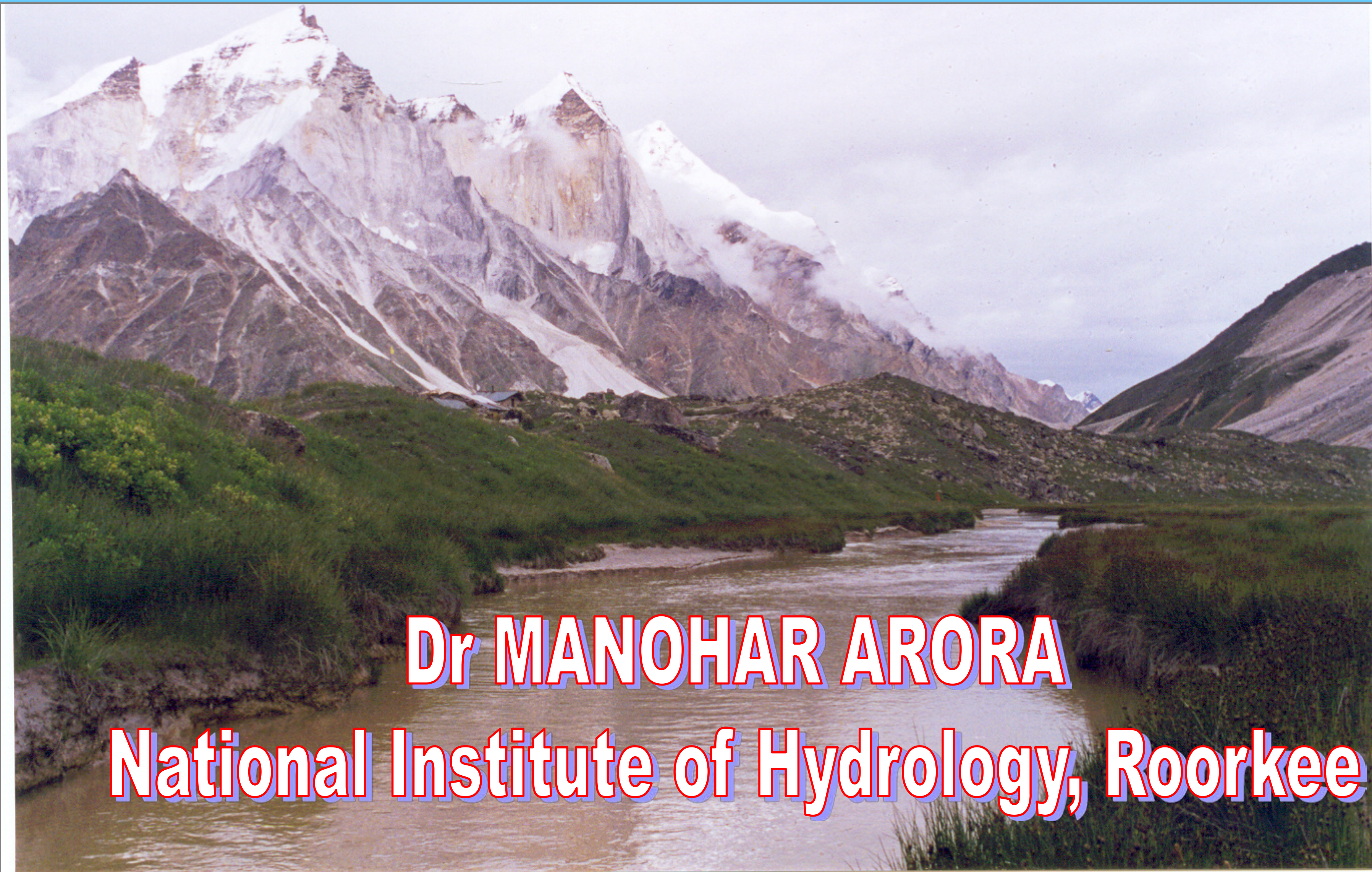
SNOW MELT MODELLING



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INTRODUCTION

- WATER IS ESSENTIAL FOR OUR DAY TO DAY LIVING
- SNOW AND GLACIER MELT RUNOFF AND RAINFALL MAKES THE HIMALAYAN RIVERS PERENNIAL
- HIGH RUNOFF COUPLED WITH WIDER RANGE OF ALTITUDE PROVIDES A LARGE POTENTIAL FOR HYDROELECTRIC POWER IN THE HIMALAYAS
- DEVELOPMENT, DEPLETION AND MELTING PROCESSES OF SNOWPACK IS ESSENTIAL

GLOBAL ICE DISTRIBUTION

Total Land Area ~ 136,000,000 km2
Total Sea Area ~ 374,000,000 km2
Total Ice covered area ~15,861,766 km2
(~11% of land area)

Mountain glaciers/icecaps ~550,000 km2
(~ 3.5% of total ice)
(50%N. America, 44% Eurasia)

Frozen fresh water in polar ice ~ 29,000,000 km3
(~ 75% of world's fresh water)

GLOBAL ICE DISTRIBUTION

Region	Surface area (km2)
Antarctica	13, 586,310
Greenland	1,736,400
North America	276,100
Asia and CIS	185,211
Europe	53,967
South America	25,908
New Zealand/subantactic islands	7,860
Total	15,681,766

FRESH WATER DISTRIBUTION

Source	Volume ($10^6 \times km^3$)	in (%)
Polar ice caps and glaciers	29.00	77.33
Groundwater in depths up to 800m	4.15	11.07
Groundwater in depths below 800m	4.15	11.07
Lake, rivers and streams	0.12	0.32
Soil mositure and seepage	0.067	0.18
Atmospheric water vapour	0.013	0.03
Total	37.50	100.0

HIMALAYAN WATER RESOURCES

- About 35% of the geographical area of India is covered by mountains and 58% of this is accounted for by the mighty Himalayas.

- There are 22 major river systems lying in the Himalayas, which originate from the snow and glacier covered areas and cover about 1×10^6 km^2 mountainous catchment area.

- In some Himalayan rivers average contribution of snow and glacier melt runoff to the annual streamflow near the foothills is more than 50%.

- There are more than 9575 glaciers in the Indian Himalayan region, covering about 38000 km^2 area.

- Glacier extent in the Karakoram, Hindukush and Nanga Parbat in the Himalayan region is about 10 times greater than the Alps.

- Himalayan Rivers receive substantial contribution from the melting of snow and glaciers. Major share of runoff, during summer, comes from seasonal snowmelt and glaciers. This is considered a dependable source of water for irrigation, hydroelectric power and drinking water.

