Snowmelt Runoff Estimation from a Himalayan Catchment Using Snowmelt Runoff Model (SRM)

B.P. PARIDA
DEPARTMENT OF CIVIL ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY, HAUZ KHAS, NEW DELHI - 110 106.

Abstract

In an attempt to augment India's power generation potential, the Central Electricity Authority (CEA), India, has identified the middle Himalayan region together with the north-east region for implementation of new hydropower projects. A general feature of the Himalayan region is that areas below an elevation of 4,200m experience seasonal variation of snow cover. As a result, during hot weather periods, additional flows take place. Hence, reliable estimation of snowmelt is necessary for successful planning and design of structures across such streams. An attempt has been made to use a simple concept to achieve this goal. The Snowmelt Runoff Model (SRM) is one such model which is based on a degree-day concept. The model has been used for the Goriganga catchment, which originates from Milam Glacier in the middle Himalayas. Apart from satellite images, streamflow, rainfall, and temperature data for the year 1987 have been used to calibrate model parameters, which in turn have been used to estimate snowmelt runoff for the year 1988. A comparison of observed and simulated flows showed a good agreement . Based on the results, the model can be implemented for other snow-bound catchments too. However, the use of a large number of images and careful determinations of lapse rate are necessary for improvement in results.

Introduction

Ongoing demand, along with scarcity of power, has necessitated exploration of potential sites for hydroelectric schemes. According to the Central Electricity Authority of India (CEA 1985), of an estimated hydropower potential of 64,000MW, a major portion is available in the north-west and middle Himalayan and north-eastern regions of the country. Choice of sites in these regions has primarily been due to two reasons, viz., (i) their eco-friendliness and (ii) availability of continuous and sufficient quantities of water with large operational heads.

A general feature of the Himalayan catchments is that major portions of such mountainous catchments above 4,200m are permanently snow covered, and below this there are seasonal variations in snow cover. As a result, during hot weather periods a large quantity of additional flow takes place in the form of snowmelt runoff, which significantly changes the runoff characteristics of the stream. Proper simulation of such flows not only obviates high storage capacity for run-of-the-river schemes but also helps in day-to-day flow regulation of the schemes once implemented.

Of several available models, the Snowmelt Runoff Model (SRM) (Martinec 1975, Martinec et al. 1983) has been chosen for application to a real-life catchment in the middle Himalayan ranges, viz., the Goriganga catchment, where a large number of hydroelectric projects are under investigation as well as being planned for implementation in several phases.

Physics of Snowmelt

Generation of snowmelt at a point/location is a thermodynamic process, and the total quantity of melt is a function of the net heat exchange between the snow-pack and its environment. Heat exchange can be due to the following major components, namely,

a. absorbed solar radiation,
b. long wave radiation,
c. convective heat transfer, and
d. advective heat transfer.

These components can be grouped into two broad concepts for calculation of snowmelt runoff, viz:

i. an energy balance approach and
ii. a degree-day index approach.

Energy Balance Approach

The total quantity of snowmelt (in mm/day) due to the heat component from various sources can be expressed as ,

$$Q = Q_s + Q_l + Q_c + Q_e + Q_g + Q_r \quad (1)$$

where,

Q_s and Q_l are melt components due to short- and long-wave radiation,

Q_c and Q_e are components due to conduction and latent heat of condensation, and

Q_g and Q_r are melting due to heat input from ground- and rainwater respectively.

The above melt components can separately be expressed by the following equations:

$$Q_s = I_s (1 - C_l) (1 - A_l) \text{ mm/day,} \quad (2)$$

where,
I_s , C_l and A_l are the incident solar radiation (mm/day), cloud cover, and albedo of snowpack respectively.

$$Q_c = [\ 0.0212\ (T_a - 32\ ) - 0.84\ ] \times 25.4\text{mm/day}, \qquad (3)$$

where,
T_a = Air temperature at 10ft (3m) over the snow surface measured in °F under clear skies. This melt component can vary considerably under different environmental conditions, e.g., forest canopy and cloud cover.

$$Q_e = [0.054\ (Z_a.\ Z_b\ )^{-1/6}\ (e_a - e_o\ )\ U_b].\ \times 25.4\text{mm/day}, \qquad (4)$$

where,
Z_a and Z_b are heights of measurement (in ft) of the air vapour pressure and wind speed above the snow surface respectively, e_a and e_o are air and snow subsurface vapour pressure in mb, and U_b is wind speed in miles per hour.

