly rainfall intensity was found to decrease with increase in elevation.

Kanestrom (1987) described the studies carried out on the distribution of rainfall and reported that orography played an important role in rainfall distribution in northern Norway. It was concluded that heavy orographic rainfall was caused by forced lifting, strong winds at low levels and high relative humidity. Niemczynowicz (1989) studied the altitude effect on rainfall in the Jamtland area in Swedish mountains. Based on three years (1985-87) intensive measurements of rainfall, the average altitude effect for all collected data was found to be 9.5% per 100m. Highest rainfall was registered behind the crest of the mountains on the leeward side.

2.2 Snowfall distribution

Rhea and Grant (1974) found that 80% of the variance of snow water content in Colorado and Utah can be accounted for in terms of two parameters: the directionally adjusted slope and number of upwind barriers to the air flow. Caine (1975) found an elevational influence in the relative variability of maximum snowpack as well as on the snow accumulation. The latter increased linearly at a rate of 655 mm/km with a correlation coefficient of 0.66 from a zero accumulation level at 2400m for San Jaun Mountains in Colorado. However, variability decreases as the elevation increases.

Golding (1968) found a linear relationship between snow water equivalent and altitude. A mean rate of increase for snow water equivalent was reported to be of the order of 873 mm/km between 1950m and 2225m. Using a step wise linear regression analysis in the Canadian Rocky Mountains covering a range of elevation from 1500 to 2800m, Loijens (1972) has shown that between 81-87% of variance of snow water equivalent has associated with physiographic variables namely elevation and slope.

Witmer et al (1986) found mean gradient of total fresh snowfall below 1100m altitude varied from 80mm/100m in south-western Alps to 730 mm/100m in northern slopes of Alps. In the Swiss Alps, snow water equivalent was observed to be maximum around 2700m altitude, and might decrease slightly above (Martinec, 1987).

For the polar regions, data on the altitudinal effect on precipitation related primarily to snow accumulation records on Greenland and Antarctic ice sheets. These have been summarized by Sudgen (1977). It is reported that accumulation in Antarctica and north Greenland increased to about 1500-1600m altitude and there after decreases.In south-east Greenland and eastern Antarctica the maximum snow occurred at about 700m. Using precipitation and accumulation data for Greenland, Ohmura (1991) showed existence of the maximum precipitation zone around 2500m at 69° North in western Greenland and descending northward to about 1500m at 76° North. In the eastern Greenland, the higher values are found along the coast.

2.3 Total precipitation distribution

In one of the most detailed studies of orographic influence on precipitation, Spreen (1947) correlated mean seasonal winter precipitation with such factors as elevation, slope, rise, orientation and exposure for western Colorado. It was found that above described five parameters together accounted for 85% of precipitation variation while elevation alone accounted for only about 30% of variation. Similar results were found by Burns (1953) in discussing the small scale topographical effects in the San Gabriel mountains in California. For the western Oregon and Washington stations also, it was found that elevation alone does not explain much of the elevation in annual precipitation which predominantly occurs in the winter. Indices of barrier elevation with a latitude index explained most of the variations (Scermerhorn, 1967)

Hamon (1971) concluded that winter precipitation increased more than four times at the 7000 ft elevation in comparison to that observed at the 4000 ft elevation in the southwestern Idaho. A three-fold increase in the hours of precipitation between 400 and 1200 m elevation during winter season has been reported by Hendrick et al (1978) for Mansfield Vermount, USA. Hanson(1982) determined the spatial distribution of mean annual precipitation in the mountainous watersheds located in the south-east Idaho and a linear relationship was shown between annual precipitation and elevation. This relationship was found to be best when the stations were grouped into downwind and upwind sites.

Storr and Ferguson(1972) made precipitation distribution studies for 5 Canadian mountainous watersheds. The gradients for mean annual precipitation and mean summer rainfall were determined to be 636 mm/km and 93.6 mm/km, respectively, implying that rate of increase of snowfall was considerably higher than that for rainfall. Elevation and barrier distance provided highest correlation with precipitation. An examination of variation of precipitation with these two parameters suggested that curvilinear relationship provided better fit. Solomon et al (1968) and Obedkoff (1970) also noted similar relationships between precipitation distribution and altitude. Various high level stations and observatories in the Alps indicated that amount of precipitation increased with elevation to the highest level of 3000-3500m (Barry, 1992).

2.4 Status of Snowfall and Rainfall Distribution Over Himalayas

Hill(1881) made a detailed study of rainfall distribution with altitude in the northwest Himalayas and found that rainfall increases with elevation up to about 1200m and thereafter it decreases as the elevation increases. To obtain a suitable relationship between mean monsoon (June-October) rainfall and elevation in the Central Himalayas (Nepal Himalayas), Dhar and Rakhecha (1981) studied the trend of rainfall variation. It was found that (i) no linear relationship exists between elevation and monsoon rainfall, (ii) elevation and rainfall parameters can best be related by a polynomial of fourth degree, and (iii) rainfall-elevation profile show that the zones of maximum rainfall occur near the foothills and at an elevation of 2000m to 2400 m. Beyond this elevation, rainfall decreases continuously as elevation increases until the great Himalayan range is reached. Higuchi et al (1982) also studied the rainfall characteristics during the monsoon season in the high mountain areas of Nepal Himalayas and reported that rainfall decreases with altitude in the range from 2800 m to 4500 m. It is still to be investigated whether variation in precipitation with elevation is due to changes in the number of storms, or in the amount of precipitation per storm (precipitation intensity) or due to a combination of both possibilities.

Singh et al. (1995) have carried out a detailed study on precipitation distribution for each range of Himalaya lying in the Chenab basin located in a section of western Himalayas. Rainfall and snowfall distributions exhibited different trends on the windward and leeward slopes of the three ranges of Himalayas. During winter, pre-monsoon and post-monsoon seasons in the outer Himalayas, rainfall increased linearly with elevation. A spill over effect was also observed on the leeward side during these three seasons in the outer Himalayas.In the monsoon season rainfall on the windward side initially increased reaching to its maximum at about 600m and thereafter it decreased. Second order polynomials equation fitted well for rainfall distribution of monsoon and annual rainfall in the outer Himalayas and for all seasons and annual rainfall distribution in the middle Himalayas. The region of maximum rainfall on windward and leeward sides was found to be between 1600 and 2200 m. In the greater Himalayan range rainfall decreased exponentially with elevation and snowfall increased linearly. It was noticed that rainfall becomes negligible at elevations beyond 4000m on the windward side of great Himalayan range.

The snowfall distribution in any part of the Himalayas is relatively unknown because very few studies were carried out to understand snow distribution. Studies in Langtang valley in Nepal between 3920 m and 5090 m show that snowfall increases with height in the winter season. Recent studies made by Singh et al (1994, 1995) for a Chenab basin have shown that snowfall has more significant variation with elevation in comparison to rainfall. In the middle Himalayan range of this basin, snowfall distribution has shown a trend of linear increasing with elevation on the windward side whereas on the leeward side it initially increases with elevation and then decreases. In this range maximum snowfall was found at about 2500m on the windward and at 1800 m on the leeward side. Over greater Himalayan range, snow distribution was carried out only for windward side and it was found that snow water equivalent (SWE) increases approximately linearly on this side.

3.0 Problem Definition

Relationships derived for a mountainous watershed generally can not be directly adapted to other watersheds even in the same region. However, similar form of equations may be applicable to adjacent watersheds (Storr and Ferguson,1972). Significant variations may occur between physiographical precipitation models over relatively short distances in the mountainous areas (Peck and Brown, 1962). Fitzharris (1975) also observed that more accurate information are possible when separate equations are developed for each zone. The same is applicable for the basins in the Himalayan region because of the irregular topography. In the present study attempts have been made to derive the precipitation distribution pattern in the Satluj and Beas basins in the western Himalayan region. Reasonably high relief changes within short distances are found in the study area which helped for better estimate of orographic effect on precipitation. Depending upon the availability of rainfall and snowfall data, studies are carried out for the outer, middle and greater Himalayan ranges of the basins. The relationships developed can be made use of the preparation of precipitation maps of the basin/region.

The Himalayan catchments receive precipitation in different seasons from different weather systems. Snowfall is experienced in the winter season and rainfall in all other seasons. Distribution of rainfall with elevation is studied therefore for each season and each mountain range. Because most of the snowfall is restricted to the winter season, therefore, snowfall distribution with elevation is carried out on the annual basis. In this study, emphasis has been laid on the analysis of average seasonal and annual precipitation distribution with a view that storm to storm variation is averaged out over a period of years, leaving only consistent pattern of topographic influences on precipitation distribution.

4.0 Study Area

4.1 Brief description of different Himalayan ranges

The Himalaya, the abode of eternal snow forms a unique environment; the highest mountain environment on the earth where snow and icy environmental conditions rival those at polar regions. The environment around the higher peaks in the greater Himalayan range, resembles the environment around poler region. The prolonged periods of day and night over the north and south polar regions are not existing in the Himalayan region. Unlike the polar regions, Himalayan region has long supported civilizations and yet it is one of the least explored geographical area on earth.

The Himalayas are an extensive mountain system of 2400 km from Nanga Parbat (8126 m) in the west to Namcha Barua (7756 m) in the east in the shape of a convex with its convexity toward the south. The Himalaya further may be subdivided laterally into western, central and eastern Himalayas. The western Himalaya extends right from Nanga Parbat to Nanda Devi and is the origin of Indus and Ganga river. The central Himalayas stretch from Ghaghra and Gandak to Kosi river system and limited to Nepal Himalayas, whereas the eastern Himalaya ranges from east of Kosi to Namcha Barua in bend of Brahamputra river (Figure 1).

The Himalayas are not a single chain of mountains. They comprise of three west to east running parallel ranges and between these ranges there are numerous narrow valleys. Three parallel ranges or geographical zones are described below:

(i) Outer Himalayas

This is the southernmost range of Himalayas and is also known as Siwalik also. Their average height varies from 900 to 1200 m asl and average width varies from 10 to 50 km. Attaining an altitude of about 600m they end abruptly and follow successive narrow parallel ridges, trending NW-SE and separated by valleys representing basins. The elevation of outer hills rarely exceeds 1200m.

(ii) Middle Himalayas

The ranges representing this part of Himalayas consist of higher mountains. These are a series of broken mountain ranges whose mean elevation varies from 2000 m to 3300 m asl. Their width varies from 60 to 80 km. These ranges have different names in the different sections of the Himalayas such as Lesser Himalayas or Pir Panjal ranges in the western Himalayas. The middle Himalaya lies between the outer Himalaya and the perpetual snow covered ranges of greater Himalaya. It is characterized by deeply cut valleys. The ridges extending in irregular direction appear to branch again and again.

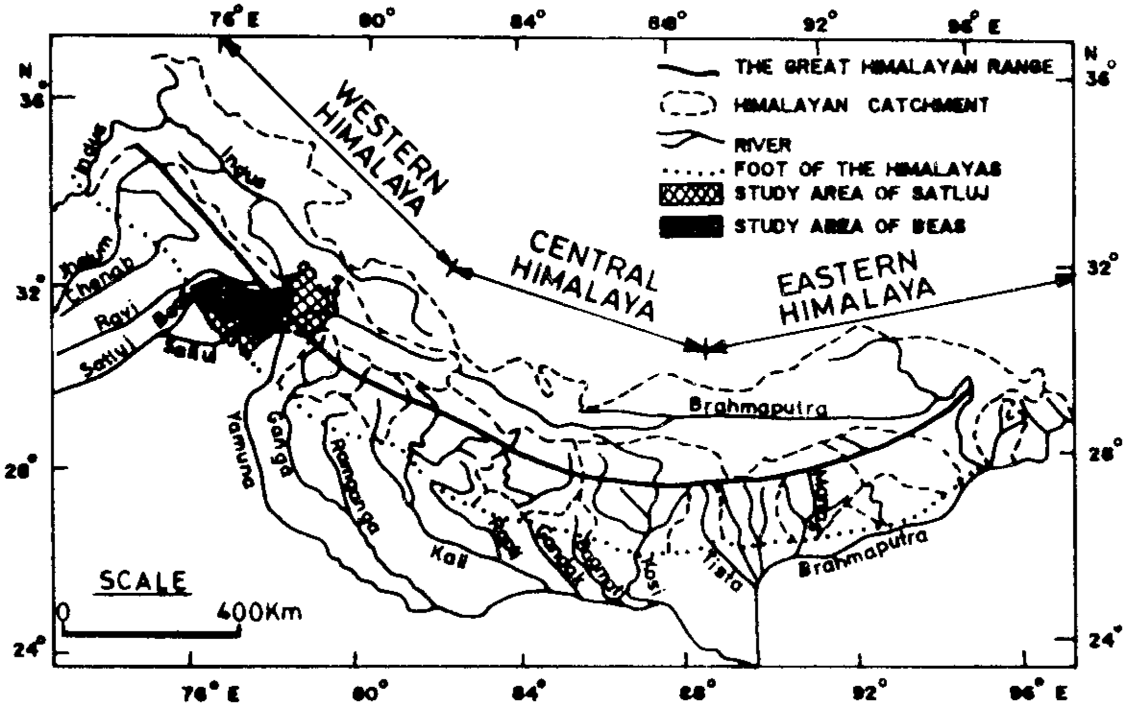


FIG. 1 : DIFFERENT SECTIONS OF HIMALAYAS AND CATCHMENTS OF THE HIMALAYAN RIVERS.

