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Modelling of streamflow and its components for a large Himalayan basin with predominant snowmelt yields

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Abstract A conceptual snowmelt model, which accounts for both the snowmelt and rainfall runoff was developed and applied for daily streamflow simulation for the Satluj River basin located in the western Himalayan region. The model, designed primarily for mountainous basins, conceptualizes the basin as a number of elevation zones depending upon the topographic relief. The basic inputs to the model are temperature, precipitation and snow-covered area. The snowmelt is computed using the degree-day approach and rain induced melting was also considered. The model was calibrated using a data set of three years (1985/86–1987/88) and model parameters were optimized. Using these optimized parameters, simulations of daily streamflow were made for a period of six years (1988/89–1990/91 and 1996/97–1998/99). The model performed well for both calibration and simulation periods. The model was also used to estimate the contribution from the snowmelt and rainfall to the seasonal and annual flows.

Key words snowmelt model (SNOWMOD); degree-day approach; snow-covered area; streamflow simulation; summer season runoff

Modélisation de l'écoulement fluvial et de ses composantes pour un grand bassin versant himalayen à dominante nivale

Résumé Un modèle nival conceptuel, qui tient compte à la fois de la fonte de la neige et de l'écoulement pluvial, a été développé et appliqué pour la simulation des écoulements journaliers dans le bassin de la rivière Satluj, dans l'ouest de la région himalayenne. Le modèle, initialement conçu pour des bassins de montagne, conceptualise le bassin sous la forme de zones altitudinales dépendant de la topographie. Les entrées de base du modèle sont la température, les précipitations et la surface enneigée. La fonte est calculée à partir de l'approche degré-jour, sachant que la fonte induite par la pluie est également prise en compte. Le modèle a été calé à partir d'un jeu de trois ans de données (1985/86–1987/88) et les paramètres du modèle ont été optimisés. Sur la base de ces paramètres optimisés, les simulations de l'écoulement journalier ont été réalisées pour une période de six ans (1988/89–1990/91 et 1996/97–1998/99). Le modèle est satisfaisant pour les périodes de calage et de validation.

Mots clefs modèle de fonte de la neige (SNOWMOD); approche degré-jour; surface enneigée; simulation d'écoulement fluvial; écoulement estival

INTRODUCTION

There is substantial contribution from snowmelt runoff to the annual streamflows of the Himalayan rivers (Singh *et al.*, 1997a; Singh & Jain, 2002). The water yield from a high Himalayan basin is roughly twice as high as that from an equivalent basin located in the peninsular part of India. A higher water yield from the Himalayan basins is mainly due to the large inputs from the snowmelt and glaciers. Depending upon the climatic conditions, the snowpack depletes either fully or partially during the forthcoming summer season. Because of variation in climatic conditions and changes

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in the areal extents of snow-covered area (SCA) and snow-free area (SFA) with time, the contributions from the rain and snow to the streamflow vary with season. The contribution from rain dominates in the lower part of the basins (about <2000 m). The middle and upper parts of the basins (about >2000 m) receive contributions from both rain and snowmelt and this changes with altitude. As the elevation of the basin increases, the rain contribution to streamflow reduces and the snowmelt contribution increases. Runoff is dominated by the snowmelt runoff above 3000 m altitude.

Modelling of streamflow involves transformation of precipitation received in the basin to the outgoing streamflow by considering losses to the atmosphere, temporary storage, lag and attenuation etc. Most hydrological runoff models, which account for snow need snowfall data as input for snowmelt estimation (Singh & Singh, 2001). For the high altitude regions in the Himalayan basins, snowfall data are not available. Poor accessibility to the high altitude sites due to rugged terrain makes it difficult to install, monitor and maintain the meteorological instruments, so the observational network is poor and application of models which need snowfall data as input is hampered. The snowmelt runoff model (SRM; Martinec *et al.*, 1994) uses snow-covered area as input instead of snowfall data, but it does not simulate the baseflow component of runoff. In other words, SRM does not consider the contribution to the groundwater reservoir from snowmelt or rainfall, nor its delayed contribution to the streamflow in the form of baseflow, which can be an important component of runoff in the Himalayan rivers, and plays an important role in making these rivers perennial. Almost all the streamflow during winter, when no rainfall or snowmelt occurs, is generated from the baseflow. A new snowmelt model, which simulates all components of runoff, i.e. snowmelt runoff, rainfall-induced runoff and baseflow, using limited data, has been developed and applied to the Satluj River basin, which is a highly snowfed basin, to simulate daily flows. Application of the model has been extended to estimate the snowmelt and rainfall contribution into seasonal and annual flows.

STUDY BASIN

The Satluj River originates from the lakes of Mansarover and Rakastal in the Tibetan plateau at an elevation of more than 4500 m a.m.s.l. This is one of the main tributaries of Indus River system located in the western Himalayan region. The total drainage area of the Satluj River up to Bhakra Reservoir is about 56 500 km^2. For the present study, the Indian part of the Satluj River basin up to Bhakra Reservoir (area: 22 275 km^2) was selected (Fig. 1). The part of the basin which lies in the Tibetan plateau experiences little or negligible rainfall; it has cold desert type of climate and does not contribute much to the runoff. The principal tributary of Satluj River, known as Spiti, joins the Satluj River just after entering India and contributes substantially to this river. The topographical setting and availability of abundant water provide great potential for hydropower generation in the Indian part of the Satluj River. Therefore, several hydropower schemes are either in existence, under execution, or planned on this river. The Bhakra Dam, the oldest dam in India, is situated on the Satluj River in the foothills of the Himalayas and serves for both hydropower and irrigation.

The elevation of the study basin varies from about 500 m to 7000 m a.m.s.l. Owing to large differences in the relief, the basin is characterized by diversified climatic patterns. Westerly weather disturbances deposit nearly all the precipitation during

