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A Simple Monthly Runoff Model for Snow Dominated Catchments in Western Himalayas

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The rivers originating from middle and greater Himalayas have a significant part of their catchments under permanent snow cover and glaciers. Modeling runoff becomes difficult with almost no data from these parts. Even in the seasonal snow covered zones, the network is generally inadequate. However precipitation characteristics show repetitiveness and snowline movement elevation wise by and large occurs the same pattern each year. The snowline movement is distinct on a monthly basis and the location of permanent snowline is also more or less constant at about 4,500 m.

A simple monthly snowmelt runoff model with relatively few parameters is proposed to take advantage of above mentioned characteristics, using the degree day method. The model uses monthly rain, snow (snow water equivalent), mean air temperature and snowline elevation as primary inputs. Model conceptualisation has been made in view of the data constraints. All parameters are estimated through few trial simulations, except the storage coefficient, which is optimised using Rosenbrock technique.

The model was applied on two sub-catchments of Chenab basin (of Indus river system) to evaluate the model capability. The results are encouraging. There is further scope for model improvement, generalisation and for application to other catchments in the Western Himalayas.

Introduction

Diverse, topographical, geological and hydrological conditions in Himalayas make snowmelt runoff modeling difficult. At higher elevations (upper Himalayas) a significant part of the catchment is under perpetual snow and glaciers. There is almost no data available from permanent snowcovered zones, except their areal extent, obtained through synoptic coverage of remotely sensed data. Even in the zone of seasonal snow cover the observational network is poor and inadequate.

Runoff modeling has been the central problem of hydrology. A simple model based on simplified assumptions was applied on a monthly basis to two subcatchments of Chenab located in upper Himalayas using conventional data of precipitation and air temperature, besides remote sensing. The simple model structure divides the catchment into several elevation bands and utilises snowline movement data along elevation bands from remote sensing imageries on a monthly basis. The designated elevation bands with mean snowfall are forced to melt as flow during each month. From all higher elevation bands, considered as reservoirs, the model draws meltwater by degree day approach using lapsed temperatures and degree-day factors. Rain on snowfree area is converted to flow using simple runoff coefficients. Finally the integrated flows are routed through a linear reservoir with an optimised storage coefficient using the least square criterion.

Review

Several snowmelt forecasting models have been developed to suit specific needs and hydrologic conditions. These are either data intensive and/ or are complex to handle. Very few models can handle varied hydrologic conditions in general. The popular ones include SAARR (US Army 1972), SRM (Martinec 1975), PRMS (Leavesley 1983), UBC (Quick *et al.* 1977) *etc.*

In India, some efforts have been made for modeling rainfall-runoff in Himalayan catchments. Roohani (1986) carried out a detailed study for modeling runoff from several subcatchments in Chenab basin. His model was based on a split watershed approach by subdividing it into permanent snow covered, temporary snow covered and snow free zones. Runoff coefficient from the above three zones along with two routing coefficients were optimised using the least-square criterion for computing daily flows. Seth (1983) developed a similar model for Sutlej basin using pattern search optimisation. Singh and Quick (1993) have applied the UBC model for simulation of flows in the Sutlej river. Kumar *et al.* (1991) applied SRM model to river Beas in Himalayas. Rao *et al.* (1991) also used SRM model with some modifications for its application to river Beas. A regression model using percentage of snowcovered area of Satluj basin above Bhakra and seasonal snowmelt runoff was developed by Ramamorthi (1983; 1987). Ferguson (1985) made a study of Indus rivers in Himlalayas and developed a model using glaciological and climatological factors, besides snow cover area on an annual basis. Some of his important findings include:

i) The melt season commences around March in Himlalayas and the contributions from snowmelt continue upto Sept.
ii) Simple degree day approach is well suited for typical conditions of data availability and physical processess in Himalayan basins.
iii) There is a good correlation between snowmelt runoff and snowcover area for Himalayan basins.

Description of Catchment

The Chenab catchment has been described in detail by Roohani (1986), Sud *et al.* (1989) and Singh *et al.* (1993). The Marusudar river subcatchment of Chenab, upto Sirshi and Kuriya bridge site relevant to the study area is however, briefly discussed here.

The Marusudar river originates at an altitude of 6,000 m in the greater Himalayas. In the beginning two streams namely Batkot and Gumbar join to form Warwan river, which is known as Marusudar River in the lower reaches. Some of the main tributaries of Marusudar are Helka Nala, Rein Nala, Kair Nala and Nath Nala upto Sirhsi bridge. River Marusudar flows almost north to south direction till its confluence with Kiyar nala upstream of Sirshi gauge site where it meanders east to west. Thereafter it traverses for 4 km southwards to join Chenab river just downstream of Kuriya gauge site at Bandalkot.

The fan shaped catchment of 5th order stream encompasses an area of 3,535 sq km and 4,812 sq km upto Shirshi and Kuriya Gauge site respectively. The elevations range from 1,700 m to 6,000 m. More than one third of the catchments is under perpetual snow and glaciers. The permanent snowline is at about 4,500 m. The seasonal snowline normally comes down to 2,000 m, covering almost the entire catchment under snow during winter. The catchment is virtually a cold desert with sparse vegetation in the lower reaches. The geologic conditions have been reported as Paleozoic sedimentary belt and Metamorphic crystalline (Roohani 1986).

The subcatchment upto Sirshi and Kuriya gauge site are shown in Fig. 1. Area elevation curve is shown in Fig. 2. Some important geomorphological parameters of the two subcatchments are presented in Table 1.

