CS/AR-38/98-99

SNOW AND GLACIER CONTRIBUTION IN THE SATLUJ RIVER AT BHAKRA DAM

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Abstract

The contribution of snow and glacier melt runoff in all the Himalayan rivers originating from Himalayas is very significant. The estimation of snow and glacier melt runoff is required for water resources development of the region. In the present study, the average contribution of snow and glacier melt runoff in the annual flow of Satluj river at Bhakra dam is estimated. This study is restricted to Indian part of Satluj basin. A water balance approach was used to determine the average snow and glacier contribution in the total annual flows. The total water budget of the basin was made for a period of 10 years (Oct. 1986 - Sept. 1996). Rainfall data of 10 stations were used to compute total rainfall input to the basin over the water budget period. Total volume of flow for the same period is computed using discharge data at Bhakra reservoir. Evapotranspiration losses from the basin are taken into account only from the snow free area considering that evaporation losses from the rain falling on the snow covered area and from the snow covered area as well, are negligible. The snow covered area in the basin has been determined using satellite data. It is observed that on average about 65% area of the basin is covered with snow in the month of March/April which reduces to about 20% in the month of September/October. Average snow and glacier runoff contribution in the annual flow of Satluj river at Bhakra is estimated to be about 61%. Evidently, the majority of the streamflow into Bhakra reservoir are generated from snow melt and glacier melt. Even during the monsoon period significant amounts of snow melt and glacier melt are generated from the high altitude region in the Satluj river.

1.0 INTRODUCTION

Snow is the solid form of water and occurs as a part of nature's hydrologic cycle. Snow and glaciers are the reservoirs with vast storage of fresh water. About 80% of fresh water on our globe is locked up in the form of snow and ice. Although only 3% of this permanent snow and ice is distributed over mountains in various continents outside Polar region (Flint, 1971). This small amount is source for sustenance of major part of population of the world. Out of the mountain glaciers, central Asian mountains contain about 50% of the glacier, a large portion of which drain into the land mass of Indian sub-continent. The present estimate of the glaciated area is 14.9 million km^2 which is about 10% of the land area of the globe (IAHS, 1993).

The Himalayan mountain system is the source of one of the world's larges supplies of fresh water. All the major rivers in south Asia originate in the Himalayas. The Indus, the Ganga and the Brahmaputra which receive substantial amount of melt water from the Himalayas are considered as the life-line of the Indian sub-continent. Majority of the rivers have their upper catchments in the snow covered areas and flow through steep mountains. The perennial nature of these rivers and appropriate topographic setting provide excellent conditions for the development of hydropower resources. These rivers have substantial exploitable hydropower potential. Rainfall during the monsoon season further adds to the potential of the resources

The storage of precipitation in the form of snow and glaciers in the mountains, like Himalayas, over a long period can provide a large amount of water potentially available and also can regulate the annual distribution of the water. The release of the water from these reservoirs provides valuable natural resource in the form of rivers, streams, springs and lakes. These natural resources are not only necessary for the survival of the people living in low lying areas but also for their prosperity. It is an important source of runoff in many parts of the world. In most of the high mountainous areas snow and glaciers are considered the major source of water yield. However, hydrological studies are considered complex in the mountain environment. They become more complicated when mountains with areas covered by snow and glaciers are dealt.

An estimation of the volume of water released from the snow and glaciers, therefore, is needed for efficient management of water resources which include flood forecasting, reservoir operation, design of hydraulic structures etc. The plans for new hydroelectric projects on the Himalayan rivers in the country further emphasizes the need for reliable estimate of snow and glacier runoff. Only for two basins, namely, Chenab and Ganga, such attempts have been made. Average snow and glacier contribution in the annual flows of Chenab river at Akhnoor was estimated to be 49 %, whereas in Ganga river at Devprayag it was about 28.68% (Singh et al., 1994; Singh et al., 1997). In the present study efforts have been made to estimate contribution from snow and glaciers in the annual flows from the Indian part of Satluj river at Bhakra. The extent of maximum and minimum (permanent) snow covered areas in the study basin have been assessed using satellite data.

2.0 THE HIMALAYAS

The Himalayas are a system of huge and lofty mountain ranges bordering our country on the north and containing some of the highest peaks in the world. They 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 Himalayas further may be subdivided laterally into western, central and eastern Himalayas. The western Himalayas extend right from Nanga Parbat to Nanda Devi and are the origin of Indus and Ganga rivers. The central Himalayas stretch from Ghaghra and Gandak to Kosi river system, whereas the eastern Himalayas ranges from east of Kosi to Namcha Barua in the bend of Brahmaputra river.

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

The outer Himalayas is the southernmost range of the Himalayas and is known as Siwalik ranges also. Their average height varies from 900 to 1200 m and average width varies from 10 to 50 km. The middle Himalayas consists of higher mountains. These are a series of broken mountain ranges whose mean elevation varies from 2000 m to 3300 m . 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 Himalayas lie between the outer Himalayas and the perpetual snow covered ranges of the greater Himalayas.

The greater Himalayas are the most northern range of the Himalayas. They are lofty, rugged chain reaching high above the perpetual snowline. The average height of this range is about 6000 m. 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 Himalayas, there are continual series of somewhat lower Trans-Himalayan zone (average altitude varying between 5000 m and 6000m) adjoining the Tibetan plateau.

The present study basins, i.e., Indian part of Satluj basin up to Bhakra Dam, covers the part of outer, middle and greater Himalayas.

3.0 STUDY BASIN AND IT'S HYDROLOGICAL CHARACTERISTICS

3.1 Satluj basin

The Satluj river rises in the lakes of Mansarover and Rakastal in the Tibetan Plateau at an elevation of about 4,572 m (Figure 1) 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 snow and 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.

This large river flows through different areas which have varying climatic and topographic features. Most of the area in Tibetan plateau and some areas down stream are without rainfall and has cold desert climate. At Namgia, near Shipki, it is joined by its principal Himalayan tributary, the Spiti, just after entering India. 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 it's tributaries. In the lower part of the basin only rainfall is experienced.

