TECHNICAL REPORT

TR (BR) 118

A RUNOFF MODEL FOR SNOW DOMINATED CATCHMENT IN GREATER HIMALAYAS

आपो हिष्टा मयोभुवः

WESTERN HIMALAYAN REGIONAL CENTRE
NATIONAL INSTITUTE OF HYDROLOGY
JAMMU - 180 003 (INDIA)

1994-95

PREFACE

The National Institute of Hydrology, Roorkee., established its second regional centre at Jammu (J & K), in 1990., with snow hydrologic studies as one of its thrust areas in the Western Himalayas. The western Himalayas have a large water resources potential from the snow dominated catchments, which at present is largely untapped.

Modelling runoff has been a central problem of hydrology. In the present report a simple model is presented to simulate snowmelt runoff on a monthly basis from a catchment in upper Himalayas. The model conceptualisation was mainly designed keeping data availability and data constraints in mind. The model uses monthly precipitation in the form of rain, snow (SWE), mean temperature and snowline elevation (from satellite imageries) as driving inputs. The results of the model are encouraging. Further scope exists, for model genralisation and application to other catchments in western Himalayas.

The case study was carried out by Sri S V N Rao, Sc C, Western Himalaya regional centre, Jammu under the guidance of Dr K S Ramasastri, Sc F.

(S.M. SETH)

Director

CONTENTS

Page No.

LIST OF FIGURES

Page No.

LIST OF TABLES

Page No.

ABSTRACT

The catchments located in upper Himalayas have a significant part under permanent snow cover and Glaciers. Modelling runoff becomes difficult with almost no data from these parts. Even in the temporary snow covered zones, the network is generally inadequate. However precipitation characteristics show repetitive patterns and snowline movement elevation wise (as observed from satellite imageries) by and large occurs in the same manner each year. The location of the permanent snowline is also more or less constant at 4500 M.

A simple runoff model is proposed on a monthly basis to take advantage of above mentioned characteristics, using the degree day approach. The model uses monthly rain, snow (SWE), mean temperature and snowline elevation as primary inputs. Model conceptualisation has been made especially, keeping data constraints in mind.

The model results are encouraging. Runoff simulation also provides a better understanding of snowmelt processes. Further scope for model genralisation and application exists, to several other catchments in Western Himalayas.

In Himalayas diverse hydrometeorologic, topographic and geologic conditions make it difficult for modelling. At higher elevations (Greater 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 of snow obtained through synoptic coverage of remote sensing pictures . Even in the seasonal snow cover zone the data network is poor and inadequate. Therefore runoff modelling becomes difficult.

In the present report a simple model based on certain simplified assumptions, keeping data constraints in mind, has been developed on a monthly basis for a subcatchment of Chenab located in upper Himalayas using conventional data of precipitation and 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 K using the least square criterion.

The model results are found to be encouraging. Further scope exists, for genralisation and application of the model to other catchments in Western Himalayas.

2.0 REVIEW:

Several snowmelt forecasting models have been developed in the western countries to suit specific needs and hydrologic conditons. 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 (Martenec, 1975), PRMS (Leavesley, 1983), etc.

In India, several efforts have been made for modelling 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 (1989) developed a similar model for Sutlej basin using pattern search optimisation.

Singh et al (1993) concluded on an average (10 years) the snowmelt and glacier contribution to be nearly 50 % in Chenab catchment upto Akhnoor. Singh (1990) in another study in Western Himalayas found that temperature lapse rate was not constant but varied significantly each month. Other relevant studies in Western Himalayas include those by Upadhayaya (1983), Upadhyaya and Bahadur (1982), Jeyram and Bagchi (1982), Bagchi (1981), Abbi(1983), Roohani and Seth (1989), Dey et al (1983), etc.

3.0THE PROBLEM

The catchments in Greater Himalayas suffer from poor rain/ snow guage network. There is also no data from permanent snow covered zones. However remote sensing pictures provide the much needed information of snowcover through repetitive coverage, though in a limited sense. Therefore certain simplified assumptions have been made to build a simple deterministic, distributed and physically based runoff model on a monthly basis, suitable to snow dominated catchments in upper Himalayas.

To illustrate the capability of the model, data from a subcatchment of Chenab basin - Marsudhar river upto Sirshi guage site is used.

4.0 DESCRIPTION OF CATCHMENT

4.1 General

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

The Marusudhar river originates at an altitude of 6000 M in the greater Himalayas. In the beginning two streams namely Batkot and Gumbar join to form Warwan river, which is known as Marusudhar river in the lower reaches. Some of the main tributaries of Marusudhar are Helka Nala, Rein Nala, Kair Nala and Nath Nala upto Sirhsi bridge. River Marusudhar flows almost north to south direction till its confluence with Kiyar nala downstream of Sirshi guage site where it meanders east to west.

The fan shaped catchment of 5th order stream encompasses an area of 3535 sqkms with elevations ranging from 1700 M to 6000 M. The mean (area) wtd elevation of the catchment is 4050 M. About one third of the catchment is under perpetual snow and glaciers. The permanent snowline is at about 4500 M. The seasonal snowline normally comes down to 2000 M, almost covering 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 catchment is shown is figures 1 through 3. Area elevation curve is shown in fig 4. Some important geomorphological parameters of the catchment are reproduced here (Table 1.) from Roohani (1986).

Table 1

Geomorphological parameters of Marsudhar subbasin

1. Area (sqkm)	3535.00
2. Basin length (km)	85.00
3. Basin shape factor	1.88
4. Length of main stream channel (km)	109.00
5. Drainage density	0.54
6. Relief ratio	0.05
7. Channel slope (%)	2.74
8. Stream frequency	0.18
10. Modified Hickok et al parameter	1782.00
11. Gray's parameter	66.33
12. Ruggedness No.	2.53

4.2 Data Availability And Data Constraints:

Daily precipitation temperature and flow data are available for 18 - 20 years since 1967. Precipitation is recorded as rain and snow (snow water equivalent) separately at 6 stations within the study catchment is shown in fig 2. The highest station

