Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

Snow and glacier melt in the Satluj River at Bhakra Dam in the western Himalayan region

PRATAP SINGH & S. K. JAIN

Snow and glacier melt in the Satluj River at Bhakra Dam in the western Himalayan region

PRATAP SINGH* & S. K. JAIN
National Institute of Hydrology, Roorkee 247667 (UP), India

Abstract Streamflow in the Himalayan rivers is generated from rainfall, snow and ice. The distribution of runoff produced from these sources is such that the streamflow may be observed in these rivers throughout the year, i.e. they are perennial in nature. Snow and glacier melt runoff contributes substantially to the annual flows of these rivers and its estimation is required for the planning, development and management of the water resources of this region. The average contribution of snow and glacier melt runoff in the annual flows of the Satluj River at Bhakra Dam has been determined. Keeping in view the availability of data for the study basin, a water balance approach was used and a water budget period of 10 years (October 1986–September 1996) was considered for the analysis. The rainfall input to the study basin over the water budget period was computed from isohyets using rainfall data of 10 stations located at different elevations in the basin. The total volume of flow for the same period was computed using observed flow data of the Satluj River at Bhakra Dam. A relationship between temperature and evaporation was developed and used to estimate the evapotranspiration losses. The snow-covered area, and its depletion with time, was determined using satellite data. It was found that the average contribution of snow and glacier runoff in the annual flow of the Satluj River at Bhakra Dam is about 59%, the remaining 41% being from rain.

Key words Himalayan mountain system; snow-covered area; hydropower potential; water budget; precipitation distribution; remote sensing; snow and glacier melt; isohyetal method

La fonte nivale et glaciaire à l'écoulement de la Rivière Satluj au niveau du Barrage Bhakra, à l'ouest de la région Himalayenne

Résumé L'écoulement dans les rivières himalayennes est dû à la pluie, la neige et la glace. La distribution de ces différentes origines est telle que l'écoulement peut être observé dans ces rivières tout au long de l'année, c'est-à-dire qu'elles sont naturellement pérennes. La fonte nivale et glaciaire contribue de manière substantielle à l'écoulement annuel de ces rivières et son estimation est requise pour l'aménagement, le développement et la gestion des ressources en eau de cette région. La contribution moyenne de la fonte nivale et glaciaire dans l'écoulement annuel de la Rivière Satluj a été estimée au niveau du Barrage Bhakra. Compte tenu des données disponibles pour ce bassin versant, le bilan hydrologique a été analysé sur la période de 10 ans allant d'octobre 1986 à septembre 1996. L'afflux pluviométrique sur le bassin, pour la période considérée, a été calculé à partir des isohyètes construites grâce à 10 stations de mesure implantées à différentes altitudes. Le volume total écoulé pendant la même période a été calculé à partir des données de la station de jaugeage de la Rivière Satluj au niveau du Barrage Bhakra. La relation entre la température et l'évaporation a été estimée et utilisée pour estimer les pertes par évapotranspiration. La zone enneigée, et son évolution au fil du temps, a été déterminée grâce à des observations satellitaires. Il a été mis en évidence que la contribution moyenne de la fonte glaciaire et nivale à l'écoulement annuel de la Rivière Satluj au niveau du Barrage Bhakra est d'environ 59%, le complément de 41% étant généré par la pluie.

Mots clefs système montagnard himalayen; région enneigée; potentiel hydroélectrique; bilan hydrologique; distribution des pluies; télédétection; fonte glaciaire et nivale; méthode des isohyètes

**Currently at:* Department of Water Resources Engineering, Lund University, Box 118, SE-22 100 Lund, Sweden; pratap.singh@tvrl.lth.se.

Open for discussion until 1 August 2002

INTRODUCTION

Seasonal snow falling during winters covers a significant area of the Earth. Depletion of seasonal snow during summer months makes this area either fully or partly snow free. In the higher reaches of mountains, where, most of the time, the temperature is below freezing, permanent snow cover or glaciers are formed. The present estimate of the glaciated area in the world is about 14.9 million km^2, which is about 10% of the land area of the globe (Singh & Singh, 2001). Although only 3% of this permanent snow and ice is distributed over mountains in various continents outside the polar region, this small amount is an important source of water for the majority of the population of the world (Flint, 1971). Of the mountain glaciers, the central Asian mountains contain about 50% of the glaciated area and a large portion of this area drains into the land mass of the Indian sub-continent. The Himalayan mountain system is the source of one of the world's largest supplies of freshwater. All the major south Asian rivers originate in the Himalayas and their upper catchments are covered with snow and glaciers. The Indus, Ganga and Brahmaputra river systems, originating from the Himalayan region, receive substantial amounts of meltwater and are considered as the life-line of the Indian sub-continent. The storage of precipitation in the form of snow and glaciers in the mountains, like the Himalayas, over a long period provides a large amount of potentially available water and also regulates the annual distribution of the water. The perennial nature of Himalayan rivers and the appropriate topographic setting of the region provide a substantial exploitable hydropower potential in this area. Singh *et al.* (1995, 2000) have studied the hydrological aspects of the Himalayan glacierized basins, including the relationship between discharge and meteorological parameters. These studies provide a better understanding of the generation of meltwater and its drainage from the glacierized basin.