The total catchment area of Satluj river up to Bhakra dam is about 56,874 km^2 of which about 22,305 km^2 lies in India including whole catchment of the Spiti basin. The elevation of the catchment varies widely from about 500 m to 7000 m, although only a very small area exists above 6000m. Mean elevation of the basin is about 3600 m. The gradient is very steep at its source and gradually reduces down stream. Owing to large differences in seasonal temperatures and great range of elevation in the catchment, the snowline is highly variable, descending to an elevation of about 2000m during winter. The permanent snowline in this part of Himalayan range is about 5400 m (BBMB, 1988). In the present study, average snow and glacier contribution in the annual flows from Indian part of Satluj basin is estimated. The main planning and work has been concentrated only in the area lying in India. The geological setting and availability of abundant water provides a huge

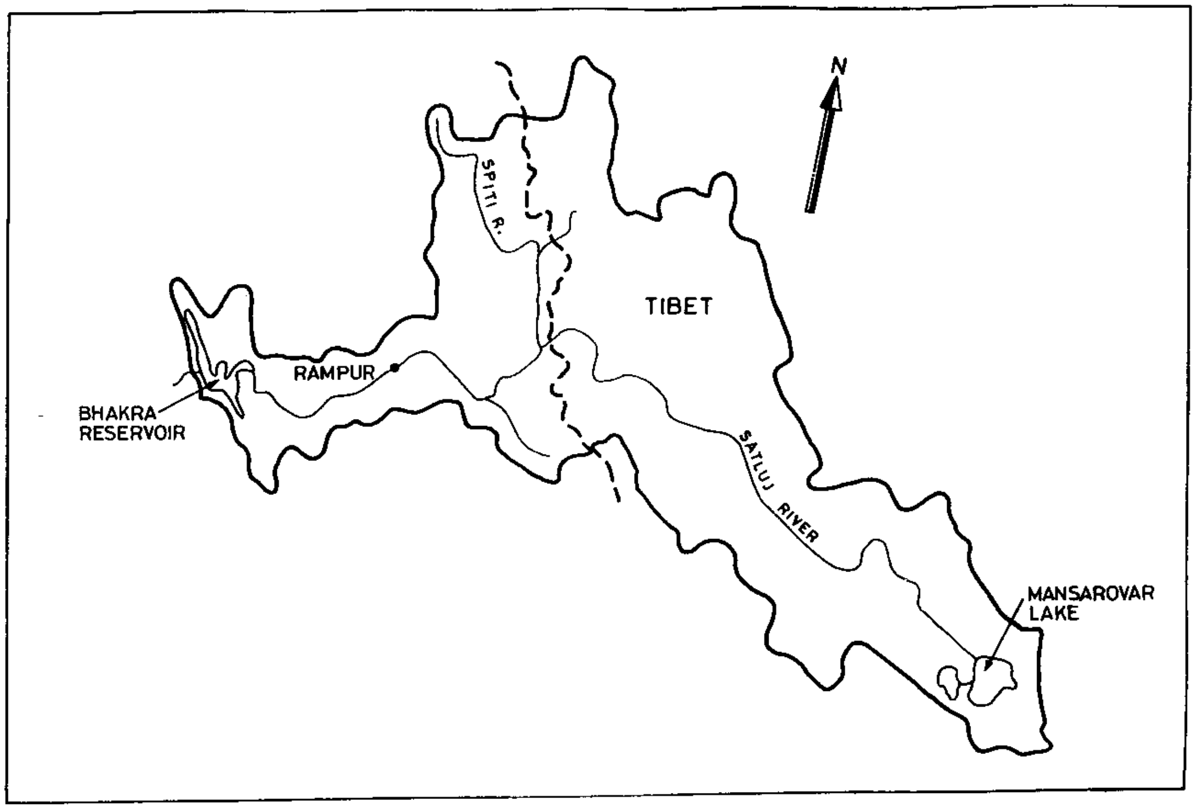

FIG.1 LOCATION MAP OF SATLUJ RIVER

hydropower generation potential in this river. Because, the hydropower potential of Satluj river is very high, therefore, several hydropower schemes are planned/coming up on this river. Upadhyay et al. (1983) reported that about 11% area of the total Satluj catchment lies under glaciers.

Indian part of the Satluj basin is elongated in shape and 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, as shown in Figure 1, is such that major part of the basin area lies in the greater Himalayas where heavy snowfall is experienced during winters. Broadly snow covered area is confined to three sub-basins namely Spiti sub-basin, Baspa sub-basin and upper Satluj sub-basin.

3.2 Seasons and weather systems in the study area

The great contrast in the geographical relief results in variety of climate in the Himalayas. Such regions are characterized by numerous small climatic differences over short horizontal distances. Principal controls producing such differences are those of altitude, local relief and mountain barrier effect. The most important factors controlling the weather and climate in the Himalayas are the altitude and aspect. Largely due to variations in altitude, the climate varies from hot and moist tropical climate in lower valleys, to cool temperate climate at about 2000 m and tends toward polar as the altitude increases beyond 2000 m. Altitude controls not only temperature but rainfall also. Usually the south facing slopes are more sunny and also get more rain. Further, in each individual range the snowline is higher on southern aspect as these slopes have more sunshine. Also, the snow line in the eastern Himalayas is higher than in the western Himalayas.

The following four seasons depending upon broad climatic conditions prevailing over the basin:

Winter season (December - March)

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. They recede to their original position which lies beyond the Himalayan mountains by the end of winter season.

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 average frequency of occurrences of these disturbances is about 3 to 5 each month which reduces as the season advances. 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 winter weather system. The precipitation associated with this weather system decreases considerably as they move eastward along the Himalaya because of increasing distance from the source of moisture. These weather systems cause snowfall at higher elevations

Premonsoon season (April - June)

Generally this seasons 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 air mass convective storms. Convection increases because of increasing trend of temperature in the Himalayan region in this season.

Monsoon season (July - September)

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 while the monsoon currents give copious rainfall over the Indian plains and lower Himalayas. At the time of 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 (October- November)

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

The presence of glacier and snowfields over an extensive area in the western Himalayas is not only a dominant feature relevant to the climate alone but is factor that significantly enters into many hydrological implications. 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 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.

3.3 Precipitation distribution in the Satluj basin

Precipitation distribution with elevation for Satluj basin has been studied by Singh and Kumar (1997). Examination of rainfall distribution in the Satluj reveals a distinct pattern of rainfall distribution for the outer, middle and greater Himalayan ranges (Table 1&2). 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. The important conclusions drawn from the recent study carried out by Singh and Kumar (1997) are as follows:

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 in Satluj basin. 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.

2. 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 and 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. Negligible rainfall is observed above 3000 m elevation. The reduction in rainfall at higher elevation

was found to be due to lesser number of rainydays at those elevations in this range.

3. It was observed that orographic effect on rainfall has led to maximum rainfall 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. Annual rainfall is further drastically reduced in the greater Himalayan range in the Satluj basin. Contribution of seasonal rainfall to annual rainfall has shown that over all the ranges of Himalayas in the Satluj basin, monsoon rainfall contributed maximum to the annual rainfall. Which is 45-71% in the Satluj 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 greater Himalayan range. Contribution of winter rainfall is also found significant in the middle Himalayan range.

4. Snowfall has shown different trends of increase with elevation in different parts of Satluj basin. For example, 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.

5. 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.

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 (Singh and Kumar, 1997).

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%)	1 416
	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

Table 2 Average annual rainydays, rainfall intensities, snowdays and snowfall intensities for different ranges of Himalayas in the Satluj basin (Singh and Kumar, 1997).