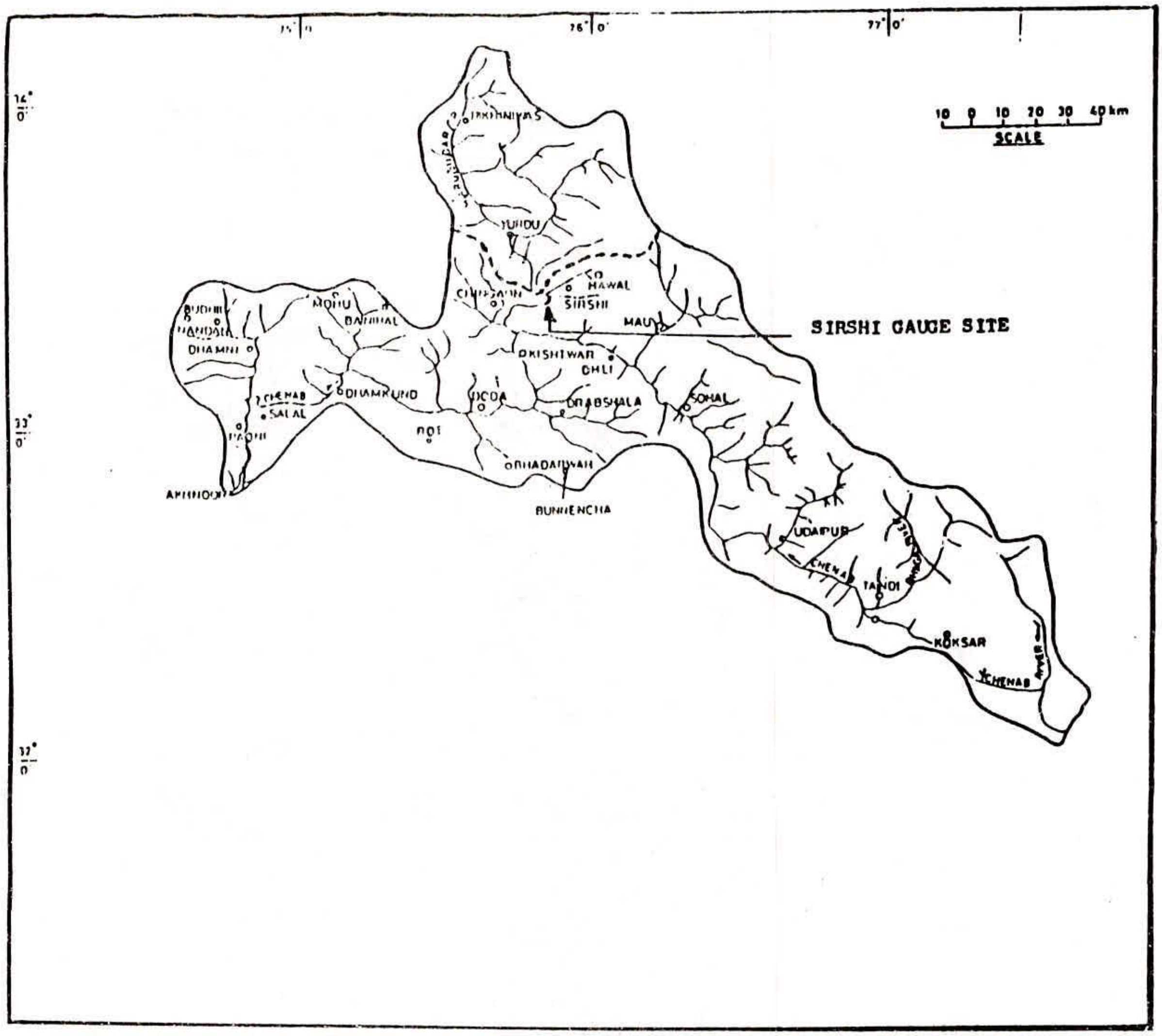


FIG. 1 CHENAB CATCHMENT UP TO AKHNOOR

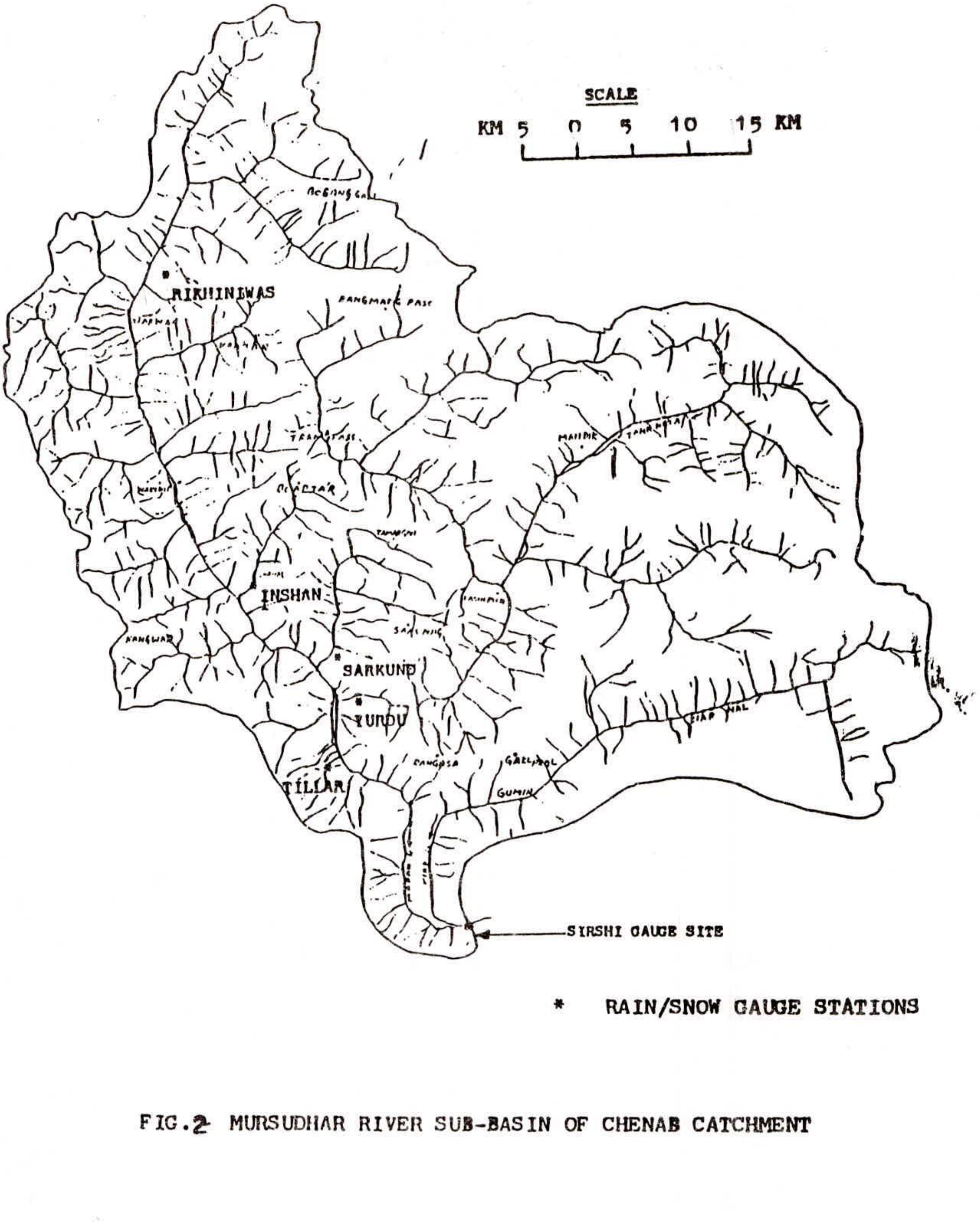


FIG.2 MURSUDHAR RIVER SUB-BASIN OF CHENAB CATCHMENT

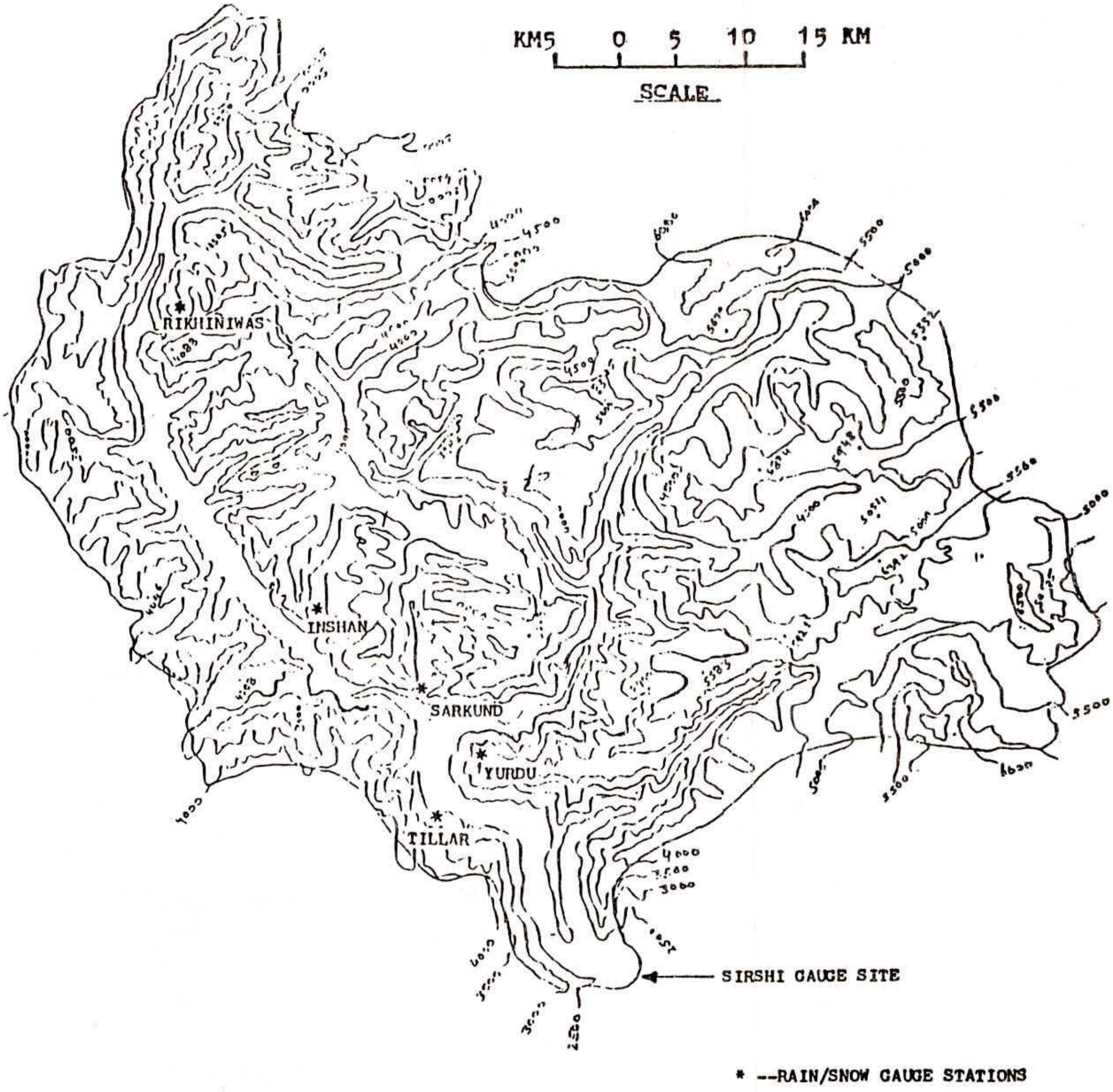


FIG. 3 MARSUDHAR RIVER SUB-BASIN OF CHENAB CATCHMENT (CONTOUR MAP)

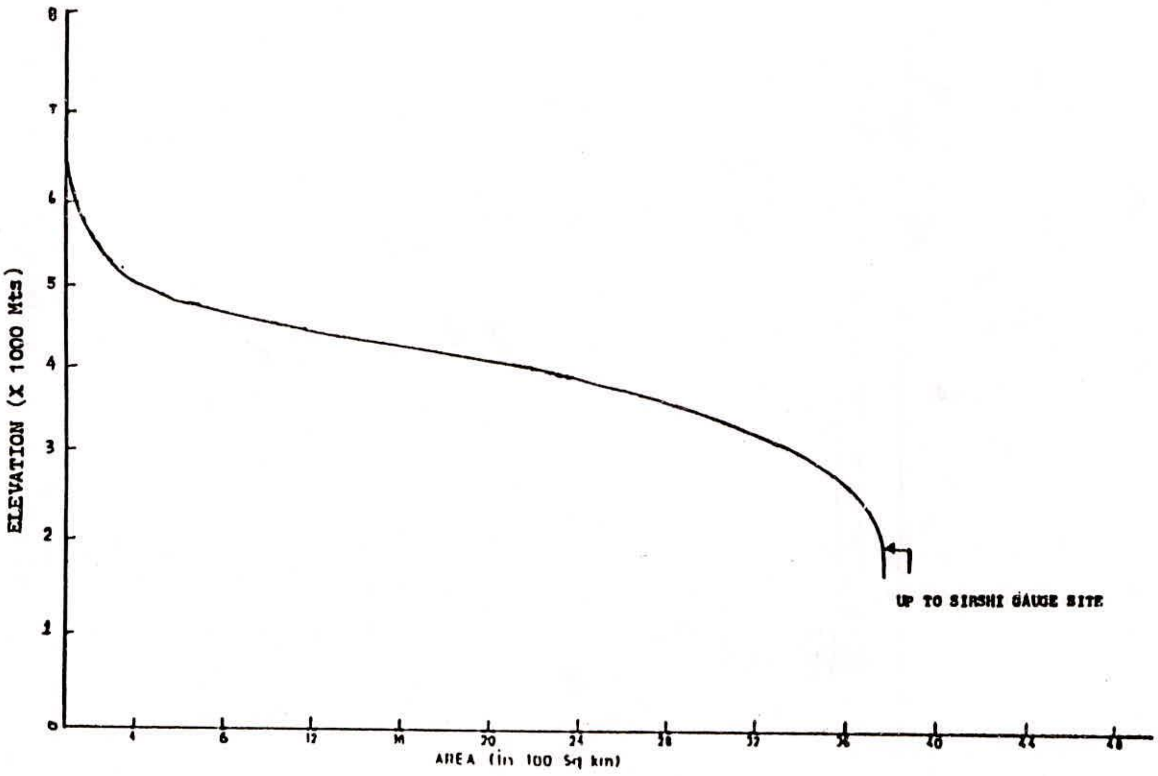


FIG. 4 AREA ELEVATION CHARACTERISTICS OF MARSUDHAR RIVER BASIN (CHENAB SUB CATCHMENT)

(Rikhinivas) is located at an altitude of 3660 M. Thus elevation wise the network covers only one third of the catchment. Temperature is recorded at Sirshi (1700 M) and Tillar (2165 M) twice a day (Max and Min) within the catchment with relatively less difference in elevation. No temperature data is recorded at higher elevations. Therefore temperature data of Sirshi alone have been used in the present study. The network of rain/ snow gauges in the catchment is shown in fig 2. A poor network of rain/ snow gauges is a severe data constraint for computing mean areal rain and snowfall.