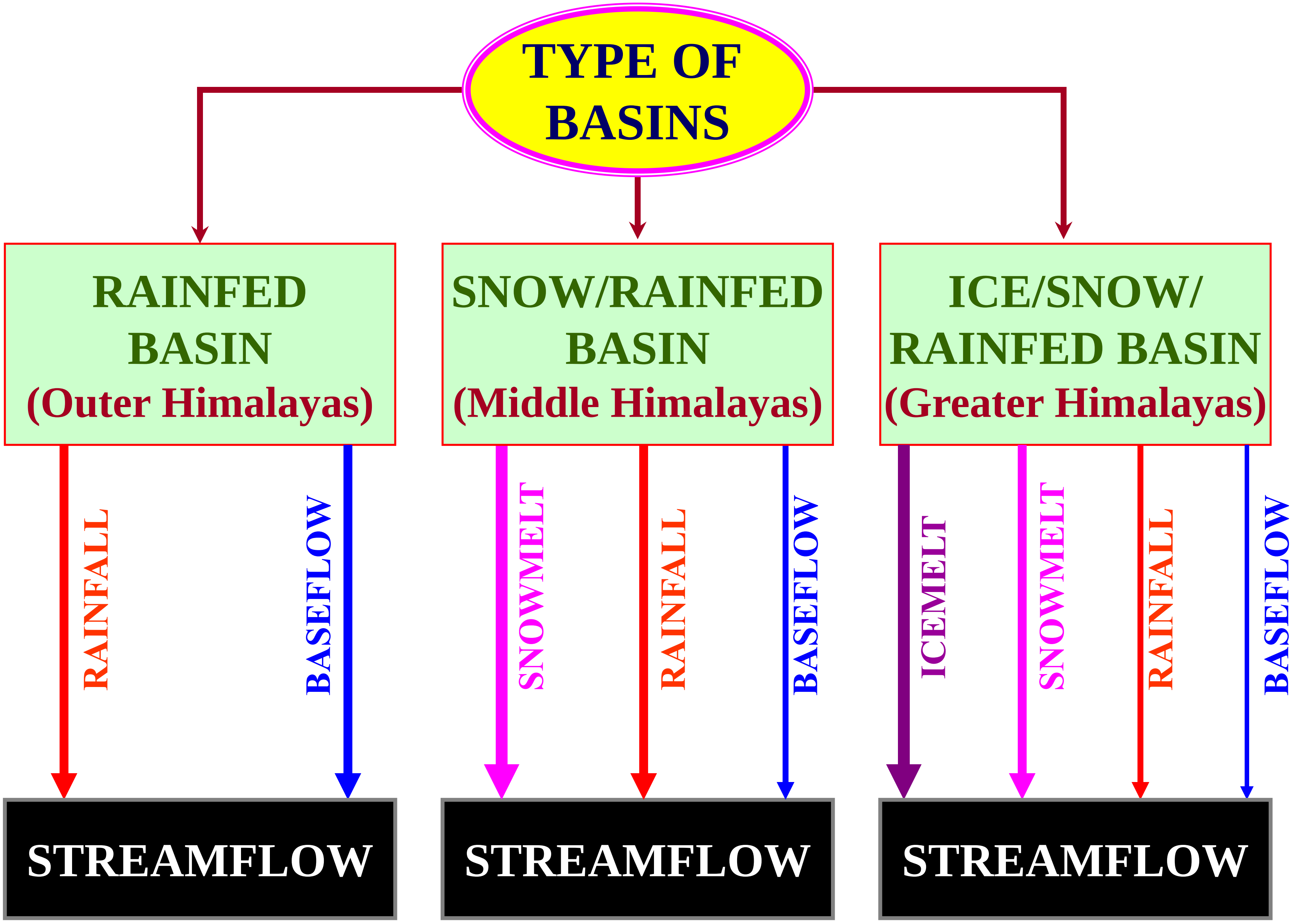
- **Total annual discharge of the country: 1880 km^3**

- **Snow and ice dominated Himalayan rivers viz. Indus, Ganges and Brahmaputra provide annual average flow of 206, 488 and 510 km^3 (total of 3 rivers: 1204 km^3, i.e., ~ 64% of total water resources of India)**

- **Average water yield per unit area of the Himalayan rivers is almost double than that of the southern peninsular river system indicating importance of snow and glacier melt.**

Principal glacier-fed river systems of the Himalaya

River	Major River System	Mountain Area (km^2)	Glacier Area (km^2)	% Glaciations
Indus	Indus System	268842	7890	3.3
Jhelum		33670	170	5.0
Chenab		27195	2944	10.0
Ravi		8092	206	2.5
Sutlej		47915	1295	2.7
Beas		12504	638	4.4
Jamuna		11655	125	1.1
Ganga	Ganga System	23051	2312	10.0
Ramganga		06734	3	0.04
Kali		16317	997	6.01
Karnali		53354	1543	2.9
Gandar		37814	1845	4.9
Kosi		61901	1281	2.1
Tista		12432	495	4.0
Raikad	Brahmaputra System	26418	195	0.7
Nanas		31080	528	1.7
Subansiri		81130	725	4.0
Brahmaputra		256928	108	0.4
Dibang		12950	90	0.7
Lohit		20720	425	2.0