Himalayan range	Side	Rainy days	Rainfall intensity (mm/rainyday)	Snow days	Snowfall intensity (mm/snowday)
Outer	Leeward	88	16	-	-
	Windward	84	14	-	-
	Average	86	15	-	-
Middle	Leeward	87	9	-	-
Greater	Leeward	35	9		
Spiti sub-basin	-	-	-	22	16
Baspa sub-basin	-	-	-	31	15
Upper Satluj sub-basin	-	-	-	18	13

3.4 Streamflow characteristics of Satluj river at Bhakra Dam

Temporal variability in discharge is another outstanding feature of the Himalayan rivers. Broadly flow in the winter season is basically from surface flow due to seasonal rains, sub-surface flow and ground water contribution. The snow melt contribution starts from about mid of March and lasts until June/July depending upon the snowpack water equivalent accumulated in the preceding winter season and prevailing temperature in the summer season. The glacier melt runoff contribution starts from July when glaciers starts becomimg snow free. The contribution of glacier melt runoff remains till September. In the annual flows of the Satluj river a substantial contribution is provided by snow and glacier melt runoff.

In the pre-monsoon season, snowmelt and glacier melt runoff produce high flows in mid or late summer. After middle of March, snowmelt exceeds the rainfall component which leads to a significant rise in the gradient of runoff of the hydrograph. The snowmelt contribution increases continuously as the snowmelt season advances. Sometimes rainfall also contributes to the flows in this season. During monsoon season, flow is augmented by monsoon rains to produce higher discharges and occasional peak floods. In the post-monsoon season, flow is believed to be from the glaciers and occasional rain events in the basin. Generally glacier contribution starts in the month of July when snow accumulated on the glaciers in the preceding winter season is ablated and continues till September/October. Glacier melt runoff in the streams coincides with the monsoon period. Thus, glacier melt runoff from the higher reaches and high runoff from the rain in the lower and middle part of the basin occurs during July and September. Peak values of total discharge in July and August are essentially due to rainfall in the lower part of the basin. Flooding in these areas results from excessive or heavy rainfall. Sometimes combination of rainfall and excessive snowmelt also cause floods. During winter season snowmelt contribution is less than rainfall runoff because the melting conditions are not adequate.

The snowmelt contribution increases continuously as the snowmelt season advances. The are essentially due to major contribution of monsoon rains in the lower catchment. The catchment area is fed by western disturbances in the form of 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 some times extending 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.

Based on 10 years (Oct., 1986 - Sept., 1996) flow data analysis, the average quarterly distribution of the annual flow volumes from Indian part of Satluj river at Bhakra has been computed and has been given in Table 3. Higher contribution from pre-monsoon season (April-June) and monsoon season (July-September) into annual flows are because of combination of rain, and snow and glacier melt runoff.

Table 3 Average distribution of the annual flows of Satluj river at Bhakra reservoir.

S. No.	Period	Average % in annual flow In volume
1.	October – December	9.9
2.	January - March	6.9
3.	April – June	26.8
4.	July - September	56.4

4.0 DATA USED

Rainfall, evapotranspiration, flow and remote sensing data is used in this study. Rainfall data of 10 stations located in the study basin has been used to compute volume of rainfall over the basin. The total rainfall depth at each station over a period of 10 years (Oct. 1986 - Sept. 1996) is obtained by making cumulative sum of daily rainfall. Total volume of rainfall over the basin is computed using cumulative depth of rainfall. The period from October to September is chosen so that complete snow accumulation and snowmelt period may be taken into account in a year. Similarly flow volume for the same period (10 years) are calculated at the Bhakra reservoir with the help of daily flow values. Estimation of evaporation losses over the basin has been made using temperature data of Bhakra and Rampur, and pan evaporation data of Bhakra only.

To find out maximum and minimum (permanent) snow covered area, remote sensing data for the months of March/April and September/October, respectively, have been used. Landsat (MSS) (80m resolution) and IRS (LISS-I) (72.5 m resolution) data were procured from National Remote Sensing Agency (NRSA) for the study period. Landsat data have been used for a period of 2 years (1986-87) whereas IRS data was used for the remaining 5 years (1988-93). For both satellites remote sensing information of band 3/4 was used. Details of the satellite coverage of this basin are given in Table 4. It is to be noted that in total 8 years data were used in the analysis and for calculation of evaporation losses from the snow-free area. For the rest two years average value of 8 years evaporation losses were used.

Table 4 Details of satellite data used in the analysis study

Year	Dates	Satellite/Sensor	Path/row
1986	17 April	LANDSAT (MSS)	146/36
	02 May	LANDSAT (MSS)	146/36
	20 June	LANDSAT (MSS)	146/36
	31 August	LANDSAT (MSS)	146/36
1987	20 March	LANDSAT (MSS)	146/36
	30 April	LANDSAT (MSS)	146/36
	07 June	LANDSAT (MSS)	146/36
	09 July	LANDSAT (MSS)	146/36
	10 August	LANDSAT (MSS)	146/36
	11 September	LANDSAT (MSS)	146/36
1988	07 April	IRS 1 (LISS1)	29/45
	12 June	IRS 1 (LISS1)	29/45
	30 September	IRS 1 (LISS1)	29/45
1989	03 March	IRS 1 (LISS1)	29/45
	26 August	IRS 1 (LISS1)	29/45
	09 October	IRS 1 (LISS1)	29/45
1990	12 March	IRS 1 (LISS1)	29/45
	25 April	IRS 1 (LISS1)	29/45
	08 June	IRS 1 (LISS1)	29/45
	22 July	IRS 1 (LISS1)	29/45
	26 September	IRS 1 (LISS1)	29/45
1991	12 April	IRS 1 (LISS1)	29/45
	04 May	IRS 1 (LISS1)	29/45
	27 October	IRS 1 (LISS1)	29/45
1993	18 April	IRS 1 (LISS1)	29/45

5.0 METHODOLOGY : A water balance approach

The snow and glacier melt contribution has been estimated using water balance approach. Generally, because of rugged terrain and inaccessibility to the higher reaches, a poor snow gauge network is found at high altitude region of Himalayas where heavy snowfall is experienced. Therefore, assessment of snowfall over the whole basin becomes very difficult in such conditions. Whereas rain gauge network is reasonably good in few basins to estimate rainfall input to the basin. Estimated rain contribution can be used to determine the snow and glacier contribution using water balance approach. The various factors considered for this approach are described below.

In the water balance analysis cumulative volumes of rain, evapotranspiration losses and flow are used. A 10 years period as water budget period has been considered keeping several aspects in view which are described below.

(i) A period of 10 years can cover several dry and wet years and an representative average value can be worked out.