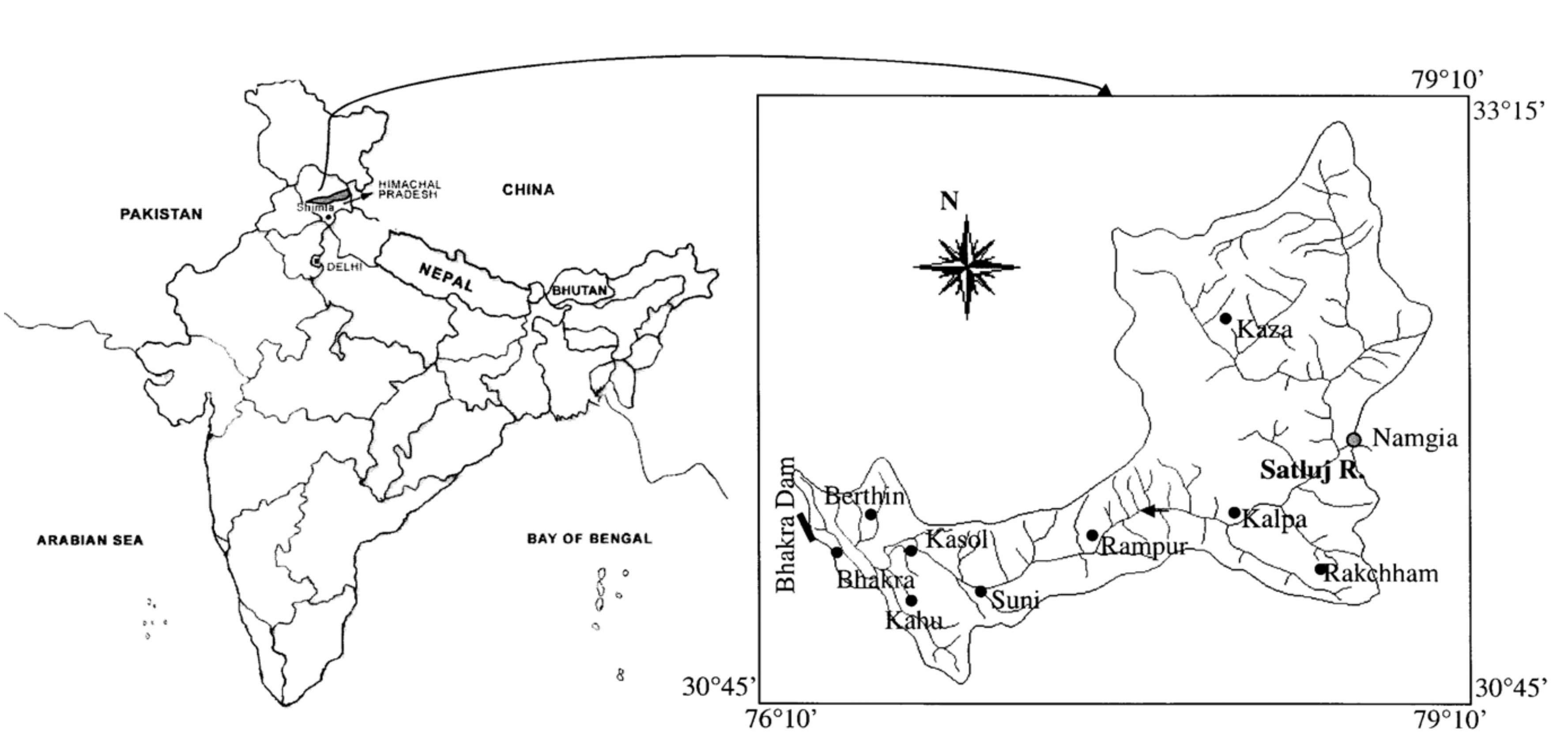

Fig. 1 Map of the Satluj basin (Indian part) up to Bhakra Reservoir with location of hydrometeorological stations.

winter in the middle and upper parts of the basin, and most of the precipitation falls in the form of snow in this season. The mean annual rainfall in the outer, middle and greater Himalayan ranges of the basin is about 1300, 700 and 200 mm, respectively (Singh & Kumar, 1997). The distribution of rainfall indicates that the rainfall is mostly concentrated in the lower part of the basin and has little influence in the greater Himalayan range. The snowline is highly variable, descending to an elevation of about 2000 m during winter and retreating to above 4500 m after the ablation period.

DATA USED

Physiographical and hydrometeorological data are required for computing the streamflow from the basin. Physiographical data represent physical features of the basin, including its total area, its altitudinal distribution through elevation zones and the areas of these zones, and the altitude of precipitation and temperature stations. Hydrometeorological data include daily precipitation, mean air temperature, snow-covered area and streamflow data. Information on the initial soil moisture status of the basin is needed at the beginning of simulation.

In order to simulate the streamflow, the daily rainfall data of nine stations and the temperature data of five stations were used. Daily mean temperatures were computed by taking the average of available daily maximum and minimum temperatures. The locations of these raingauges and temperature stations are shown in Fig. 1. Data availability and the altitudes of the stations are given in Table 1. The difference between discharges available at Namgia and Bhakra provided the total discharge from the study area. Following the trends of variation in discharge during a year, the period November–October was considered as the hydrological year, as used by Gupta *et al.* (1982) in their study of the Beas River basin, which adjoins the present study basin.

Table 1 Hydrometeorological data and elevation of different stations used in the study: rainfall (P), temperature (T), discharge (Q).

Station	Elevation (m)	Data used
Bhakra	518	P, T, Q
Berthin	657	P
Kahu	649	P
Suni	625	P
Kasol	661	P
Rampur	1066	P, T
Kalpa	2439	P, T
Rakchham	3130	P, T
Namgia	2910	Q
Kaza	3639	P, T

Remote sensing data were used to obtain snow-covered area data for the study period to prepare snow cover depletion curves. Landsat data (MSS, 80-m resolution) for two years (1985/86 and 1986/87), IRS data (LISS-I, 72.5-m resolution) for four years (1987/88–1990/91) and IRS data (WiFS, 188-m resolution) for three years (1996/97–1998/99) were procured from the National Remote Sensing Agency

(NRSA), Hyderabad, India. Keeping in view the cost of procuring remote sensing data, the satellite data were obtained at the frequency of 15 days/ one month and interpolated/extrapolated for the intermediate periods.

STRUCTURE OF THE MODEL AND ITS APPLICATION TO THE SATLUJ RIVER

The snowmelt model (SNOWMOD) is designed to simulate daily streamflow for mountainous basins having contribution from both snowmelt and rainfall. The process of generation of streamflow from such basins involves primarily the determination of the input derived from snowmelt and rain, and its transformation into runoff. For simulating the streamflow, the basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model deals with snowmelt and rainfall runoff by performing the following three operations at each time step: (a) available meteorological data are extrapolated to the different elevation zones, (b) rates of snowmelt and/or rainfall are calculated at different points, and (c) snowmelt runoff from SCA and rainfall runoff from SFA are integrated, and these components are routed separately with proper accounting of baseflow to the outlet of the basin. The model optimizes the parameters used in routing of the snowmelt runoff and rainfall runoff. The structure of the model is shown by means of the flow chart in Fig. 2. Details of computation of melt runoff and generation of sreamflow from the basin are discussed below. This model has also been used to study the impact of climate change on the depletion of snow-covered area in a Himalayan basin (Singh & Bengtsson, 2003).

Division of catchment into elevation zones As temperature and precipitation vary with elevation, the basin is divided into a number of elevation zones depending upon topographic relief. For the purpose of computing the different components of runoff, each elevation zone is treated as a separate watershed with its own characteristics. Total streamflow for the whole basin is obtained by synthesizing the runoff from all elevation zones. In the present study, the digital elevation model (DEM) of the study basin was prepared and used to derive the area–elevation curve of the basin. The basin was divided into 10 elevation zones with an elevation difference of 600 m (Table 2). Table 2 shows the area of each elevation zone. The distribution of basin area with altitude indicates that more than 55% of the basin area lies between 3600 and 5400 m altitude.