Estimation of the rate and volume of water released from the snow and glaciers is needed for the efficient management of water resources, including flood forecasting, reservoir operation, design of hydraulic structures, etc. Planning of new hydroelectric projects on the Himalayan rivers emphasizes the need for reliable estimates of snow and glacier runoff. At present such attempts have been made for specific sites for only two basins (the Chenab and Ganga basins). The average snow and glacier contribution in the annual flows of the Chenab River at Akhnoor was estimated to be 50% and that for the Ganga at Devprayag was about 30% (Singh *et al.*, 1994; Singh *et al.*, 1997). The present study focuses on the Satluj River (Indian part) at Bhakra Dam, located in the foothills of the Himalayas. Bhakra Dam is the oldest dam constructed in India for hydropower generation and is considered a boon to north India. The suitable geological setting and availability of abundant water provide a huge hydropower generation potential in the Satluj River basin. Consequently, several hydropower schemes are planned/under construction on this river. The extent of snow-covered area and its depletion during the melt season have also been estimated and used in this study.

THE STUDY BASIN

The Satluj River has its source area in the Mansarovar and Rakastal lakes in the Tibetan Plateau at an elevation of about 4572 m (Fig. 1). It is one of the main

Fig. 1 Location map of the Satluj River.

tributaries of the Indus River and flows through different areas having different climatic and topographic features. The Tibetan Plateau receives hardly any rainfall and thus has a cold desert type of climate. Therefore, very little flow is observed in this river when it passes through this dry region. After entering Indian territory, the Satluj River flows through Himachal Pradesh and receives runoff from snow and glaciers as well as rain. In the high altitude region, numerous glaciers drain directly into the Satluj River at various points along its course. The lower part of the basin experiences a considerable amount of rainfall.

The total catchment area of the Satluj River up to Bhakra Dam is about 56 874 km^2. The Indian part of the Satluj basin, for which the present study is carried out, covers an area of about 22 305 km^2, including the whole catchment of the Spiti basin (a major tributary of the Satluj). This basin is elongated in shape and covers outer, middle and greater Himalayan ranges. The elevation of the study basin varies from about 500 to 7000 m, although only a very small area exists above 6000 m. Owing to large differences in the elevation range and seasonal temperatures, the snow line descends to an elevation of about 2000 m during winter and crosses 5000 m altitude by the end of the summer season. The permanent snow line in this part of the Himalayan region is observed at about 5400 m (BBMB, 1988).

STREAMFLOW CHARACTERISTICS OF THE SATLUJ RIVER

The streamflow of the Satluj River consists of the contribution from rain, snow and glaciers and the respective contribution of each component varies with time of the year. Generally, the snowmelt contribution starts from March and lasts until June/July, depending upon the snowpack water equivalent accumulated in the preceding winter season and the prevailing temperatures in the summer season. As the summer season progresses, the snowmelt contribution increases continuously and exceeds the rainfall component. Thus in the pre-monsoon season (April–June), a major part of the streamflow is generated from seasonal snow. During the monsoon season (July–September), flow is augmented by monsoon rains, producing higher discharges in the river. Generally, high discharges and floods are observed in the months of July and August and these are essentially due to heavy rain in the lower part of the basin. Usually, seasonal snow accumulated on glaciers during the winter season is ablated by the end of May/June and glaciers start contributing to streamflow thereafter. Glaciers contribute to their maximum in the months of July and August. As such, glacier melt runoff contribution lasts till September/October. In the post-monsoon season, streamflow is believed to be partly from the glaciers and some occasional rain events. Minimum streamflow is observed during winter because no melting takes place due to low temperatures. The baseflow contribution sustains the flow in the river during this period.

Based on analysis of 10 years (October 1986–September 1996) of flow data, the monthly distribution of streamflow at Bhakra Dam is shown in Fig. 2 and quarterly distribution is given in Table 1. It may be seen that maximum flow is observed in the month of July, followed by August, and the minimum in the month of February. About 83% of the total annual flow is observed during the pre-monsoon and monsoon

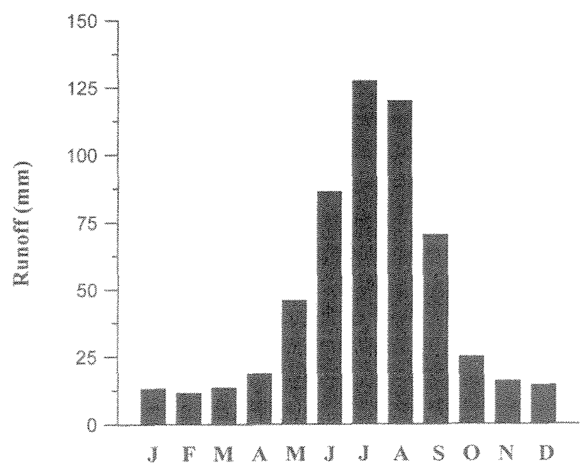

Fig. 2 Monthly average discharge of the Indian part of the Satluj River observed at Bhakra Dam.

Table 1 Quarterly distribution of the annual flows of Satluj River at Bhakra Dam.