Besides topographic sheets (SOI), snowline movement along time period (months) using remote sensing imageries for 4 years (1974 - 79) were obtained from Roohani's (1986) Phd thesis (see fig 5. & 6.). Precipitation, temperature and discharge data were obtained from CWC Publications (1990, 1991, 1993).

4.3 Precipitation and Runoff Characteristics of Study Catchment:

The precipitation and runoff characteristics in Himalayas have been dealt at length by Upadhayaya and Bahadur (1982), singh (1993), Roohani (1986) etc. However they are briefly discussed here relevant to the study area.

Precipitation in greater Himalayas is predominantly in the form of snow. Precipitation occurs almost through out the year in the form of rain or snow. The most important factors controlling weather and climate in Himalayas are the altitude and aspect. Al-

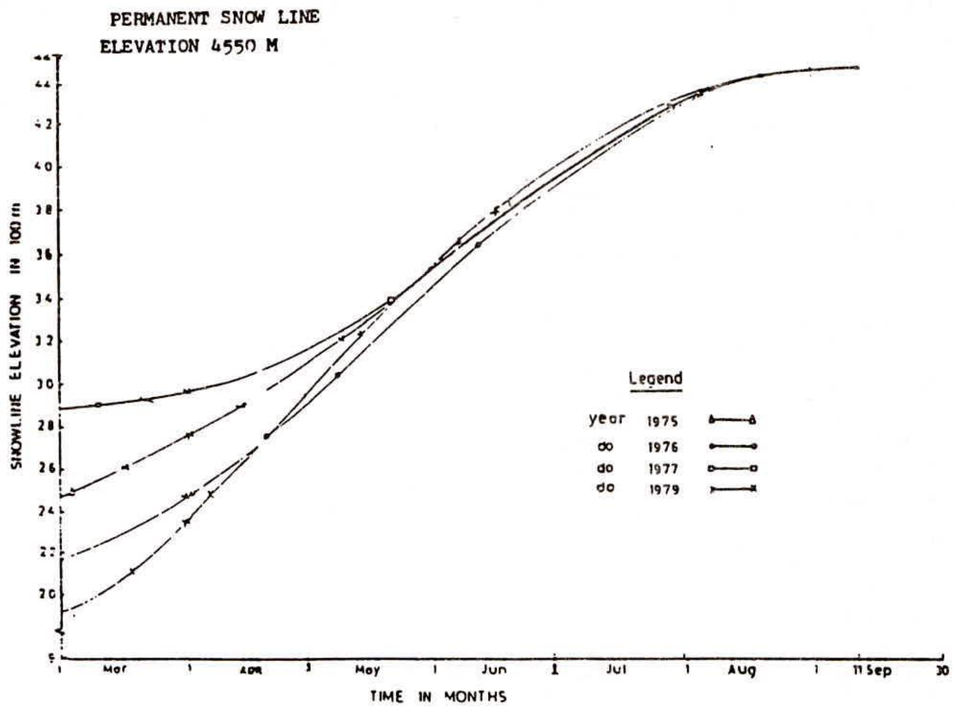
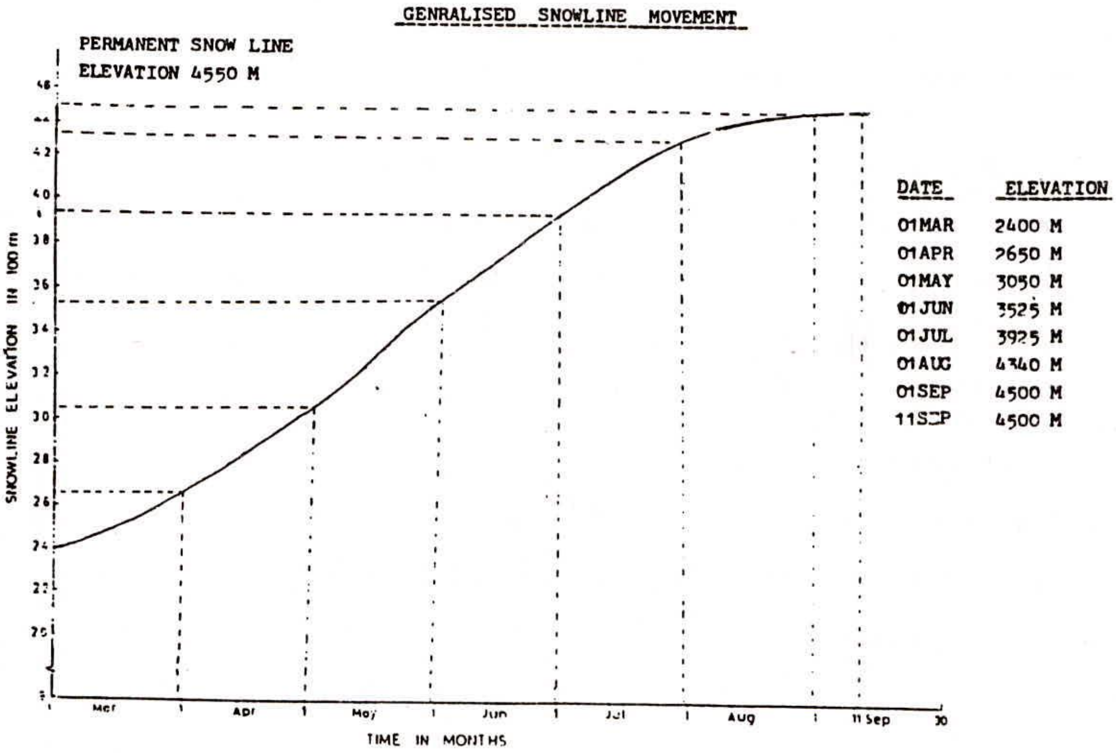


Fig:5 RELATIONSHIP BETWEEN SNOW LINE ELEVATION AND TIME FOR MARSUDHAR RIVER BASIN (CHENAB SUB CATCHMENT) (Source: Roohani, 1986)



DATE	ELEVATION
01MAR	2400 M
01APR	2650 M
01MAY	3050 M
01JUN	3525 M
01JUL	3925 M
01AUG	4340 M
01SEP	4500 M
11SEP	4500 M

Fig:6 RELATIONSHIP BETWEEN SNOW LINE ELEVATION AND TIME FOR MARSUDHAR RIVER BASIN (CHENAB SUB CATCHMENT) though rain contribution is relatively greater during Monsoon season its areal influence tapers to elevations at about 4000 M.

The winter precipitation resulting from western disturbances leads to accumulation of snowpack from November to March. The snowline descends to an average elevation of 2000 M almost covering the entire catchment. Subsequent spells of snowfall during April/ May are not common and are confined to higher elevations only. With increase in temperatures snowmelt begins during Mar/ Apr and the snowline gradually shifts upwards to permanent snowline at about 4500 M towards the end of June /July.

The precipitation pattern in Marsudhar river subcatchment of Chenab is depicted in the table 2. below showing 20 year normals of six rain/ snow guage stations (also see fig 2).

Table 2.
Precipitation pattern in Marsudhar river subbasin (20 Year Normals)

S.No	Station	Ele (M)	Annual PPT (Cms)	Percentage Rain	Snow	Monsoon
1.	Sirhshi	1700	103	71	29	26
2.	Tillar	2130	104	67	23	26
3	Yardu	2165	75	64	36	22
4.	Sarkund	2350	61	62	38	26
5.	Inshan	2440	102	53	47	26
6.	Rikhinivas	3660	154	33	66	18

Note: Monsoon % included in Rain also.

The above table gives a picture of rain as a major contributor of river flows. It is not actually so, instead the converse is true (as will be discussed later). This is because the rainfall by and large becomes negligible beyond 4000 M, while snowfall increases with elevation. The area ofthe catchment below 4000 M is less than 40 % of the area of the catchment. The water balance of permanent snowcovered zone (about one third the area) is not known. It could be negative or positive for several years continuously. During monsoon period the air temperatures are at the peak (relatively), which result in snowmelt from both temporary and permanent snow zones. The monsoon flows carry (generally) a greater component of snowmelt compared to flows resulting from monsoon rains.

The premonsoon showers occur mostly in the form of rain in lower elevations starting in Mar/ Apr and extend upto May/ June. During this period rain-on-snow is common on lower reaches and occasionally at higher reaches.

The flows during October includes mostly subsurface and base flows. The period of Nov to Feb exibit minimum deviation in flows which essentially constitute the base flow. The temporal variability of flows are diagrammatically represented in fig 7.