TYPE OF BASINS
RAINFED BASIN
(Outer Himalayas)
SNOW/RAINFED BASIN
(Middle Himalayas)
ICE/SNOW/ RAINFED BASIN
(Greater Himalayas)
RAINFALL
BASEFLOW
SNOWMELT
RAINFALL
BASEFLOW
ICEMELT
SNOWMELT
RAINFALL
BASEFLOW
STREAMFLOW
STREAMFLOW
STREAMFLOW

AVERAGE SNOW COVERED AREA IN DIFFERENT HIMALAYAN BASINS

Basin	Total Area (km^2)	Max. SCA (km^2)	Min. SCA (km^2)
Chenab Basin up to Akhnoor	22200	15590 (70%)	5400 (24%)
Ganga Basin up to Devprayag	19700	9080 (46%)	3800 (19%)
Satluj Basin up to Bhakra Dam	22275	14498 (65%)	4528 (20%)
Beas Basin up to Pandoh Dam	5278	2700 (51%)	780 (14%)

SNOW AND GLACIER MELT RUNOFF IN DIFFERENT HIMALAYAN BASINS

River	Site	Av. snow & glaciers melt contribution to annual flows
Chenab River	Akhnoor	49%
Satluj River (Indian part)	Bhakra Dam	60%
Ganga River	Devprayag	30%

Snow Melt Runoff Simulation Models

- Snowmelt Model

- Transformation Model

The snowmelt model generates liquid water from the snowpack that is available for runoff.

The transformation model converts the liquid output at the ground surface to runoff at the basin outlet.

- Lumped – Whole catchment as a single unit
- Distributed – These models account for the spatial variability

Lumped and Distributed models can be further classified as

- **Energy balance**
- **Temperature index**

ENERGY BALANCE AND MODELLING STUDIES

- **Snow and glacier melt runoff modelling using energy balance approach is complex.**

- **Availability of climatic data *viz.* Radiation, turbulent heat exchange, albedo, cloudiness, wind speeds etc. is required.**

- **A temperature index or the degree day - approach is generally considered to be a good model of heat transfer.**

- **Air temperatures are generally most readily available data in high altitude regions.**

Energy Balance Approach

The energy balance equation can be written in the form :

$$Q_m = Q_n + Q_h + Q_e + Q_p + Q_g + Q_q$$

Q_m = heat used for melting

Q_n = net radiation (long and short wave)

Q_e = latent heat transfer

Q_h = sensible heat transfer

Q_p = the heat content of rain water

Q_g = the heat gained through conduction from underground

Q_q = the change of internal energy storage of the snowpack

TEMPERATURE INDEX APPROACH

- **Air temperature expressed as degree-days are used in snowmelt computations as an index of the complex energy balance tending to snowmelt.**

- **A unit expressing the amount of heat in terms of persistence of a temperature for 24-hour period of 1ºC departure from a reference temperature.**