Period	Average runoff (mm)	Contribution to annual flow (%)
October–December	55.0	9.9
January–March	38.1	6.9
April–June	150.9	26.8
July–September	317.4	56.4
Year (October–September)	**561.4**	**100**

seasons, because a high contribution from all the sources of runoff is produced in these two seasons. In the other two quarters, flow is only 17% of the total annual flows. [It can also be seen from Table 4 that annual runoff depth from the study basin varied from 464 to 632 mm.]

DATA USED

Rainfall, temperature, evaporation, discharge and remote sensing data were used in this study. The daily rainfall data of 10 stations located at different altitudes were available and used to compute the total rainfall input over the basin. The runoff depth over the water budget period was calculated at the Bhakra Dam using daily streamflow data. The period from October to September was chosen for the analysis so that a complete snow accumulation and ablation period could be taken into account in a year.

In order to find out the snow-covered area in the basin, remote sensing data were used. Landsat (MSS, 80 m resolution) and IRS (LISS-I, 72.5 m resolution) data for the study period were procured from the National Remote Sensing Agency (NRSA), Hyderabad, India. Landsat data (path/row 146/36) were used for 1986 and 1987, whereas IRS data (path/row 29/45) were used for 1988–1991 and 1993. For both satellites, remote sensing information of band 3/4 was used. For some years, information already available on the snow-covered area was used (Paul *et al.*, 1994). The estimation of evapotranspiration losses over the study basin was made by correlating temperature with the pan evaporation data of Bhakra and then extending this relationship for other parts of the basin.

METHODOLOGY

Because of the rugged terrain and inaccessibility to the higher reaches, a poor snow gauge network exists in the high altitude region of the Himalayas, particularly where heavy snowfall is experienced. Therefore, assessment of snowfall over the whole basin becomes very difficult under such conditions. A network of raingauges is reasonably good in the few Himalayan basins, including the present study basin, and this allows for better estimates of rainfall input to the basin. Thus, rainfall input along with streamflow and evapotranspiration information can be used for assessing the snow and glacier melt contribution. To assess the contribution of snow and glacier melt runoff into annual flows of the Satluj River, the following water balance approach was used:

$$SGC = Q - (R - E) \qquad (1)$$

where SGC is the contribution from snow and glacier melt runoff, Q is the observed flow, R is the rainfall input to basin and E is the evapotranspiration loss from the basin. Application of the water balance approach for estimating the average contribution of snow and glacier melt runoff to annual flows requires a long water budget period for the analysis. There are two important reasons for that. First, a long water budget period of 10 years (as chosen in the present study) or so can cover several dry and wet years and the outcome from the analysis would represent a true average value. Secondly, it can be assumed that all the losses from the rain and snowmelt in the form of infiltration and percolation, except evapotranspiration, would reach the outlet of the basin within the water budget period. This also allows for no separate consideration of baseflow in the analysis. Further, consideration of a 10-year period as a water budget period is needed for reliability, especially for such mountainous catchments having significant relief variation from the outlet to the upper part of the basin. In such basins, the time taken by the infiltrated and percolated water will be very much less than that in the plain basins. Various components needed in the analysis were determined as follows.

Rainfall

The total rainfall depth at each station over the water budget period was obtained by making a cumulative sum of daily rainfall. Then isohyets were drawn and the rainfall input to the study basin was estimated. The average annual isohyetal pattern of the Satluj basin up to Bhakra Dam is shown in Fig. 3. The isohyetal method is considered more reliable for mountainous basins, where topography influences the precipitation due to the high relief and different orientations. Such effects can be observed from the