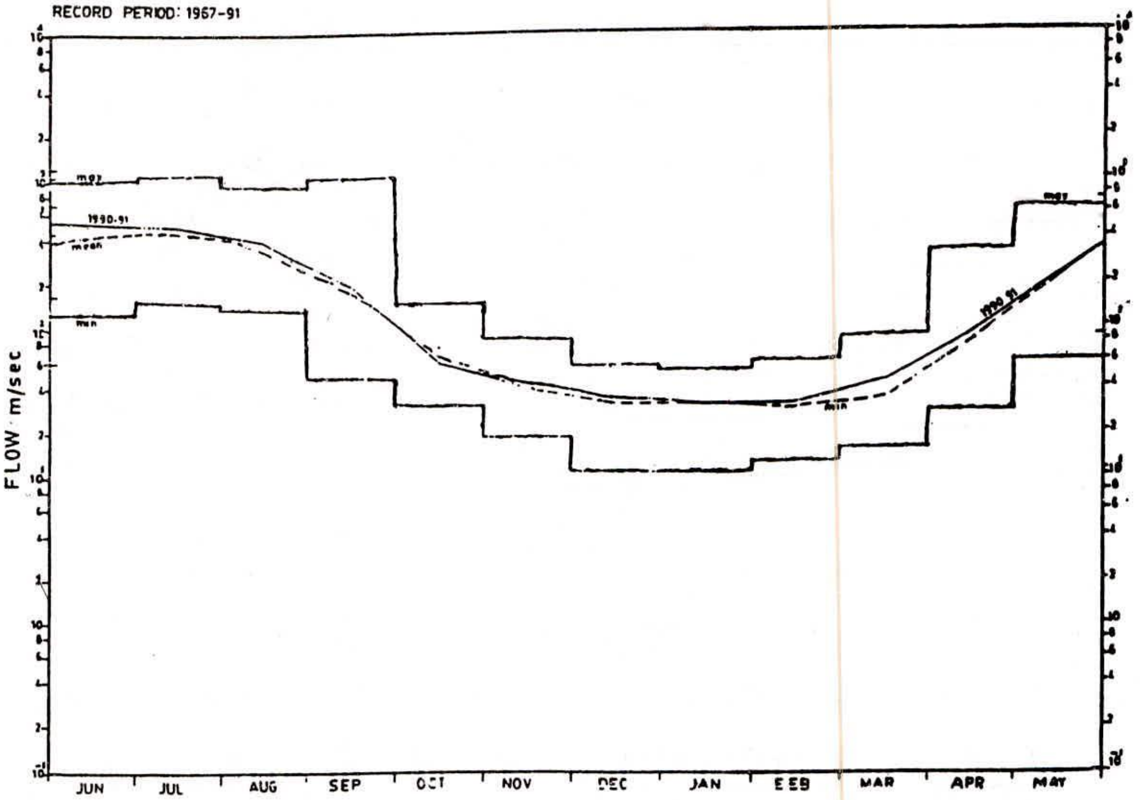


Fig: 7. VARIATION OF MONTHLY FLOWS AT SIRSHI, GDS, MARSUDHAR RIVER
(Source: Water year Book 1990-91, CWC)

5.0 SIMULATION AND RUNOFF MODELING:

5.1 General:

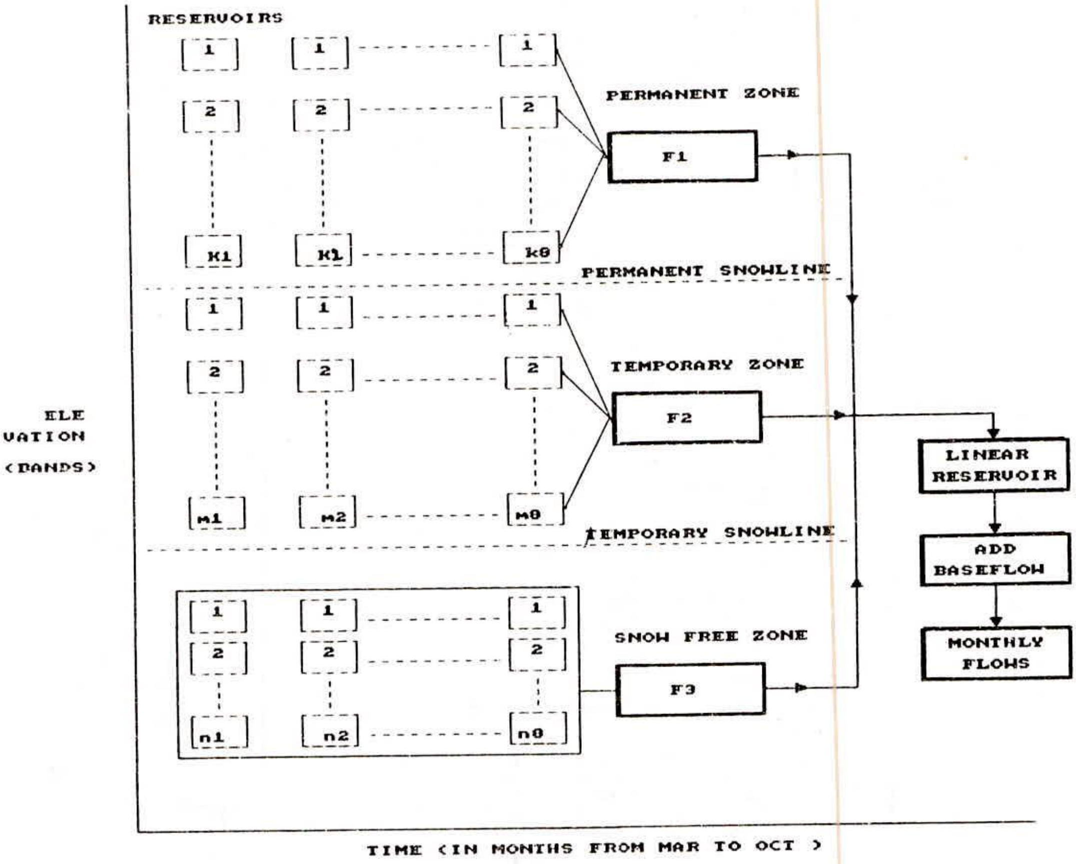
A simple deterministic model based partly on degree day method is developed to simulate runoff (volumes) on a monthly basis from a snow dominated catchment, using meteorological inputs of precipitation and mean temperature. The catchment is subdivided into several elevation bands to give a distributed 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.

5.2 Model structure

The model fundamentally 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 along the area elevation curve.

The conceptual model algorithm based on certain assumptions may be described in following steps. The basis of assumptions are also briefly discussed.The model is schematically represented in figs 8 & 9.

1. Rain and snow (Snow water equivalent) are handled sepa-



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
F1 = Flow restricted by lapsed temps and degree day factors
F2 = Flow restricted by availability of snow pack and
degree day factors
F3 = Flow from rainfall using runoff coefficients

FIG : 8 SCHEMATIC DIAGRAM OF MONTHLY RUNOFF MODEL

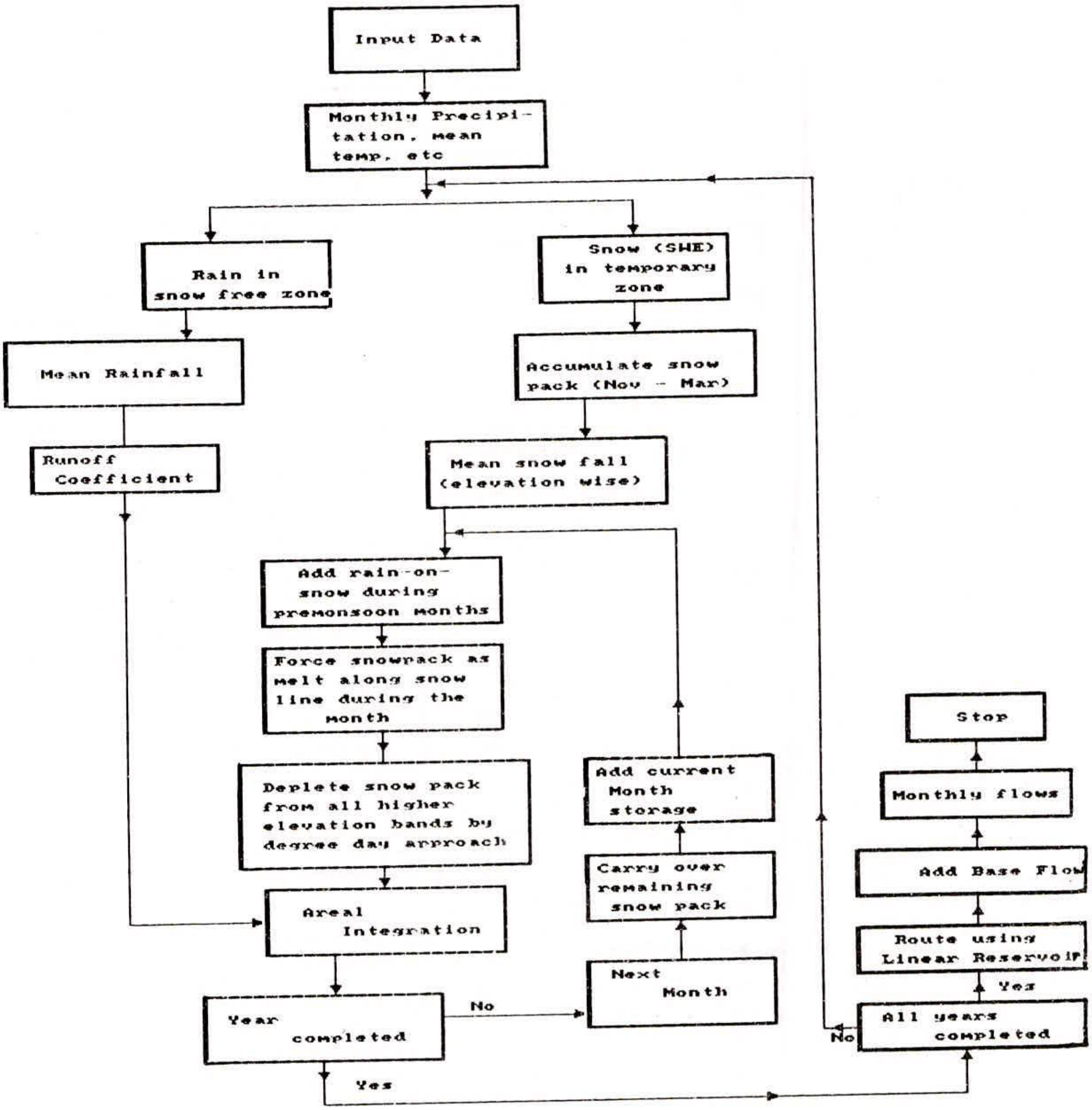


FIG:9. LOGICAL REPRESENTATION OF MODEL.

rately on a monthly basis starting November each year(time lumped as one month) by the model. It is assumed that snow pack is zero and snowline is located at permanent line beginning November.