(ii) It can be assumed that all the losses from the rain and snowmelt in the form of infiltration and percolation, except evapotranspiration, will be reflected at the outlet of the basin within this period of 10 years. It is considered as a very safe assumption specially for the mountainous catchments with very high relief variation from the outlet to upper most part of the basin. In such watersheds time taken by the infiltrated and percolated water to reach outlet will be very less than in the flat watershed. As such the amount of water which is percolated very deep and not contributing at the outlet of the basin within a period considered for this study, is assumed negligible.

(iii) It can be assumed that soil moisture status of the basin is same after 10 years period. However, there may be changes on the annual basis but moisture status can be considered of same order after 10 years period.

Snow and glacier contribution in the 10 years volume of flow from the Indian part of Satluj river at Bhakra has been estimated using following water balance approach;

Snow & glacier runoff volume = Observed flow volume - (Rainfall volume - evapotranspiration)

As explained earlier it is assumed that all the losses from the rain and snowmelt in the form of infiltration and percolation will be reflected within a period of 10 years considered for this study for volume computation. Therefore, base flow is not considered separately in the above equation.

5.1 Rainfall

Rain input to the basin over a period of 10 years period (Oct. 1986- Sept., 1996) has been estimated using isohyetal technique. Accumulative isohyetal pattern of the Satluj basin up to Bhakra dam is shown in Figure 2. This method is considered more reliable for the mountainous area where topography of the basin influences the precipitation due to high relief and different orientations. Such effects can be observed from the rainfall distribution in the basin shown by the isohyets. The range of the 10 years cumulative isohyets varies from 1000 mm to 14000 mm. Such high variation in rainfall are very well taken into account by isohyetal technique when calculating mean rainfall depth over the basin.

The distribution of isohyets in the study area show that lower catchment experiences very heavy rainfall at few locations. The general trend of rainfall exhibits that lower and middle part of the basin experience good rainfall whereas upper part of the basin experiences less rainfall.

5.2 Snow covered area

The snow cover in the Himalayas occurs and exists depending on the terrain and climatic conditions of the region. This snow cover can be categorized into temporary snow cover, seasonal snow cover,

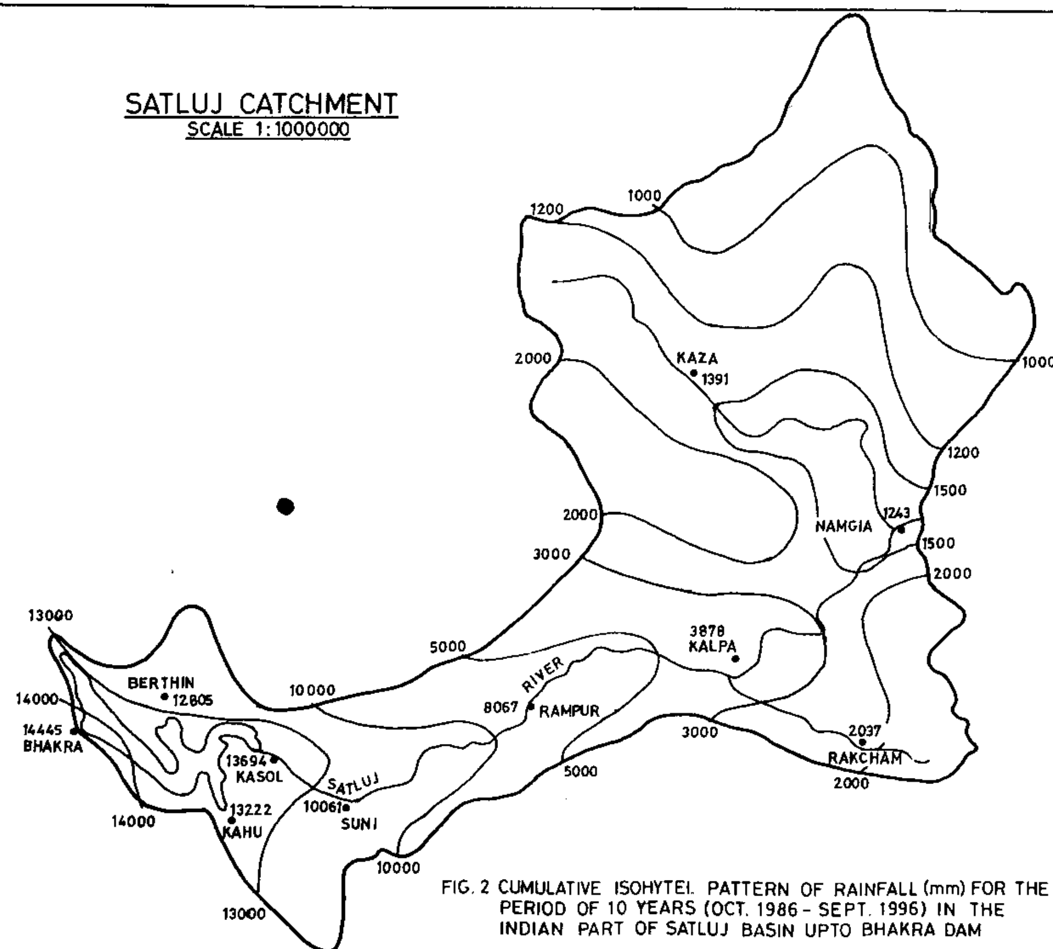

FIG. 2 CUMULATIVE ISOHYTEL PATTERN OF RAINFALL (mm) FOR THE PERIOD OF 10 YEARS (OCT. 1986 - SEPT. 1996) IN THE INDIAN PART OF SATLUJ BASIN UPTO BHAKRA DAM

permanent snowfields and glaciers. Snow cover that stays for a few days and then melts away is termed as "temporary snow cover". This usually occurs at lower altitudes during winter and even sometimes at higher altitudes during summer. Snow cover that is formed over weeks or months by consecutive snowfalls and which melts away gradually during the following summer is termed as "seasonal snow cover". Above a certain altitude and in certain situations, some amount of snow is carried over to the next winter season without melting during summer, and this turns into 'firn' and ultimately ice, adding to the permanent snowfields and glaciers. The seasonal snowpack contributes to the water resources during summer months, and therefore is very important for hydrological studies.

Snow cover serves as the vast store-house of the water for the great rivers which take their birth in the Himalayas. Conventional methods have limitations in the monitoring of snow covered area in the Himalayan basins because of inaccessibility. Conventional methods have limitations in the monitoring of snow covered area in the Himalayan basins because of inaccessibility. Satellite data is considered a very prominent means of attempting snow related studies and for snow cover mapping in particular. This technique finds increased importance and wide application for difficult terrain and inaccessible areas and is considered most suitable means of detailed survey. Also, the advantage of satellite remote sensing like multi-spectral, synoptic and repetitive coverage is ideally suited to monitor snow and deciphering meaningful information. The usual problems like location, recognition and measurement encountered in remote sensing are virtually not found when the target is snow. Snow has the unique physical property of a high albedo in the visible/near infrared portion of the spectrum. Thus, by virtue of the high reflectivity, snow is one of the objects on the surface of earth which is readily detected or identified on any visible or near IR remotely sensed image. Fresh snow has a very high reflectivity in the visible wavelengths. However, it decreases as the snow ages. The reflectivity of snow is dependent on many snow characteristics like shape and size of snow crystals, liquid water content (especially of the near surface layers), impurities in the snow, depth of snow, surface roughness etc. In addition, the solar elevation also influences the spectral reflectance to a large extent.