While a nominal value of 0.508mm/day is taken for Q_g , Q_r is computed from

$$Q_r = (P_r T_r / 80) \qquad (5)$$

where,
P_r is rainfall depth in mm and T_r is the temperature of the rainwater in °C.

It is evident from the above that several climatic data are required for computation of snowmelt.

Degree-day Approach

The basic concept used in this approach is to express the snowmelt as a function of daily average temperature in degree-days. Because of the fact that air temperature data are usually available, this concept is very useful for easy implementation. The normal degree-day equation can be stated by

$$\text{Snowmelt} = AN\ (\ T_a - T_b\ ), \qquad (6)$$

where,
T_a = is the mean daily air temperature in °C,
T_b = is the base temperature in °C, and
AN = is the degree-day factor.

This concept is considered to have the best applicability to large basins and offers the twofold advantage of simplicity and speed with a reasonable degree of accuracy of forecast .

Choice of 'SRM'

A select list of various snowmelt models developed by various agencies, using the above two broad concepts, has been presented in Table 1.

Table 1. List of Some Snowmelt Runoff Models as Used in Various Parts of the World

S. No	Model Name	Location / Organisation	Year	Approach
1.	UBC Watershed Model	University of B.C., Canada	1974	Degree-day index equation
2.	CEQUEAU Model	University of Quebec, Canada	1971	Degree-day index modulated by a solar radiation factor
3.	ERM (Empirical Regression Model)	Bratislava, Czechoslovakia	1978	Degree-day index equation
4.	HBV Model	Swedish Meteorological and Hydrologic Institute	1976	Degree-day index equation
5.	Tank Model	National Research Centre for Disaster Prevention, Japan	1963	Degree-day index equation
6.	SRM	Federal Institute for Snow and Avalanche Research, Switzerland, and NASA, USA	1973	Degree-day index equation
7.	SSARR Model (Streamflow Synthesis and Reservoir Regulation)	Corps of Engineers, Portland, Oregon, USA	1967	Degree-day index equation
8.	PRMS Model (Precipitation Runoff Modelling System)	U.S. Geological Survey, USA	1973	Energy balance approach
9.	IHDM (Institute of Hydrology Distributed Model)	U.K., Denmark, France	1979	Energy balance approach

In arriving at a choice between the two concepts, it is important to know what information is available and, more so, the economic feasibility of procuring the elaborate data base necessary for use in the energy balance concept. On the other hand, if energy exchange processes are reasonably represented by air temperature variations, then the degree-day concept makes good sense. In light of these considerations, the SRM, based on the degree-day concept, emerges as one good option, as it is simple and does not require an elaborate historical data base. Also, the model can usefully be applied to catchments varying from 2.65sq.km to 4,000sq.km. in area, with a decrease in the degree of accuracy with increasing area (Rango 1985). More specifically, the model uses temperature, precipitation and snow-cover data on a daily basis, separate runoff coefficients for snow-covered and other areas, the temperature lapse rate, degree-day factors for snowmelt, the recession coefficient of discharge and time-lag information for the basin under consideration. What it probably does not perform in a rigorous manner is the water or snow budget analysis. However, considering its several other advantages, as noted above, the model has been chosen for study.

Brief Description of SRM

The structure of the SRM may be represented by a flow chart, as shown in Figure 1. The chief constituents of the model are (a) Pre-Processor, (b) Simulation Model, and (c) Model Output. A brief description of each follows.