Data Availability

Daily data of precipitation temperature and flow are available for 18-20 years since 1967. Precipitation is recorded as rain and snow (snow-water equivalent) separately at 8 stations within the study catchments described earlier. The highest station (Rikhinivas) is located at an altitude of 3,660 m. Elevation wise the network covers only one third of the catchment upto Shirshi and nearly half upto Kuriya gauging stations. Further, the entire network of stations is below the mean weighted elevations of the the two subbasins (3,848 m and 4,076 m). Temperature is recorded at Sirshi (1,700

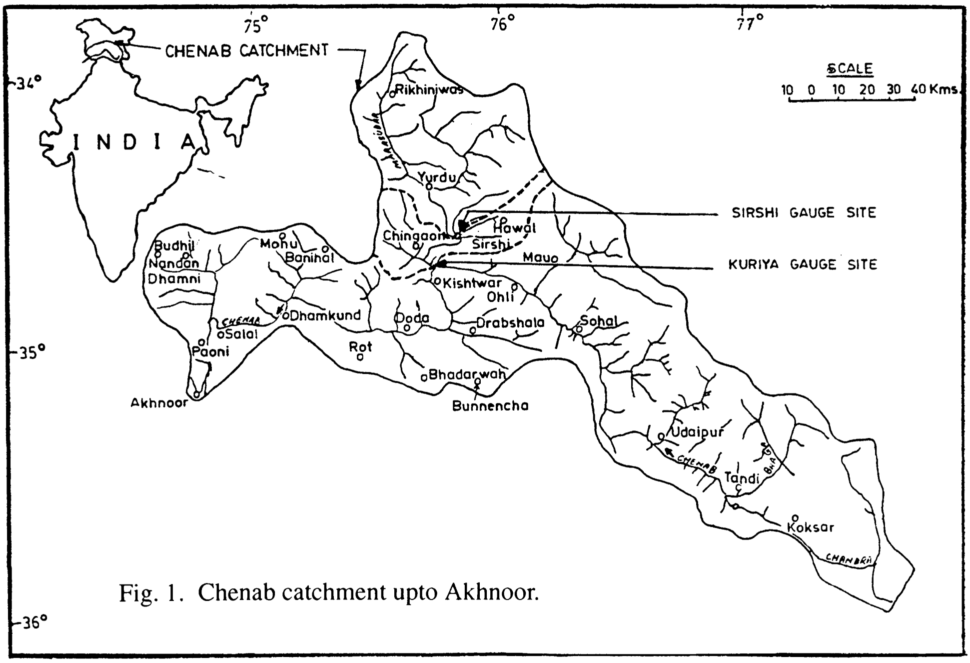


Fig. 1. Chenab catchment upto Akhnoor.

Table 1 – Geomorphological parameters of Marusudar subbasin

		Upto Sirshi Gauge site	Upto Kuriya Gauge site
1.	Area (km^2)	3,535.00	4,812.00
2.	Basin length (km)	85.00	96.20
3.	Basin shape factor	1.88	1.87
4.	Length of main stream channel (km)	109.00	142.80
5.	Drainage density	0.54	0.56
6.	Relief ratio	0.05	0.05
7.	Channel slope (%)	2.74	2.51
8.	Stream frequency	0.18	0.19
10.	Modified Hickok *et al.* (1959) parameter	1,782.00	2,537.00
11.	Gray's (1961) parameter	66.33	90.06
12.	Ruggedness No.	2.53	3.05

Source: Roohani (1986).

m) and Tillar (2,165 m) twice a day (max and min) within the catchment. No temperature data is observed at higher elevations. Precipitation, temperature and discharge data were obtained from publications of Central Water Commission (1990, 1991, 1993) and monthly movement of snowline elevation wise from landsat satellite (band 5) imagery.

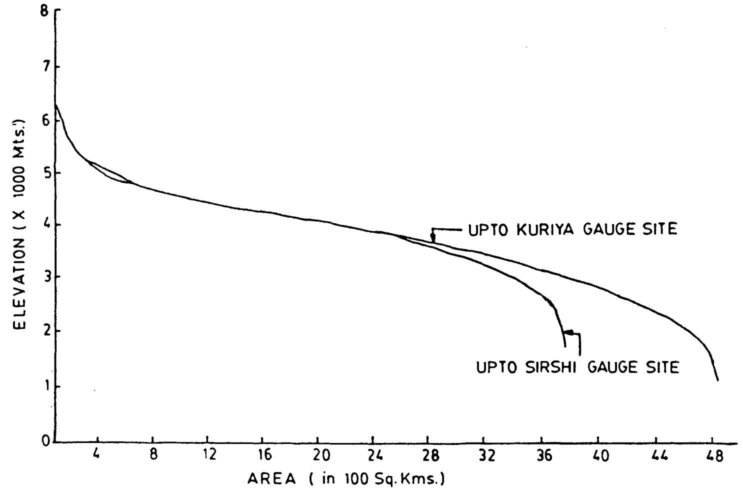


Fig. 2. Area Elevation characteristics of Marusudar river subbasin.

Precipitation and Runoff Characteristics of Study Catchments

The precipitation and runoff characteristics in Himalayas have been described in great detail by Upadhayaya and Bahadur (1982), Roohani (1986) and Singh *et al.* (1993). The details relevant to the study area are briefly discussed here.

Precipitation in greater Himalayas is predominantly in the form of snow. Precipitation occurs almost throughout the year in the form of rain or snow. The most important factors controlling weather and climate in Himalayas are the altitude and aspect. While a significant amount of rainfall occurs during monsoon season its areal influence tapers to elevation at about 4,000 m.

The winter precipitation from western disturbances results in accumulation of snowpack from November to March. The snowline descends to an average elevation of 2,000 m almost covering the entire subcatchments. In some years snowfall occurs during April and May also and are confined to higher elevations only. With rise in temperatures in spring, snowmelt begins during March/April and the snowline gradually shifts upwards to permanent snowline to about 4,500 m towards the end of July/August.