Precipitation form and its distribution Some of the most significant data-related problems in mountainous basins are associated with the measurement of the amount and spatial distribution of precipitation. A comparative study of various snowmelt models (WMO, 1986) indicated that precipitation distribution assumptions and the determination of the form of precipitation (rain or snow) were the most important factors in producing accurate estimates of runoff volume. In the present study, rain on an elevation zone is added directly to the moisture input, whereas snow is added to the previously accumulated snow, if any. The temperature in a particular elevation zone determines the form of precipitation and the model handles it accordingly. A

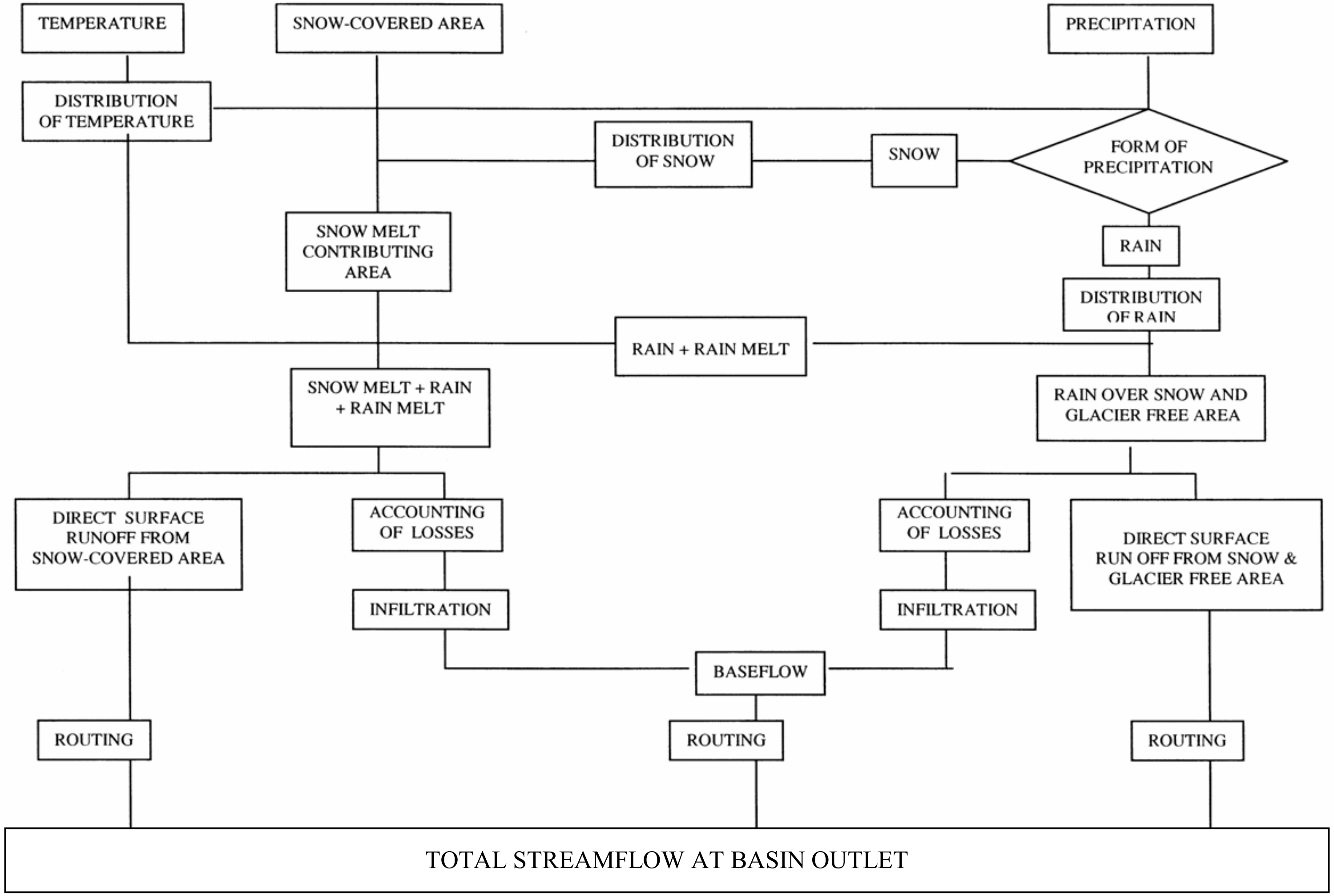

Fig. 2 Structure of the snowmelt model (SNOWMOD).

Table 2 Study basin area covered in different elevation zones.

Elevation zones	Elevation range (m)	Zone area (km^2)	Zone area as % of total area of study basin	Cumulative area (km^2)
1	<600	308.8	1.38	308.8
2	600–1200	1702.6	7.64	2011.4
3	1200–1800	2283.2	10.25	4294.6
4	1800–2400	1660.0	7.45	5954.6
5	2400–3000	955.6	4.29	6910.2
6	3000–3600	2073.7	9.33	8983.9
7	3600–4200	4121.9	18.50	13105.8
8	4200–4800	5460.3	24.51	18566.1
9	4800–5400	3275.8	14.71	21841.9
10	>5400	433.3	1.95	22275.2

critical temperature, T_c, is specified in the model to determine whether the measured precipitation was rain or snow. Direct observations suggest that T_c is generally higher than 0°C (Charbonneau, 1981). In the present study, T_c is considered to be 2°C. The algorithm used in the model to determine the form of precipitation is as follows:

If $T_m \geq T_c$, all precipitation is considered as rain

If $T_m \leq 0°C$, all precipitation is considered as snow

where T_m is mean air temperature. In the cases $T_m \geq 0°C$ and $T_m \leq T_c$, the precipitation is considered as a mixture of rain and snow and their proportion is determined as follows:

$$Rain = (T_m/T_c) \times P \quad (1)$$

$$Snow = P - Rain \quad (2)$$

where P is the total observed precipitation. The rainfall from the raingauging stations was assigned to different elevation zones according to their altitude and location within each elevation zone. For the second elevation zone, the rainfall data were available for four stations located very close to each other and having about the same elevation. Therefore, for this zone, the average value of the four stations, viz. Suni, Berthin, Kasol and Kahu, was used. The distribution of precipitation with altitude was not considered simply because such information is not available.

Snowmelt, temperature and degree-days Estimation of snowmelt using the energy balance approach requires climatic data such as radiation, cloudiness, wind speed, etc. and such meteorological data are scarce in the Himalayan region. Therefore, for the development of a conceptual model, the temperature index or degree-day approach was considered suitable for snowmelt computation. The temperature index provides a reasonably good estimate of snowmelt as compared with detailed evaluation of the various components in the energy balance approach (US Army Corps of Engineers, 1971; Anderson, 1973). An early application of a degree-day approach was made by Finsterwalder & Schunk (1887) in the Alps and since then this approach has been used widely all over the world for the estimation of snowmelt (Martinec *et al.*, 1994; Quick & Pipes, 1995; Singh & Singh, 2001). The simplest and most common expression relating snowmelt to temperature index is:

$$M = D(T_i - T_b) \tag{3}$$

where M is the depth of meltwater (mm) produced in a unit of time (one day in the present case), D is the degree-day factor (mm °C^{-1} day^{-1}), T_i is the index air temperature (°C), and T_b is the base temperature (usually, 0°C). Clearly, D is used to convert the degree-days to snowmelt expressed in depth of water; it is influenced by the physical properties of snowpack and changes with time because properties of snow change with time. The value of D is lower at the beginning of the melt season and higher towards the end. In the present study, the value of D varied from 1 to 2.5 mm °C^{-1} day^{-1}. The seasonal variation in D is well illustrated by Anderson (1973). Singh & Kumar (1996) and Singh *et al*. (2000) computed the value of D for a Himalayan basin for a specific time and compared those with available information.