Since very little information on snow is collected regularly in the Himalayas, remote sensing remains the only practical way of obtaining at least some information of the snow cover in the large number of basins in the Himalayas. The availability of satellite data provides useful periodic information about extent of snow cover and thus form a base in snow covered mountains. At present the visible, near IR and thermal IR data from various satellite (LANDSAT, IRS, NOAA) are being used for mapping the areal extent of snow cover in the Himalayan basins. When Landsat MSS started to acquire data in 1972, the average resolution was 80 m. As subsequent Landsats were launched , the resolution was improved to 30 m. IRS satellites provided resolution from 72 to about 20 m. In these types of satellites, the main problem is the poor observational frequency. As a result of the frequency of observation problem, many users have turned to the NOAA polar orbiting satellite, which a has a resolution about 1 km in the 0.58 – 0.68 μm red band. The frequency of coverage is twice every 24 hours.

The duration for which the seasonal snow cover stays in the basin is variable from basin to basin and also from year to year. In the present study, LANDSAT/IRS data in the form of b/w positive, FCC and digital data was used. In this study visual interpretation technique has been applied. For two years for which digital data was available, digital processing was done. First of all a base map of the study area was prepared using toposheets from Survey of India. These base maps were overlaid on the positive prints developed from the film negatives of band ¾ and also on FCC. The registration of the maps with imageries was carried out. Because whole area of the basin was not covered in a single imagery, therefore, the data of the closest date of adjoining imagery was used to find out the snow covered area in the basin.

When mapping the snow cover there are several possible features on the imagery, which were considered in order to prevent misidentification of snow and snow free areas. For example, cloud tops exhibit a very bright reflectance in the visible/infrared bands that is often indistinguishable from snow. These aspects have been kept in view when delineating snow covered area. Small portions in snow covered area, which are under shadow (either from terrain features or clouds) have been considered as snow bound. The maps depicting snow covered areas for

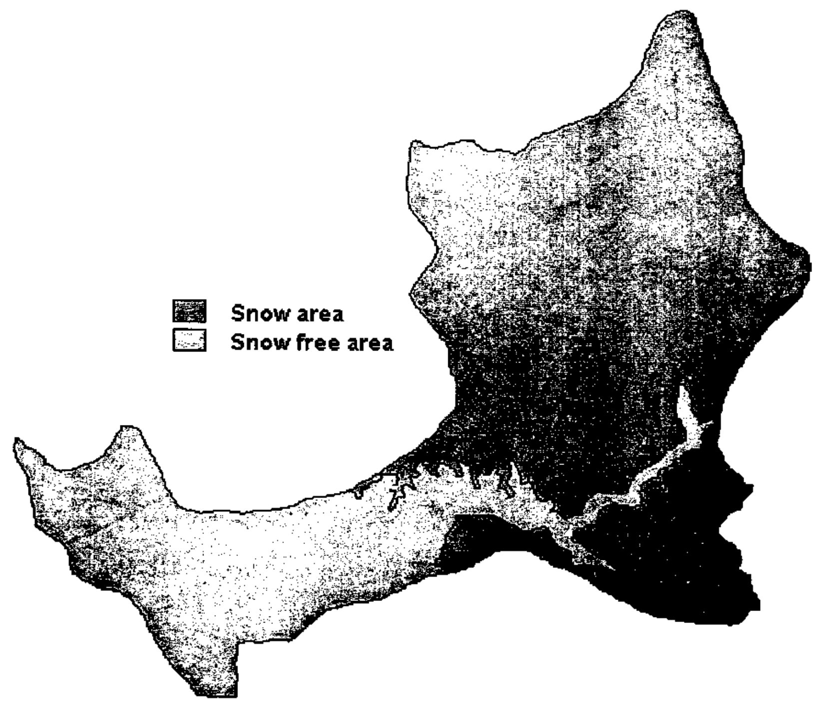

Fig.3a Snow covered area in Satluj catchment up to Bhakhra (7 April, 1988)

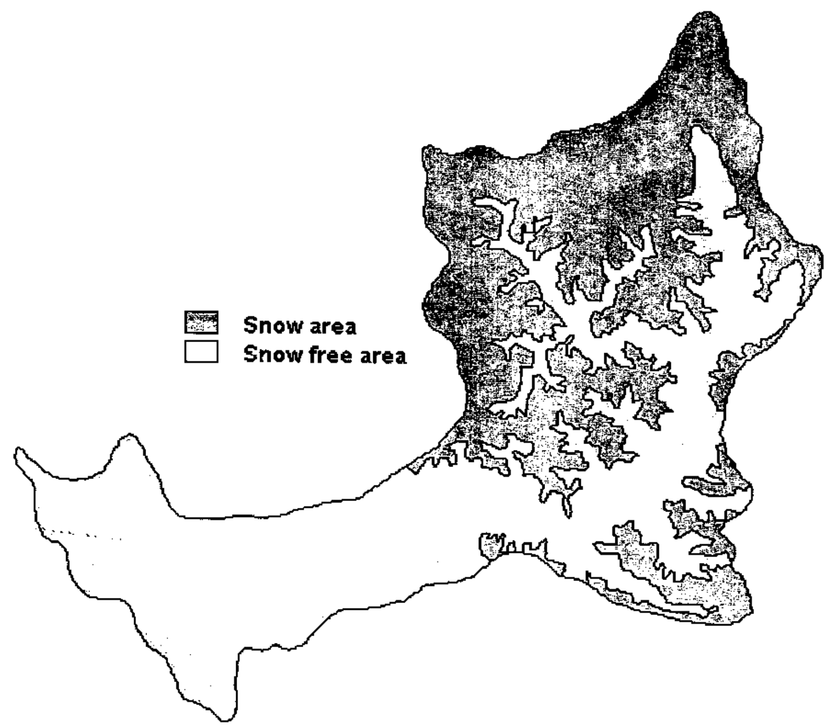

Fig. 3b: Snow covered area in Satluj catchment up to Bhakhra (30 Sep., 1988)