The precipitation pattern in Marusudar river subcatchments of Chenab is depicted in Table 2, showing 20-year averages of precipitation at eight rain/snow gauge stations covering the two subbasins. Table 2 gives a picture of rain as a major contributor of river flows. This is however not true, instead the converse holds good. This is because the rainfall by and large becomes negligible beyond 4,000 m, while snowfall increases with elevation. The area of the catchment upto Shirshi and Kuriya Gauge site below 4,000 m is less than 40% and 55% of the area of the total catch-

Table 2 – Precipitation pattern in Marusudar river subbasin (20-year averages)

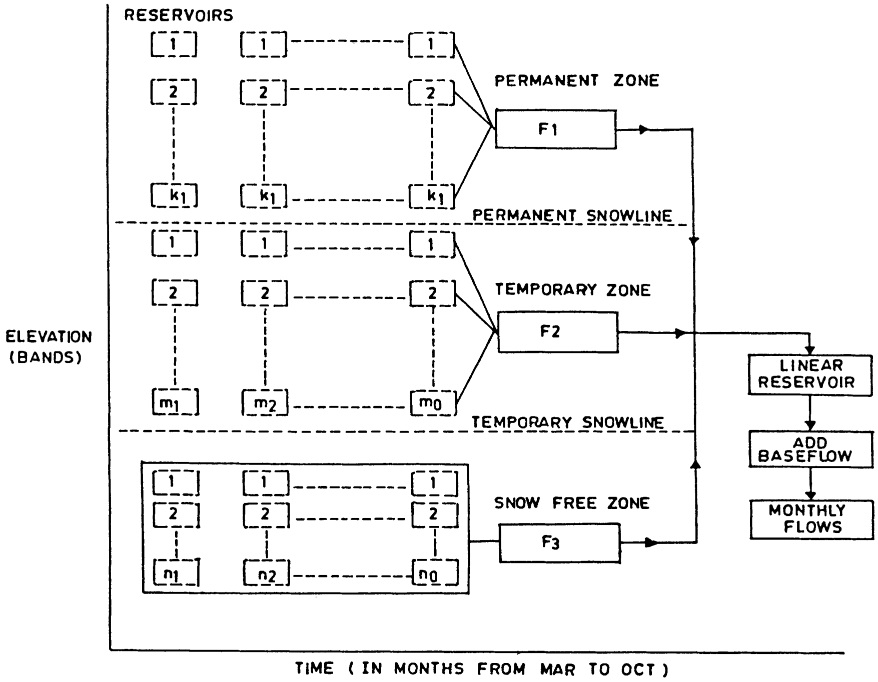
S.No	Station	Ele (m)	Annual Ppt (cm)	Monsoon Rain (cm)	Percentage Rain	 Snow
1.	Sirshi	1,700	103	27	71	29
2.	Chigoan	1,840	184	42	61	39
3.	Tillar	2,130	104	27	67	23
4.	Yardu	2,165	75	15	64	36
5.	Sarkund	2,350	61	16	62	38
6.	Inshan	2,440	102	26	53	47
7.	Hawal	2,745	193	50	48	52
8.	Rikhinivas	3,660	154	28	33	66

ment. The water balance of permanent snowcovered zone is not known. It could be negative or positive for several years continuously. The precipitation during the premonsoon season occurs mostly in the form of rain in lower elevations starting in March/April and extend upto May/June. During this period rain-on-snow is common in lower reaches and occasionally at higher reaches.

During monsoon period, the air temperatures are highest which result in snowmelt from both temporary and permanent snow zones. The monsoon flows generally carry a greater component of snowmelt compared to flows resulting from monsoon rains (as will be seen later). The flows during October comprise of mostly subsurface and base flows. Flows during the period of November to February essentially constitute the base flow and their variation from year to year is generally small.

Simulation and Runoff Modeling

A simple deterministic and continuous model based partly on degree-day method is proposed to simulate runoff on a monthly-basis from snow dominated catchments, using meteorological inputs of precipitation and mean-air temperature. The model is designed to simulate flows from relatively large catchments in western Himalayas on a monthly timestep and therefore has a coarse resolution. Monthly time step was chosen considering the sparse data generally available along time from remote sensing imageries, and hence the model is not intended for operational purposes. The catchment is subdivided into several elevation bands to give a distributed effect to the model. The snowline movement (snow depletion) data from remote sensing imageries used by the model lends a reasonable physical basis to the model. The model is however not designed for water balancing and as such no soil moisture accounting is performed.



Note:

k = No. of elev. bands in perm. snow zone connected in parallel (constant) (suffix indicates months starting March to October)

m = No. of elev. bands in temp. snow zone connected in parallel (variable)

n = No. of elev. bands in snow free zone (variable & taken as cumulative sum each month) k•m•n is always constant

F_1= Flow restricted by lapsed temps. and degree day factors

F_2= Flow restricted by availability of snow pack and degree day factors

F_3= Flow from rainfall using runoff coefficients

Fig. 3. Schematic diagram of monthly runoff model.

Model Structure

Conceptually the model divides the catchment into 3 zones. These include the permanent snowcovered zone, the temporary snow covered zone and the snowfree zone. Each zone is further subdivided into several elevation bands through the area elevation curve.

The conceptual model algorithm based on certain assumptions may be described in a number of steps as follows. The basis of assumptions are also briefly described. The model is schematically represented in Figs. 3 and 4.

1) Rain and SWE (Snow-water equivalent) are handled separately on a monthly basis starting November each year (time lumped as one month) by the model. It is assumed that snow pack is zero below permanent snowline beginning November.