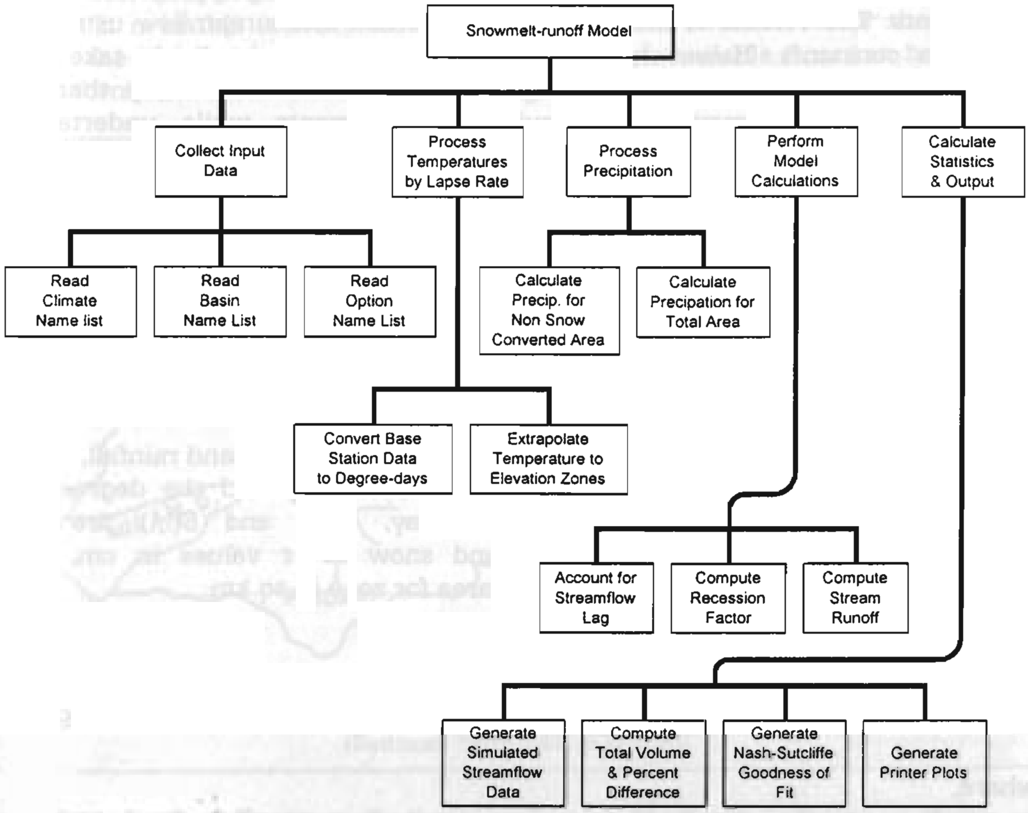

Fig.1: Fuctional Flow Chart of the Snowmelt-runoff Model Computer Programme

Pre-Processor

In the pre-processor of the SRM, data related to climate, basin, and programme execution options are read from the input file. Temperature data are then processed to compute degree-days at the hypsometric mean elevation for each zone, using the input lapse rate. Based on the degree-days, precipitation data are processed for the elevation zone and condition of snowpack.

The final degree-day factor, which is used to convert degree-days derived from temperature data to snowmelt, expressed in depth of water, is given by

$$AN = 1.1\ (e_s/e_w), \qquad (7)$$

where,

AN = degree-day factor (cm $^{\circ}C^{-1}$ x day^{-1}) with a range of 0.35 to 0.6,

e_s = density of snow, and
e_w = density of water

The Simulation Model

In the simulation model, runoff contributions due to snowmelt and precipitation from all the elevation zones are computed for each day using appropriate runoff coefficients. The volume of melt is then transformed into streamflow using the recession constants. However, runoff coefficients, which implicitly take into account other losses, have usually a higher value for snowmelt (C_s) than for rainfall (C_r). These may require suitable adjustments while undertaking simulation exercises, if runoff values appear too high or too low.

Contribution of snowmelt and precipitation to runoff on any day from all zones is given by

$$SUMRO(i) = \sum_j [C_s(i,j).AN(i,j).Z(j).S(i,j)+C_r(i).P(i,j).AREA(j).0.01/86400] \quad (8)$$

where,

i, j	=	are the day and zone index ,
$C_s(.,.)$ and $C_r(.)$	=	are the runoff coefficients for snow and rainfall,
Z(.) and AN(.,.)	=	are the degree-days in °C/day and the degree-day factors in cm/°C/day, P(.,.) and S(.,.) are the precipitation and snow cover values in cm, and AREA(.) is the area for zone in sq.km.

Total daily runoff is then calculated as

$$R_2 = M_2 (1- k) + R_1. k, \quad (9)$$

where,
R_2 = runoff on day 2 ; M_2 = melt on day 2 ; R_1 = runoff on day 1; and
k = Recession coefficient .

Model Output

As output the SRM produces discharge values on a daily basis from the start till the end of a snowmelt period, using the actual sequence of temperature and snow cover depletion data. Where flow observations are available, accuracy of such outputs is assessed using a Nash-Sutcliffe goodness-of-fit index based on percentage difference in volumes.