2. The period from Nov - Feb is considered to be the base flow, since it exhibits minimum deviation (see fig 7). Rainfall if any is converted to flow using simple runoff coefficients. Snowmelt is assumed to take place only between March and October .

3. The permanent 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 yield restricted by lapsed temperatures and degree day factors. The assumption is based on snowline movement data (see fig 6) of 4 years wherein the permanent snowline is more or less at 4500 M. Variable temperature lapse rate each month is assumed with base temperature at zero degree Celsius based on a study by Singh (1990).

4. The temporary zone is assumed to be constituted of a variable number of elevation bands (with reservoirs connected in parallel) determined by a genralised snow movement line (see fig 6) each month. Snowline movement (snow depletion curve) has been genralised 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, however distinct on monthly basis. Flow from temporary zone is taken as the sum of:

i) Flow obtained by forcing snowpack as melt from relevant bands along snowline movement, each month upto permanent snowline position (4500 M) (see table 4.).

ii) Flow obtained from all higher elevation bands connected in parallel using degree day approach. Flows are however restricted by availability of snowpack (mean) in temporary zone. Flows from permanent zone are guided by step 3 discussed above.

5. Snowpack left in each elevation band is carried over to next month starting March to October in the temporary zone. Snowpack left after October is carried over to March next year assuming no melt during Nov to Feb.

6. The snowfree zone is similarly assumed 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 fixed for each month.

7. Rain-on-snow is a complex phenomena occurring mostly during premonsoon (Mar, Apr & May). A large amount of heat is

added to the snowpack. The model handles this in a simplified manner. Since rainguage elevations are known, mean rainfall is added to snowpack in all elevation bands beyond snowline and upto and slightly beyond the reporting rainguage elevation. The model implicitly forces snowpack as melt in relevant elevation bands as described in step 3. 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.

8. Accuracy in computations for mean areal snowpack and rainfall primarily depend on good or bad network and can be arrived at by various methods. The model computes this as a mean wtd rainfall and snowpack (actual method used for the catchment under study is discussed later).

9. Initially the snowpack is accumulated from Nov to Mar during winter and mean snowpack 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 (no orography is considered). Snowfall occurring during subsequent months is accounted each month, along the melt season.

10. Rainfall is assumed to be negligible beyond 4000 M.

11. Flows from the three zones discussed above are integrated

(areal convolution) and routed through a linear reservoir with an optimal K using least square criterion (Rosenbrock technique) to obtain computed flows. All other parameters are estimated through trial simulations.

5.3 Sources of Error in Model

Following error are likely to occur, when model assumptions do not hold good or have not been considered.

1. Spatial variability is not accounted properly as result poor network of rain/ snowguages.
2. Aspect and orographic effect 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 adquate simulation.

5.4 The program:

The program was coded using fortran 77. However, some minor changes are required for application to other catchments. The listing is presented in appendix 1.

6.0 MODEL APPLICATION

5.1 General:

The model was applied on study catchment discussed earlier. The catchment was subdivided into 36 elevation bands. The permanent zone was constituted of ten elevation bands starting at 4500 M (see fig 8. and 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 snowdepth located in one or more adjacent elevation bands. Mean rainfall was computed as wtd 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 approach is believed to induce isoheytal pattern to rainfall in snowfree zone (however, simple arithmetic mean computed rainfall did not change model results significantly).

Water year was assumed to commence from Nov when the snowpack was practically zero and permanent snow line at 4500 M. Ten years of concurrent monthly data of rain, snow (SWE), mean temperature and flow from 1974 to 1984 were used. Abstractions from snowmelt were assumed to be negligible. Runoff coefficients were assumed to account for losses from rainfall during monsoon season.

6.2 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 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. The genralised curve for snowline movement (fig 6) was assumed to hold good for entire calibration period. All the parameters were estimated using trial and error simulation except routing coefficient K (being sensitive), which was optimised using least square criterion by Rosenbrock technique. The parameter adjustment through trial simulation include:

1. Degree day factors for each month from Mar to Oct.
2. Monthly Rainfall runoff factors
3. Moving snowline position slightly either side.
4. Monthly temperature lapse rates.

Table 3. shows some of the parameters arrived through trial simulations (should be near optimal). Table 4. indicates the snowline movement along elevation bands consistent with fig 6. Parameter for optimisation and optimised value of storage coefficient K (for linear reservoir) is given in table 5.

Table 3.

Parameters arrived through trial simulation

	1	2	3	4	5	6	7	8	9	10	11	12
Month	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
LR	-	-	-	-	3.5	2.9	2.2	2.3	3.7	4.0	3.7	3.0
RF	0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.8	0.8	0.7	0.7
BF	2.4	2.3	1.8	1.6	1.3	1.3	2.0	2.7	3.0	3.5	3.0	2.5
IF	0.3	0.2	0.2	0.05	0.03	0.14	0.2	0.33	0.4	0.45	0.45	0.4
DF	-	-	-	-	0.01	0.02	0.04	0.1	0.31	0.17	0.09	0.03

Note:

LR = Temperature lapse rate in degree Centigrade/ Km

RF = Rainfall runoff coefficient

BF = Base flow in depth (Cms), assumed based on 20 year flows during Nov to Feb

IF = Area integration factor is the ratio of cumulative area of elevation bands upto snowline to total area of catchment.

DF = Degree day factors (Cms).

Table 4.

Snowline position along time (Months)

Area in elevation band (sqkm)	Mean elevation (M)	Month starting November
10	2000	5
90	2200	5
85	2500	5
100	2750	6
100	2950	6
100	3025	6
100	3150	7
100	3250	7
100	3300	7
100	3350	8
100	3500	8
100	3600	8
100	3750	8
100	3800	8
100	3900	9
100	3950	9
100	4025	9
100	4060	9
100	4130	10
100	4170	10
100	4240	10
100	4270	10
100	4320	10
100	4360	10
100	4400	10
100	4430	10
100	4500	10
100	4530	11
100	4610	-
100	4650	-
100	4825	-
100	4900	-
100	5050	-
100	5150	-
100	5500	-
150	5900	-

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

Table 5.

ROSENBROCK OPTIMISATION PARAMETERS

```
MAXK=  1000     MKAT= 30      MCYC= 50      NSTEPP= 2

ALPH= 2.00     BETA=  .50     EPSY=       .00100000


TOTAL NO OF STAGES=  8

TOTAL NUMBER OF FUNCTION EVALUATIONS=    23

FINAL VALUE OF OBJECTIVE FUNCTION=     801.96220000


Optimised value of K

X( 1) =      .24445310E+02

       =      24.44 days
```

6.3 Results and Discussion:

The simulated and observed flows for calibration and validation periods are shown in fig 10. through 11. For validation none of the parameters were changed except the forcing of snowpack along snow movement line was confined to elevation bands less than 4000 M. This is because, the snowline movement normally goes beyond this elevation. The model performance parameters are shown in table 6.

Table 6

Performance Parameters of the Model

	Calibration	Validation
1. Period (Years)	6.0	4.0
2. Standard error (CMS)	28.30	34.80
3. Efficiency (%)	91.88	80.90
4. Average absolute error (CMS)	2.02	2.61
5. Percentage absolute error (%)	2.81	5.56

The model results are reasonably good considering the data constraints. The results generally improved by manipulation of temperature lapse rate, degree day factors, snowline position and increasing the number of elevation bands (i.e subdivision of drainage).

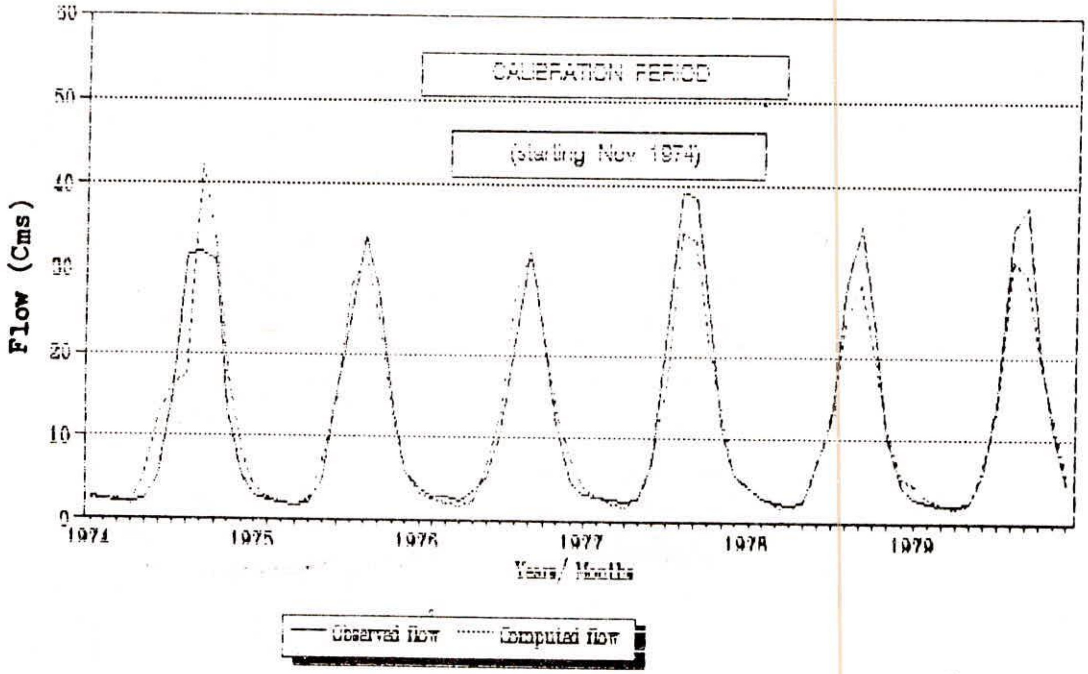

CALIBRATION PERIOD
(starting Nov 1974)
Flow (Cms)
60
50
40
30
20
10
0
1974
1975
1976
1977
1978
1979
Years/ Months
Observed flow
Computed flow

Fig: 10.