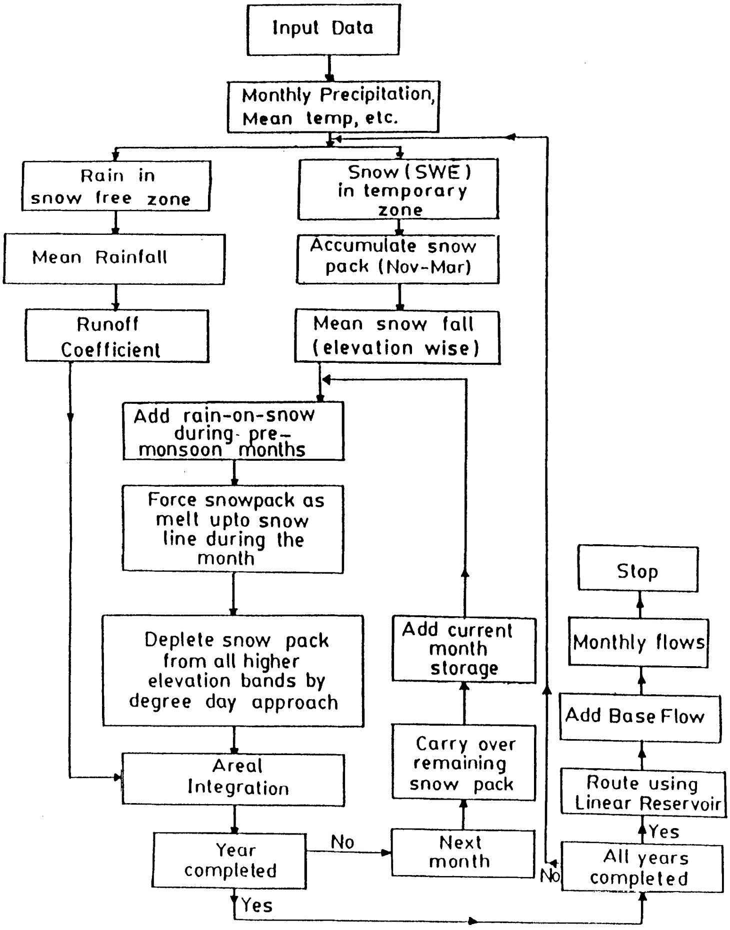


Fig. 4. Logical representation of model.

2) Low flows during the period from November-February is considered to be the base flow, since it exhibits minimum deviation. Precipitation falling as rain at lower elevations if any during this period is converted to flow using simple runoff coefficients. Snowmelt is assumed to take place only during the period starting March through October .
3) The permanent snowcover zone is assumed to be constituted of a fixed number of reservoirs connected in parallel and located in various elevation bands. Each reservoir is assumed to be of "large" capacity with melt controlled by lapsed temperatures and degree day factors. The assumption is based on snowline movement during 4 years (see Fig. 5), wherein the permanent snowline is more or less at 4,500 m. Variable temperature lapse rate each month is assumed (see Table 3) with base temperature at 0°C based on a study by Singh (1991).

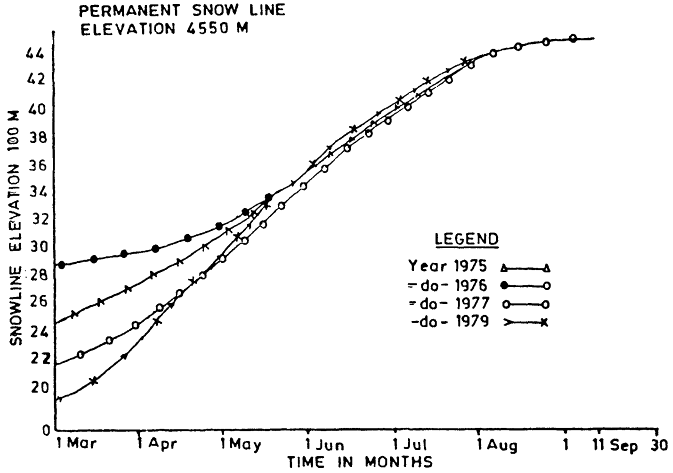


Fig. 5. Relationship between snowline elevation and time for Marusudar river subbasin (Source: Roohani 1986).

Table 3 – Parameters arrived through trial simulation

Month	1 Nov	2 Dec	3 Jan	4 Feb	5 Mar	6 Apr	7 May	8 Jun	9 Jul	10 Aug	11 Sep	12 Oct
LR	–	–	–	–	3.5	2.9	2.2	2.3	3.7	4.0	3.7	3.00
LR	–	–	–	–	3.5	3.0	2.2	2.3	3.7	4.0	3.7	3.80
RF	0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.8	0.8	0.7	0.70
RF	0.6	0.5	0.5	0.5	0.4	0.5	0.6	0.6	0.8	0.8	0.7	0.50
IF	0.3	0.2	0.2	0.05	0.03	0.14	0.2	0.33	0.4	0.45	0.45	0.40
IF	0.4	0.4	0.2	0.05	0.02	0.14	0.25	0.38	0.45	0.45	0.40	0.10
DF	–	–	–	–	0.01	0.02	0.04	0.10	0.31	0.17	0.09	0.03
DF	–	–	–	–	0.03	0.01	0.04	0.08	0.21	0.12	0.08	0.01

Note:

1. First row for each parameter represents Marusudar subcatchment upto Sirshi Gauge site and second upto Kuriya Gauge site.
2. LR ≡ Temperature lapse rate in degree Centigrade/Km
3. RF ≡ Rainfall runoff coefficient
4. IF ≡ Area integration factor is the ratio of cumulative area of elevation bands upto snowline to total area of catchment. It also depends on areal extent of rainfall once the snowline exceeds 4,000 m. by Jul/August.
5. DF ≡ Degree day factors (cm/ deg C/ day).

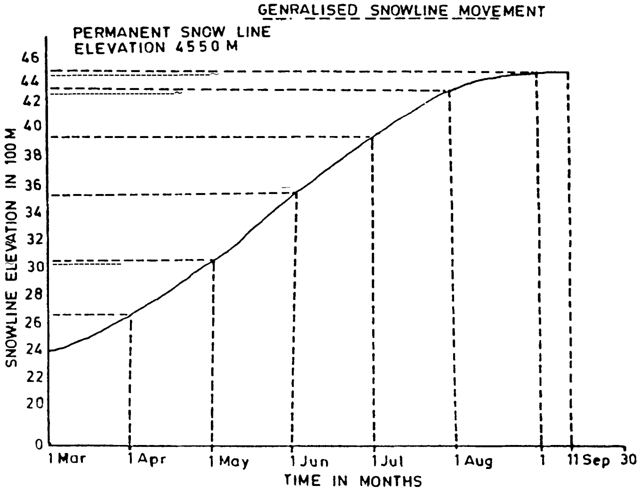


Fig. 6. Generalised relationship between snowline and elevation.

4) The seasonal snow cover (temporary) zone is assumed to be constituted of a variable number of elevation bands (with reservoirs connected in parallel) determined by a generalised snow movement line (see Fig. 6) each month representing snowline movement. The generalised snow depletion curve has been drawn based on 4 years of data. Area of elevation bands (under snow) is numerically a step function of the elevation determined by snow movement line along time (months). Snowline elevation is, distinct on a monthly basis. Flow from temporary snow cover zone is taken as the sum of:

   i) Flow obtained by forcing snowpack as snow melt from different elevation bands along the snowline, each month upto the permanent snowline position (4,500 m).
   ii) Flow obtained from all higher elevation bands using the degree day approach. Flows are however restricted by availability of snowpack in the temporary zone. Flows from permanent zone are guided by procedure described in step 3 above.