The daily mean temperature is the most commonly used index of temperature for snowmelt. Where only maximum, T_{max}, and minimum temperatures, T_{min}, are available, T_i, representing the number of degree-days, is computed as:

$$T_i = T_m = (T_{max} + T_{min})/2 \tag{4}$$

For accurate snowmelt computations in the mountain regions, ideally, temperature data should be available for all the elevation zones of the basin. But, in general, air temperatures are available at few locations in the basin. These point values are extrapolated or interpolated to the mid elevation of each elevation zone using a pre-defined temperature lapse rate, as given below.

$$T_{i,j} = T_{i,\mathrm{base}} - \delta(h_j - h_{\mathrm{base}}) \tag{5}$$

where $T_{i,j}$ is the daily mean temperature (°C) on the ith day in zone j, $T_{i,\mathrm{base}}$ is the daily mean temperature (°C) on the ith day at the base station, h_j is the zonal hypsometric mean elevation (m), h_{base} is the elevation of the base station (m) and δ is the temperature lapse rate (°C 100 m^{-1}). The temperature lapse rate must be carefully selected on the basis of prior climatic knowledge. Generally, the mean temperature is lapsed at 0.65°C 100 m^{-1} or at a specified rate to the mean hypsometric elevation of each elevation zone (Singh, 1991). Like rainfall, the temperatures of different base stations were assigned to different elevation zones.

Snow-covered area and depletion curves The information on SCA is determined from the satellite imageries/digital data. The satellite data were processed using ERDAS IMAGINE image processing software. First, snow cover area maps were prepared for the study basin and then the SCA for each elevation zone was estimated and plotted against the elapsed time to construct the depletion curves for the various elevation zones in the basin. In order to simulate daily runoff, daily SCA for each zone is required as input to the model. Daily values of SCA were obtained by interpolating/extrapolating the derived depletion curves. The trends of depletion of snow in the study basin for different years are shown in Fig. 3. The depletion of snow-covered area is controlled by the snow that has accumulated during the preceding winter and by temperature patterns during the melt period. Because the amount of snowfall/snow-covered area and temperature conditions fluctuate from year to year, snow-covered area and depletion trends also vary from year to year. Seasonal snow

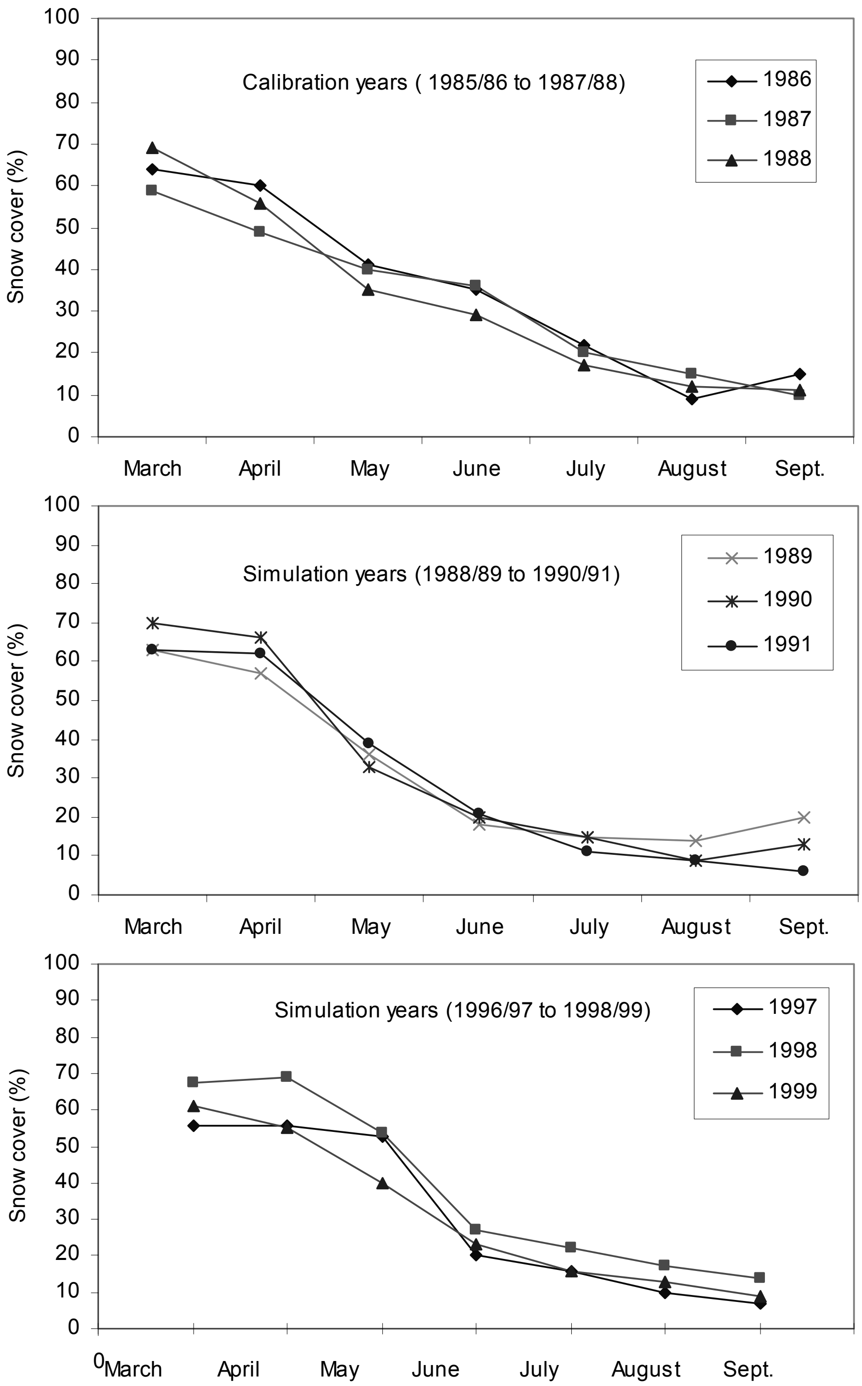

Fig. 3 Snow-cover depletion curves for Satluj Basin for different years

cover will disappear at a faster rate during warmer climatic conditions, while it will follow slow depletion under a colder temperature regime.

Rain on snow When rain falls on the snowpack, it is cooled to the temperature of snow. The heat transferred to the snow by rainwater is the difference between its energy content before falling on the snow and its energy content on reaching thermal equilibrium within the snowpack. For snowpacks isothermal at 0°C, the release of heat results in snowmelt, while for the colder snowpack this heat tends to raise the snowpack temperature. In case the snowpack is isothermal at 0°C, the melt occurring due to rain is computed by:

$$Q_p = \rho C_p(T_r - T_s)P_r/1000 \tag{6}$$

where Q_p is the energy supplied to the pack by rain (kJ m^{-2} day^{-1}); ρ is the density of water (1000 kg m^{-3}); C_p is the specific heat of water (4.20 kJ kg^{-1} °C^{-1}); T_r is the temperature of the rain (°C); T_s is the temperature of the snowpack (°C); and P_r is the depth of rain (mm day^{-1}).