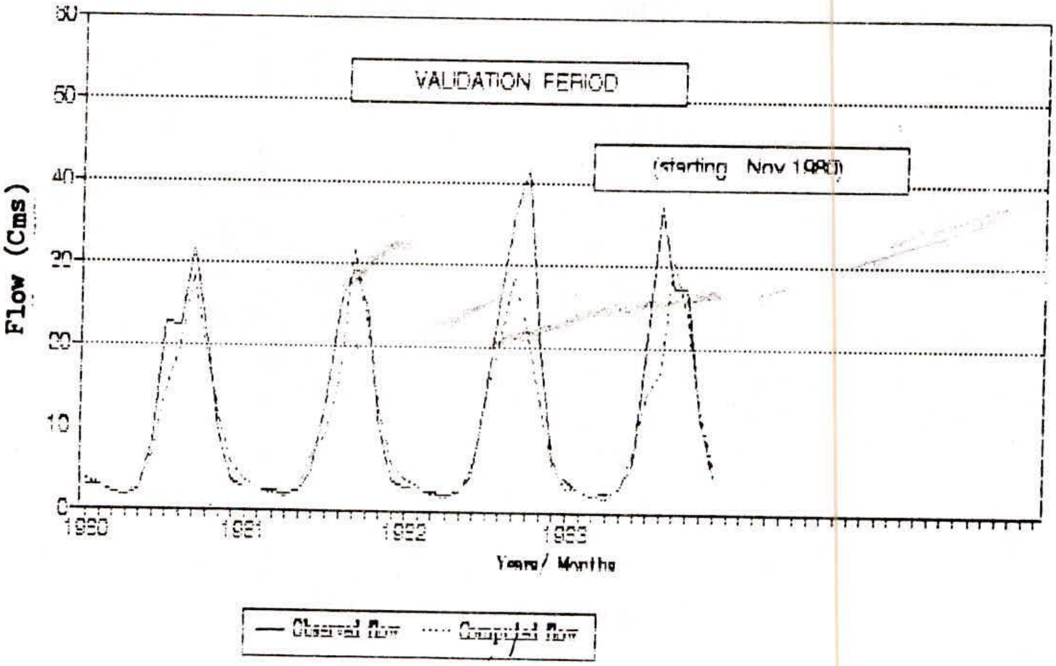

VALIDATION PERIOD
(starting Nov 1980)
Flow (Cms)
60
50
40
30
20
10
0
1980
1981
1982
1983
Years/ Months
Observed flow
Computed flow

Fig: 11.

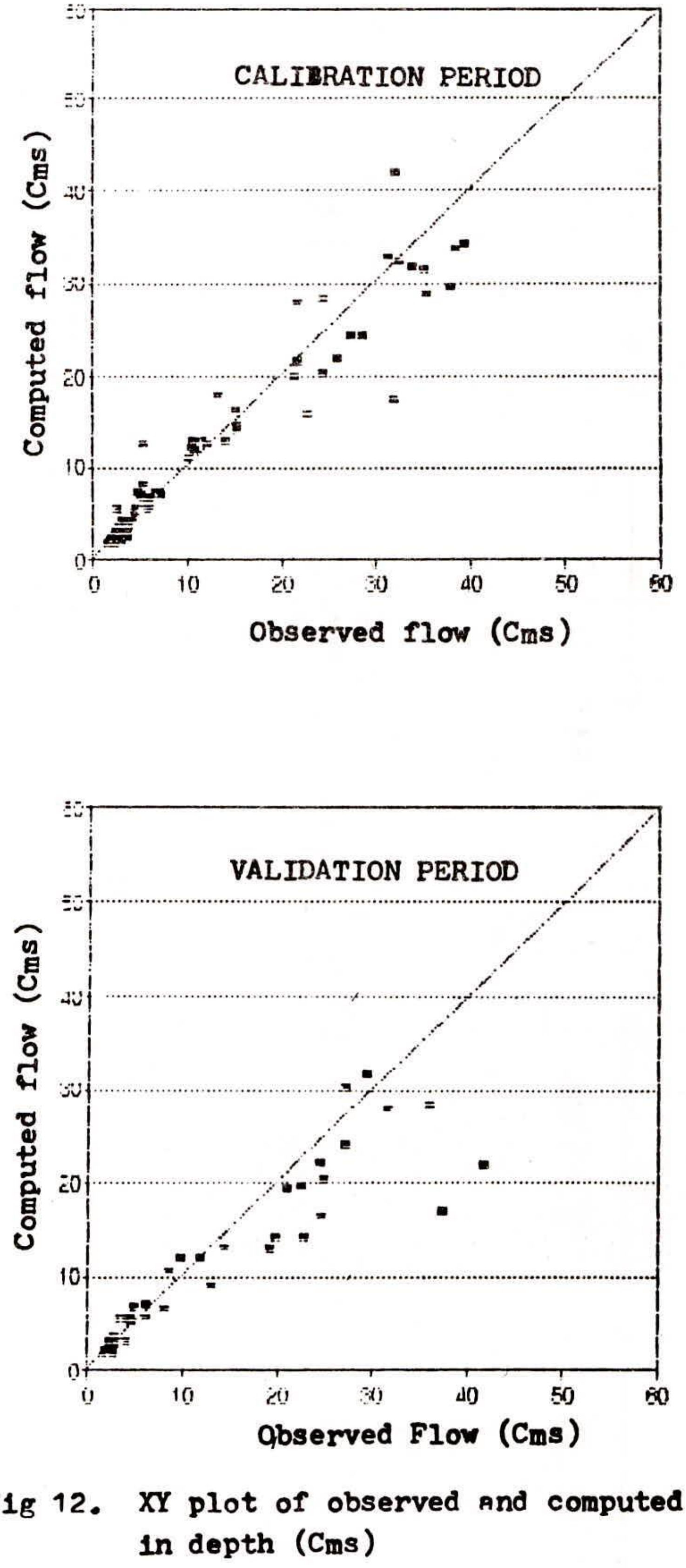


Fig 12. XY plot of observed and computed flow in depth (Cms)

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 (4500 M) degree day factors are completely responsible for snowmelt quantities (i.e no elevation band will be forced by the model as melt). Several simulation trials indicatted that the temporary snow zone by and large depleted completely by end of June/ July. Gross snowmelt contribution (assuming baseflow to be snowmelt) generally varied from 85 to 93 percent of the total simulated flows each year during the calibration period of 6 years.

6.0 CONCLUSIONS:

In view of data constraints in catchments located in greater Himalayas the assumptions made in the conceptualisation of the proposed model are reasonably valid. The model results are very encouraging. None of the model parameters are optimised except the storage constant K. With little changes the model can be run on a ten daily basis. Snow cover data instead of snowline elevation data should be more useful in modelling.

Further scope exists, for application and genralisation of the model to other catchments in western Himalayas.

REFERENCES

Abbi, S D S.,Upadhyay D S and Mathur H P (1983),'Estimation of flow yield in a snowbound catchment', First national sym on seasonal snow cover, New Delhi.

Bagchi A K (1981), 'Snowmelt runoff in Beas Basin using Satellite images, Phd Thesis, Department of Civil Engg, University of Roorkee, Roorkee. (India).

Dey B. and Goswami, D.C.(1983),'Utilisation of satellite snowcover observations for seasonal streamflow estimates in the western Himalayas, Nordic Hydrology, Vol 14 No 5 pp 257-266.

Jeyram A and Bagchi A K (1982)'Snow covered area estimation in Tos Basin using landsat images. Proc of Int sym on hydrological aspects of mountainous watersheds, Uni of Roorkee. PP VI-19-23.

Leavesley G (1983), Precipitation runoff Modelling System', USGS Publn Denver, Colarado. USA.

Martenec J (1975), 'Snowmelt-Runoff model for streamflow forecasts', Nordic Hydrology 6 No 3 PP 145-154.

Meteorological data of Chenab basin, 1993. CWC Publication Part I Data of Sishi station, N Circle. GOI

Precipitation data of Meteorological stations, 1991. CWC publications. Norther Circle. Govt of India. Vol I & II.

Rao Mohan N et al, 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.

Roohani M S and S M Seth (1989),'Relation between hydrological and Morphometeric parameters in the Chenab Basin. Ptd at the Second National symposium on Hydrology. Jan 4-5 1989. Jammu.

Roohani M S (1986).'Studies on hydromorphometery and snowmelt runoff using data of Chenab Catchment'. Phd Thesis submitted to the University of Roorkee.

Singh P (1991).'A Temperature lapse rate study in western Himalayas' Hydrology Jr of IAH Vol XIV no 3, 1991.

Singh P et al (1993)' Snow and Glacier contribution in the Chenab river upto Akhnoor. NIH Pbln - CS(AR) 131.

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

Sud S C et al (1989). Water resources assessment of Chenab basin. C55 R & D session paper 17, CWC N Delhi.

Upadhayaya D S and J Bahadur, 1982. 'On some hydrometeorological aspects of Precipitation in Himalayas' Proc Int Sym on Hydrological aspects of mountainous watersheds, School of Hydrology. Uni of Roorkee Nov 4-6, 1982 vol 1.

Discharges of Chenab basin (1967-89), CWC Northern Circle, Jammu GOI. and water year book (1990-91).