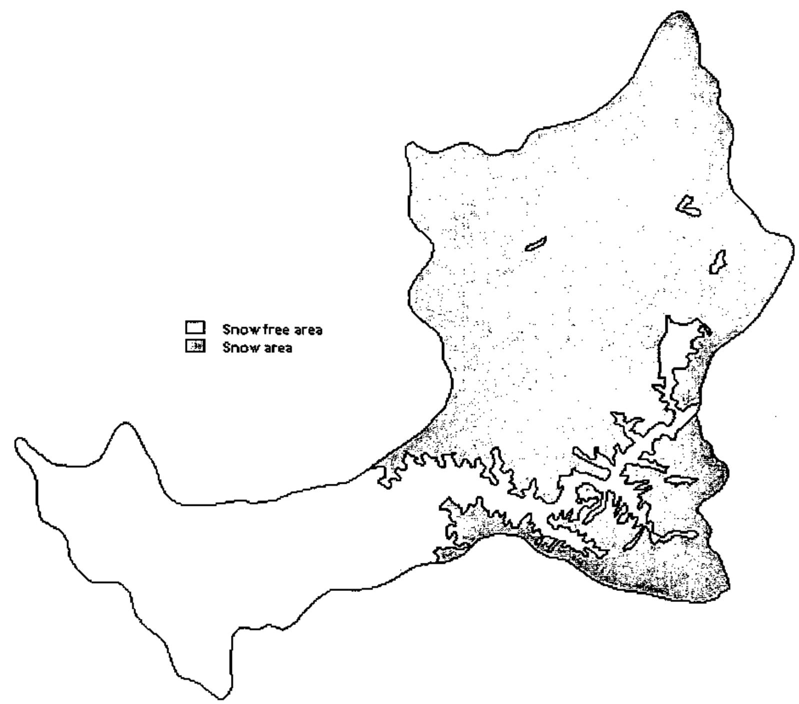

Fig. 3c: Snow covered area in Satluj catchment up to Bhakhra (3 March, 1989)

Fig.3d:Snow covered area in Satluj catchment up to Bhakhra (9 Oct., 1989)

Fig.3e:Snow covered area in Satluj catchment upto Bhakhra (12 March, 1990)

Fig.3t:Snow covered area in Satluj catchment up to Bhakhra (22 July, 1990)

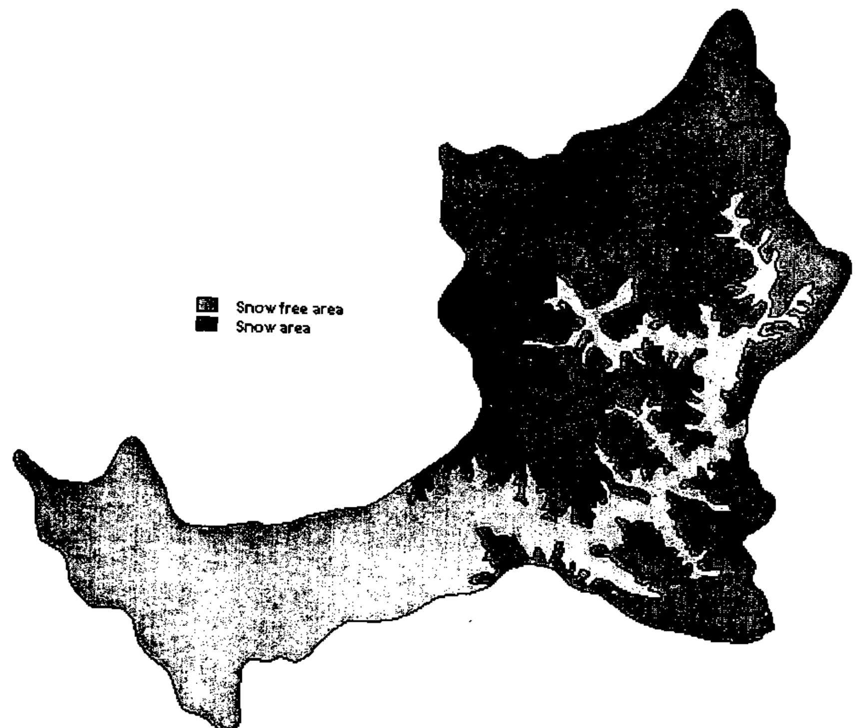

Fig. 3g:Snow covered area in Satluj catchment up to Bhakhra (4 May, 1991)

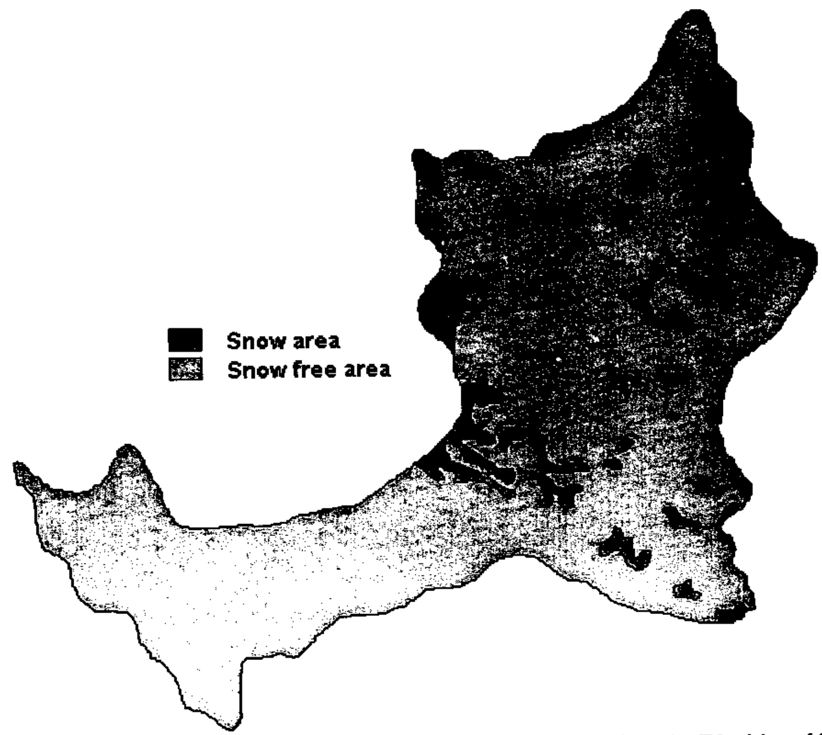

Fig.3h: Snow covered area in Satluj catchment up to Bhakhra (27 Oct., 1991)