(iii) Greater Himalayas

This is the most northern range of the Himalayas. Its lofty, rugged chain of mountain peaks reach high above the perpetual snowline. The average height of this range is about 6000 m asl. In this great Himalayan range as many as 13 peaks exceed 6000m elevation. A still large number of peaks range from 4500 m to 6000 m. Beyond the main ranges of Himalaya there is a continual series of somewhat lower Trans Himalayan zone (average altitude varying between 5000 m and 6000m) adjoining the Tibetan plateau.

4.2 General Precipitation and climatic characteristics of Satluj and Beas basins

The presence of glacier and snowfileds over an extensive area in the western Himalayas is not only a dominant feature relevant to the climate but is also a factor that significantly controls many hydrological processes. Accumulation of snow during winter and period of snowmelt coinciding with the gradual rise in temperature, actually regulate the flow and make it available at the time of year when it is needed most. In the rivers flowing through eastern Himalayas, monsoon flow behaves in a most erratic manner, causing havoc of flow in the downstream areas. Differences in elevation and aspect give rise to micro climates. In general, the various climatic zones range from subtropical to (450-900m), warm temperate (900-1800m), cool temperate (1800-2400m), cold high mountain (2400-4000m),snowy and frigid (above 4000m). The varied topographic and agroclimatic conditions permit the cultivation of a wide variety of crops and fruits in the Himalayan region.

For the optimum development of water resources and planning of agriculture operation in a given basin/region, basic knowledge of precipitation distribution during individual months, seasons and the year is of vital importance. Seasonal and annual precipitation distribution over Satluj and Beas basins have been studied for each Himalayan range separately. For this purpose a year has been divided into the following four seasons depending upon broad climatic conditions prevailing over the basin. Normally monsoon onsets in the last of June and withdraws by the end of September in this region.

(i) Winter season (December-March)
(ii) Premonsoon season (April-June)
(iii) Monsoon season (July-September)
(iv) Post monsoon (October-November)

The source of precipitation and its distribution in each of the season is described in the following sectior

Winter Season

The precipitation during this season is caused by extratropical weather system of mid-latitude region originating from Caspian sea and moving eastward. This winter weather system is known as western disturbances and approach India from the west through Iran, Afghanistan and Pakistan. With the setting of the winter season these western disturbances have the tendency to move along lower latitudes. Ordinarily these disturbances remain at high latitudes and do not influence the Himalayas. But, as the season advances they come lower and lower and by the end of December they cover more or less whole Himalaya. By the end of winter they recede to their original position which lies beyond the Himalayan mountains.

The precipitation during this season 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. Precipitation occurs at intervals throughout the winter season. It is found that the average frequency of occurrence of these disturbances is about 5 to 6 each month which reduces as the season advances (Rao, 1983). The higher precipitation in the western Himalayas during these months is the combined effect of the nearly east-west configuration of the Himalayas and eastward movement of the western disturbances system. The precipitation associated with these weather systems decreases considerably as they move eastwards along the Himalayas because of increasing distance from the source of moisture and the tarrain. These weather systems cause rainfall at the lower elevation and snowfall at higher elevations.

Pre-monsoon Season

Generally this season lasts for about a period of 3 months from April to June and is considered as transit period between winter and southwest monsoon. Light to moderate rains are essentially caused by local convective storms. Convection increases because of higher temperature in the Himalayan region in this season.

Monsoon Season

Normally precipitation over the Himalayas is caused by the moist air currents from Bay of Bengal in this season. Sometimes, in association with certain weather situations both branches of monsoon (i.e., the Bay of Bengal and Arabian sea) arrive simultaneously in this region heralding the onset of monsoon. These currents after striking the Burma and eastern Himalayas are deflected westwards and travel along the Himalayas. Rainfall decreases westward because of increasing distance from the source of moisture i.e. Bay of Bengal or Arabian Sea, which results in less amount of moisture content in the air currents. Consequently lesser precipitation is observed as one moves further west. This is the season of abundant rain and rivers are generally flooded. Snow and glaciers at very high altitudes continue melting during this season. The monsoon normally starts withdrawing from this region towards the end of September.

It was observed that the monsoon currents give copious rainfall over the Indian plains and lower Himalayas. After crossing 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. It results in insignificant rainfall in the trans-Himalayan region.

Post Monsoon

During this season clear autumn weather sets in and there is generally little rainfall. This is considered as the the dry season in the entire Himalaya as well as in the plain areas.

4.3 Description of Study Areas

Precipitation distribution has been studied for Satluj basin up to Bhakra (Indian part of the basin only) and Beas basin up to Pong dam separately.The general features of these basins are described below.

(a) Satluj basin

The Satluj river rises in the lakes of Manasarover and Rakastal in the Tibetan Plateau at an elevation of about 4,572 m (Figure 2) and forms one of the main tributaries of Indus river. It travels about 322 km in the Tibetan province of Nari-Khorsam forming a plateau by successive deposits of boulders, gravel, clay and mud. The flow of Satluj, obtained mainly from glaciers has cut a valley about 914 m deep through these deposits. After flowing in north-westerly direction, it changes direction towards south-west and covers another 322 km up to Bhakra gorge, where the 225.55 meters (740 ft) high straight gravity dam (Bhakra/Govind Sagar) has been constructed. Most of the area in Tibetan plateau and some areas down stream are without rainfall and has cold desert climate. This large river flows through different areas which have varying climatic and topographic features. At Namgia, near Shipki, it is joined by its principal Himalayan tributary, the Spiti. Below this dry region, it flows through the Kinnaur district of Himachal Pradesh, where it gets both snow and rain. Numerous glaciers drain directly into Satluj at various points along its course and many Himalayan glaciers drain into its tributaries. In the lower part of the basin only rainfall is experienced.

The total catchment area of Satluj is about 56,874 km^2 of which 37,048 km^2 lies in Tibet and remaining 19,826 km^2 in India. However, main planning and work has been concentrated only in the area lying in India. Approximate height of snowline at the start and end of snowmelt season has been reported to be approximately 11000 ft and 17500 ft respectively (Chatterji and Chopra, 1976). The permanent snowline in this portion of Himalayan range is at an elevation of 5400 m (BBMB, 1988). Upadhyay et al (1983) reported that about 11% area of the total Satluj catchment lies under glaciers. The geological setting and availability of abundant water provides a huge hydropower generation potential in this river. Several schemes are planned/coming up on this river.

In the annual flows of the Satluj river a substantial contribution is provided by snow and glacier melt runoff. During winter season snowmelt contribution is less than runoff due to rainfall because the unfavourable conditions for melting. After middle of March, snowmelt exceeds the rainfall component which leads to a significant rise in the runoff. The snowmelt contribution increases continuously as the snowmelt season advances. The south-west monsoon activity is experienced in the lower catchment area during the period normally from the end of June to middle of September. Peak values of the total discharge in

SATLUJ CATCHMENT UP TO BHAKRA
(INDIAN PART).

SCALE :- 1 : 1,000,000

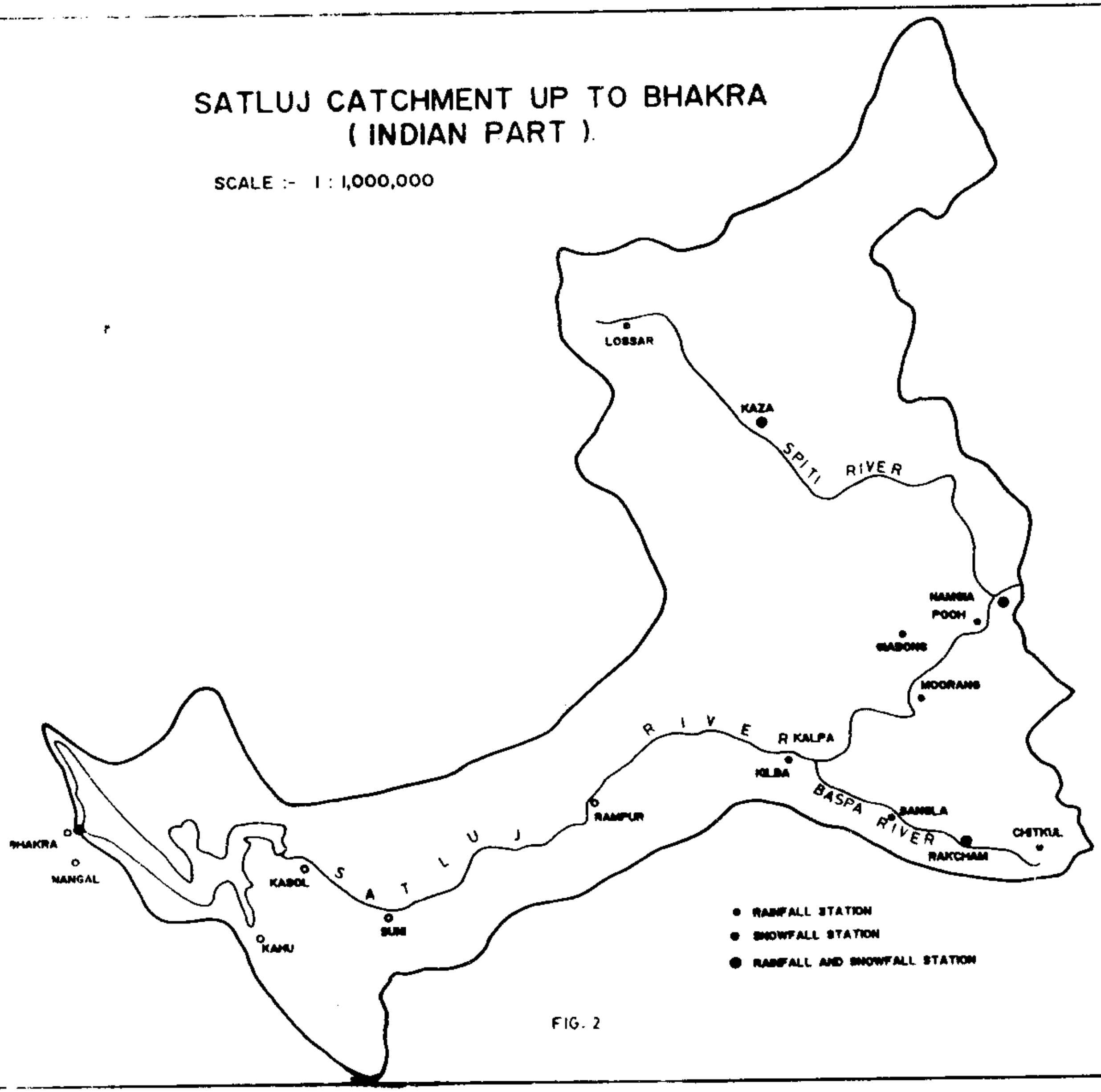


FIG. 2

July and August are essentially due to major contribution of monsoon rains in the lower catchment. The catchment area is fed by winter precipitation comprising snowfall at high altitude and winter rainfall in the lower catchment area. The main snowfall period for Satluj catchment is from December to March and in some years extends from October to April. Due to large differences in seasonal temperature and great range of elevation variation in the catchment, the snowline changes its position considerably from place to place and from year to year.