Case Study

The Study Area

For real-life application of the SRM, the Goriganga River basin bounded between 29° 45'N and 30° 38' N latitudes and 79° 59' E and 80° 30' E longitudes, and located in the Pithoragarh district of Uttar Pradesh, India, has been chosen. This river originates from the Milam glaciers in the Himalayan ranges at an elevation of 3,600m, primarily carrying snowmelt runoff, and then flows in a south-south-eastern direction till it meets the river Kali at Jauljibi, as shown in Figure 2. The catchment area covered by the river up to Devbagar is 1,600sq.km. Looking at the perennial flow availability, together with the availability of potential head, the National Hydro Power Corporation of India has identified four power generation sites (two up to Devbagar) with a target generation of 320MW of power. It is in this context that the basin has been considered for the present study, the idea being that a realistic estimation of available flow can be arrived at for formulation of other structural designs.

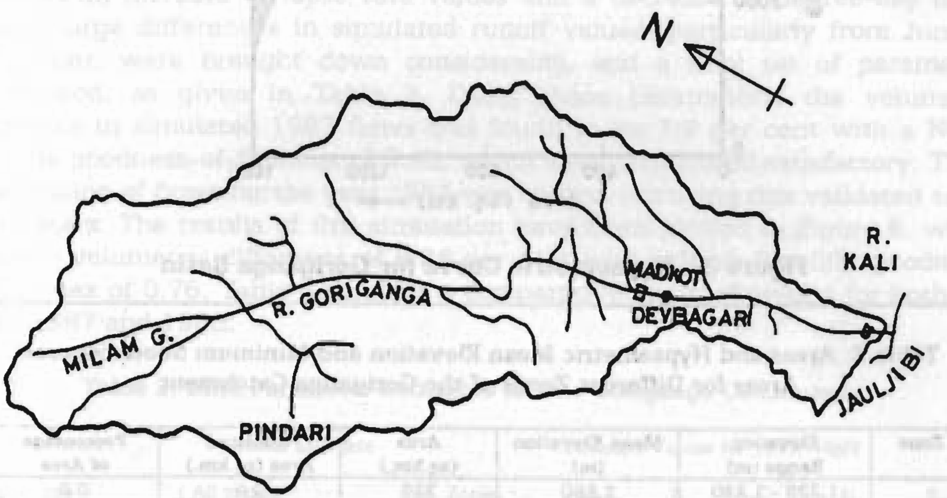

Figure 2: Catchment Plan of River Goriganga
(Reduced from 1:50,000 map)

Climatologically, the area experiences snowmelt during the months of March to September, while during the months from June to September the area receives an additional contribution from monsoon rains.

Data Base and Initial Assumptions

Daily rainfall, streamflow, and air temperature data were available at Devbagar for the years 1987 and 1988 for this study. To obtain the hypsometric mean elevation for this area, the catchment has been divided into five zones (viz: A,B,C,D and E) and the hypsometric mean elevations computed for each zone, as shown in Figure 3, have been tabulated in Table 2.

The glaciated area in each zone has been taken to be the minimum snow cover in such zones. To establish the snow depletion curve for each zone, available LANDSAT images of 12.3.87, 12.5.87, and 18.8.87, covering this catchment, have been used. However, in the absence of more images and other data, the depletion curve has been assumed to follow the general trend of retreat in the Himalayas, as shown in Figure 4.

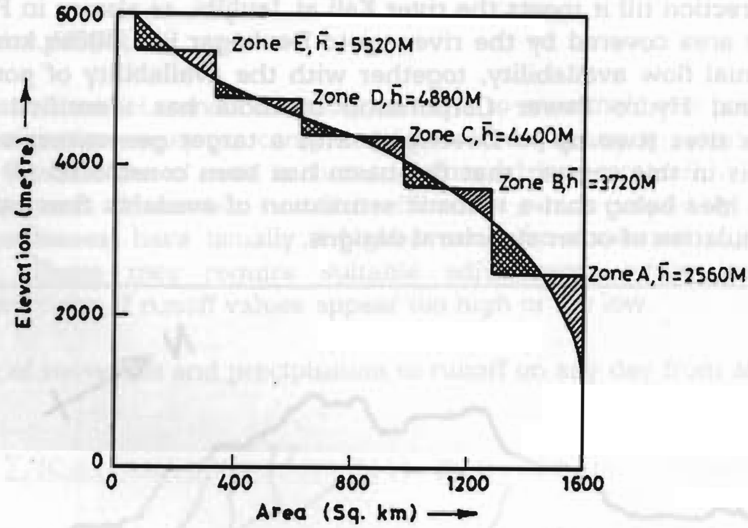

Figure 3: Hypsometric Curve for Goriganga Basin

Table 2: Areas and Hypsometric Mean Elevation and Minimum Snow-covered Areas for Different Zones of the Goriganga Catchment