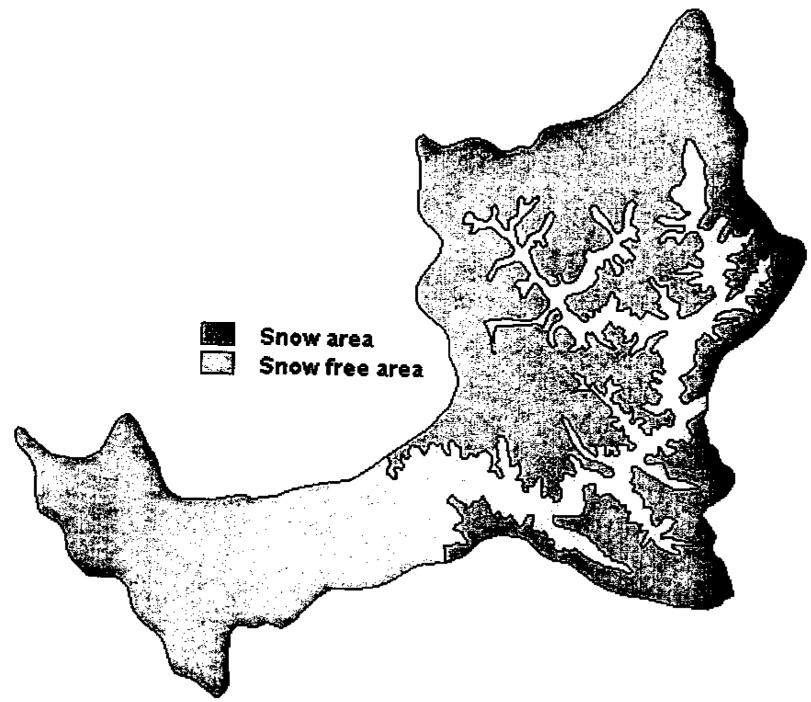

Fig.3i: Snow covered area in Satluj catchment up to Bhakhra (18 April, 1993)

March/April and September/October have been prepared for the period for which data was available. After preparation of final maps, these were digitized using digitizing module of Integrated Land and Water Information System (ILWIS). It is a PC based system developed by International Institute for Aerospace Survey and Earth Sciences (ITC), Enscehede, the Netherlands. After digitization the snow covered area has been computed. The snow covered area obtained from March/April and September/October for different years are given in Table 5. The results indicate that a major portion of the basin is covered by snow in the month of March/April (Figure 3a to 3i).

Information available on snow cover area for Satluj basin from Paul et al. (1995) was also used in this study. They estimated snow covered area for Satluj basin from the digital analysis of NOAA –AVHRR data, and supported by LANDSAT-MSS &TM and IRS-LISS data. Snow covered area was determined from February to July for a period 1986 to 1993, using all relatively cloud free images. They used a digital terrain model (DTM) of 1 km resolution to extrapolate snow cover under clouds. The digital basin mask was used along with the classified image to compute the snow covered area. The snow covered area on different dates were plotted against time and curves were drawn to obtain depletion curves for each year. Interpolation/extrapolation of these curves provided the information on snow covered area for the months for which snow covered area was not available.

The range of snow covered area in the month of March for different years varied from 58 - 72% of the total basin area. The average value of maximum snow covered area in the basin was found to be 65%, i.e., 14,498 km^2. The minimum snow covered area in the basin was observed in the month of September. The range of minimum snow covered area is very much effected by the amount of early snowfall in a particular year. On average minimum snow covered area in the basin was found to be 20.3%, i.e., 4528 km^2. Results indicate that on average about 9970 km^2 area becomes snowfree during the melt season.

Table 5 Snow covered area (SCA) and permanent snow covered area (PSCA) in the Indian part of Satluj basin up to Bhakra reservoir. Total area of the Indian part of Satluj river up to Bhakra reservoir is 22305 km^2.

Year	Month	Snow covered area expressed as % of total basin area	Month	Permanent snow covered area expressed as % of total basin area (%)
1986	March	64	September	15
1987	March	59	September	12
1988	March	71	September	35
1989	March	63	September	20
1990	March	70	September	17
1991	March	63	September	30
1992	March	72	September	16
1993	March	58	September	17
	Average	65		20.3

5.3 Evapotranspiration

The net rain input to the basin can be obtained by subtracting cumulated volume of evapotranspiration losses from the cumulated rainfall volume over 10 years period. For the catchments which are partly snow covered, the information on the snow free and snow covered area is needed to estimate losses through evapotranspiration from the basin. This is because evapotranspiration losses from the snow covered area are very less (Bengtsson, 1980) whereas those from the snow free area are significant. In the present study it is assumed that rainfall occurring over the snow covered area contributes about in totality to the flow within 10 years period whereas the contribution from the rain falling on the snow free area is reduced in accordance with the evapotranspiration losses occurred from snow free area.

Snow covered and snow free area in the basin are determined from the satellite data. The snow free area in the basin is obtained by simply subtracting snow covered area from the total drainage area of the basin. The information on snow covered area was worked out for different months during the study period. Because evaporation losses were carried out on monthly basis and these values were used to compute cumulated volume of losses, therefore, a monthly distribution of snow covered/ snow free area was needed. For this purpose, a linear interpolation was adopted to estimate snow covered area for the months having now snow cover information. Such trend was observed by the authors in an another study on snow cover area variability for a near by basin. However, physical reasons for the validity of linear interpolation can also be explained as follows: It is obvious that depletion of snow covered area in the basin or receding of snowline depends upon the depth of snow and atmospheric temperature causing snowmelt. In the spring months snow disappears from the lower elevation where snow depth is less, and temperatures are not very high during these months. While in the summer months at higher elevations temperatures are high in comparison to the spring period, but snow depth is also much at higher elevations. These trends of temperature and snow depth support linear interpolation of the snow cover area. This information in conjunction with actual evapotranspiration (AET) was used to get total volume of evapotranspiration losses occurred over the basin.

Most of the evaporation takes places in the lower and middle part of the basin. The required data was available at two stations in this part of the basin. The pan evaporation and air temperature data were available at Bhakra (518m) which lies on the lower catchment boundary of the basin and only air temperature was available at Rampur (1066m) located in the middle part of the basin. For estimation of evapotranspitation, attempts were made to correlate mean monthly maximum temperature, minimum temperature and mean temperature with monthly pan evaporation. Out of these temperatures, mean monthly maximum temperatures provided the best correlation with monthly pan evaporation (r^2 =0.84). Relationship between mean monthly maximum temperature and monthly pan evaporation is shown in Figure 4. This relationship was used to compute evapotranspiration from the snow free area. To obtain the representative value of evaporation losses from rain for the snow free part of the basin, evaporation was computed at mid elevation of snow free area. The mid elevation of snow free area was determined using information on snow covered area and area-elevation curve of the basin. As the melt season advances, the snow covered area reduces and snow free area increases. Therefore, mid elevation of the snow free area changes with time. It increases in summer and lowers down in the winter period. The available mean monthly temperatures were extrapolated to the mid elevation of snow free area using a temperature lapse rate of 0.60°C/km and monthly potential evaporation was computed using established relationship between mean monthly temperature and monthly evaporation. Monthly PET values at mid elevation of snow free area were computed by multiplying estimated pan evaporation values by 0.7.