Indian part of the Satluj basin covers outer Himalayas (Siwalik ranges), middle Himalayas (Dhauladhar range) and greater Himalayas (Greater Himalayan range and Zaskar range). The shape and location of this basin is such that major part of the basin area lies in the greater Himalayas where heavy snowfall is experienced during winters (Figure 2). Broadly snow covered area is confined to three sub-basins namely Spiti sub-basin, Baspa sub-basin and upper Satluj sub-basin. All these sub-basins lie in the north of the greater Himalayan ranges and have been considered separately for snow distribution.

(b) Beas Basin

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 Kullu District of Himachal Pradesh at an elevation of about 4085 m. It flows nearly north south direction up to Larji and after taking a right turn towards west, it flows up to Pandoh dam at Pandoh after traversing a distance of about 100 km with a catchment area of about 5300 km^2 (Figure 3). Pandoh is a diversion dam constructed for inter basin transfer of maximum quantity of about 240 cumecs from Beas into Satluj river through the Beas Satluj Link (BSL), a water conductor system. It further travels about 130 km in the east-west direction up to Pong dam in Punjab with additional catchment area of about 7200 km^2. The total area of the Beas basin up to Pong dam becomes 12300 km^2. Like Satluj basin, this basin also comprises of outer, middle and greater Himalayan ranges. This basin has permanent snow bound area about 775 km^2 which lies above 5500m (BBMB, 1988).

Some of the major tributaries of Beas which join upstream of Pong dam are: Solan Nallah, Parbati river, Tirthan and Sainj rivers. Parbati river is one of the important tributaries contributing both snowmelt and rainfall runoff. All the tributaries are perennial in nature because they are fed by snow and glacier, besides significant rainfall in the lower part of the basin. Minimum discharge is observed in the river during winter season. Winter rains increase discharge for short duration. In the premonsoon period maximum snowmelt runoff feeds the river. There is substantial rainfall during monsoon season in the lower part of the basin and river discharge swells up during this period. Most of the catchemnt area comprises of steep slopes except in the Kangra valley located in the lower part of the basin. There is scope for further hydropower production on this river also.

5.0 Data

5.1 Satluj basin

To study the distribution of rainfall in the Satluj basin, daily rainfall data of 10 stations located at different elevations are used. For this basin snow distribution was also carried out using daily snowfall data of 4 stations in the greater Himalayan range. For both rain and snow, average value of 10 years was considered for the analysis. Rainfall data was available for the period from 1983/84-1992/93, whereas snow data was available for the period from 1984/85-1993/1994. However, rainfall data for one station (Rakchham), could be available only for 9 years period. Contribution of snow in total precipitation has been determined using rainfall and snowfall data belonging to the same period. The list of rainfall and snowfall observing stations with respect to orientation in the three ranges for Satluj basin is given in Appendix-I.

Mean monthly, seasonal and annual values of precipitation were computed from the daily data. Similarly mean annual rainydays and snowydays were determined and used to compute mean seasonal/annual rainfall and snowfall intensities. Data for snowfall and rainfall have been recorded separately at each station. A period from October-September is considered in terms of annual analysis so that complete snow cycle is covered. Generally snowfall starts in or after October at higher reaches in the basin.

5.2 Beas basin

Daily rainfall data of 13 stations located in different ranges of Himalayas have been used in studying the rainfall distribution of rainfall in the Beas basin. Average values of 10 years rainfall (1983/84-1992/93) of each station was considered in the analysis. Mean seasonal and annual rainfall, rainydays and rain intensity were computed as in the case of Satluj basin. Details of rainfall stations for this basin are given in Appendix-II. Snowfall data were not available for the Beas basin.

6.0 Results and Discussions

Seasonal and annual rainfall distribution has been studied for different ranges of Himalayas covered in Satluj and Beas basins. The results are presented and discussed separately for each basin.

Variation in rainfall with altitude in the Satluj basin

Outer Himalayas

To study the rainfall distribution over the outer Himalayan range of the Satluj basin data of only 5 stations were available. Further division of these stations with respect to the windward and leeward sides of the outer Himalayas provided 2 stations on the windward side and 3 stations on the leeward side. Because of availability of only 2 stations on the windward side, no trend could be ascertained. However, it was found that there is not much variation in the amount of rainfall, rainydays and rainfall intensity observed at these two stations. This is possible because of not much difference in elevation and proximity of these two rainfall stations.

The distribution of rainfall with altitude on the leeward side during all the seasons along for annual rainfall, rainydays,rainfall intensity have been shown in Figure 4. It is observed that in the postmonsoon, premonsoon and monsoon seasons rainfall linearly increases with altitude on the leeward side of the outer Himalayan range in this basin. During monsoon period orographic effect is found relatively dominant. Magnitude and trend of annual rainfall distribution is governed by the monsoon rainfall. In the winter season not much variation is noticed with altitude on the leeward side of this range. Both higher number of rainydays and high rainfall intensity are found responsible to increase rainfall with altitude in this range. The linear increase in rainfall with altitude on the leeward side of the outer Himalayan range in this basin is possible broadly because of the following two processes depending upon the movement of clouds. However, in both cases rainfall will increase with altitude.

(i) The first situation may be that clouds formed at lower elevation ascend over the mountain barrier providing higher

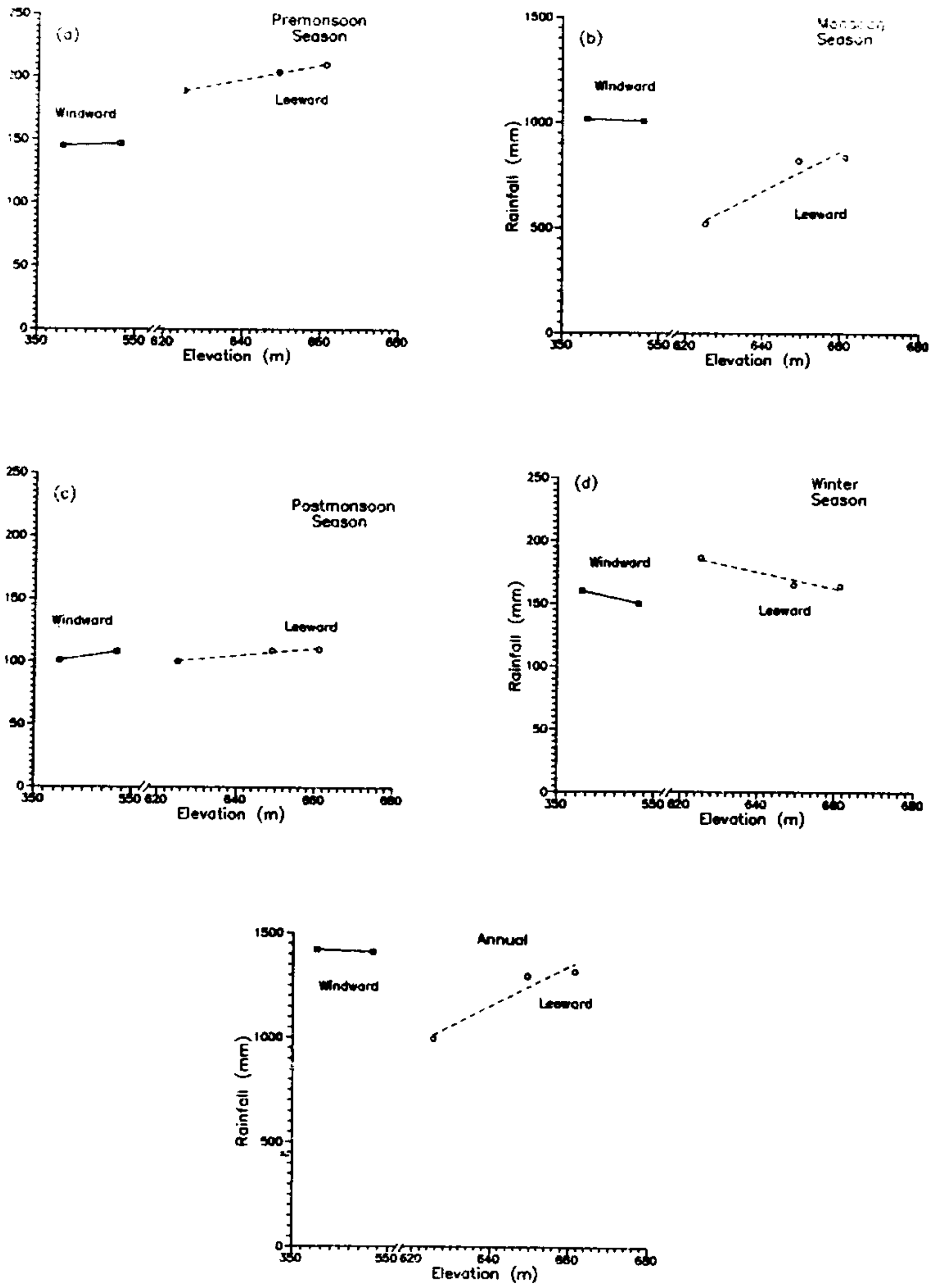


Figure 4 :Variation in rainfall with elevation in the outer Himalayan range of Satluj basin

rainfall at higher elevations because of orographic effect i.e. higher rate of condensation occurs resulting in higher rainfall at higher elevations. During postmonsoon and premonsoon seasons this situation may occur when convective storms are responsible for rainfall and clouds are formed generally to the respective side of the valley.

(ii) The other possible situation may be when clouds cross over a mountain range and reach on the leeward side of mountain. Under such conditions clouds descend from high altitude to lower elevation on this side. Sufficient moisture content along with high elevation provide a favourable situation for higher rainfall at higher elevations in such case. As clouds move down, they are left with lesser moisture content providing less amount of rainfall at lower elevations. Because of well established weather system during monsoon, this type of situations are possible. Monsoon currents carrying sufficient moisture with them approach leeward side of the outer Himalayan range after crossing the outer Himalayan range.

Middle Himalayas

The rainfall distribution in the middle Himalayan range could not be studied because data of not more than one station in this range was available. Also this range covers very less area of this basin. Average seasonal and annual rainfall and other related information for this station is given in Table 1&2.

Greater Himalayas

Rainfall data were available for four stations on the leeward side of this range while no data was available on the windward side. This has limited the analysis to only leeward side of this range. Very little rain is observed in this range of Himalayas because most of the moisture is precipitated over outer and middle Himalayan ranges. The trend of rainfall variation with altitude for different seasons in this range is shown in Figure 5. It is evident that for all the seasons rainfall decreases as altitude increases. A definable trend is noticed for postmonsoon, winter, premonsoon and annual rainfall. It is found that rainfall exponentially decreases with elevation in the postmonsoon, premonsoon seasons. The annual distribution also follows this exponentially decreasing trend with altitude. However, during winter season as such there is no rainfall above 3000 m elevation. The rainfall linearly decreases with elevation in this season. Rainfall distribution in the monsoon season has shown no specific

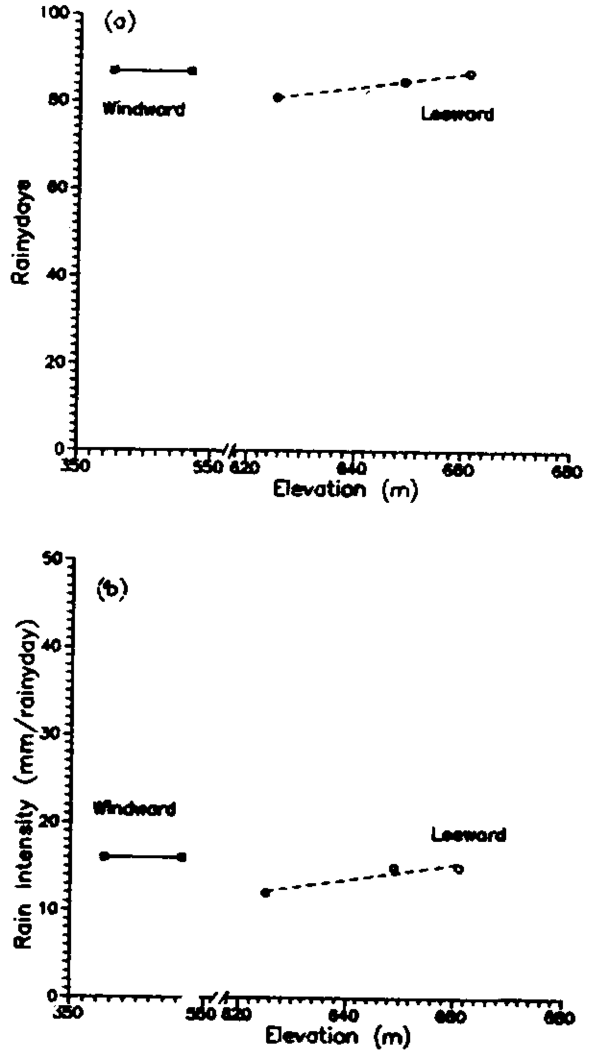


Figure 5: Variation in annual rainydays and rain intensity with elevation in the outer Himalayan range in Satluj basin

decreasing trend with altitude in this basin. It seems that rainfall at station (2910)has some peculiar reasons for low rainfall during monsoon season. One of the reason may be its farther location in a very narrow valley. Distribution of annual rainydays and rain intensity is illustrated in Figure 6 and their role in annual rainfall is described in the next section.