Substituting the values of various parameters in the above equation, it reduces to:

$$Q_p = 4.2T_rP_r \tag{7}$$

Usually, rain temperature is considered equal to the air temperature on that day. The melt, M_r caused by the energy supplied by rain is computed as:

$$M_r = Q_p/(\rho h_f B) = Q_p/325 \tag{8}$$

or

$$M_r = 4.2T_rP_r/325 \tag{9}$$

where M_r is in (mm day^{-1}), h_f is the latent heat of fusion of water (335 kJ kg^{-1}), and B is the thermal quality of snow (0.95–0.97). Only high rainfall events occurring at higher temperatures would cause the melting due to rain, otherwise this component would not be significant (Singh *et al.*, 1997b).

Computation of different components of runoff

The computation of runoff for each component was made for each elevation zone separately and then output from all the zones was integrated to provide the total runoff from the basin. Computations of different runoff components of streamflow are discussed below.

Surface runoff from snow-covered area The runoff from snow-covered area consists of: (a) snowmelt caused due to prevailing air temperature, (b) under rainy conditions, snowmelt due to heat transferred to the snow from rain, and (c) runoff from rain itself falling over the SCA. This was computed as follows:

(a) Snowmelt runoff for each elevation zone of the basin was computed using degree-day approach and extent of SCA in that zone:

$$M_{s,i,j} = C_{s,i,j}D_{i,j}T_{i,j}S_{c,i,j} \tag{10}$$

where M_s is the snowmelt in terms of depth of water (mm day^{-1}); C_s is the runoff coefficient for snowmelt; D is the degree-day factor (mm °C^{-1} day^{-1}); T is the temperature (°C); and S_c is the ratio of SCA to the total zone area. Subscripts i and j refer to day and zone, respectively.

(b) Runoff depth due to snowmelt from the heat transferred to snow by the rain falling on the SCA in an elevation zone is given by:

$$M_{r,i,j} = 4.2T_{i,j}P_{i,j}S_{c,i,j}/325 \tag{11}$$

where M_r is the snowmelt due to rain on snow (mm day^{-1}); and P is rainfall on snow (mm day^{-1}).

(c) Runoff depth from rain itself falling over the snow-covered area, R_s, is given by:

$$R_{s,i,j} = C_{s,i,j}P_{i,j}S_{c,i,j} \tag{12}$$

For the computation of runoff from rain, the coefficient C_s is used (not the rainfall runoff coefficient, C_r), because the runoff from the rain falling on the SCA behaves like the runoff from the melting of snow.

The daily total discharge from the SCA is computed by adding the contribution from each elevation zone. Thus, discharge from the SCA, Q_{SCA}, for all the zones is given by:

$$Q_{SCA} = \alpha\sum_{j=1}^{n}\left(M_{s,i,j} + M_{r,i,j} + R_{s,i,j}\right)A_{SCA,i,j} \tag{13}$$

where n is the total number of zones; A_{SCA} is the snow-covered area (km^2); and α is a factor (1000/86400 or 0.0116) used to convert the runoff depth (mm day^{-1}) into discharge (m^3 s^{-1}). This discharge is routed to the outlet of the basin following the procedure described below.

Surface runoff from snow-free area The only source of surface runoff from the SFA is rainfall. As for snowmelt runoff computations, runoff from the SFA was computed for each zone using the following expression:

$$R_{f,i,\mathrm{j}} = C_{r,i,j}P_{i,j}S_{f,i,j} \tag{14}$$

where S_f is ratio of SFA to the total zone area.

Because SCA and SFA are complimentary, $S_{f,i,j}$ can be directly calculated as $1 - S_{c,i,j}$. The total runoff from SFA, Q_{SFA} for all the zones is thus given by:

$$Q_{SFA} = \alpha\sum_{j=1}^{n}R_{f,i,j}A_{SFA,i,j} \tag{15}$$

where A_{SFA} is the snow-free area. The discharge from the SFA was also routed to the outlet of the basin.

Estimation of subsurface runoff The subsurface flow or baseflow represents the runoff from the unsaturated zone of the basin to the streamflow. After accounting for the direct surface runoff from snowmelt and rainfall, the remaining water contributes to the groundwater storage through infiltration and appears at the outlet of the basin with much delay as subsurface flow or baseflow. Depletion of this groundwater storage also results from evapotranspiration and percolation of water to the deep groundwater zone. It is assumed that half of the water percolates down to shallow groundwater and contributes to baseflow, while the rest is accounted for by the loss from the basin in the from of evapotranspiration and percolation to the deep groundwater aquifer, which may appear further downstream or become part of deep inactive groundwater storage. The depth of runoff contributing to baseflow from each zone is given by:

$$R_{b,i,j} = \beta[(1 - C_{r,i,j})R_{f,i,j} + (1 - C_{s,i,j})M_{t,i,j}] \tag{16}$$

where $M_{t,i,j} = M_{s,i,j} + M_{r,i,j} + R_{s,i,j}$ and β is 0.50. The baseflow, Q_b, is computed by multiplying the depth of runoff by the conversion factor α and area, and is given as:

$$Q_b = \alpha \sum_{j=1}^{n} R_{b,i,j} A_{i,j} \tag{17}$$

where A is the total area (km^2) and represents the sum of A_{SCA} and A_{SFA}. This component is also routed separately.

Total streamflow The daily total streamflow from the basin is calculated by adding the three different routed components of discharge for each day:

$$Q = Q_{SCA} + Q_{SFA} + Q_b \tag{18}$$

Routing of different components of runoff

Routing of surface runoff The catchment routing refers to the transformation of input to the basin in the form of either rainfall or snowmelt to the outflow from the basin. Because the hydrological response of runoff from SCA and SFA differs, the routing of runoff from these areas was done separately by a cascade of equal linear reservoirs, known as the Nash Model.

To account for the variation in response of these components with time, the storage coefficients, k_r for SFA and k_s for SCA, were assumed as the functions of total snow-free area (A_{SFA}) and total effective snow-covered area (A_{ESCA}) of the basin, respectively. The term A_{ESCA} is defined as the extent of SCA which contributes to the melt. In other words, it represents the extent of SCA which has temperature above 0°C. The ratio of A_{ESCA} to A_{SCA} varies between 0 and 1, being at a minimum at the beginning and end of the melt season, and at a maximum during the summer when melting takes place from the whole SCA. The value of A_{ESCA} can be easily obtained for each time step by subtracting the area of those elevation zones which do not contribute to melt from A_{SCA}. The storage coefficients were related to SCA and SFA in nonlinear form as follows:

$$k_r = a_r(A_{SFA})^{br} \tag{19}$$

$$k_s = a_s(A_{ESCA})^{bs} \tag{20}$$

where k_r is the storage coefficient for SFA; k_s is the storage coefficient for SCA; A_{SFA} is the total snow-free area in the basin; A_{ESCA} is the total effective snow-covered area in the basin; a_r and b_r are model parameters for SFA; and a_s and b_s are model parameters for effective SCA.