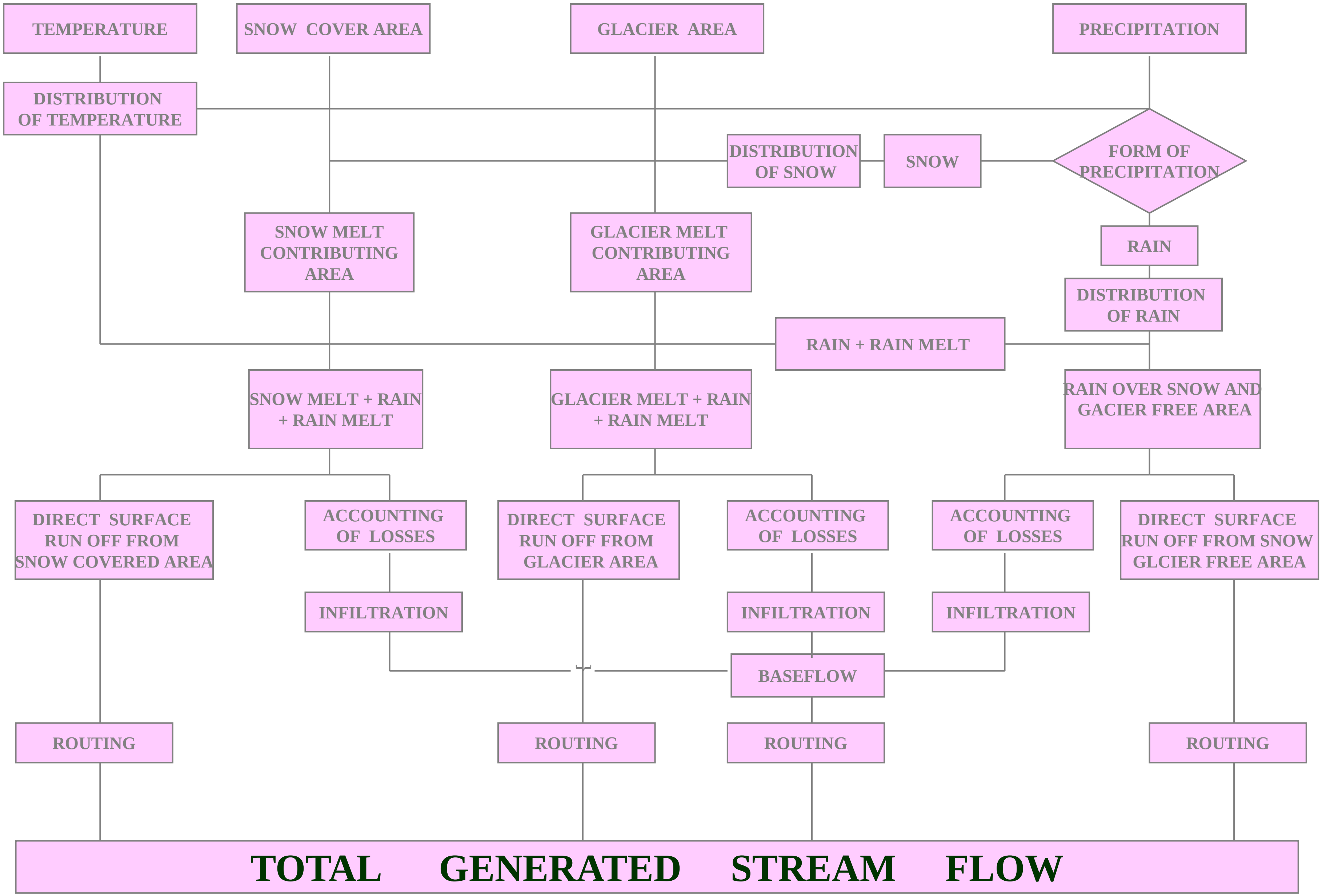
- **Expression relating snowmelt to TI : $M = D(T_i - T_b)$**

- **Daily mean temperature is most commonly used index temperature for snowmelt. $T_i = T_{mean} = (T_{max} + T_{min})/2$**

- **When the basin is subdivided based on elevation zones, the degree days are extrapolated to an elevation zone by using a a suitable lapse rate i.e., $T_{ij} = \delta\ (h_z - h_{st})$**

MODELLING OF SNOW AND GLACIER MELT RUNOFF

- Division of a basin into elevation zones
- Handling of meteorological data
  - temperature distribution
  - precipitation distribution
- Form of precipitation
- Depletion of snow covered area
- Glacier extent and its exposing trends
- Rain-induced melt
- Accounting of losses
- Routing of surface and subsurface flow