****

APPENDIX

```
C          MAIN PROGRAMME
C          TO COMPUTE FLOWS ON A MONTHLY BASIS
C          FROM A SNOW/ GLACIER DOMINATED CATCHMENT
           DIMENSION TEMP(12),AESL(36,3),TEM(12,36),RL(12)
           DIMENSION AMELT(12,36),SP(14,36),TMELT(12),FA(72)
           DIMENSION PPT(12,15),FLOW(12),BF(12),FDF(12),FC(72)
           DIMENSION FLO(12),RWT(6,12),SPI(36),RF(12),FL(72)
           DIMENSION AMR(12),WTARE(12),DF(12),NM(12),SEL(8,2)
           DIMENSION D(3),V(3,3),BL(3,3),BLEN(3),EPS(3),tr(10),tf(10)
           DIMENSION AJ(3),E(3),AL(3,3),AFK(3),BK(3),BK1(1)
           CHARACTER*10 FILE1
           WRITE(*,*)'GIVE OUT PUT FILE NAMES FOR UNIT 6'
           READ(*,44)FILE1
 44        FORMAT(A6)
           OPEN(1,FILE='COMB',STATUS='OLD')
           OPEN(2,FILE='TP',STATUS='OLD')
           OPEN(3,FILE='FW',STATUS='OLD')
           OPEN(4,FILE='XXXX1',STATUS='OLD')
           OPEN(5,FILE='YYYY',STATUS='OLD')
           OPEN(6,FILE=FILE1,STATUS='NEW')
           OPEN(7,FILE='ZZZZ1',STATUS='OLD')
           OPEN(8,FILE='OPT11',STATUS='NEW')
           OPEN(9,FILE='TTT44',STATUS='NEW')
           AREA=3535.00
C          READ FROM SCREEN
           READ(7,*)(RL(I),I=1,12)
C          WRITE(*,*)'GIVE FACTOR FOR OROG AND LR'
C          WRITE(6,47)(RL(I),I=1,12)
47         FORMAT('MEAN RAINFALL',12F8.2)
C          WRITE(*,*)'GIVE RAINFALL RUNOFF FACTORS FOR 12 MONTHS'
           READ(7,*)(RF(I),I=1,12)
C          WRITE(*,*)'GIVE BASEFLOWS FOR 12 MONTHS'
           READ(7,*)(BF(I),I=1,12)
C          WRITE(*,*)'GIVE WTD AREA FOR 12 MONTHS (SNOWFREE) -12 MONTHS'
           READ(7,*)(WTARE(I),I=1,12)
C          WRITE(*,*)'GIVE INITIAL SNOW PACK DEPTHS (CAL) - 36 BANDS'
           READ(7,*)(SPI(I),I=1,36)
           READ(7,*)(DF(I),I=1,12)
           READ(7,*)(NM(I),I=1,12)
           READ(7,*)(FDF(I),I=1,12)
C          WRITE(7,*)'GIVE OPTI PARAMETERS'
           READ(7,*)KM,MAXK,MKAT,MCYC,NSTEPP
C          WRITE(*,*)KM,MAXK,MKAT,MCYC,NSTEPP
           READ(7,*)(EPS(I),I=1,KM)
           READ(7,*)EPSY,ALPH,BETA
           READ(7,*)(BK1(I),I=1,KM)
C          READ FROM FILES
           READ(7,*)((SEL(J,K),K=1,2),J=1,7)
           READ(4,*)((AESL(J,K),K=1,3),J=1,36)
           READ(5,*)((RWT(I,J),J=1,12),I=1,6)
           KN=1
           NR=0
500        DO J=1,12
           READ(1,*)(PPT(J,K),K=1,13)
           READ(2,*)TEMP(J)
```

```
      READ(3,*)FLOW(J)
      FLOW(J)=FLOW(J)-BF(J)
45    FORMAT(36F8.1)
      END DO
C     ACCUMULATE THE SNOW DURING THE YEAR
      P=0.
      Q=0.
      R=0.
      S=0.
      T=0.
      U=0.
      DO J=1,5
      P=P+PPT(J,3)
      Q=Q+PPT(J,5)
      R=R+PPT(J,7)
      S=S+PPT(J,9)
      T=T+PPT(J,11)
      U=U+PPT(J,13)
      END DO
C     WRITE(*,*)'CHECK2'
      DO J=1,36
      IF(J.EQ.1)SP(5,1)=P/10+SP1(J)
      IF(J.EQ.2)SP(5,2)=(Q+R)/20+SP1(J)
      IF(J.EQ.3)SP(5,3)=(S+T)/20+SP1(J)
      IF((J.GT.3).AND.(J.LT.11))SP(5,J)=(S+T+U)/30.+SP1(J)
      IF((J.EQ.11).OR.(J.EQ.12))SP(5,J)=U/10+SP1(J)
      IF(J.LE.12)GO TO 666
      IF((J.GE.13).AND.(J.LE.27))THEN
C     OROGRAPHIC FACTOR KEPT ZERO
      SP(5,J)=SP(5,J-1)+SP1(J)
      ELSE
      SP(5,J)=SP1(J)
      ENDIF
666   END DO
C     COMPUTE MEAN WEIGHTED RAINFALL MONTHWISE
      DO K=1,12
      NN=1
      PP=0
      DO M=2,12,2
      PP=PP+PPT(K,M)*RWT(NN,K)
      NN=NN+1
      END DO
      AMR(K)=PP/10
      END DO
C     WRITE(9,47)(AMR(K),K=1,12)
      bbc=0.
      cbc=0.
      DO 50 N=1,12
C     WRITE(9,45)(SP(N,J),J=1,36)
      IF(N.GE.5)GO TO 100
      FLO(N)=RF(N)*AMR(N)*WTARE(N)
      bbc=bbc+flo(n)
      cbc=cbc+flo(n)
      GO TO 50
C     CALL SUBROUTINE LAPSE TO COMPUTE TEMPS ELEVATION WISE
```

```
100     CALL LAPSE(N,TEMP,AESL,TEM,RL)
        IF(N.EQ.5.OR.N.EQ.6.OR.N.EQ.7)THEN
        CALL RAINSNO(SP,N,AMR,SEL,PPT,AESL,KN)
        ELSE
        ENDIF
5000    T=0
C       CALL SUBROUTINE ADDSNO TO ADD SNOW DURING CURRENT MONTH
        IF(N.GE.6)CALL ADDSNO(N,PPT,SP)
        DO 75 LP=1,36
333     FORMAT(I2,36F9.2)
        IF(LP.GT.27)GO TO 33
        IF(SP(N,LP).EQ.0)GO TO 75
        IF((AESL(LP,3).EQ.N).AND.(N.LE.10).AND.(LP.LE.27))THEN
        AMELT(N,LP)=SP(N,LP)
        GO TO 66
        ELSE
        ENDIF
33      AMELT(N,LP)=FDF(N)*TEM(N,LP)*NM(N)
        IF(AMELT(N,LP).GE.SP(N,LP))AMELT(N,LP)=SP(N,LP)
66      SP(N+1,LP)=SP(N,LP)-AMELT(N,LP)
        IF(N.EQ.12)THEN
        SP(N,LP)=SP(N,LP)-AMELT(N,LP)
        SP1(LP)=SP(13,LP)
        ELSE
        ENDIF
        SM=(AMELT(N,LP)*AESL(LP,1))/AREA
        T=T+SM
75      CONTINUE
        TMELT(N)=T
C       WRITE(9,333)N,(SP(N,J),J=1,36)
C       IF(N.EQ.12)WRITE(9,333)N,(SP1(I),I=1,36)
C       IF(N.EQ.12)WRITE(9,333)N,(AMELT(N,I),I=1,36)
        FLO(N)=RF(N)*AMR(N)*WTARE(N)+TMELT(N)
        bbc=bbc+flo(n)-tmelt(n)
        cbc=cbc+flo(n)+bf(n)
50      CONTINUE
        tr(kn)=bbc
        tf(kn)=cbc
2000    FORMAT(3F12.3)
        DO J=1,12
        NR=NR+1
        FA(NR)=FLOW(J)
        FC(NR)=FLO(J)
        END DO
        KN=KN+1
        IF(KN.LE.6)GO TO 500
        DLT=30.62
        BK(1)=BK1(1)
C       CALL SUBROUTINE ROSEN TO OPTIMISE STORAGE COEFFITIENT K
        CALL ROSEN(BK,EPS,KM,MAXK,MKAT,MCYC,NSTEPP,ALPH,BETA,
     1  V,EPSY,D,BL,BLEN,AJ,E,AL,AFK,FA,DLT,FC)
C       CALL SUBROUTINE OBJECT REQUIRED BY SUBROUTINE ROSEN
        CALL OBJECT(FA,FL,BK,SUMN,DLT,FC)
        JK=1
        DO NR=1,72
```

```
      FA(NR)=FA(NR)+BF(JK)
      FC(NR)=FC(NR)+BF(JK)
      FL(NR)=FL(NR)+BF(JK)
      JK=JK+1
      IF(JK.EQ.13)JK=1
      WRITE(6,2000)FA(NR),FC(NR),FL(NR)
      END DO
      write(6,5555)(tr(i),i=1,6),(tf(i),i=1,6)
5555  format('rain and snow contribution',/,6f8.2,//,6f8.2)
C     CALL SUBROUTINE ERROR TO COMPUTE THE STATISTICAL PARAMETERS
      CALL ERROR(FA,FL,SE,EFF1,AV,PAV)
      WRITE(*,3000)SE,EFF1,AV,PAV
      WRITE(6,3000)SE,EFF1,AV,PAV
3000  FORMAT(//,10X,'STATISTICAL PARAMETERS',/,10X,4F8.2)
      STOP
      END
C
C     SUBROUTINES
C
C     SUBROUTINE FOR COMPUTING LAPSE RATES
      SUBROUTINE LAPSE(N,TEMP,AESL,TEM,RL)
      DIMENSION TEMP(12),TEM(12,36),RL(12),AESL(36,3)
      TT=TEMP(N)
      DO LK=1,36
      TEM(N,LK)=TT-(((AESL(LK,2)-1700)/1000)*RL(N))
      IF(TEM(N,LK).LT.0.)TEM(N,LK)=0.
      IF(TEM(N,LK).GE.16)TEM(N,LK)=16
      END DO
      RETURN
      END
C     SUBROUTINE TO COMPUTE OBJECTIVE FUNCTION