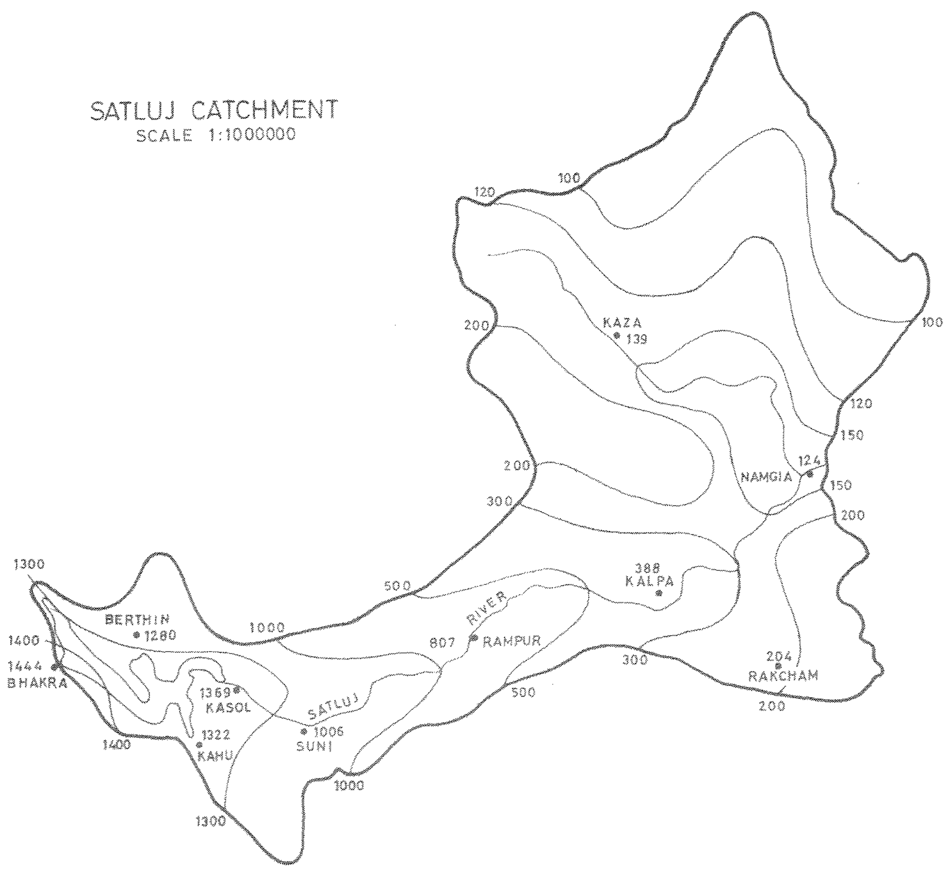

Fig. 3 Average annual isohyetal pattern of rainfall in the Indian part of Satluj basin up to Bhakra Dam.

rainfall distribution in the basin shown by the isohyets. The distribution of isohyets shows that a high rainfall is observed in the lower and middle parts of the basin, whereas it is less in the upper part. The range of annual isohyets varies from 100 to 1400 mm. Such high variation in the rainfall is a compound effect of several factors, such as the height of the mountain barrier, the strength of moisture bearing air currents, the moisture content of winds and the orientation of the mountain range with respect to the prevailing wind direction. [Table 4 shows that the annual rainfall for the whole study basin varied from 313 to 423 mm.] Detailed investigations on precipitation distribution in the study basin have been made by Singh & Kumar (1997). They reported that the annual rainfall in this basin decreases from the outer to the greater Himalayan range. Different patterns of precipitation distribution were found for different Himalayan ranges covered by this basin. Similar patterns of rainfall were found for other basins of the Himalayas (Singh *et al.*, 1995b; Singh & Kumar, 1997).

Snow-covered area

Snow cover serves as a vast storehouse of water for all the major Himalayan rivers. Conventional methods of monitoring snow-covered areas for inaccessible regions like the Himalayas have limitations. Satellite data have become increasingly important and widely applied for difficult terrain and inaccessible areas and are considered a most suitable means of detailed survey. Also, the advantage of satellite remote sensing, such as multi-spectral, synoptic and repetitive coverage, is ideally suited to monitoring snow and deciphering meaningful information. Thus, satellite data are considered an important means for mapping the snow-covered area in the Himalayas. The usual problems in remote sensing data analysis related to location, recognition and measurement, are virtually not present in the case of snow. Snow has the unique physical property of a high albedo in the visible/near infrared (IR) portion of the spectrum. Thus, by virtue of the high reflectivity, snow is one of the objects on the surface of the Earth which is easily detected on any visible or near IR remotely sensed image.

The duration of seasonal snow cover varies from basin to basin and also from year to year. In the present study, LANDSAT/IRS satellite data in the form of black and white positive, false colour composites (FCCs) and digital form were used. Depending upon the availability of data, either visual interpretation or digital processing of data was made. For estimating snow-covered area in the basin, a base map of the study area was prepared using standard toposheets from the Survey of India. This base map was overlaid on the positive prints developed from the film negatives of band 3 and 4 or on FCCs and registration of the map with imageries was carried out. Because the whole area of the basin was not covered in a single imagery, the data of the closest date of adjoining imagery were used to find out the snow-covered area in the basin. Some information already available on snow-covered area for Satluj basin was also used in this study.

To prevent misidentification of snow, several possible features on the imagery which can introduce errors were taken into account. For example, cloud tops exhibit a very bright reflectance in the visible/infrared bands and often are indistinguishable from snow. Such a source of errors was detected and ignored in computation of the snow-covered area. Further, small portions of snow-covered area, which are under shadow (either from terrain features or clouds), were considered as snow bound. After

Table 2 Maximum and minimum snow-covered area in the Indian part of Satluj basin up to Bhakra Dam (total area: 22 305 km^2).

Year	Month	Snow-covered area as % of total basin area	Month	Snow-covered area 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**

preparation, the final maps were digitized using the digitizing module of the Integrated Land and Water Information System (ILWIS) developed at the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands, and the snow-covered area was computed.

The snow-covered area in the basin for the months of March/April and September/October, which usually indicates the maximum and minimum snow-covered area in the basin, respectively, were determined for different years (Table 2). Based on 10 years of data analysis, it was found that about 65% (14 498 km^2) of the basin is covered by snow by the end of March/April, and after the melt season it reduces to 20.3% (4528 km^2). The distribution of maximum and minimum snow-covered area in the basin for 1989 is shown in Fig. 4. The results indicate that about 9970 km^2 becomes snow free during the melt season. For estimating evapotranspiration losses, monthly snow-covered area data were required. These were either computed using satellite data, or linearly interpolated using available snow cover information. The average snow-cover depletion curve for the study basin was derived and is shown in Fig. 5.