Contribution of Seasonal rainfall into annual rainfall

To compare average seasonal rainfall and their contribution in the annual rainfall at both sides of Himalayan ranges, an average rainfall is computed by taking average of all stations on each side of the mountains. The values of seasonal and annual rainfall and their contribution in annual rainfall is given in Table 1.It is evident that monsoon rainfall contributes maximum in the annual rainfall all over the ranges of Himalayas in the Satluj basin. The range of this contribution varies from 45%-71% in different ranges. Maximum rainfall is received in the monsoon season on the windward side of the outer Himalayas. Monsoon rainfall on the leeward side of outer Himalayas is also substantial. Minimum rainfall is experienced in the postmonsoon season in the outer and middle Himalayas whereas in the greater Himalayan range minimum rainfall is experienced in the winter season. This is true because most of the precipitation occurs in the form of snow in the greater Himalayan range during winter season. Contribution of premonsoon rainfall in annual rainfall increases from outer Himalayas to greater Himalayas and becomes significant in the annual rainfall in the greater Himalayan range.

Based on the available data,it was observed that maximum annual rainfall occurs on the windward side of the outer Himalayan range. Annual rainfall on the leeward side of the middle Himalayan range is about half of rainfall over outer Himalayan range on either side. This reduction in rainfall is caused by lesser rain intensity in the middle Himalayas because of availability of lower amount of moisture content in the clouds during monsoon season when most of the rainfall occurs. As such there is not much change in the number of rainydays over these ranges of Himalayas. Figure 7 shows that rainfall further reduces on the leeward of the greater Himalayan range due to lesser number of rainydays. The average rain intensity was found to be same on the leeward side of the middle and greater Himalayan ranges (Table 2). Highest annual rainfall, rainydays, rainfall intensity on the windward of outer Himalayas are expected because of its location with respect to the monsoon currents.

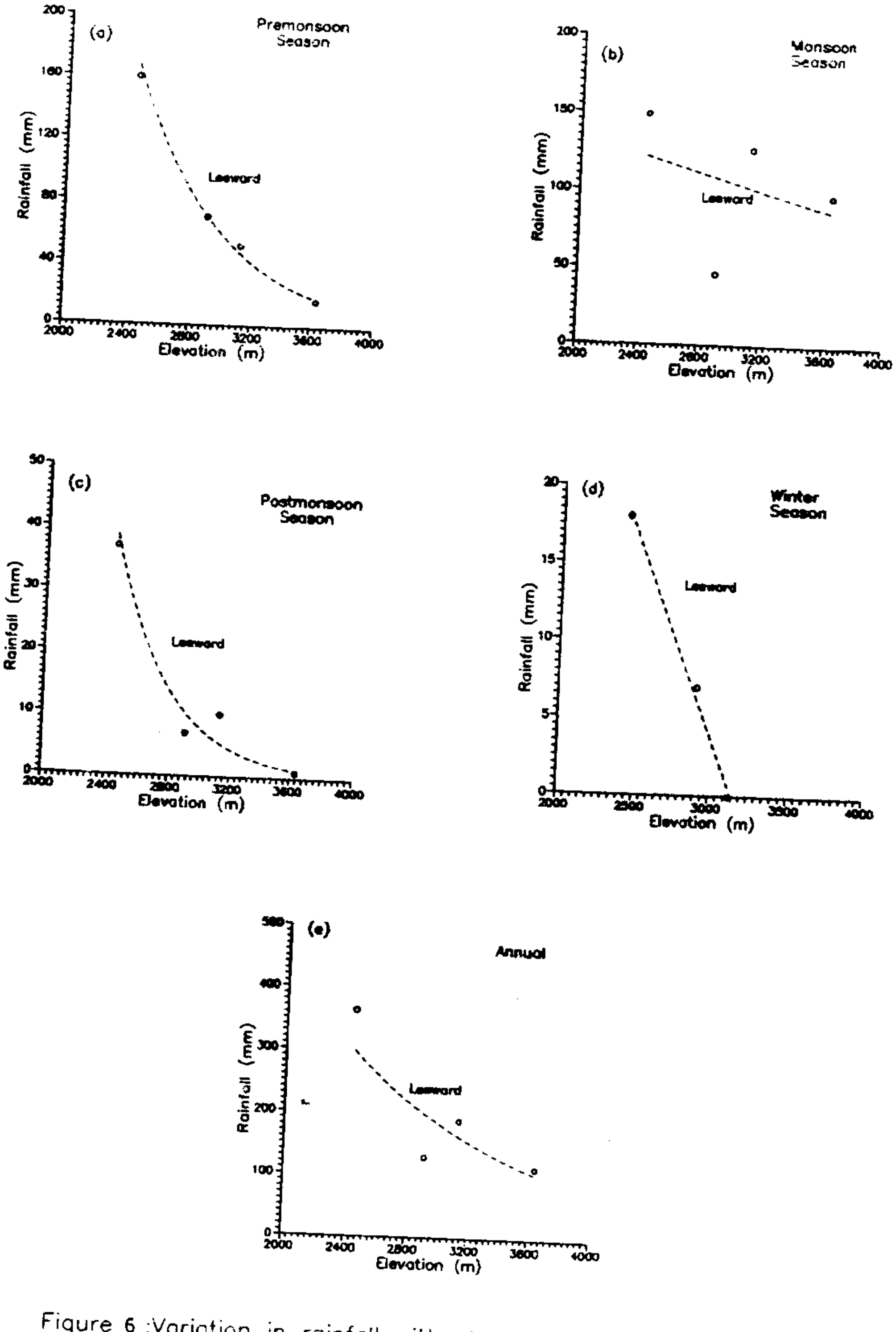
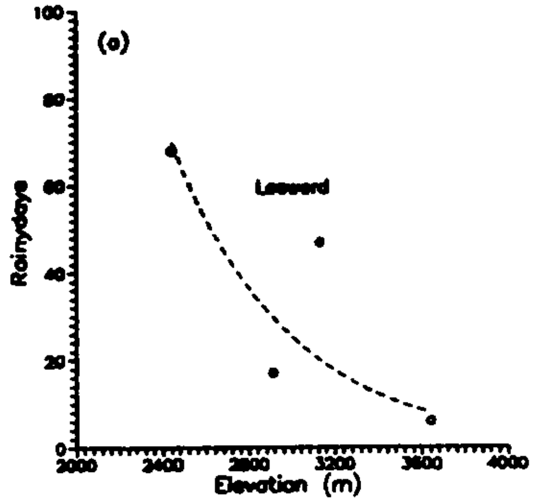


Figure 6 :Variation in rainfall with elevation in the greater Himalayan range of Satluj basin



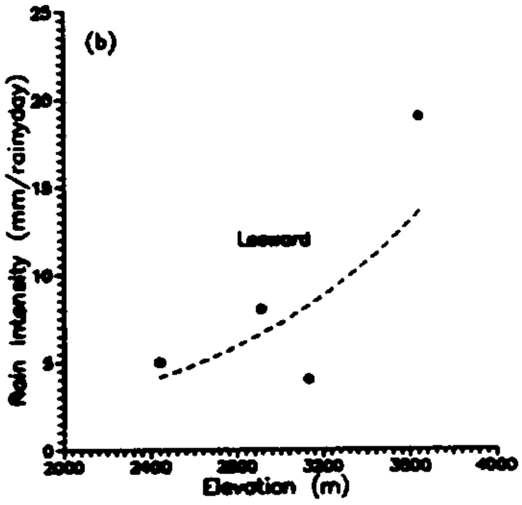


Figure 7: Variation in annual rainydays and rain intensity with elevation in the greater Himalayan range in Satluj basin

Table 1: Seasonal distribution of average rainfall in different ranges of Himalayas in the Satluj basin. The contribution of respective season in the annual rainfall is also indicated.

Range	Aspect	Rainfall (mm)				
		Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Outer Himalayas	Windward (South)	155 (10.9%)	146 (10.3%)	1010 (71.3%)	105 (7.4%)	1416
	Leeward (North)	171 (14.2%)	201 (16.7%)	725 (60.3%)	106 (8.8%)	1203
	Average	163 (12.4%)	174 (13.3%)	868 (66.2%)	106 (8.0%)	1311
Middle[+] Himalayas	Leeward (North)	209 (28.0%)	128 (17.2%)	336 (45.0%)	73 (9.8%)	746
Greater Himalayas	Leeward (North)	6 (3.0%)	75 (37.5%)	105 (52.5%)	14 (7.0%)	200

[+]based on only single station rainfall data.

Table 2 : Average annual rainydays, rainfall intensities, snowydays and snowfall intensities for different ranges of Himalayas in the Satluj basin.

Range	Aspect	Rainy days	Rainfall intensity (mm/rainyday)	Snowy days	Snowfall intensity (mm/snowday)
Outer Himalayas	Windward (South)	88	16	-	-
	Leeward (North)	84	14	-	-
	Average	86	15	-	-
Middle[+] Himalayas	Leeward (North)	87	9	-	-
Greater Himalayas	Leeward (North)	35	9		
Spiti sub-basin		-	-	22	16
Baspa sub-basin				31	15
Upper Satluj sub-basin		-	-	18	13

+ based on only single station rainfall data

Table 3 : Average annual snowfall over greater Himalayan range in the different sub-basins of Satluj basin.

Range	basin	Snowfall (mm)
greater Himalayas (Leeward)	Spiti sub-basin	380
	Baspa sub-basin	454
	Upper Satluj sub-basin	246

Variation of snow with altitude in the Satluj basin

Snow distribution with altitude has been studied for the greater Himalayan range of Satluj basin because snowfall data were not available for other ranges lying in basin. As described above that major part of the study 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 the basins are located on the leeward side of the greater Himalayan range. These basins have different orientation and relief. Therefore, snow distribution analysis has been carried out separately for each sub-basin of this region.