5) Initially the snowpack is accumulated from November to March during winter and mean snowpack (SWE) is allocated to each elevation band. Snowfall occurring at highest station is assumed to hold good for elevation bands beyond and upto the permanent snowline. Snowfall occurring during subsequent months is accounted each month, through the melt season.
6) During the period March to October in the temporary snow zone, snowpack left in each elevation band is carried over to next month. Snowpack left after October is carried over to the next melt season (starting March) and it is considered that no melt occurs during the period from November to February.

7) The snowfree zone is similarly considered to be constituted of a variable number of elevation bands in accordance with snow movement line each month. Rain falling on snowfree area (taken as cumulative area of elevation bands below snowline and assumed as a single reservoir – lumped spatially) is converted as flow using simple runoff coefficients and area integration factors fixed for each month. Area integration factor (IF) is the ratio of the area of below snowline (snowfree area) to the total area along the melt season.
8) Rain-on-snow is a complex phenomena occurring mostly during premonsoon months of March to May. During this process a certain amount of heat is added to the snowpack. The model handles this in a simplified way. Since raingauge elevations are known, mean rainfall is added to snowpack (as SWE) in all elevation bands beyond snowline and upto and slightly beyond the reporting raingauge elevation. The model implicitly forces snowpack as melt in relevant elevation bands as described in step 4i). For higher bands the increased snowpack due to rain on snow is depleted by normal method of degree day approach. Increased air temperatures responsible for rain-on-snow are expected to account for the melt from higher elevation bands.
9) Accuracy in computations of mean areal snowpack and rainfall primarily depends on adequacy of network and may be computed by various methods. The actual method used for computing the mean rain and snow for the two subcatchments under study is discussed later.
10) Rainfall is assumed to be negligible beyond 4,000 m based on the study by Singh *et al.* (1993).
11) Flows from the three zones discussed above are integrated (areal convolution) and routed through a linear reservoir (Chow 1991) with an optimal storage coefficient K using least square criterion (Rosenbrock technique) to obtain computed flows. All other parameters are estimated through trial simulations.
12) The area integration factor (IF) are (see Table 3) kept constant depending on area of snowfree zone each month (although areal extent of rainfall varies with each individual storm event). Once the snowline exceeds 4,000 m by July/August, the IF value depends on average areal extent of rainfall each month arrived through optimisation. This is reasonable for a model with coarse temporal resolution.

Sources of Error in Model

Following errors are likely to occur, when model assumptions are violated or have not been considered.

1) Spatial variability may not be accounted for properly due to inadequate network of rain/snowgauges.

Table 4 – Snowline position along Elevation bands and time (Months)

Shirshi Gauge site			Kuriya Gauge site		
Area in km^2	Mean Elevation (m)	Month starting Nov	Area in km^2	Mean Elevation (m)	Month starting Nov
10	2,000	–	98	1,710	–
90	2,200	5	71	1,950	–
85	2,500	5	105	2,100	–
100	2,750	6	120	2,300	5
100	2,950	6	84	2,450	5
100	3,025	6	86	2,550	5
100	3,150	7	85	2,650	5
100	3,250	7	100	2,750	6
100	3,300	7	114	2,850	6
100	3,350	8	114	2,950	6
100	3,500	8	107	3,050	7
100	3,600	8	100	3,150	7
100	3,750	8	124	3,250	8
100	3,800	8	148	3,350	8
100	3,900	9	148	3,450	8
100	3,950	9	164	3,550	8
100	4,025	9	164	3,650	9
100	4,060	9	169	3,750	9
100	4,130	10	191	3,850	9
100	4,170	10	194	3,950	9
100	4,240	10	225	4,050	9
100	4,270	10	217	4,150	10
100	4,320	10	100	4,250	10
100	4,360	10	100	4,300	10
100	4,400	10	200	4,350	10
100	4,430	10	222	4,450	10
100	4,500	10	224	4,550	10
100	4,530	11	191	4,650	–
100	4,610	–	145	4,750	–
100	4,650	–	129	4,850	–
100	4,825	–	107	4,950	–
100	4,900	–	105	5,100	–
100	5,050	–	95	5,300	–
100	5,150	–	90	5,560	–
100	5,500	–	110	5,900	–
150	5,900	–	70	6,250	–

2) Orographic effect beyond highest reporting raingauge elevation has not been considered.
3) Movement of snowline may not confirm to that used for calibration at all times.
4) Permanent snowline position may vary year after year.
5) Rain-on-snow needs energy budget approach for adequate simulation.
6) The time step (Delta = 1 month) used in linear reservoir routing has been taken as constant (30.6 days average) instead of 30 and 31 days during March to October.
7) Effect of slope and aspect have not been considered.
8) There may be correct simulation due to compensating effect of two incorrect parameters *e.g* lapse rate and degree day factor in a given month (Martinec 1986)

Model Application

The model was applied on study catchments discussed earlier using available data to evaluate model capability. Satellite data of Landsat 2 and 3 (MSS for band 5) having a frequency of 18 days as analysed by Roohani (1986) for snowline elevation along melt season for 4 years (see Fig. 5) was used. Each catchment was subdivided into 36 elevation bands. The permanent zone constituted of ten elevation bands starting at about 4,500 m approximately (Table 4). The remaining elevation bands were distributed among temporary and snowfree zones consistent with snowline position each month. Mean snowfall was computed elevation wise as average of SWE from snowgauges located in one or more adjacent elevation bands. Mean rainfall was computed as weighted average. Weights were assigned as ratios of 20-year mean monthly rainfall at a station to the sum of the 20-year mean-monthly rainfall of all stations within the basin. This gives greater weight to stations in high rainfall zones. However, simple arithmetic mean-computed rainfall did not change model results significantly. Mean temperatures at Shirshi station were used for both the subcatchments.