Zone	Elevation Range (m)	Mean Elevation (m)	Area (sq.km.)	Glaciated Area (sq.km.)	Percentage of Area
A	1,226 - 3,280	2,560	320	0.0	0.0
B	3,280 - 4,120	3,720	320	12.5	3.94
C	4,120 - 4,640	4,400	320	140.0	44.0
D	4,640 - 5,120	4,880	320	191.0	59.6
E	5,120 - 6,000	5,520	320	224.0	70.0

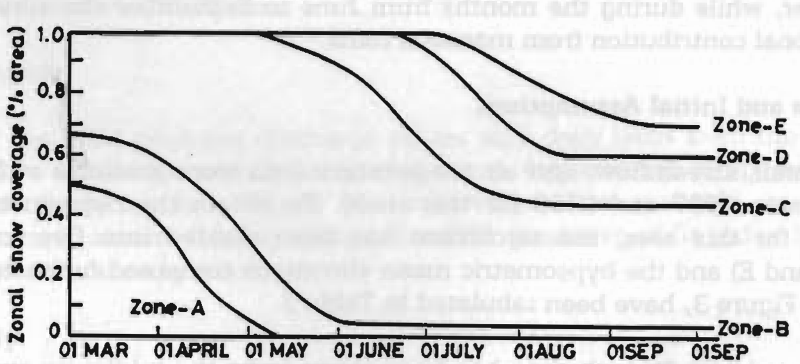

Figure 4: Snow Depletion Curves in Goriganga Basin

As an initial estimate, a lapse rate of 0.65°C/100m has been assumed for all altitudes. A critical temperature of 1°C has been assumed for the months of June to September, while 3° C has been assumed for all other months. Initial values of the degree-day factor for the period from March to September have been taken between 0.15 and 0.6, while the coefficient of runoff for snow and rain has been adopted as 0.59 to 0.75 and 0.9 to 0.6 respectively from the beginning of the snowmelt season to its end.

Analysis of Results

Using the above initial values of parameters, along with other observed data, starting from March 1987, flow simulation was carried out for the year 1987, which resulted in large differences between the observed and simulated flows. Through an increase of lapse rate values and a decrease in degree-day index values, large differences in simulated runoff values, particularly from June to September, were brought down considerably, and a final set of parameters determined, as given in Table 3. Using these parameters, the volumetric difference in simulated 1987 flows was found to be 7.9 per cent with a Nash-Sutcliffe goodness-of-fit index of 0.83, which were considered satisfactory. Then, a simulation of flows for the year 1988 was carried out using this validated set of parameters. The results of this simulation have been plotted in Figure 5, which shows a volumetric difference of 9.28 per cent with a Nash-Sutcliffe goodness-of-fit index of 0.76. Table 4 displays a comparative study of results for both the years 1987 and 1988.

Table 3: SRM Parameter Estimates for the Goriganga Catchment

Parameter	Initial Estimate	Adopted Values for 1987/ 1988					
1. Lapse rate	(All zones)	Zones	A	B	C	D	E
	0.65 MAR to SEP	MAR	.85	.85	.85	.75	.75
		APR	.80	.80	.75	.70	.70
		MAY	.75	.75	.70	.70	.70
		JUN	.70	.70	.70	.65	.65
		JUL	.75	.75	.70	.70	.70
		AUG	.85	.85	.80	.75	.75
		SEP	.90	.90	.85	.75	.75

Parameter	Initial Estimate	Adopted Values for 1987/ 1988
2. Critical temp. for snowmelt	3.0 MAR to APR 2.5 MAY 1.0 JUN to SEP	3.0 MAR to APR 2.5 MAY 1.0 JUN to SEP
3. Precipitation method option	0. MAR to APR 1.0 MAY to SEP	0. MAR to APR 1.0 MAY TO SEP
4. Coefficients of runoff for snow (0.95-0.75)	0.95 MAR 0.90 APR 0.80 MAY to SEP	0.95 MAR 0.90 APR 0.80 MAY to JUL 0.75 AUG to SEP
5. Coefficients of runoff for rain (0.9-0.6)	0.80 MAR APR 0.70 MAY 0.65 JUN to SEP	0.80 MAR 0.75 APR 0.65 MAY 0.60 JUN to SEP
6. Degree-day factor	0.15 MAR 0.20 APR 0.25 MAY 0.35 JUN 0.45 JUL 0.55 AUG 0.60 SEP	0.15 MAR 0.15 APR 0.16 MAY 0.20 JUN 0.20 JUL 0.20 AUG 0.22 SEP