Spiti Sub-basin

As described above, Spiti sub-basin lies in the leeward side of the greater Himalayan range and has south-east orientation. It covers major portion of the study area and considered a most inaccessible part and various passes to Spiti such as Kanzam (4551m) and Pin Parbati (4802m) are open only for 3-4 months in a year. This basin experiences heavy snowfall and consequently a substantial runoff is derived from snowmelt from this basin through Spiti river into Satluj river. It follows north-west direction. The variation of snow water equivalent (SWE) with altitude in the Spiti is shown in Figure 8. It can be seen that it increases linearly with elevation in this basin. Snow

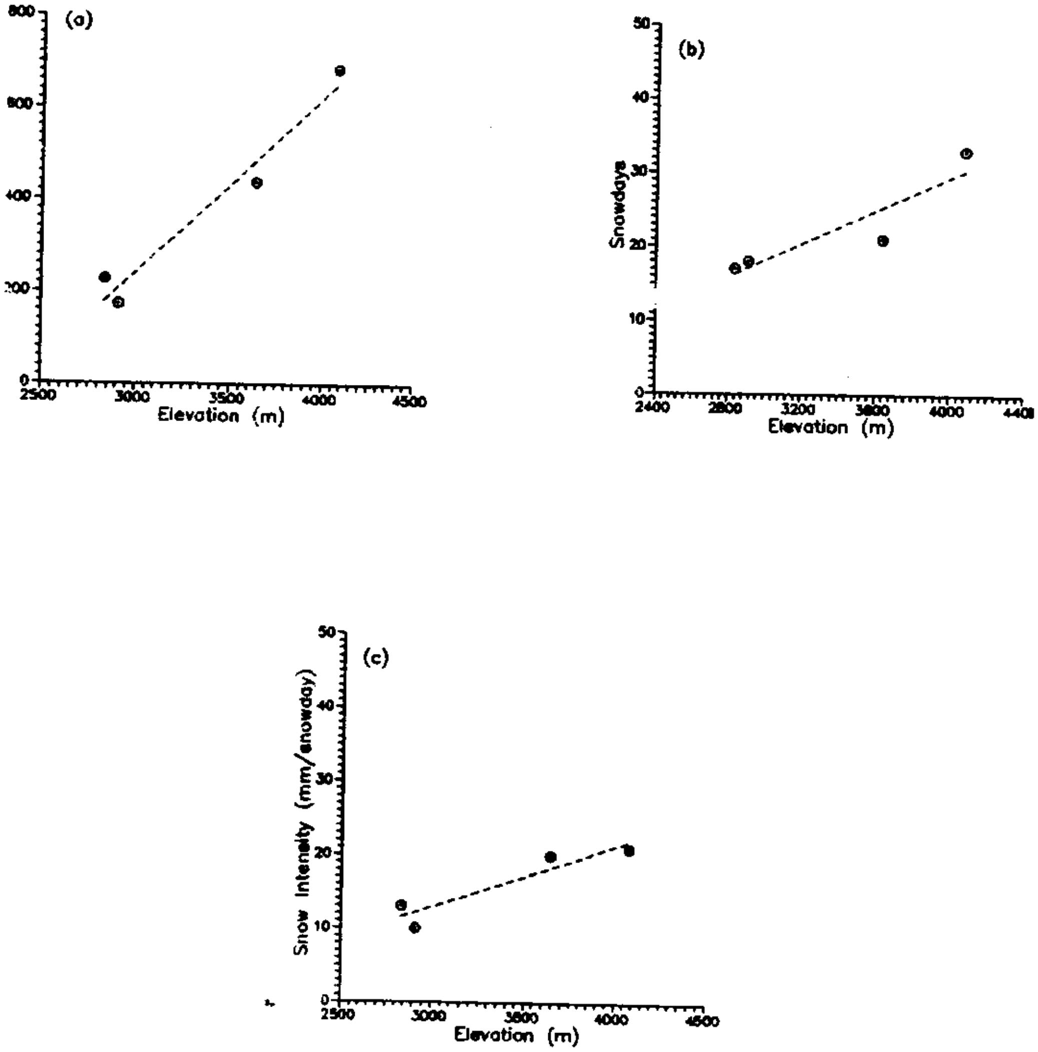


Figure 8: Variation in annual snow water equivalent, snowdays and snow intensity in the Spiti basin.

gradient is estimated to be of the order of 380 mm/km. Analysis of snowdays and snow intensity also indicates a linear trend of increase with elevation in the Spiti. Figure 8 shows that higher number snowdays and intensity both are responsible for higher amount of snow at high elevations in Spiti. Results indicate a significant variation in observed number of snowdays in comparison to the snow intensity for this basin.

Baspa sub-basin

The Baspa sub-basin is located in the south of Spiti and follows north-west orientation. The trend of snow variation with altitude in the Baspa has been found to be similar to Spiti i.e. it linearly increases with elevation (Figure 9). However, snow gradient was found to be of the order of 94 mm/km for this part of the basin which is lower than the snow gradient in the Spiti basin. The distribution of snowdays has not shown a specific trend of increase with altitude and no significant variation in snow intensity was found in this basin. However, broadly it is concluded that higher number of snowdays at high elevations contribute much to the higher amount of snow at those elevations (Figure 9b&c). Like Spiti basin, a significant variation is observed in number of snowdays in comparison to the snow intensity.

Upper Satluj sub-basin

The upper Satluj sub-basin falls in greater Himalayan range and has east-west orientation. The eastern part of this valley meets Spiti valley while western part is joined by Baspa valley. The relief of this part of the basin is lesser than the Spiti and Baspa.

The trend of the snow distribution observed in the upper Satluj sub-basin is shown in Figure 10. It is clear that distribution of snow is very much influenced by the snowfall at Kalpa (2349 m) elevation. This station experiences very heavy snowfall even though it is not at a very high altitude. The reason of heavy snowfall at this station is sudden increase in elevation which behaves as a barrier and most of the moisture is precipitated. Under this situation, this station experiences higher number of snowdays that too with higher intensity as compared with other stations in the same sub-basin (Figure 10b&c). It results in less snowfall on the other higher stations because of less moisture content in currents. A second order polynomial fitted well for the snow distribution in this sub-basin. Snowdays

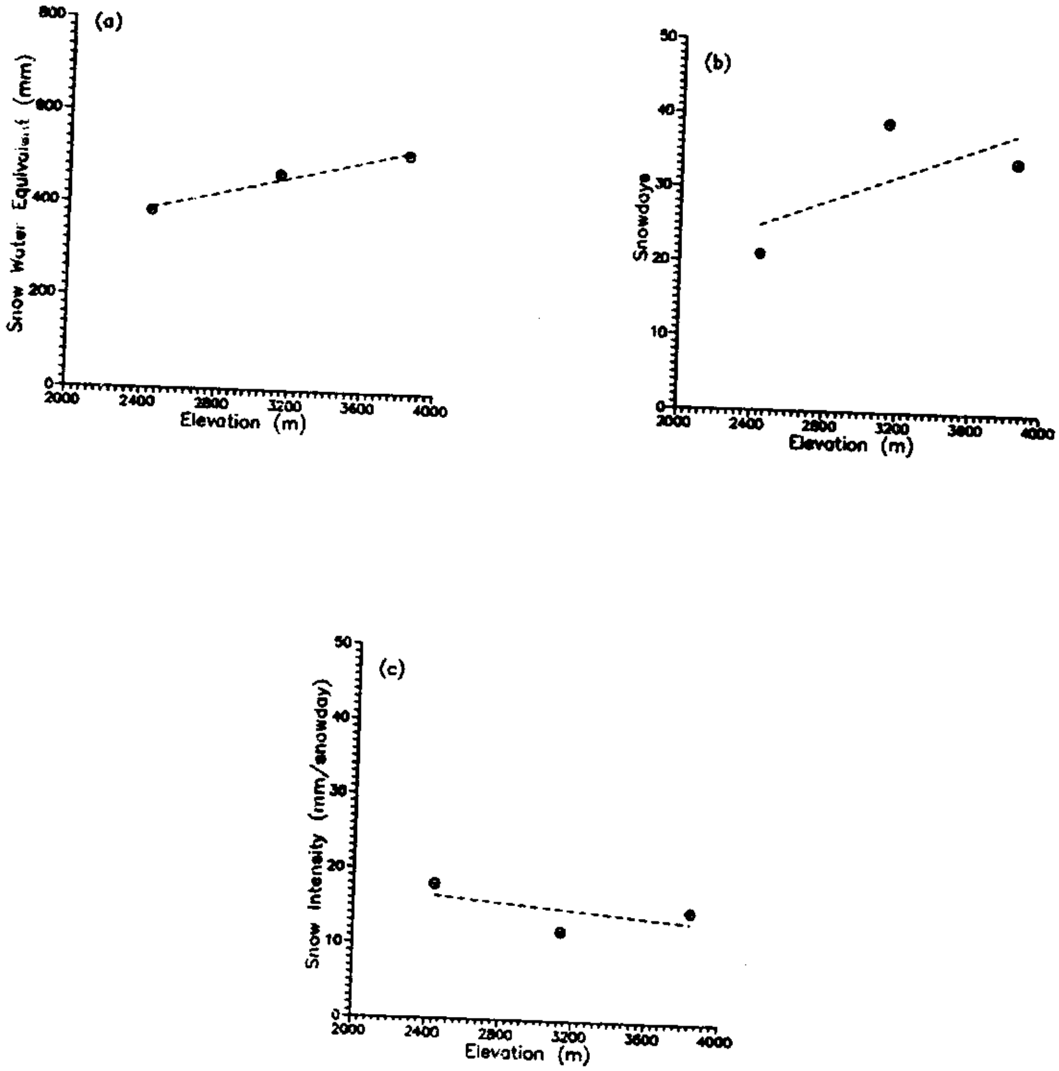


Figure 9: Variation in annual snow water equivalent, snowdays and snow intensity in the Baspa basin.

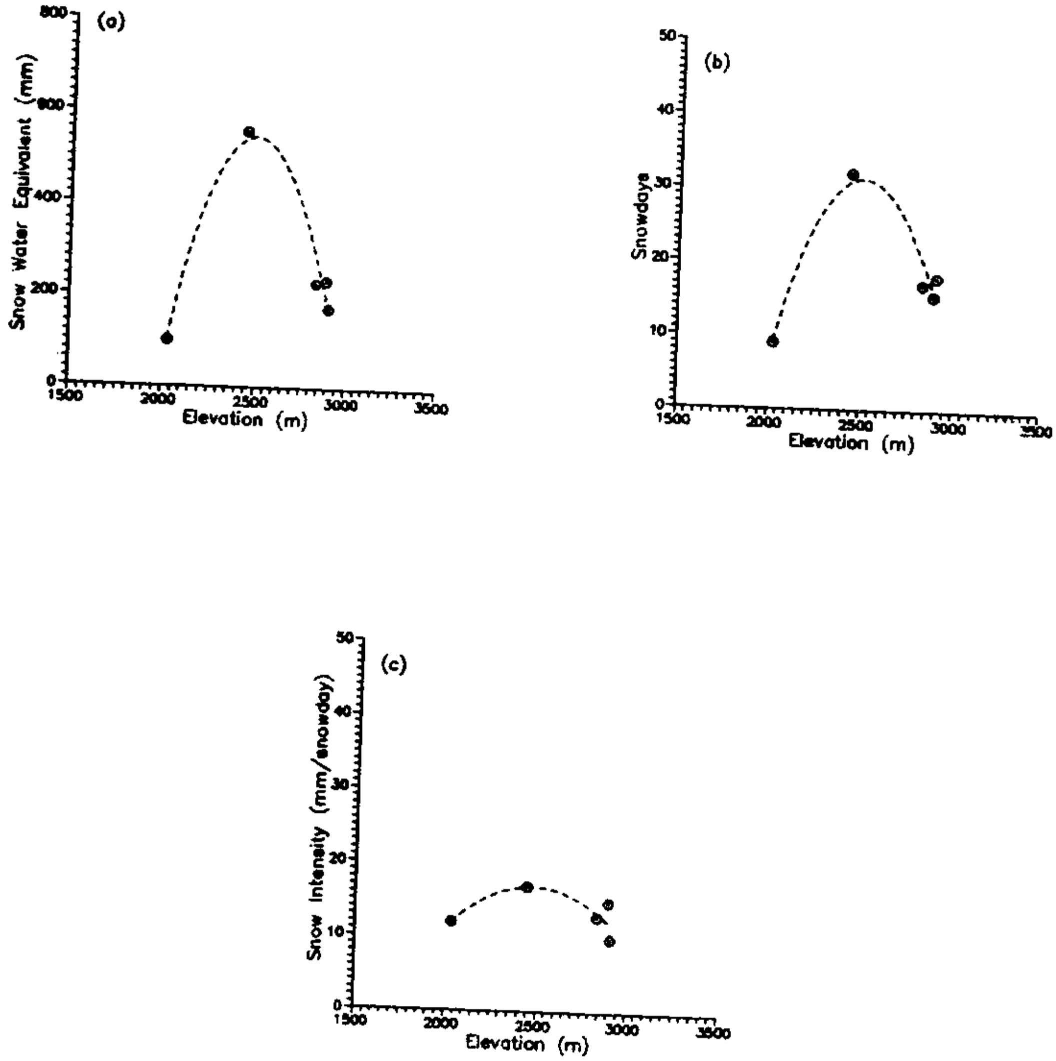


Figure 10 : Variation in annual snow water equivalent, snowdays and snow intensity in the upper Satluj basin

and snow intensity also follow the same trend in this part of the basin.