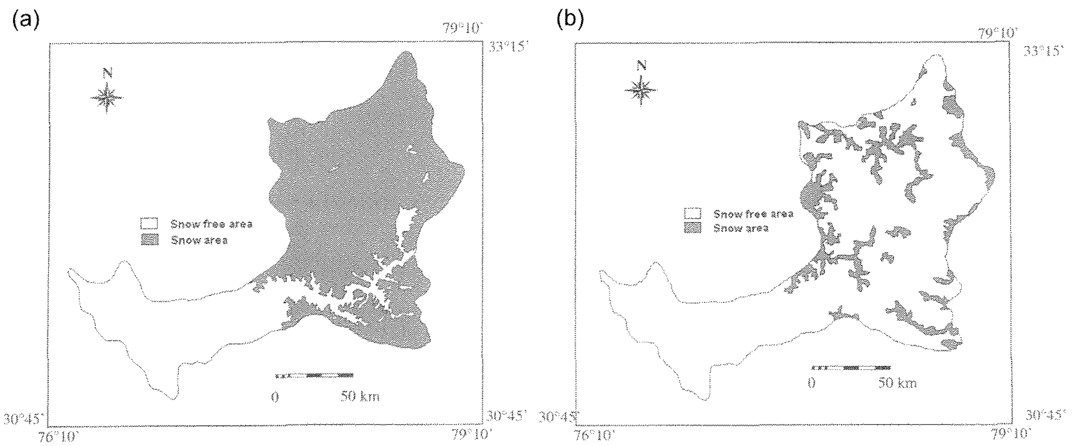

Fig. 4 Snow-cover distribution in the Satluj basin (a) for 3 March 1989, and (b) for 9 October 1989.

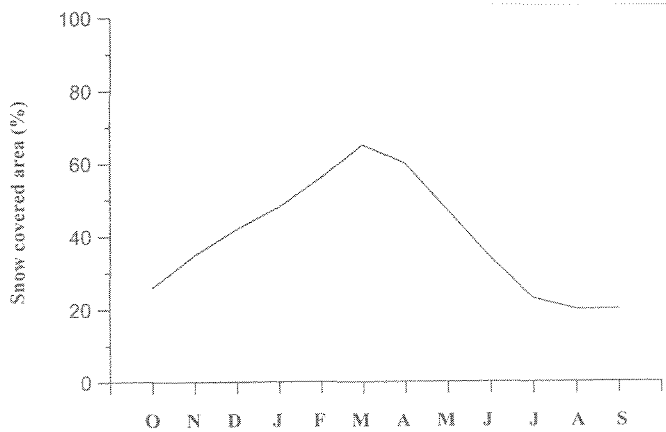

Fig. 5 Variation in snow-covered area in the study basin with time.

Evapotranspiration

The net rain input to the basin can be obtained by subtracting the total evapotranspiration losses from the total rainfall depth over the water budget period. Evapotranspiration losses from the snow-covered area are very small (Bengtsson, 1980), whereas those from the snow-free area may be significant, depending upon the soil moisture conditions. Therefore, identification of snow-covered and snow-free areas is required for estimation of evapotranspiration losses from the whole basin. It should be pointed out that rainfall occurring over the snow-covered area is absorbed or infiltrated through the snowpack without significant evaporation losses and this rainfall contributes almost totally to the flow within the considered water budget period. The evapotranspiration was estimated with the help of two methods—the mid-elevation approach and a distributed approach.

Estimation of monthly evapotranspiration losses, in conjunction with the information on the snow-free area, makes it possible to compute the total losses from the basin. Due to the warmer climate in the lower and middle parts of the basin, most of the evapotranspiration takes place in these areas. Because no other data were available for estimating evapotranspiration in the basin, temperature and pan evaporation data (US Weather Bureau Class A pan evaporimeter) for Bhakra (518 m a.m.s.l.), which lies on the lower catchment boundary of the basin, were used. The monthly pan evaporation observed at Bhakra was correlated with the mean monthly maximum temperature, and minimum and mean temperatures observed at the same station. It was found that, of these three relationships, the mean monthly maximum temperature provided the best correlation with monthly pan evaporation (r^2 = 0.84). In another study, Singh *et al.* (1995a) studied the relationship between pan evaporation and different meteorological parameters, namely, maximum and minimum temperatures, wind speed, relative humidity and hours of sunshine. They also found that, of these five meteorological parameters, the highest correlation (r^2 = 0.85) was obtained for the maximum air temperature and evaporation relationship. The relationship between mean monthly maximum temperature, T_{max}, and monthly pan evaporation, *Evap*, for the study basin is shown in Fig. 6 and can be expressed as:

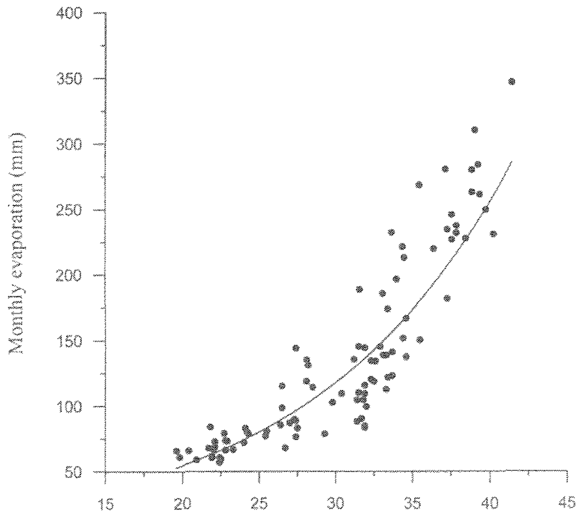

Fig. 6 Relationship between mean monthly maximum temperature and monthly pan evaporation at Bhakra.

$$Evap = 11.63 \times \exp(0.077 \times T_{max}) \tag{2}$$

This relationship was used to compute evapotranspiration from the snow-free area. In order to be representative of the snow-free part of the basin, it was computed at mid elevation of the snow-free area. This was determined using information on the snow-covered area and the area–elevation curve of the basin. As the melt season advances, the snow-covered area reduces, resulting in increase in snow-free area. Therefore, mid elevation of the snow-free area changes with time, increasing in summer as the snow line moves up and decreasing in winter when the snow line descends. The available mean monthly temperatures of Bhakra were extrapolated to the mid elevation of the snow-free area using a temperature lapse rate in the following relationship:

$$T_{max} = T_{bmax} - \gamma \times (H - H_b) \tag{3}$$

where, T_{max} is the mean monthly maximum temperature (°C) at elevation H (m) in the basin, γ is the temperature lapse rate (0.6°C 100 m^{-1}), T_{bmax} is the mean monthly maximum temperature of Bhakra (°C) and H_b is the elevation of the base station (518 m a.m.s.l.).

The monthly potential evapotranspiration from the snow-free area was computed by multiplying the estimated pan evaporation by the pan coefficient. True values of pan coefficient of between 0.6 and 0.8 have been reported for the US Weather Bureau Class A pan evaporimeter, but an average value (0.7) is recommended for use (Chow, 1964).

In addition to the mid elevation approach, evapotranspiration losses from the basin were also estimated using a distributed approach. A digital elevation model (DEM) of the basin was prepared and used for computation of the elevation of a desired point in the basin. This helped in the generation of a mean monthly temperature distribution map of the basin, which was used with equation (2) to prepare the distributed map of monthly evapotranspiration.

Actual evapotranspiration (*AET*) from the basin can be computed using potential evapotranspiration (*PET*), provided that information on the *AET*/*PET* relationship is available. No study to determine *AET*/*PET* has been reported for this region which could usefully be adopted for the present project. Therefore, few studies carried out in other basins wherein *AET*/*PET* was estimated were reviewed. An average annual value of *AET*/*PET* (= 0.40) was estimated for the Ganjal sub-basin of Narmada by applying the Système Hydrologique Européen (SHE) model (NIH, 1990). This value was adopted for the present study. Further, estimation of monthly distribution of *AET*/*PET* was done in such a way that annual *AET*/*PET* could be maintained. For this purpose, *AET* and *PET* were considered closer for July and August due to the availability of sufficient soil moisture to evaporate in the monsoon season. The value of *AET* was kept at a minimum in January and February, because very low or negligible evapotranspiration takes place during winter due to the low temperatures in this period. For a particular month, the estimated monthly *AET* and the extent of snow-free area provided actual evapotranspiration losses. The cumulative monthly values over the water budget period give the annual evapotranspiration losses from the basin.

Using the above two approaches, evapotranspiration losses were estimated for all the years for which snow-covered/snow-free data are available. Using the available information, the average yearly evapotranspiration was obtained and used for the years for which data were not available.

The monthly evapotranspiration obtained using the two approaches for different years are given in Table 3. The distribution of monthly actual evapotranspiration for a year is shown in Fig. 7. For different years, the variation in the annual evapotranspiration computed from these two different approaches ranged between 2 and 8%. The total cumulative evapotranspiration losses over the water budget period were estimated to be 1486 and 1413 mm, using the mid elevation approach and the distributed approach, respectively. It may be seen that there is only about 5% difference in the total evapotranspiration losses obtained using the two approaches. An average value of the evapotranspiration losses for the water budget period (145 mm year^{-1}) was obtained from the above two computed values and used in further calculations.

Table 3 Monthly evapotranspiration (mm) computed for different years for the Indian part of the Satluj basin up to Bhakra.