No study has been reported for this region to provide AET and PET ratio which can be adopted. Therefore, few studies carried out in other basins wherein such estimates have been made, were reviewed. In a study carried out in the Ganjal sub-basin of Narmada basin applying Systeme Hydrologique European (SHE model), an average AET/PET value was estimated to be 0.40 (NIH, 1990). The Ganjal sub-basin is located in plain region and experiences only moderate rainfall. Keeping in view a warmer climate in the lower part of Satluj basin, Climate of Ganjal basin is warmer than the Chenab basin. Therefore, keeping in view the rainfall, location and climate of the Satluj basin, annual AET and PET ratio is assumed to be 0.40 for this basin. Annual AET values are distributed over a period of 12 months. For each month value of AET/PET value varies in such a way that annual AET/PET ratio is maintained. AET and PET are considered closer in the months

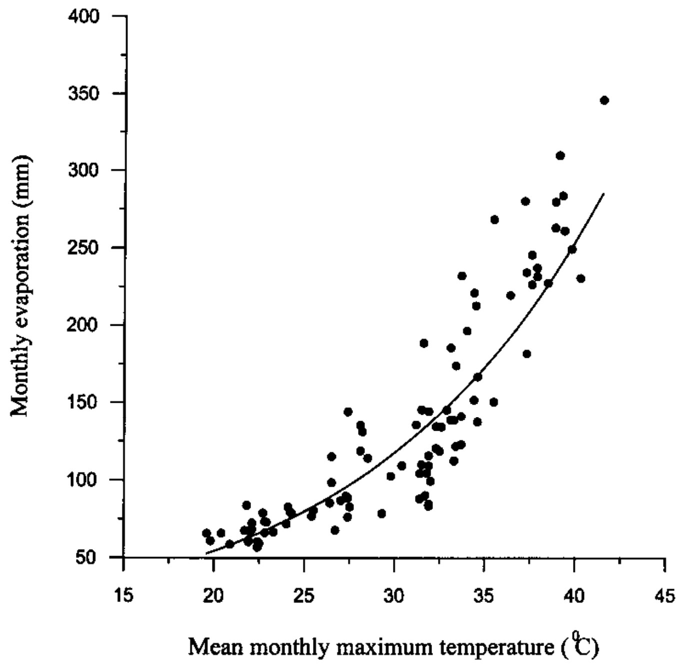

Figure 4: Relationship between mean monthly maximum temperature and monthly evaporation at Bhakra

of July and August which falls under monsoon season and sufficient soil moisture in available to evaporate whereas AET is kept minimum in the months of January and February when temperatures are very low resulting in less evapotranspiration losses. Monthly snow free area and AET values are used to estimate the actual evapotranspiration losses from the basin and has been cumulated over a period of 10 years to give total evapotranspiration volume from the basin. Based on this approach evapotranspiration losses were estimated for the years for which snow covered/snow free data was available and an average yearly value of evapotranspiration was obtained. Using this value evapotranspiration losses for the 10 years period were computed and used in water balance analysis.

Air temperature data available at two stations was used for this study. When mean monthly maximum temperature of Bhakra was extrapolated to mid elevation of snow free area and used for evaporation computation, cumulative value of evaporation for 10 years period was estimated to be 33.21 km^3. Whereas use of Rampur temperature data with same approach gave cumulative evaporation 36.52 km^3. In order to get more reliable value of evaporation, a mean value of evaporation obtained from using both stations data was adopted. Thus total loss from the study basin in the form of evaporation was computed to be 34.86 km^3.

6.0 SNOW AND GLACIER CONTRIBUTION

The location of gauging site where snow and glacier contribution is to be computed has a specific importance in all the rivers originating from the Himalayas. The percentage of contribution of the snow and glacier melt runoff into total streamflow will increase in the head catchment region, whereas the same will decrease at a the downstream site. Obviously, this is because of decrease in ratio of snow covered area and total drainage area in the downstream. Based on the water balance approach, average snow and glacier contribution in the annual flow of Satluj River at Bhakra is found to be about 58%. Details of all other parameters are illustrated in Table 6.

Table 6 Rainfall and snow and glacier contribution in the Satluj River at Bhakra. The volumes of rainfall, evapotranspiration, runoff and snow & glacier melt are given for a period of 10 years (1986/87-95/96).

Total rainfall volume (km^3)	Total Evapotranspiration losses (km^3)	Total runoff volume (km^3)	Rain Contribution		Snow & glacier Contribution	
			Vol.(km^3)	%	Vol.(km^3)	%
83.60	34.86	125.21	48.74	38.92	76.47	61.07

7.0 CONCLUSIONS

In the present study attempts have been made to estimate an average contribution of snow and glacier contribution in the annual flows of Satluj river (Indian part) at Bhakra dam over a period of 10 years (Oct., 1986- Sept., 1996). Variability of snow covered area has also been studied for this basin for the same period. The following conclusions are drawn from this study:

1. On average about 14, 498 km^2 area which is 65% of the total drainage area of the Satluj River up to Bhakra Dam is covered by snow in the month of March and about 4,528 km^2 (20.3%) remains covered by perpetual snow and glaciers in the month of September. However, the range of seasonal snow covered area and permanent snow covered area varied between 58 -72% and 12 - 35%, respectively. It shows that a major portion of the basin is covered by snow in the month of March. As such on average about 9970 km^2 area becomes snow free during the melt season

2. Based on 10 years analysis, an average snow and glacier melt contribution in the annual flow of Satluj river (Indian part) at Bhakra Dam is found to be about 61%. The rest contribution is from the rain.

Acknowledgements

Authors are thankful to Bhakra Beas Management Board (BBMB) for providing the data for the analysis carried out in this report.

References

Bengtsson, L. (1980) Evaporation from a snow cover, Nordic Hydrology, Vol.11, pp.221-234.

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

Flint, R. F. (1971) Glacial Quaternary Geology, Wiley, New York.

International Association of Hydrological Sciences (IAHS) (1993) Snow and Glacier Hydrology, IAHS Publication No. 218.

Paul, P.R., Ch. L.V.R. Rao and E.Siva Sankar (1994) A new approach in operational long-term snowmelt runoff forecasting in Sutlej Basin using snowcover depletion patterns. International Symposium on Snow and related Manefestations (Extended abstract), 26-28 sept, 1994, SASE, Manali (India).

Singh, P., S. K. Jain and Naresh Kumar (1977) Snow and glacier melt runoff contribution in the Chenab river at Akhnoor. Mountain Research Development, USA, Vol. 17, pp.49-56.

Singh, P. and N. Kumar (1997) Effect of orography on precipitation in the western Himalayan region. Journal of Hydrology, Vol. 199, pp. 183-206.

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

Singh, P., K. S. Ramasastri and N. Kumar (1995) Topographical influence on precipitation distribution in different ranges of western Himalayas. Nordic Hydrology, Vol. 26, pp. 259-284.

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, 76-103.

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