The nonlinear relationship between storage coefficients of snowmelt and rainfall with their respective area was adopted considering the nonlinear trend of removal of snow from the basin, as shown by snow depletion curves (Fig. 3). The variation in depth of snow with altitude also controls the depletion trend of snow. In the initial stage of the melt season, as the temperature increases, snow from the lower part of the basin depletes at a faster rate because of the shallow snow depth in the area. In other words, SCA is converted into SFA at a faster rate. In the later part of the melt season, the snow line moves up in the basin, where the depth of snow is greater, and, therefore, the SCA converts into SFA at a reduced rate as compared to that at the beginning of the melt season. Thus, the conversion of SCA to SFA follows a nonlinear trend with time. Because k_s and k_r are dependent on SCA and SFA, respectively, the above relationship was considered.

Routing of subsurface runoff The movement of subsurface runoff to the channel is very slow in comparison to the direct surface runoff. The method adopted for the model to represent recession of baseflow is:

$$Q(t) = Q_0 e^{-t/k} \tag{21}$$

where Q_0 is the discharge at time $t = 0$. The parameter k is known as the recession constant, or depletion factor. In logarithmic form, this equation can be written as:

$$\ln Q = \ln Q_0 - \frac{t}{k} \tag{22}$$

In order to determine the storage coefficient, k_b, for the baseflow, the streamflow of the recession period was plotted against time on semi-log paper and a straight line was fitted, whose slope gives the value of k_b. In the present study, to compute k_b, the recession trends of flow, the streamflow records were examined for a number of years. It was found that the minimum flow in the Satluj River was observed during the winter period. There was continuous recession of flow from the basin during this period, except for some anomalous change in the flow due to local rain events. The recession trends for three different years along with the respective derived equation for each case are shown in Fig. 4. The values of storage coefficient for baseflow for 1985/86, 1986/87 and 1987/88 were obtained as 105, 111 and 113, respectively. The average value of k_b, i.e. 110 days, was finally adopted for the routing of the baseflow. Due to the slow response of subsurface flow, it is routed through a single linear reservoir.

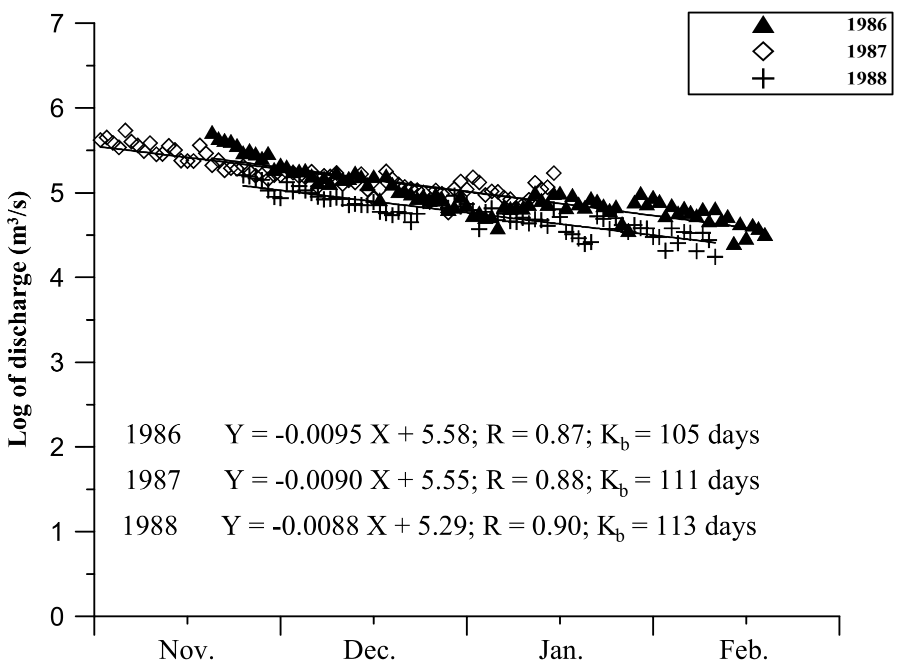

Fig. 4 Plot of log-transformed streamflow for the recession period for different years.

CALIBRATION OF THE MODEL

Hydrological models are generally calibrated using computed and observed streamflow records, while the available data set is split into two parts: one being used to calibrate the model and the other being used to validate it, i.e. to check how the model performs in simulation mode (Blackie & Eles, 1985). In the present study, the Rosenbrock optimization technique was used for optimization of parameter values (Kuester & Mize, 1973). A suitable objective function is employed to determine the acceptable degree of agreement between the observed, Q_o and estimated flows, Q_e. The most commonly used objective function, F, to be minimized represents a simple summation of the squares of residuals:

$$F = \sum (Q_e - Q_o)^2 \tag{23}$$

The model was calibrated for a period of three years (1985/86–1987/88) by varying the initial parameters, and optimization of the four model parameters (a_r, b_r, a_s and b_s) was carried out. The calibrated values of the parameters were computed considering the overall performance of the model and reproduction of the flow hydrograph for all the three years. The value of SMI used in this study was 150 mm, determined on the basis of an appropriate match between observed and computed streamflow for the initial period of calibration. The optimized values of a_r, b_r, a_s and b_s were 0.46, 0.073, 0.99 and 0.15, respectively.

The observed and computed streamflow values for the calibration period are given in Fig. 5(a). All three components of streamflow, namely, snowmelt runoff, rainfall runoff and baseflow, are also shown separately in this figure. Low flows and almost all the peaks in the streamflow are usually well reproduced, including the highest peak observed in September 1988. For the calibration period of three years, the model simulated daily streamflow with an efficiency, R^2 (Nash & Sutcliffe, 1970), ranging from 0.85 to 0.93 and the difference in volume of observed and computed streamflow was computed to be between 2 and 11% (Table 3). The results indicate a good performance of the model for all the calibration years.

SIMULATION OF DAILY STREAMFLOW AND ITS COMPONENTS

After successful calibration of the model for a period of three years, the model was run to simulate daily streamflow using independent data for six years (1988/89–1990/91 and 1996/97–1998/99) without changing the model parameters. The comparison of daily observed and simulated streamflow is shown in Fig. 5(b) and (c). For the simulation period, R^2 varied between 0.85 and 0.90 and the difference in the volumes of computed and observed streamflow was between 0.3 and –8.8% (Table 3). The overall efficiency of the model over the study period of nine years was 0.90 and the difference in volume of computed and observed streamflow was only –3.3%. The results indicate that the model performed equally well for the simulation years as for the calibration years.