Year/ Month	1986/87		1987/88		1988/89		1989/90		1990/91		1991/92		1992/93	
	*E*1	*E*2	*E*1	*E*2	*E*1	*E*2	*E*1	*E*2	*E*1	*E*2	*E*1	*E*2	*E*1	*E*2
Oct.	8.0	7.6	8.6	7.9	7.0	5.6	10.0	8.9	8.7	6.9	8.2	6.8	9.1	8.3
Nov.	6.4	8.5	6.2	8.2	4.8	5.7	5.7	7.3	7.0	9.1	5.5	6.7	5.8	7.2
Dec.	3.5	4.3	4.2	4.7	3.3	3.7	3.5	3.7	3.9	4.4	3.7	3.4	3.6	4.0
Jan.	2.6	3.0	2.4	2.6	1.8	1.8	2.6	2.8	2.4	2.7	1.9	2.0	2.0	2.2
Feb.	3.2	3.5	3.2	3.4	2.4	2.6	2.4	2.5	2.9	3.2	2.5	2.4	3.2	3.8
Mar.	2.9	2.9	2.5	2.0	2.7	2.5	2.0	1.7	2.8	2.7	2.2	1.8	2.6	2.6
Apr.	6.7	7.0	7.0	6.1	5.7	5.7	5.5	5.0	5.5	5.4	6.3	6.4	6.6	6.8
May	4.7	4.5	7.9	6.6	7.5	6.8	7.8	7.6	7.7	7.0	7.5	7.5	9.5	9.5
June	12.9	12.4	14.1	14.5	10.9	8.3	14.5	14.3	13.9	14.8	15.0	16.5	15.8	17.1
July	45.7	40.6	28.3	25.6	35.7	32.6	30.4	27.4	44.8	43.9	34.4	33.2	32.6	30.9
Aug.	36.3	33.5	29.5	25.3	35.2	32.6	33.6	30.8	33.1	29.6	32.8	30.7	44.3	40.7
Sept.	27.6	26.0	23.2	19.5	26.3	24.0	23.4	21.7	23.5	20.3	25.8	24.1	22.5	20.8
Total	**160.5**	**153.8**	**137.1**	**126.4**	**143.3**	**131.9**	**141.4**	**133.7**	**156.2**	**150.0**	**145.8**	**141.5**	**157.6**	**153.9**

*E*1: monthly evapotranspiration computed using the mid-elevation approach.
*E*2: monthly evapotranspiration computed using the distributed approach.

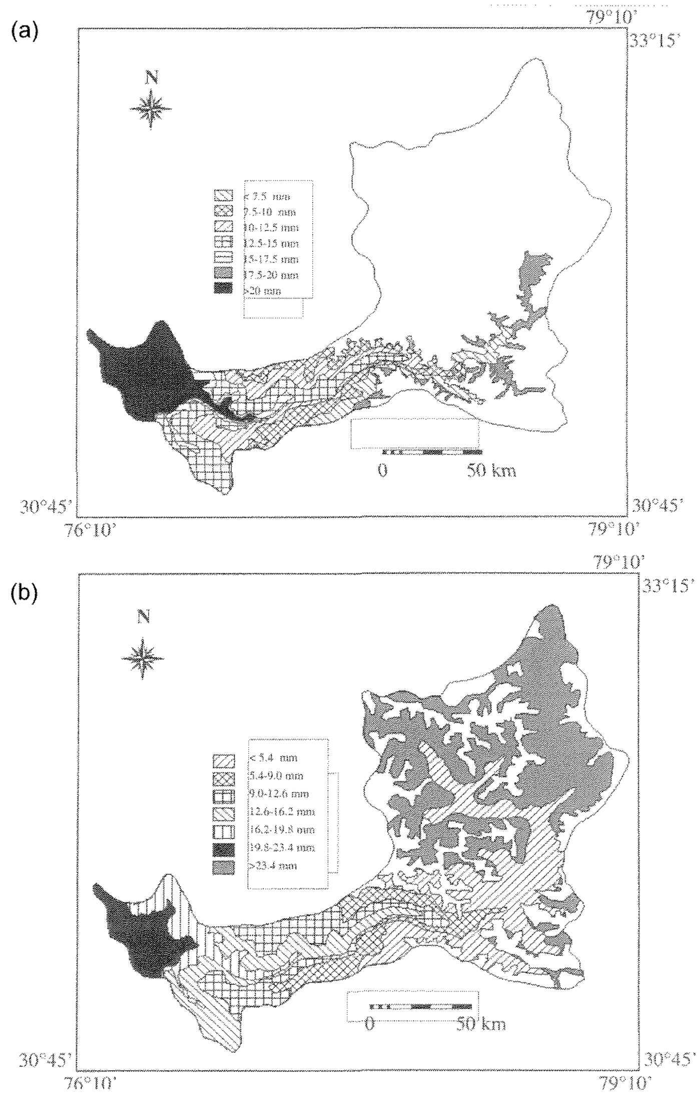

Fig. 7 Monthly evapotranspiration distribution in the Satluj basin (a) for March 1989, and (b) for October 1989.

SNOW AND GLACIER CONTRIBUTION

The average snow and glacier contribution to the annual flow of Satluj River at Bhakra Dam was computed using the water balance approach. Runoff depth, rainfall input and evapotranspiration losses for different years are listed in Table 4. The cumulative values of each component for the water budget period were used to estimate the contribution of rainfall, and snow and glacier melt to the total annual runoff from the basin (Table 5). The average snow and glacier melt runoff contribution to annual flows was found to be about 59% and the rest (41%) was from rain.

Table 4 Computed runoff, rainfall, evapotranspiration for different years for Satluj River basin.

S. no.	Year	Runoff (mm)	Rainfall (mm)	Evapotranspiration losses (mm)
1	1986/87	519.2	373.5	157.2
2	1987/88	588.8	464.8	131.8
3	1988/89	517.6	366.2	137.6
4	1989/90	631.6	423.4	137.8
5	1990/91	571.8	313.1	153.1
6	1991/92	553.9	366.2	143.7
7	1992/93	464.0	352.8	155.8
8	1993/94	610.4	360.4	145.2*
9	1994/95	560.4	382.0	145.2*
10	1995/96	595.8	346.0	145.2*

* Average annual value.