A comparison of snowfall distribution in different sub-basins

A comparison of snow distribution in the Spiti and Baspa indicates that Baspa experiences lower snow gradient in comparison to the Spiti sub-basin. This reduction in snow gradient can be explained on the basis of location and topography of the basins. The Spiti sub-basin is located in the north of the Baspa sub-basin and altitude of the greater Himalayan range lying in the Spiti basin is higher that those in the Baspa basin. The combination of higher greater Himalayan range in the Spiti and its location with respect to moisture content of western disturbances, results in greater amount of snow at high altitudes in the Spiti. By virtue of location, the western disturbances passing over the Spiti greater Himalayan range contain relatively higher moisture content in comparison to Baspa greater Himalayan range because Spiti is located in the north. The moisture content of the western disturbances decreases as they move from west to east. Thus snowfall is reduced considerable at lower elevations in Spiti basin because most of the moisture is precipitated at higher elevations of this basin resulting in higher snow gradient. Such drastic reduction in snow distribution is not observed in the Baspa basin. It is expected that due to lesser height of the greater Himalayan range in the Baspa, a significant part of the moisture is left in the airmass which is precipitated on the lower elevations on the same side. Therefore, a good snowfall is experienced at lower elevations in the Baspa. These conditions provide lower snow gradient in the Baspa in comparison to the Spiti.

Snow distribution in the upper Satluj sub-basin has shown different trend and has not been compared with Spiti and Baspa. The average values of snowfall computed from the available data for each sub-basin shows that maximum average annual snowfall is experienced in the Baspa sub-basin (Table 3). Spiti, however, receives, highest snowfall at higher reaches of the basin, but because of higher gradient in snowfall average value of snowfall is reduced over the basin. the same is applicable for snow intensity in the Spiti basin. Upper Satluj sub-basin receives lesser snowfall out of these three sub-basins. Maximum and second to maximum snow is observed in the month of March and February, respectively in all the sub-basin in the greater Himalayan range of the Satluj basin.

Snowfall Contribution in annual precipitation

Based on the rainfall and snowfall data at four stations located at different elevations in the greater Himalayas, a ratio of total annual snowfall to total annual precipitation has been worked out. This ratio is mainly dependent on the temperature and moisture available for precipitation in the region and therefore, varies with altitude. It is very well known that temperature decreases as the elevation increases and during winter moisture is carried by western disturbances which precipitates in the form of snow. It results in an increase in contribution of snowfall in the annual precipitation. The trend of increase of this ratio with elevation has been illustrated in Figure 11. It is found that ratio of snowfall to the annual precipitation varies linearly with altitude. All the stations recorded more than 60% snow contribution in the annual precipitation. The elevation where all the precipitation falls in the form of solid precipitation could not be determined because rainfall and snowfall data beyond 3639 m were not available. However, based on extrapolation of this linear relationship one can expect that above 6000 m elevation, whatever precipitation occurs may be falling as snow only.

Beas Basin

The rainfall distribution with altitude could be studied only for the leeward side of outer Himalayas, windward and leeward sides of middle Himalayas, because rainfall data were available only for these ranges of Himalayas. Snow distribution also could not be carried out for this because of non- availability of snow data. Results of the rainfall distribution are presented and discussed below.

Variation of rainfall with altitude in the Beas basin

Outer Himalayas

Rainfall distribution over the leeward side of the Outer Himalayas for the Beas basin is illustrated in Figure 12. Results show that for all the seasons rainfall increases linearly with elevation on this side. Same trend is followed by the annual rainfall also. It is seen from Figure 13 that annual rainydays and rain intensity do not follow the trend of rainfall on the leeward side of outer Himalayas. The second order polynomial fitted well for rainydays and rain intensity distribution. Figure

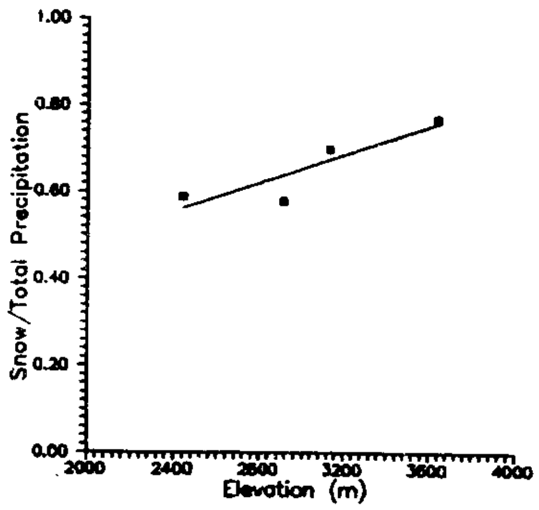


Figure 11: Variation in snow contribution to total precipitation with altitude in the greater Himalayan range of the Satluj basin

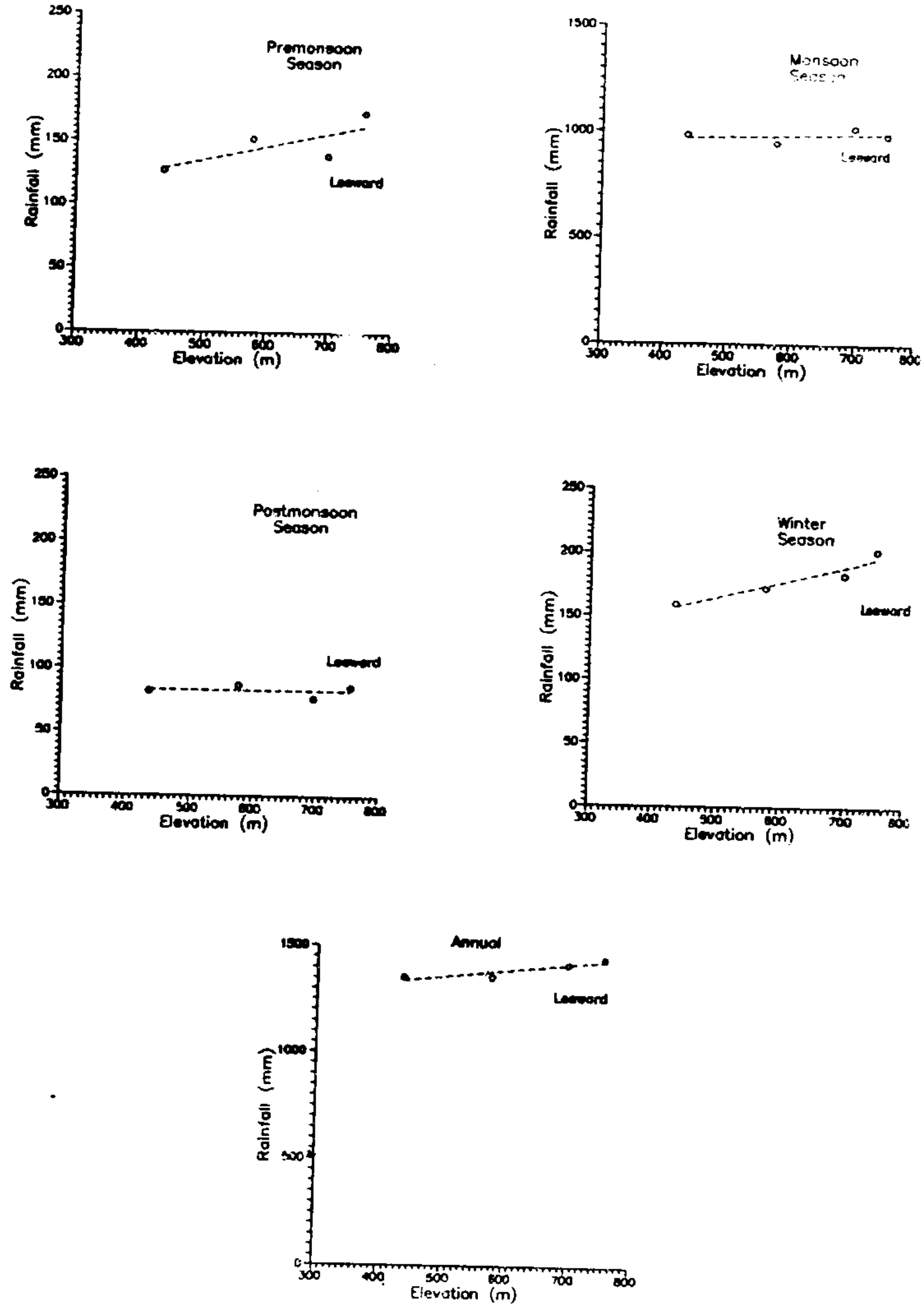


Figure 12 :Variation in rainfall with elevation in the outer Himalayan range of Beas basin

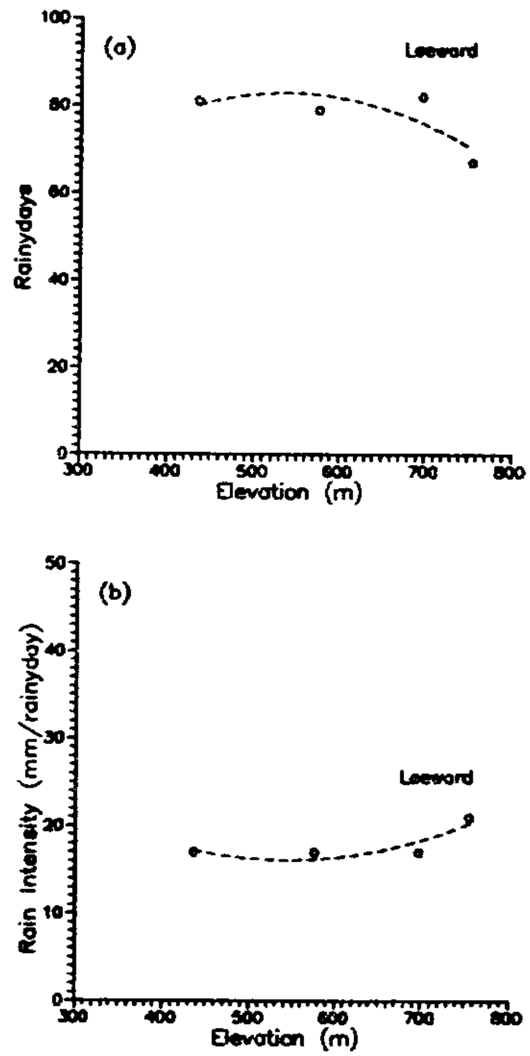


Figure 13: Variation in annual rainydays and rain intensity with elevation in the outer Himalayan range in Beas basin

13 makes clear that higher rainfall at higher elevations on this side is because of higher intensity of rain.

Middle Himalayas

Rainfall distribution with altitude for middle Himalayan range of Beas basin has been carried out for both windward and leeward sides. Relatively a better network is available for this part of the basin. A very wide valley known as 'Kangra valley' exists between outer Himalayan range and middle Himalayan range of this basin and plays a significant role in rainfall distribution. The sudden rise in relief, from 900m in the valley to over 3700 m in the middle Himalayas (Singh, 1989), gives a significant effect of orography on precipitation on the windward side of middle Himalayan range of this basin. It results in heavy rainfall at all the stations on this side. Based on the present analysis of 10 years rainfall data, it is seen that on average Dharamshala experiences exceptional heavy rainfall (1972 mm) during monsoon season due to the effect of orography. It is worth to mention that heavy rainfall, flat and fertile land area leads to vital role of Kangra valley in the production of food grains in the Himachal Pradesh.