Water year was assumed to commence from November when the snowpack was practically zero and permanent snow line at 4,500 m. Ten and nine years of concurrent monthly data of rain, SWE, mean temperature and flow from 1974 to 1984 and 1976 to 1985 were used for the two subbasins. Base flow was assumed on the basis of low flows during Nov-Feb of 20 years. This works out an average of 1.8 cm (depth). However, the flows were varied in a range from 1.3 to 3.5 cm to indicate seasonal variation. Assuming constant base flow of 1.8 cm did not change the model results significantly. To account abstractions, computed snowmelt during each month was reduced by a factor of 0.95. Runoff coefficients were assumed to account for losses from rainfall.

Table 4 **Note:**
Nov is the starting month in column 3 & 6. Hence 5 indicates March, 6 April and so on.

Model Calibration and Parameter Estimation

Monthly time series data of rain, snow, mean temperature and flow were examined to obtain an understanding of the hydrology of the catchment for the calibration period. The rain contribution was confined to lower reaches as is evident from area elevation curve and rainfall data.

Six years of data was used for model calibration, although snowline elevation data was available for only 4 years (concurrent). The generalised curve for snowline movement (Fig. 6) was assumed to be representative for entire calibration period. All the parameters were estimated using trial and error simulation except the storage coefficient *K* which was optimised using least square criterion by Rosenbrock technique. The parameters calibrated through trial simulation included:

1) Degree day factors for each month from March to October.
2) Monthly Rainfall runoff factors
3) Monthly temperature lapse rates.
4) Area integration factors.

Table 3 shows values of the parameters obtained through trial simulations (should be near optimal). The storage coefficient *K* was, optimised at 24.6 and 24.8 days, respectively for the two subcatchments. Table 5 indicates snowline position consistent with Fig. 6.

Table 5 – Model performance evaluation parameters

	Upto Sirshi Gauge site		Upto Kuriya Gauge site	
	A	B	A	B
Period (Years)	6.0	4.0	6.0	3.0
1. Standard error (cm)	28.3	34.8	23.5	21.5
2. Efficiency (%)	91.8	80.9	93.1	86.1
3. Average absolute error (cm)	2.0	2.6	1.8	2.4
4. Percentage absolute error (%)	2.8	5.5	2.6	6.6

Note:

A = Calibration
B ≡ Validation

Results and Discussion

The simulated and observed flows for calibration and validation periods are shown in Fig. 7, through Fig. 9. For validation none of the parameters were changed. The model performance parameters are shown in Table 5.

The performance of the model can be considered to be reasonably good in view of Table 5 and data constraints so common in Himalayan catchments. The results generally improved by increasing the number of elevation bands (*i.e* subdivision of

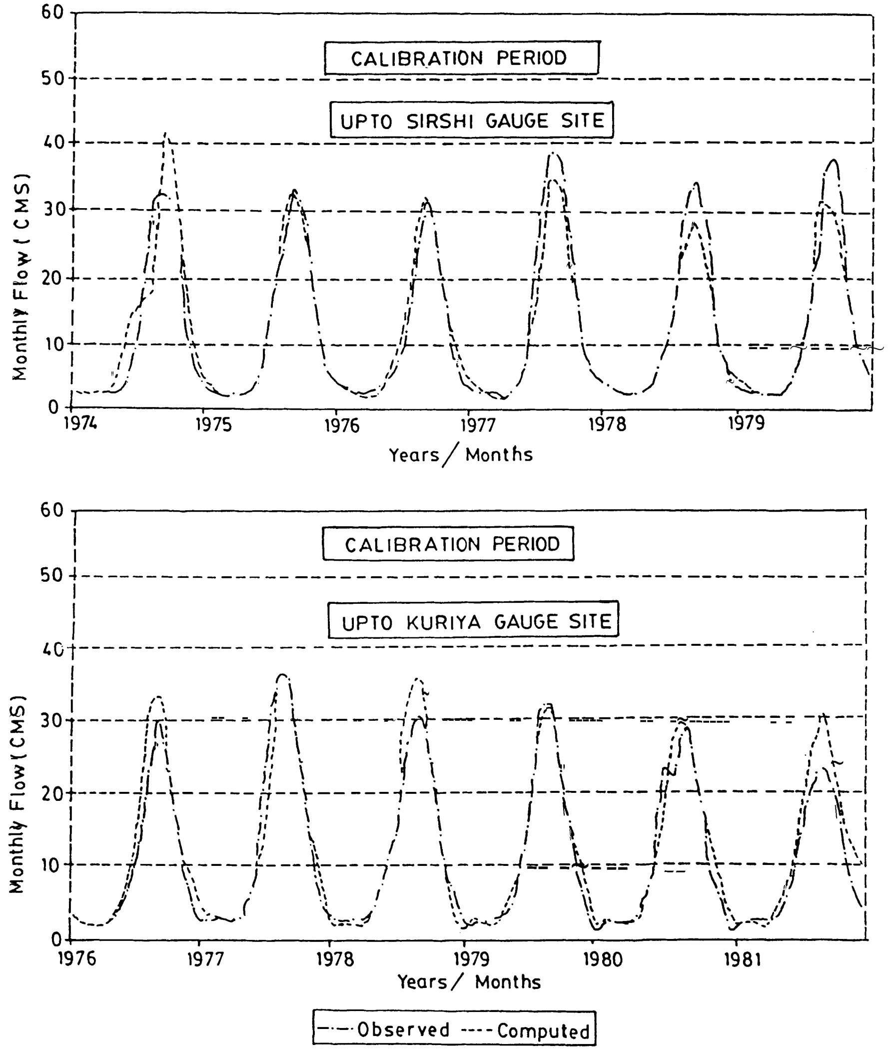


Fig. 7. Calibration at Shirshi and Kuriya Gauge sites.

drainage basin). The degree day factors indicated in Table 3, reflect partial (or complete) snowmelt flows in any given month depending on the position of snowline. Once the snowline reaches its permanent position degree day factors and lapse rates completely control the snowmelt quantities.