Figure 5(a)–(c) also shows the different components of the simulated streamflow. It is clearly observed that all the high peaks in the streamflow are attributed to rain, but prolonged high flows are due to snowmelt. Moreover, most of the high peaks occurred

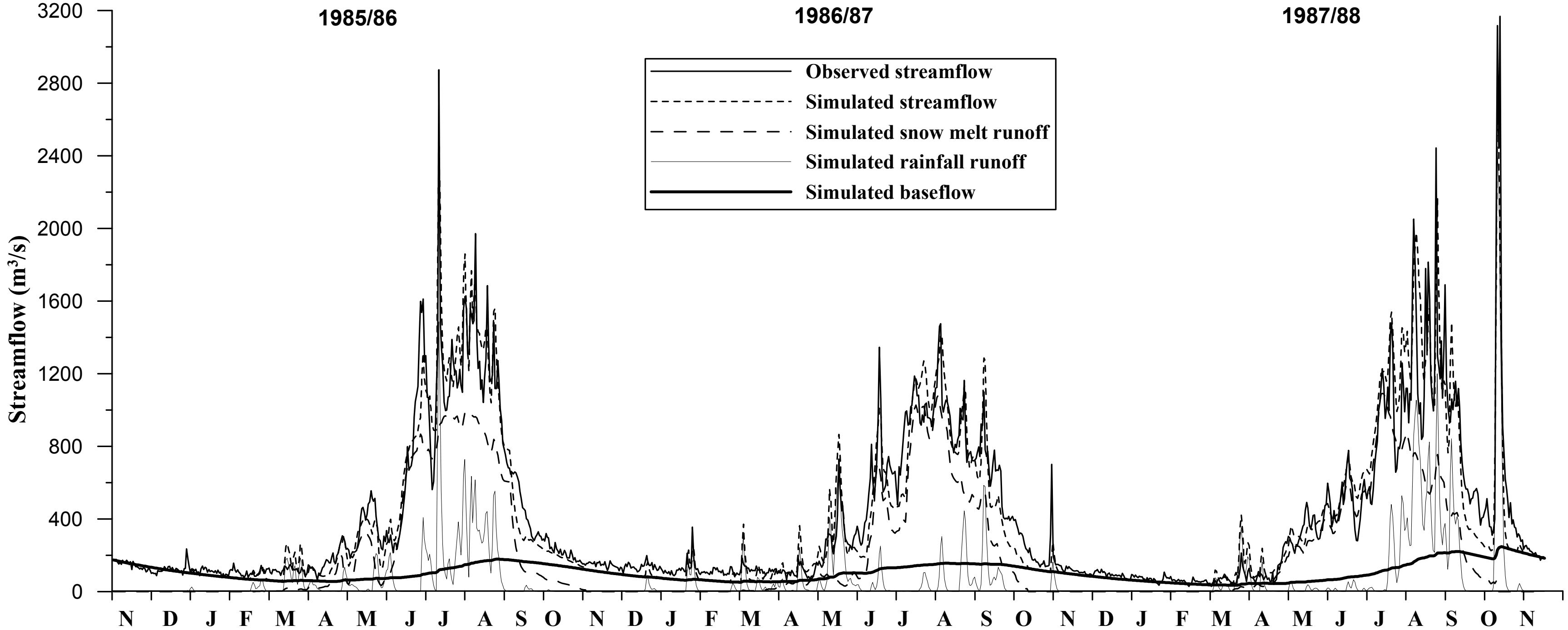

Fig. 5(a) Observed and simulated daily streamflow for the Satluj River (Indian part) at Bhakra Reservoir for the period 1985/86–1987/88.

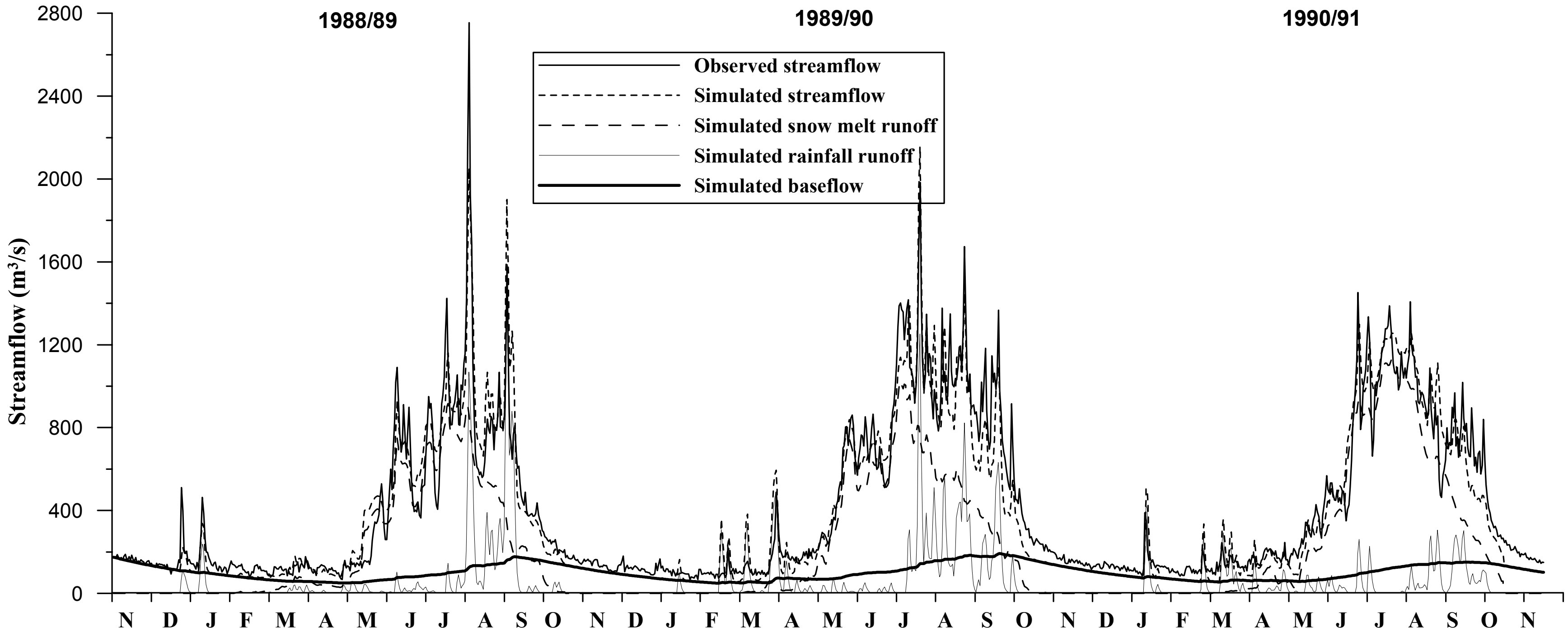

Fig. 5(b) Observed and simulated daily streamflow for the Satluj River (Indian part) at Bhakra Reservoir for the period 1988/89–1990/91.