      SUBROUTINE OBJECT(FA,FL,AKE,SUMN,DLT,FC)
      DIMENSION FA(72),FC(72),FL(72),AKE(3)
      AK=AKE(1)
      C1=DLT/(AK+0.5*DLT)
      C2=1.0-C1
      FL(1)=FC(1)
      DO I=2,72
      FL(I)=C1*FC(I)+C2*FL(I-1)
      END DO
      SUMN=0.0
      DO I=1,72
      SUMN=SUMN+(FL(I)-FA(I))**2
      ENDDO
      WRITE(*,*)'SUMN',SUMN
      RETURN
      END
C     SUBROUTINE ROSENBROCK TO OPTIMISE STORAGE COEFFICIENT
      SUBROUTINE ROSEN(AKE,EPS,KM,MAXK,MKAT,MCYC,NSTEPP,ALPH,BETA,
     1 V,EPSY,D,BL,BLEN,AJ,E,AL,AFK,FA,DLT,FC)
      DIMENSION AKE(3),D(3),V(3,3),BL(3,3),BLEN(3),EPS(3),AJ(3)
      DIMENSION E(3),AL(3,3),AFK(3),FC(72),FA(72),FL(72)
      WRITE(8,1001)
*C    WRITE(*,*)MAXK,MKAT,MCYC,NSTEPP,ALPH,BETA,EPSY
      WRITE(8,1002)MAXK,MKAT,MCYC,NSTEPP,ALPH,BETA,EPSY
```

```
          KAT=1
          DO II=1,KM
          DO JJ=1,KM
          V(II,JJ)=0.
          IF(II-JJ)001,002,001
002       V(II,JJ)=1.0
001       END DO
          END DO
C         WRITE(*,*)'CHECK1'
          CALL OBJECT(FA,FL,AKE,SUMN,DLT,FC)
C         WRITE(*,*)'CHECK2'
          SUMO=SUMN
          DO 003 K=1,KM
          AFK(K)=AKE(K)
003       CONTINUE
          KK1=1
          IF(NSTEPP-1)004,005,004
005       GO TO 051
004       CONTINUE
          DO 006  I=1,KM
          E(I)=EPS(I)
006       CONTINUE
051       DO 007 I=1,KM
          WRITE(*,*)'CHECK 4'
          FBEST=SUMN
          AJ(I)=2.
          IF(NSTEPP-1)008,009,008
008       GO TO 007
009       CONTINUE
          E(I)=EPS(I)
007       D(I)=0.0
          III=0
38        III=III+1
258       I=1
033       DO 010 J=1,KM
010       AKE(J)=AKE(J)+E(I)*V(I,J)
          CALL OBJECT(FA,FL,AKE,SUMN,DLT,FC)
          KAT=KAT+1
          SUMDIF=FBEST-SUMN
          IF(ABS(SUMDIF)-EPSY)011,011,012
011       GO TO 015
012       CONTINUE
          IF(KAT-MAXK)013,014,014
014       GO TO 015
013       CONTINUE
          IF(SUMN-SUMO)016,016,017
016       GO TO 018
017       CONTINUE
          DO 019 J=1,KM
          AKE(J)=AKE(J)-E(I)*V(I,J)
019       CONTINUE
          E(I)=-BETA*E(I)
          IF(AJ(I)-1.5)020,021,021
020       AJ(I)=0.0
021       CONTINUE
```

```
          GO TO 022
018       D(I)=D(I)+E(I)
          E(I)=ALPH*E(I)
          SUMO=SUMN
          DO 023 K=1,KM
          AFK(K)=AKE(K)
023       CONTINUE
          IF(AJ(I)-1.5)024,024,025
025       AJ(I)=0.
024       CONTINUE
022       DO 026 J=1,KM
          IF(AJ(J)-0.5)026,026,027
027       GO TO 028
026       CONTINUE
          GO TO 029
028       IF(I-KM)030,031,030
031       GO TO 032
030       CONTINUE
          I=I+1
          GO TO 033
032       DO 34 J=1,KM
          IF(AJ(J)-2.0)035,034,034
035       GO TO 258
034       CONTINUE
          IF(III-MCYC)036,037,037
036       GO TO 038
037       CONTINUE
          GO TO 015
029       CONTINUE
          DO 039 I=1,KM
          DO 039 J=1,KM
039       AL(I,J)=0.0
*         ROTATE AXIS
          DO 041 I=1,KM
          KL=I
          DO 041 J=1,KM
          DO 042 K=KL,KM
042       AL(I,J)=D(K)*V(K,J)+AL(I,J)
041       BL(I,J)=AL(I,J)
          BLEN(1)=0.0
          DO 043 K=1,KM
          BLEN(1)=BLEN(1)+BL(1,K)*BL(1,K)
043       CONTINUE
          BLEN(1)=SQRT(BLEN(1))
          DO 044 J=1,KM
          V(1,J)=BL(1,J)/BLEN(1)
044       CONTINUE
          DO 045 I=2,KM
          II=I-1
          DO 045 J=1,KM
          SUMAVV=0.
          DO 046 KK=1,II
          SUMAV=0.
          DO 047 K=1,KM
047       SUMAV=SUMAV+AL(I,K)*V(KK,K)
```

```
046   SUMAVV=SUMAV*V(KK,J)+SUMAVV
045   BL(I,J)=AL(I,J)-SUMAVV
      DO 048 I=2,KM
      BLEN (I)=0.0
      DO 267 K=1,KM
267   BLEN(I)=BLEN(I)+BL(I,K)*BL(I,K)
      BLEN(I)=SQRT(BLEN(I))
      DO 048 J=1,KM
048   V(I,J)=BL(I,J)/BLEN(I)
      KK1=KK1+1
      IF(KK1-MKAT)049,050,050
050   GO TO 015
049   GO TO 051
015   WRITE(8,1007)KK1
      WRITE(8,1008)KAT
      WRITE(8,1009)SUMO
      DO 052 IX=1,KM
      WRITE(8,1010)IX,AKE(IX)
052   CONTINUE
1001  FORMAT(///10X,'ROSENBROCK MINIMISATION PROCEDURE')
1002  FORMAT(//,2X,'PARAMETERS :'/,2X,'MAXK=',I6,4X,'MKAT=',
     2I3,4X,'MCYC=',I3,4X,'NSTEPP=',I2,//,'ALPH=',F5.2,4X,
     3'BETA=',F5.2,4X,'EPSY=',F13.8)
1003  FORMAT(//,2X,'STAGE NUMBER',I2)
1004  FORMAT(/,7X,'VALUE OF THE OBJECTIVE FUNCTION=',E16.8)
1005  FORMAT(/,7X,'VALUES OF THE INDEPENDENT VARIABLES'/)
1006  FORMAT(/,7X,2HX(,I2,4H)= ,E16.8)
1007  FORMAT(///,2X,'TOTAL NO OF STAGES=',I3)
1008  FORMAT(/,2X,'TOTAL NUMBER OF FUNCTION EVALUATIONS=',I5)
1009  FORMAT(/,2X,'FINAL VALUE OF OBJECTIVE FUNCTION=',F16.8)
1010  FORMAT(/,2X,2HX(,I2,4H) = ,E16.8)
      WRITE(*,*)'CHECK10'
      RETURN
      END
C     SUBROUTINE TO COMPUTE STATISTICAL PARAMETERS
      SUBROUTINE ERROR(FA,FL,SE,EFF1,AV,PAV)
      DIMENSION FA(72),FL(72)
      DM=0.
      PK=0.
      DO J=1,72
      DM=DM+FA(J)
      PK=PK+(FA(J)-FL(J))**2
      ENDDO
      SE=SQRT(PK)
      DM=DM/72.
      FO=0.
      F1=0.
      DO K=1,72
      FO=FO+(FA(K)-DM)**2
      F1=F1+(FA(K)-FL(K))**2
      END DO
      EFF1=((FO-F1)/FO)*100.
      F2=0.
      DO L=1,72
      F2=F2+ABS(FA(L)-FL(L))
```

```
      ENDDO
      AV=F2/72
      PAV=(AV/72)*100.
      RETURN
      END
C     SUBROUTINE TO COMPUTE ADDITIONAL SNOWPACK DURING THE MONTH
      SUBROUTINE ADDSNO(N1,PT,SSP)
      DIMENSION PT(12,15),SSP(14,36)
      P2=PT(N1,3)
      Q2=PT(N1,5)
      R2=PT(N1,7)
      S2=PT(N1,9)
      T2=PT(N1,11)
      U2=PT(N1,13)
      DO J=1,27
      IF(J.EQ.1)SSP(N1,J)=SSP(N1,J)+P2/10.
      IF(J.EQ.2)SSP(N1,J)=SSP(N1,J)+(Q2+R2)/20.
      IF(J.EQ.3)SSP(N1,J)=SSP(N1,J)+(S2+T2)/30.
      IF((J.GT.3).AND.(J.LT.11))SSP(N1,J)=SSP(N1,J)
     * +(S2+T2+U2)/30.
      IF((J.GT.10).AND.(J.LE.27))SSP(N1,J)=SSP(N1,J)+U2/10.
      ENDDO
 222  FORMAT(27F7.2)
      RETURN
      END
C     SUBROUTINE TO COMPUTE RAIN ON SNOW DURING PREMONSOON
C     MONTHS OF MAR, APR AND MAY
      SUBROUTINE RAINSNO(SP,N,AMR,SEL,PPT,AESL,KN)
      DIMENSION SP(14,36),AMR(12),SEL(8,2),PPT(12,15),AESL(36,3)
      NN=14
      IF(PPT(N,12).EQ.0)NN=8
      IF((PPT(N,12).EQ.0).AND.(PPT(N,8).EQ.0))NN=4
      DO 20 J=1,NN
      IF(AESL(J,2).LT.SEL(N,2))GO TO 20
      SP(N,J)=SP(N,J)+AMR(N)
      WRITE(9,25)KN,N,J,AMR(N)
  25  FORMAT(3I5,F9.2)
  20  CONTINUE
      RETURN
      END
```

DIRECTOR	Dr S M Seth
COORDINATOR	Dr K S Ramasastri
STUDY GROUP	Sh S V N Rao
	Sh Puran Singh
	Sh V K Agrawal
	Sh Vishal Gupta
	Sh M K Sharma