Several simulation trials indicated that snowpack in temporary snow zone by and large depleted completely by end of June/July instead of observed August/September. The reason could be attributed to orographic factor not being considered for elevations beyond the snowgauge at highest elevation (Rikhiniwas at 3,660 m) or due

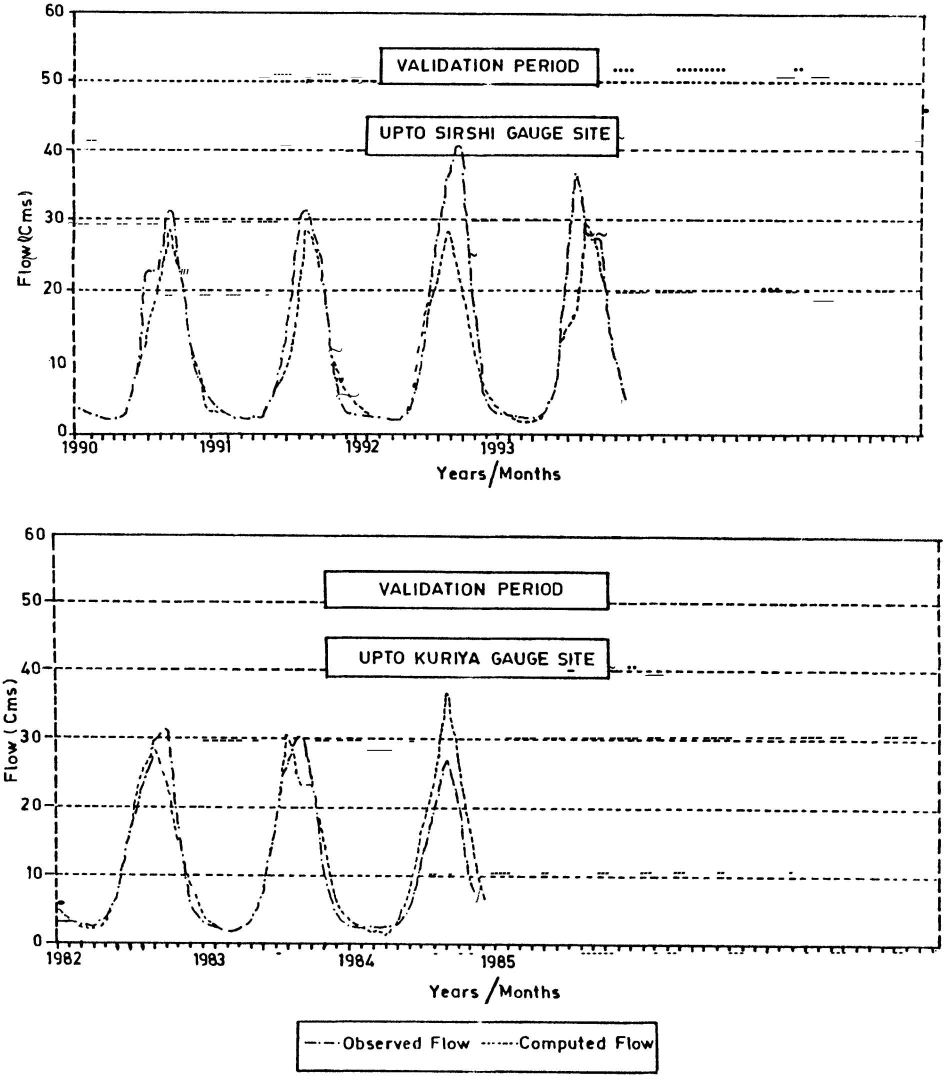


Fig. 8. Validation at Shirhi and Kuriya Gauge site.

to an inadequate network. Simulations with an arbitrarily introduced orographic factor were however, not attempted. During September/October of certain years when little or no rainfall was observed the simulated flows were reasonably good *i.e* consistent with model assumption related to permanent zone yielding flows as a result of lapsed air temperature and degree day factors only.

A good correlation was observed between mean monthly temperatures and parameters arrived through simulation trials in Table 3, indicating a sinusoidal pattern along season. A simple linear relation for lapse rates, degree day factors and runoff

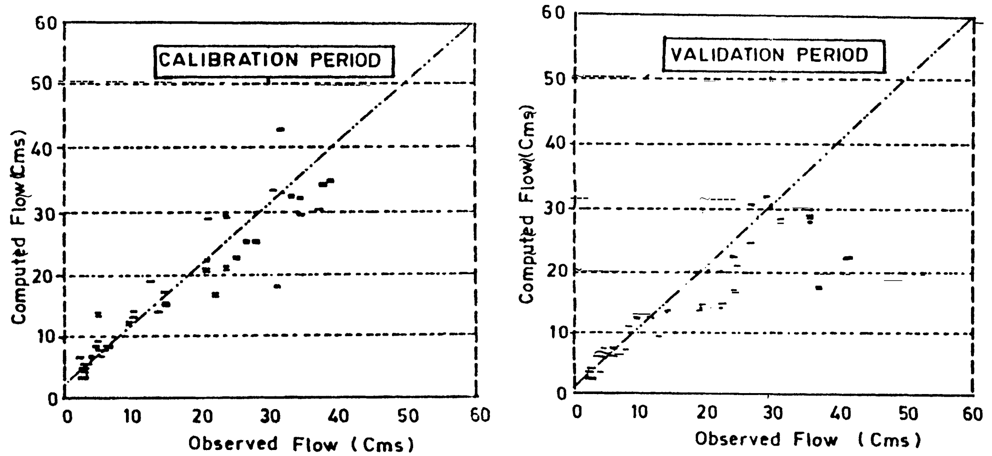


Fig. 9a. XY plot of observed and computed monthly flows at Shirshi gauge site.