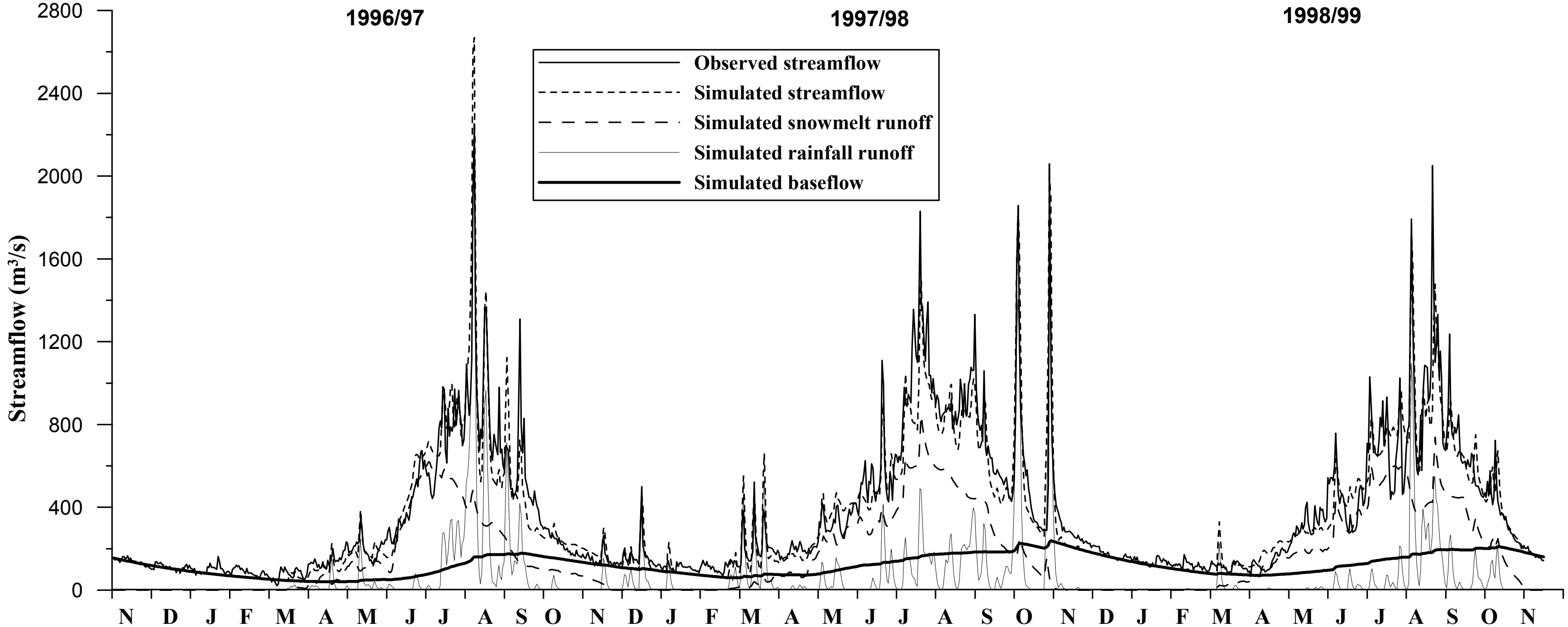

Fig. 5(c) Observed and simulated daily streamflow for the Satluj River (Indian part) at Bhakra Reservoir for the period 1996/97–1998/99.

Table 3 Model efficiency for simulating streamflow for the study basin for the different years.

	Year/Period	R^2	Volume difference, D_v (%)	Root mean square error (RMSE)
Calibration	1985/86	0.93	–2.1	0.29
	1986/87	0.85	–10.9	0.30
	1987/88	0.88	–2.4	0.41
Simulation	1988/89	0.90	–2.6	0.32
	1989/90	0.89	–4.2	0.31
	1990/91	0.90	0.3	0.28
	1996/97	0.87	–9.3	0.37
	1997/98	0.88	–8.8	0.30
	1998/99	0.85	–3.3	0.34
	Over 9 years	0.90	–3.3	0.32

during the summer period. No high peak was observed in the spring season from either rainfall or snowmelt. The simulation of baseflow indicates that the baseflow contribution to the streamflow increases with time, being at a maximum around the late summer period, and then decreasing. Higher contributions from the snowmelt and rainfall to the groundwater reservoir during the summer contribute to the higher baseflow. The baseflow sustains the flow of the river during the winter period, when there is neither snowmelt nor rainfall. Based on analysis of nine years data, it is found that the contribution of annual melt produced by rain to the total annual melt is not very significant (0.4–1.8%).

ESTIMATION OF SNOWMELT RUNOFF INTO SEASONAL AND ANNUAL STREAMFLOW

The ability of the model to simulate snowmelt runoff and rainfall runoff separately enabled to estimate the contribution of each component to the seasonal and annual total streamflows. The baseflow was separated into snowmelt and rainfall components using the contribution of these components to the baseflow both in different seasons and annually. On average over 500 mm annual runoff is generated from the whole basin and about 60% of this is received during the summer season. The estimated contribution of snowmelt and rainfall to the seasonal and annual flows is shown in Table 4. The snowmelt and rainfall contributions to the streamflow vary significantly from season to season. For winter and autumn, the rainfall contribution exceeds the snowmelt contribution, while for spring and summer, the snowmelt contribution is higher. The maximum rainfall and snowmelt contributions are generated during the summer season and the major share (about 60%) of the annual flow occurs during this season. This study suggests that about 75% of the summer runoff is generated from snowmelt runoff and the remaining 25% is from rain. The average contributions from snowmelt and rainfall to the annual runoff are estimated to be about 68 and 32%, respectively. In another study for this basin, Singh & Jain (2002) estimated the contribution of snowmelt and rainfall to the annual flows to be 59 and 41%, respectively, using the water balance approach, where runoff components were simulated and no seasonal estimates were made. The present study provides more accurate estimates.

Table 4 Contribution of snowmelt and rainfall to the seasonal and annual flows.

Season/annual	Total simulated runoff (mm)	Rainfall contribution: (mm)	% of total runoff	Snowmelt contribution: (mm)	% of total runoff
Winter	49.2	46.6	94.7	2.6	5.3
Spring	80.5	25.9	32.2	54.6	67.8
Summer	324.5	83.1	25.6	241.4	74.4
Autumn	79.2	41.9	52.9	37.3	47.1
Annual	533.4	171.5	32.2	361.9	67.8

CONCLUSIONS

The performance of the model to simulate daily streamflow and its components (rainfall, snowmelt and baseflow) for a highly snow-fed large Himalayan basin can be seen as satisfactory.

The model was calibrated for the study basin using continuous data of three years (1985/86–1987/88) and then used for simulating the daily streamflow for an independent data set of six years (988/89–1990/91 and 1996/97–1998/99). The model efficiency (R^2) for the calibration period varied from 0.85 to 0.93, while for the simulation period it varied between 0.85 and 0.90. Keeping in view the size of the basin and limited data availability, the results indicate that the model successfully simulated the streamflow for all the simulation years. It was observed that most of the peaks in the streamflow are generated by rainfall, but prolonged high flows are generated by the melting of snow. The model was also applied to estimate the contribution from snowmelt and rainfall to seasonal and annual flows. The analysis suggests that more than two-thirds of annual flow is generated from snowmelt runoff. The seasonal distribution of streamflow indicates that about 60% of annual flows is generated during the summer season and about 75% of this summer flow is obtained from snowmelt. Such estimates are useful for planning and management in this basin. This augurs well for the applicability of the model for other Himalayan basins.

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