The trend of rainfall variation with altitude on windward and leeward sides is shown in Figure 14. It can be seen that over this range, a second order polynomial is well fitted to explain the behaviour of rainfall variation for all the seasons on both sides. Annual rainfall also follows similar distribution. Rainfall increases with elevation up to a certain altitude and thereafter decreases. The lower rainfall beyond the elevation of maximum rainfall can be explained by the availability of lower moisture content in the clouds after a certain height. Once the clouds have precipitated on the side of mountain producing maximum rainfall, they are still forced to rise along the slope of mountains barrier. Because of availability of lower moisture content within the clouds at this stage, rainfall is significantly reduced. Broadly it is understood that higher number of rainydays and high rain intensity contribute to increase rainfall on the windward side, whereas higher intensity contribute much to increase rainfall on the leeward side of middle Himalayan range of Beas basin (Figure 15 & Table 5).

In all the cases maximum rainfall is occurring between 1200 and 1400 m elevation on the windward side of middle Himalayan range and it has the maximum rainfall magnitude when compared with

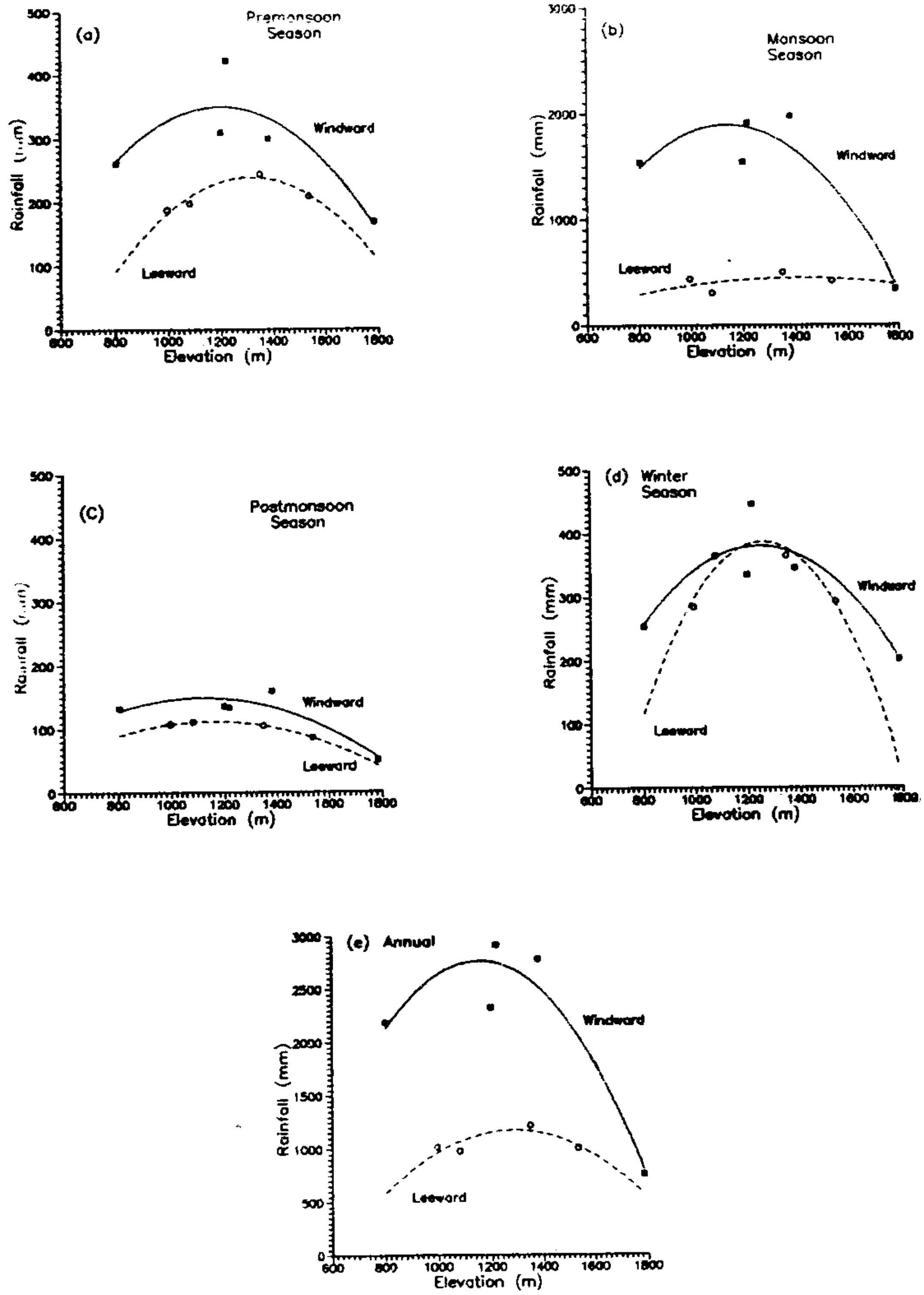


Figure 14 :Variation in rainfall with elevation in the middle Himalayan range of Beas basin

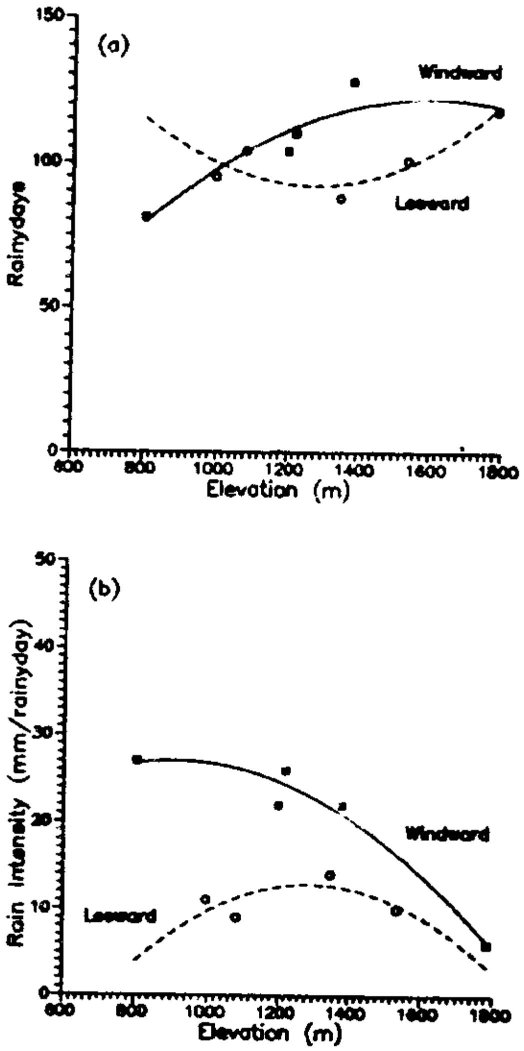


Figure15:Variation in annual rainydays and rain intensity with elevation in the middle Himalayan range in Beas basin

other range of this basin. It is interesting to note that maximum rainfall on the leeward side also has maxima at about same elevation range as on the windward side. Moreover, it is evident that once maxima of rainfall is produced on either side of mountain, it reduces significantly after that event.

Variability in rainfall on the windward side is found relatively more in the winter, premonsoon and postmonsoon seasons than monsoon season. Different cloud formation mechanism in the different seasons may be responsible for it. A well established continuous weather system in the monsoon season could have reduced variability significantly. Variability on leeward side is always less than on windward slopes.

Contribution of Seasonal rainfall into annual rainfall

The contribution of seasonal rainfall in annual rainfall has been worked out for outer and middle Himalayas of the Beas basin. As expected, it is found that monsoon rainfall contribute maximum and post monsoon rainfall contribute minimum in the annual rainfall over both outer and middle Himalayan range of this basin (Table 4). The contribution of premonsoon and winter season rainfall in annual rainfall is found to be about equal on the leeward side of the outer Himalaya and windward side of the middle Himalayas. The role of winter rainfall becomes significant in the annual rainfall on the leeward side of the middle Himalayas,.

A comparison of magnitude of rainfall on the windward and leeward side could be made only for the middle Himalayan range because rainfall data for both sides were available only for this range. Higher magnitude of rainfall is observed on the windward side during premonsoon and monsoon seasons. Particularly, a significant variation in the magnitude of rainfall is found in the monsoon season on both sides which is reflected in the annual rainfall also. There is not much variation in average rainfall in the winter and post monsoon seasons on both sides. In the monsoon, moist airmass first strike the windward side and gives significant amount of rainfall on this side due to elevation of relief barrier and availability of moisture content. In the premonsoon season higher convective activity is expected on windward side (south slope) because south slope receives more solar radiation in comparison to the leeward (north slope) which can provide higher rainfall on the windward side.

Table 4: Seasonal distribution of average rainfall in different ranges of Himalayas in the Beas basin. The contribution of respective season in the annual rainfall is also indicated.

Range	Aspect	Rainfall (mm)				
		Winter	pre-monsoon	monsoon	post-monsoon	Annual
Outer Himalayas	Leeward (North)	179 (12.8%)	148 (10.6%)	985 (70.6%)	83 (5.9%)	1395
Middle Himalayas	Windward (South)	317 (14.5%)	292 (13.3%)	1459 (66.6%)	122 (5.6%)	2190
	Leeward (North)	327 (31.1%)	210 (19.9%)	413 (39.2%)	102 (9.7)	1052

Table 5 : Average annual rainydays and rainfall intensities for different ranges of Himalayas in the Beas basin.

Range	Aspect	Rainydays	Rain Intensity (mm/rainyday)
Outer Himalayas	Leeward (North)	77	18
Middle Himalayas	Windward (South)	108	21
	Leeward (North)	97	11

Comparison of rainfall characteristics for the Satluj and Beas basins

Comparison of rainfall characteristics in Satluj and Beas could be made only for the leeward side of the outer Himalayan ranges. It was noticed that average annual rainfall on the leeward side of the outer Himalayan range of Satluj (1203 mm) and Beas (1395mm) basins indicated that slightly higher rainfall is observed in the Beas basin. It was noted that this difference is caused mainly by variation of rainfall in the monsoon season (for Satluj 725 mm; Beas 985 mm). It may be because of lower elevation of outer Himalayan range in the Beas basin which helps in crossing the monsoon winds resulting in higher moisture content on the leeward side. It is evident that in the Beas basin maximum rainfall is observed in the middle Himalayan range whereas in the Satluj basin it is in the outer Himalayan range.

7.0 Conclusions

Knowledge of rainfall distribution with elevation is considered as one of the important requirement for the simulation of runoff from a basin and to prepare the precipitation maps of the basin/region. The purpose of the study was to determine

Beas basins reveals a distinct pattern of rainfall distribution for the outer, middle and greater Himalayan ranges. Snow distribution with altitude has been studied for the greater Himalayan range of Satluj basin because snowfall data were available only for this range. Snow distribution in the greater Himalayan range of Satluj basin was studied sub-basin wise because snowfall data are recorded at number of stations. Conclusions drawn from the present study are as follows:

Rainfall Distribution

1. The rainfall distribution with altitude on the leeward side of outer Himalayas has shown that for all the seasons rainfall increases linearly with elevation for both Satluj and Beas basins. based on limited rainfall data on the windward side of the outer Himalayas in the Satluj basin, it was observed that rainfall on the windward side is higher than that of on the leeward side. Both higher number of rainydays and high rainfall intensity are found responsible to increase rainfall with altitude in the outer Himalayan range in the Satluj basin. However, in the Beas basin rainfall intensity is observed to play important role in increasing rainfall with elevation.

2. A sudden rise in altitude of middle Himalayan range after Kangra valley behaved as a giant mountain barrier and increased rainfall very significantly on the windward side of this range. On average Dharamshala experiences exceptional heavy rainfall (1972 mm) during monsoon season due to the effect of orography. It is shown that rainfall first increases with elevation and decreases after a certain elevation. Second order polynomial fitted well to rainfall distribution for the seasons on both sides in this range. Annual rainfall also follows similar distribution. Broadly it is found that higher number of rainydays and high rain intensity contribute to increase rainfall on the windward side, whereas higher intensity contribute much to increase rainfall on the leeward side.