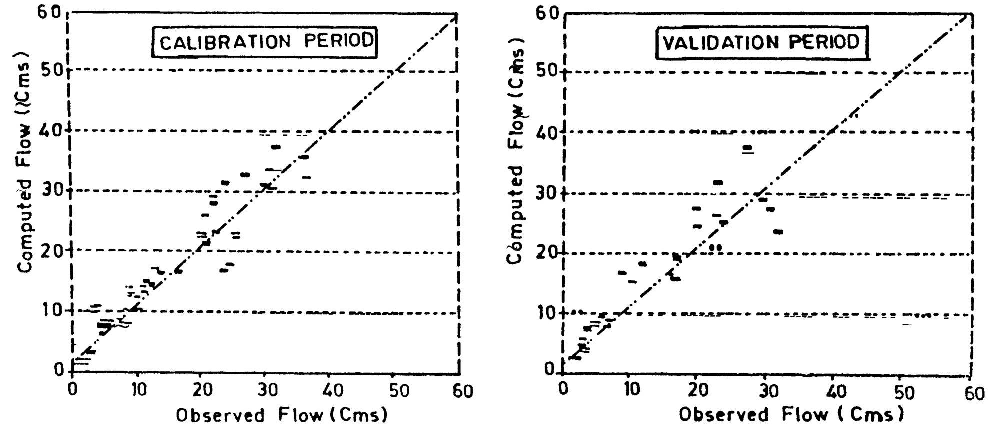


Fig. 9b. XY plot of observed and computed monthly flows at Kuriya gauge site.

coefficients should be helpful for model application to other catchments in western Himalayas. Calibrations could be improved by further fine tuning the parameters by trial and error as in the present study.

Storage constant *K* (and hence the routing coefficient in the linear reservoir) was found to be the most sensitive parameter, followed by lapse rate and degree day factors. Base temperature of -1.1 °C instead of 0 °C used in degree-day method was found to be more suitable for the model on a monthly basis. Since the model handles rain and snow separately, snowmelt contribution could be easily computed. The snowmelt component generally varied from 80 to 90 per cent of the total yearly simulated flows for the two subbasins.

Conclusions

In view of data constraints in catchments located in upper Himalayas the assumptions made in the conceptualisation of the model proposed are reasonably valid. The model results are encouraging. Data on snow-cover area instead of snowline elevation should be more useful in modeling. With little changes, the model could be run on a fortnightly basis also. The model however cannot be used for water-balance computations.

There is scope for further improvement in the model, its generalisation and application to several other catchments in western Himalayas. The model on a monthly timestep should be useful for initial project planning, assessment and application to ungauged basins if not for operational hydrology.

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References

CWC (1990, 1991, 1993) Central Water Commission, Northern Circle, Govt of India, Jammu, Meteorological, Precipitation and discharge data of Chenab Basin, Vol. I & II.

Chow, Ven Te, Maidment, D. R., and Mays, L. W. (1991) *Composite models*, Applied Hydrology, Mc Graw Hill International Edition, New York, pp. 264.

Dey, B., and Goswami, D. C.(1983) Utilisation of satellite snowcover observations for seasonal streamflow estimates in the western Himalayas, *Nordic Hydrology, Vol. 14*, pp. 257-266.

Gray, D. M. (1961) Synthetic Unit hydrograph for watersheds, *Jr. of Hydrology Div, Proc. of ASCE, Vol. 87*, HY4, pp. 33-54.

Hickok, R. B., Keppel, R. V., and Rafferty, J. (1959) Hydrograph synthesis for small aridland watersheds, *Agricultural Engg, Vol. 40*, pp. 608-611.

Kumar, Shashi, V., Haefner, H., and Seidel, K. (1991) Satellite snow cover mapping and snowmelt runoff modelling in Beas basin, Proceedings of the Vienna Symposium, August 1991, IAHS publ. No. 205, pp. 101-109.

Leavesley, G. (1983) *Precipitation runoff Modeling System*, USGS Publ., User manual, Denver, Colarado, USA.

Martinec, J. (1975) Snowmelt-Runoff model for streamflow forecasts, *Nordic Hydrology, Vol. 6, pp.* 145-154.

Martinec, J. (1986) Note on the assessment of model parameters. In: Intercomparison of models of snowmelt runoff (ed by WMO) Annex XVII, WMO operational Hydrology report No. 23, WMO Geneva.

Quick, M. C., and Pipes, A. (1977) UBC Watershed model, Hydrological sciences bulletin, Vol. XXII.

Rao, Mohan N., Bandopadhyaya, B. K., and Vardhan, A. (1991) Snow hydrology studies in the Beas basin for developing snow melt runoff model, Paper ptd at the annual paper meeting at Lucknow Institution of Engineers, Jun 1991, UDC 551.491.6

Roohani, M. S. (1986) Studies on hydromorphometery and snowmelt runoff using data of Chenab Catchment, Ph.d. Thesis submitted to the University of Roorkee, India, pp. 21.

Ramamoorthi, A. S. (1983) Snowmelt runoff assessment and forecasting using satellite data, Proc of first national Sym. on Seasonal snowcover, SASE, Manali, India, 28-30 Apr, 1983 Vol. II, pp 117.

Ramamoorthi, A. S. (1987) Snow cover area (SCA) is the main factor in forecasting snowmelt runoff from major river basins, Proceedings of the Vancouver Symposium, August 1987, IAHS Publ 166, pp. 187-197.

Singh, P. (1991) A Temperature lapse rate study in western Himalayas, *Jr. of Indian Association of Hydrologists, Vol. XIV*, No. 3.

Singh, P., and Jain, S. K. (1993) Snow and Glacier contribution in the Chenab river upto Akhnoor, National Institute of Hydrology Publication Roorkee (UP) India - CS(AR) 131.

Singh, P., and Quick, M. C. (1993) Streamflow simulation of Sutlej River in the Western Himalayas, IAHS Publ. 218, pp. 261-271.

Seth, S. M. (1983) Modelling daily snowmelt runoff during premonsoon months for Beas basin upto Manali. First national sym. on seasonal snowcover, Manali, India, 28-30 Apr, 1983, pp. 104-115.

SSARR (1972) Stream flow synthesis and reservoir regulation, U S Army Corps of Engineers, North Pacific, Portland, Oregon.

Sud, S. C., Bhatija, T. S., and Ghosh, U. K. (1989) Water resources assessment of Chenab basin, C55 R & D session paper 17, CWC N Delhi.

Upadhayaya, D. S., and Bhadur, J. (1982) On some hydrometeorological aspects of Precipitation in Himalayas, Proc Int Sym on Hydrological aspects of mountainous watersheds, School of Hydrology, Univ. of Roorkee, india, Nov 4-6, 1982 vol. I.

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