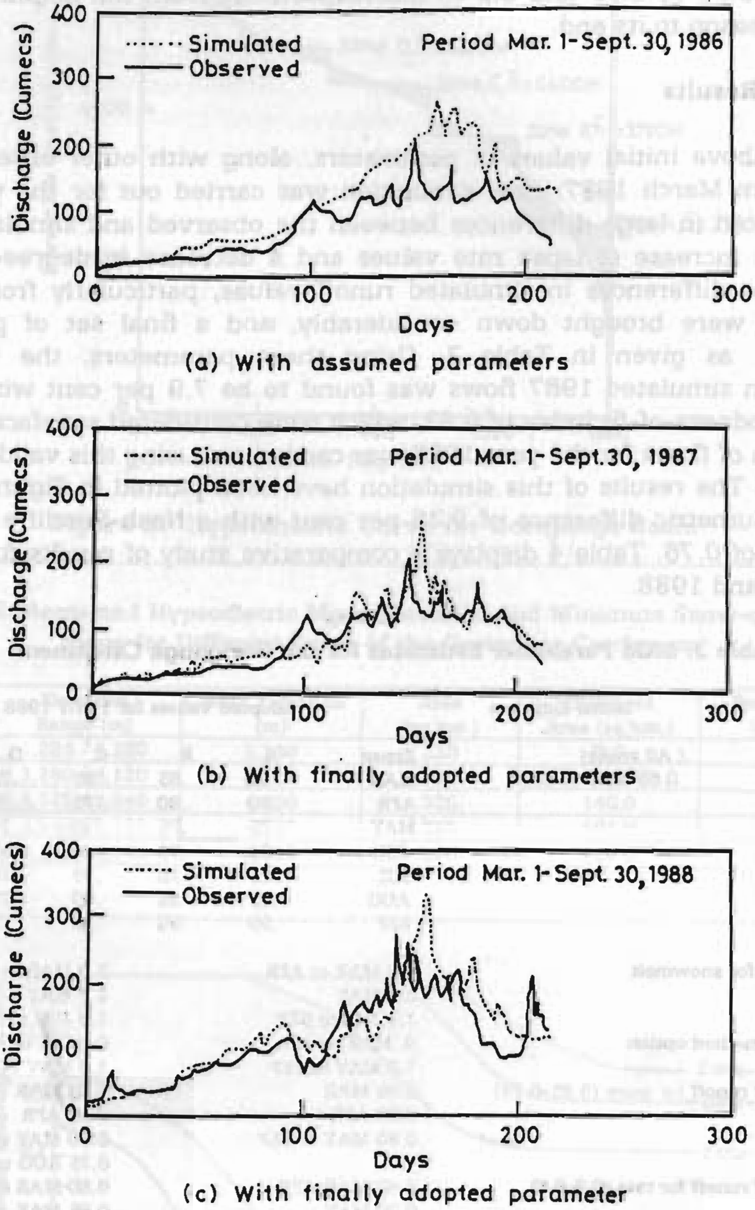

Figure 5: Observed and Simulated Flows or River Goriganga at Devbagar

Table 4. Model Calibration and Validation Results for the Goriganga Catchment

Item	Observed volume (cum)	Observed mean flow (cumec)	Computed volume (cum)	Computed mean flow (cumec)	Total diff. in vol. (%)	N-S fit index
Year 1987 (assumed parameters)	16,743.95	78.24	23,926.68	111.8	42.91	-
Year 1987 (adopted parameters)	16,743.95	78.24	18,076.68	84.47	07.95	0.85
Year 1988 (adopted parameters of 1987)	23,571.20	110.14	25,758.81	120.36	9.28	0.76

Conclusions

From the study, it may be concluded that flow simulation for a fully or partially snow-covered mountainous catchment using SRM seems to be satisfactory. Since the model is easily implementable and does not require an elaborate data base, it can be used in cases of adopted other such snow-bound catchments for flow simulation on a daily basis. It was found that since the SRM is very sensitive to parameters such as lapse rate and the degree-day index, it thus needs careful tuning. Another important factor on which the runoff depends is the snow cover depletion rate curve, and this needs to be established and updated using frequently obtained images if better simulation results are to be obtained.

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