3. It is observed that in all the cases maximum rainfall occurred between 1200 and 1400 m elevation on both windward and leeward sides of middle Himalayan range of Beas basin.Rainfall data of only one station was available in the middle Himalayan range of Satluj basin, and, no study of distribution was carried out for middle Himalayan range of this basin.

4. Rainfall analysis of the greater Himalayan range has revealed that little rain is observed in this range.It is possible because

most of the moisture of monsoon currents (which contributes maximum in annual rainfall), is precipitated over outer and middle Himalayan ranges. Rainfall variation with altitude has shown that it exponentially decreases with elevation in the postmonsoon, premonsoon seasons. The annual distribution also followed this exponentially decreasing trend with altitude. Rainfall distribution in the monsoon season has shown no specific decreasing trend with altitude in this basin. The winter season rainfall decreases linearly with elevation in this range as such there negligible rainfall observed above 3000 m elevation. The reduction in rainfall at higher elevation was found to be caused by lesser number of rainydays at those elevations in this range.

5. It was observed that orographic effect on rainfall has led to maximum rainfall in middle Himalayan range in the Beas basin and in the outer Himalayan range in the Satluj basin. Average annual rainfall decreases considerably from outer Himalayan range to middle Himalayan range in the Satluj basin while reverse is found true for the Beas basin.Typical topography (sudden increase in elevation of middle Himalayan range) of the Beas basin is responsible for higher rainfall in the Beas basin as compared to the outer Himalayan range of the same basin. Annual rainfall is further drastically reduced in the greater Himalayan range in the Satluj basin and same is expected for this range of Beas basin. Contribution of seasonal rainfall to annual rainfall has shown that over all the ranges of Himalayas in the Satluj and Beas basins, monsoon rainfall contributed maximum to the annual rainfall. Which is 45%-71% in the Satluj basin and 39%-71% in the Beas basin. Minimum rainfall is experienced in the postmonsoon season in the outer and middle Himalayas because of less moisture content availability in this season. In the greater Himalayan range minimum rainfall is experienced in the winter season in the Satluj basin because most of the precipitation falls in the form of snow over this range. Contribution of premonsoon rainfall in annual rainfall increases from outer Himalayas to greater Himalayas and becomes significant in the annual rainfall in the greater Himalayan range. Contribution of winter rainfall is also found significant in the middle Himalayan range for both basins.

Snow Distribution

6. It is observed that snow increases linearly with elevation in the Spiti and Baspa basins, whereas for the upper Satluj sub-basin it first increases and then decreases. Maximum and second to maximum snow is observed in the month of March and February, respectively in all the valleys in the greater Himalayan range of

the Satluj basin.

7. Based on the rainfall and snowfall data at four stations located at different elevations in the greater Himalayas, a ratio of total annual snowfall to total annual precipitation has been worked out. It is found that ratio of snowfall to the annual precipitation varies linearly with altitude. All the stations recorded more than 60% snow contribution in the annual precipitation. An extrapolation of this linear relationship indicates that above 6000 m elevation, whatever precipitation occurs may be falling as snow only.

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References

Barry, G.B. (1992) Mountain Weather & Climate, 2nd Edition, Routledge, New York.

Bergeron, T. (1960) Preliminary results of Project Pluvius, Helsinki, Int. Ass. Sci. Hydrol. Pub. No. 53, pp.226-237.

Bergeron, T. (1965) On the low level redistribution of atmospheric water caused by orography. Proc. Int. Conf. on Cloud Physics, Tokyo and Sapporo, 24th May-1st June, 1965, Rpt. 5, 96-100.

Bhakra Beas Management Board (1988) Snow hydrology studies in India with particular reference to the Satluj and Beas catchments, Proc. Workshop on Snow Hydrology,23-26 Nov. 1988, Manali, India.

Burns, J.I. (1953) Small-scale topographic effects on precipitation distribution in San Dimas experimental forest.Trans. Amer. Geophys. Un. 34, 761- 768.

Caine, N. (1975) Anelevational control of peak snowpack variability. Wat. Res. Bull. 11, 613-621.

Chaterji A K and S D Chopra (1976) Snow melt contribution in Satluj catchment, Proc. symposium on flow control with special reference to Beas and Satluj, October 15, Nangal (Punjab) India.

Dhar, O.N. and P.R. Rakhecha (1981) The effect of elevation on monsoon rainfall distribution in the Central Himalayas, Proc. International Symposium on Monsoon Dynamics, Cambridge University Press, pp.253-260.

Duckstein, L. ,M. M. Fogel and J.L. Thames (1972) Elevation effects on rainfall: A stochastic model, Journal of Hydrology, Vol.18, pp.21-35.

Engman, E.T. and D.M. Hershfield (1969) Precipitation climatology of the Sleepers river watershed near Danville, Vermount Paper ARS 41-148, USDA, Agr. Res.

Fitzharris, B.B. (1975) Snow accumulation and deposition on awest coast mid latitude mountain. Ph.D. Thesis, Dept.of Geography, University of British Columbia, Canada.

Golding, D.L. (1968) Snow measurement in Marmot basin. Proc. National Workshop Seminar on Snow Hydrology, Fredericton, N.B., February, 1968.

Hamon, W.R. (1971) Reynolds Creek, Idaho Agr. Res. Precipitation Facilities and Related Studies, USDA ARS pp.41-176.

Hanson, C.L. (1982) Distribution and stochastic generation of annual and monthly precipitation on mountainous water shed in southwest Idaho. Water Resour. Bull. 18, 875-883.

Hendrick, R. L., R.J. DeAngelis and S.L. Dingman (1978) The Role of elevation in determining spatial distribution of precipitation, snow and water input at Mt Mansfield, Vermount, Proc. Workshop on Modelling of Snowcover and Runoff, US Army Cold Region Research and Engineering Lab.

Higuchi K., Y. Ageta, T. Yasunari and J. Inoue (1982) Characteristics of precipitation during monsoon season in high mountain areas of the Nepal Himalayas, Hydrological Aspects of Alpine and High Mountain Areas, IAHS Publication No. 138, pp.21-30.

Hill, S.A. (1881) The meteorology of North-West Himalaya, Ind. Met. Mem. I(VI), 377-429.

Howell, W.E. (1949). On the climatic description of physiographic regions, Annals of the Ass. Am. Geog. Vol.39,1, pp.13.

Kanestorm, I. (1987) Distribution of Heavy precipitation in Northern Norway and effect of orography, Proc. Nordic Symposium on Climatological Extremes in the Mountains, Dept. of Physical Geography, Uppsala University, Rapport Nr 65, pp.53-67.

Linsley, R.K., Kholer, M.A. and J.R.H.Paulhas (1949) Applied Hydrology, McGraw-Hill, New York.

Loijens, H.S. (1972) Snow distribution in an alpine watershed of the Rocky Mountains, Canada, Proc. WMO Symposium on Distribution of Precipitation in Mountainous Areas, Vol.II,175-183, 31st July -5th Aug., Geilo, Norway.

Loukas, A. and M. C. Quick (1993) Rain distribution in a mountainous watershed, Nordic Hydrology, 24, pp.225-242.

Martinec, J. (1987) Importance and effects of seasonal snow cover, In B.E. Goodison, R.G. Barry, and J. Dozier (eds.), Large Scale Effects of Seasonal Snow Cover, IAHS Publ. No. 166, Wallingford, UK, 107-120.

Murphy, T.D.and S. Schamach (1966) Mountain versus sea level rainfall measurements during storm at Juneau Alaska, Journal of Hydrology, Vol.4, pp.12-20.

Niemczynowicz, J. (1989) Altitude effect on summer precipitation measured in Swedish mountains, Proc. Seventh Northern Research Basins Symposium, May 25-Junl 1, Llulissat, Greenland.

Obedkoff, W.(1970) A study of the grid square method for estimating mean annual runoff, M.A.Sc. Thesis,University of British Columbia, Canada.

Ohmura, A. (1991) New precipitation and accumulation maps for Greenland, J. Glacio., Vol.37, pp.140-148.

Peck, E.L. and M.J.Brown (1962) An approach to the development of isohyetal maps for mountainous areas, J. Geophys.Res. Vol.67, pp.681-694.

Rao Mohan N. (1983) Some observations on seasonal snow cover, Proc. First National Symposium on Seasonal Snow cover,28-30 April, SASE, Manali, Vol.I.,pp65-78.

Rhea, J.O. and L.O. Grant (1974) Topographic influences on snowfall patterns in mountainous terrain, In Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 182-192 ,Washington,D.C., National Academy of Science.

Rumley,G.B. (1965) An investigation of the distribution of rainfall with elevation for selected stations in Ecuador, M.S. Thesis, Texas A&M University, USA.

Salter, M.de.C.S. (1918) The relation of rainfall to configuration, British Rainfall, 1918, 40-56.

Schermerhorn V.P. (1967) Topography and annual precipitation, Water Resources Research, Vol.3, pp.707-711.

Singh, Pratap, K S Ramasastri and Naresh Kumar (1994) Study on snow distribution in Chenab basin, International Symposium on Snow and Its Manifestations, 26-28 sept, 1994, SASE, Manali (India).

Singh, Pratap, K S Ramasastri and Naresh Kumar (1995) Topographical influence on precipitation distribution in different ranges of western Himalayas, Nordic Hydrology (in press).

Singh, R L (1989) India- A Regional Geography, UBS Publishers Distributors Ltd., New Delhi.

Solomon, S.I., J.P. Denouvillies, E.J. Chart, J.A. Woolley and C. Cadou. (1968) The use of a square grid system for computer estimation of precipitation, Trans. Am. Geophys. Un. pp.285-290.

Spreen, W.C. (1947) Determination of the effect of topography on precipitation, Trans. Am. Geophys. Un. 28, 285-290.

Storr, D.and H.L. Ferguson (1972) The distribution of precipitation in some mountainous Canadian watersheds, Proc. WMO Symposium on Distribution of Precipitation in Mountainous Areas, Vol.II, pp. 241-263, 31st July-5th Aug., Geilo, Norway.

Sugden, D.E. (1977) Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide ice sheetat its maximum. Arct. Alps. Res. 9, 21-47.

Thornthwaite, C.W. (1961) The measurement of climatic fluxes, Lab. Climatol. Centerton N.J., Tech. Rep.1, Contract No. 2997(00), NR 389-101.

Upadhayay D S, J N Chaudhary and K N Katyal (1983) An empirical model for prediction of snowmelt runoff in Satluj, Proc. First National Symposium on Seasonal Snowcover, 28-30 April, Vol. II, pp.76-103.

Witmer, U., P. Filliger, S. Kunz, and P. Kung (1986) Erfassung, bearbeitung and kartieren von schneedaten in der schweiz. Geogr. Bernensia G25.

Appendix-I

Rainfall and snowfall stations of Satluj basin used for analysis

Windward side (South)	Elevation (m)	Snow(S)/ rain(R)	Leeward side (North)	elevation (m)	Snow(S)/ rain(R)
(a) Outer Himalayas					
1. Nangal	400	R	3. Suni	625	R
2. Bhakra	518	R	4. Kahu	649	R
			5. Kasol	661	R
(b) Middle Himalayas					
			6. Rampur	1066	R
(c) Greater Himalayas					
			7. Kilba	2030	S
			8. Kalpa	2439	R&S
			9. Sangla	2439	S
			10. Moorang	2744	S
			11. Pooh	2835	S
			12. Giabong	2896	S
			13. Namgia	2910	R&S
			14. Rakchham	3130	
			15. Chitkul	3841	S
			16. Kaza	3639	R&S
			17. Lossar	4079	S

Appendix-II

Rainfall stations of Beas basin used for analysis

Windward side (South)	Elevation (m)	Snow(S)/ rain(R)	Leeward side (North)	elevation (m)	Snow(S)/ rain(R)
(a) Outer Himalayas					
			1. Ghamrur	436	R
			2. Dehra Gopipur	576	R
			3. Harsur	697	R
			4. Shahpur	755	R
(b) Middle Himalayas					
5. Kangra	803	R	10. Larji	995	R
6. Palampur	1198	R	11. Bhuntar	1080	R
7. Joginder Nagar	1219	R	12. Sainj	1348	R
8. Dharmshala	1381	R	13. Banjar	1536	R
9. Janjeli	1784	R			

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