Table 5 Snow and glacier melt for Satluj River at Bhakra using 10 years of data (1986/87–1995/96).

Runoff (mm)	Rainfall (mm)	Evapotranspiration losses (mm)	Rain contribution to runoff		Snow and glacier contribution to runoff	
			(mm)	(%)	(mm)	(%)
5614	3748	1450	2298	41	3314	59

The location of the gauging site where the snow and glacier melt contribution is being computed is important, because the percentage of snow-covered area in the total drainage area changes from site to site. In the present case, for all the sites upstream of Bhakra, the snow and glacier contribution to the annual flows will be higher, because the percentage of snow-covered area is higher than that in the total drainage area of the basin. Most of the new projects on the Satluj River are being carried out upstream of Bhakra. Therefore, the value of snow and glacier contribution obtained in the present study is the lowest value for all the upstream project sites. In other words, the snow and glacier contribution for all the upstream project sites would be higher than 59%.

CONCLUSIONS

Attempts have been made to estimate the average contribution of snow and glacier melt runoff to the annual flows of the Satluj River (Indian part) at Bhakra Dam. The analysis was made using the water balance approach and a period of 10 years (October 1986–September 1996) was considered as the water budget period. The runoff depth from the study basin and the rainfall input to the basin were determined using observed data, whereas evapotranspiration losses were estimated using a derived relationship. The average contribution of snow and glacier melt in the annual flow of Satluj River at Bhakra was found to be about 59%, the remaining 41% being from rain, showing that snow and glaciers provide a substantial contribution to the flows of Satluj River. For all the sites upstream of Bhakra, the contribution of snowmelt runoff would be higher than 59% due to higher percentage of snow-covered area in the total drainage area. Thus, the results of the present study also become very important for all the projects planned/under execution upstream of the Bhakra Dam.

The study shows that a major portion of the basin is covered by seasonal snow during winter. Using satellite data of various years, it is found that, on average, about

14 498 km^2 (65% of the total drainage area) of the Indian part of the Satluj River basin up to Bhakra Dam is covered by snow in the month of March. After the snowmelt season, in September, about 4528 km^2 (20.3% of the total drainage area) remains covered by perpetual snow and glaciers. As such, an area of about 9970 km^2 becomes snow-free during the melt season.

Acknowledgements The authors are thankful to Bhakra Beas Management Board (BBMB) for providing the data used in this study.

REFERENCES

Bengtsson, L. (1980) Evaporation from a snow cover. *Nordic Hydrol.* **11**, 221-234.

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

Chow, V. T. (1964) *Handbook of Applied Hydrology*. McGraw-Hill, New York, USA.

Flint, R. F. (1971) *Glacial Quaternary Geology*. John Wiley & Sons, New York, USA.

NIH (National Institute of Hydrology) (1990) Application of SHE model to the Ganjal sub-basin of river Narmada. Report CS-28, NIH, Roorkee, India.

Paul, P. R., Ramana Rao, C. L. V. & Siva Sankar, E. (1994) A new approach in operational long-term snow melt runoff forecasting in Satluj basin using snow cover depletion patterns. In: *Proc. Int. Symp. on Snow and its Manifestations* (Extended abstracts) (26–28 September 1994), 340–342. Snow and Avalanche Study Establishment, Manali, India.

Singh, P. & Kumar, N. (1997) Effect of orography on precipitation in the western Himalayan region. *J. Hydrol.* **199**, 183–206.

Singh, P., Jain, S. K. & Kumar, N. (1997) Snow and glacier melt runoff contribution in the Chenab river at Akhnoor. *Mountain Res. Devel.* **17**, 49–56.

Singh, P., Ramasastri, K. S. & Kumar, N. (1994) Study on snow distribution in Chenab basin. In: *Proc. Int. Symp. on Snow and its Manifestations* (26–28 September 1994). Snow and Avalanche Study Establishment, Manali, India.

Singh, P., Ramasastri, K. S. & Kumar, N. (1995b) Topographical influence on precipitation distribution in different ranges of western Himalayas. *Nordic Hydrol.* **26**, 259–284.

Singh, P., Ramasastri, K. S., Kumar, N. & Arora, M. (2000) Correlations between discharge and meteorological parameters and runoff forecasting from a highly glacierized Himalayan basin. *Hydrol. Sci. J.* **45**(5), 637–652.

Singh, P., Ramasastri, K. S., Singh, U. K., Gergan, J. T. & Dobhal, D. P. (1995) Hydrological characteristics of Dokriani glacier in the Garhwal Himalayas. *Hydrol. Sci. J.* **40**(2), 243–257.

Sing, P. & Sing, V. P. (2001) *Snow and Glacier Hydrology*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Singh, R., Prakash, O. & Khicher, M. L. (1995a) Estimation of evaporation from different meteorological parameters. *Annals of Arid Zones* **34**, 263–265.

Received 17 November 2000; accepted 27 August 2001