Flow chart of the snowmelt model (SNOWMOD)

Precipitation

if $T_m \geq T_c$, precipitation is considered as rain
if $T_m \leq 0°C$, precipitation is considered as snow

T_m = Daily mean temperature
T_c = Critical temperature

In case, $T_m \geq 0°C$ and $T_m \leq T_c$, the precipitation is considered as a mixture of rain and snow and their proportion is determined as follows

$$\text{Rain} = (T_m / T_c) \times P$$
$$\text{Snow} = P - \text{Rain}$$

P is total observed precipitation

Melt, temperature and degree-days

$$M = D\,(T_i - T_b)$$

M = depth of melt water (mm) produced in a unit time,
D = degree-day factor (mm °C^{-1} d^{-1}),
T_i = index air temperature (°C),
T_b = base temperature (usually, 0°C)

T_{mean} or the number of degree-days are computed as

$$T_i = T_{mean} = (T_{max} + T_{min})/2$$

Temperature Extrapolation

Temperature extrapolation for each elevation zone using temperature lapse rate

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

$T_{i,j}$ is daily mean temp. on i^{th} day in j^{th} zone (^oC)

$T_{i,base}$ is daily mean temp. (^oC) on i^{th} day at base station

h_j is zonal hypsometric mean elevation (m)

h_{base} is elevation of base station (m) and

δ is temperature lapse rate (^oC/100m)

Computation of different components of runoff

(i) Surface runoff from glaciated area

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

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

$M_{s,i,j}$ = snowmelt in terms of depth of water on i^{th} day for j^{th} zone (mm d^{-1})

$C_{s,i,,j}$ = runoff coeff. for snow melt on i^{th} day for j^{th} zone

$D_{i,j}$ = degree-day factor on i^{th} day for j^{th} zone (mm^{o}C^{-1}d^{-1})

$T_{i,j}$ = temperature on i^{th} day for j^{th} zone (^{o}C)

$S_{c,i,,j}$ = ratio of SCA to the total area of j^{th} zone on i^{th} day

Rain induced melt

$$Q_p = \rho\, C_p\, (T_r - T_s)\, P_r / 1000$$

Q_p = energy supplied to the pack by rain (kJ $m^{-2} d^{-1}$)

ρ = density of water (1000 kg m^{-3})

C_p = specific heat of water (4.20 kJ $kg^{-1}\ {}^0C^{-1}$)

T_r = temperature of rain (°C)

T_s = temperature of snow/ice (°C)

P_r = depth of rain (mm d^{-1})

Substituting the values of various parameters

$$Q_p = 4.2\, T_r\, P_r$$

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

$$M_r = Q_p / (\rho\, h_f\, B) = Q_p / 325$$

or

$$M_r = 4.2\, T_r\, P_r / 325$$

M_r is melt caused by the energy of rain (mm d $^{-1}$)
h_f is the latent heat of fusion of water (335 kJ kg^{-1})
B is the thermal quality of snow (0.95-0.97)

(b) The depth of snowmelt caused by rain in a elevation zone

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

$M_{r,i,j}$ = snowmelt in terms of depth of water due to rain on snow on i^{th} day for j^{th} zone (mm d^{-1})

$P_{i,j}$ = rainfall on snow on i^{th} day for j^{th} zone (mm d^{-1})

(c) Runoff depth from rain itself falling over SCA

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

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

$$Q_{sca} = \alpha\,(M_{s,i,j} + M_{r,i,,j} + R_{s,i,j})\, A_{sca,i,j}$$

n is the total number of zones,

$A_{sca,i,j}$ is SCA in the j^{th} zone on the i^{th} day (km^2)

α is a factor (1000/86400 or 0.0116) used to convert the runoff depth ($mm\ d^{-1}$) into discharge ($m^3\ s^{-1}$)

Surface runoff from snow/ice free area

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

$P_{i,j}$ = rainfall on snow on i^{th} day for j^{th} zone (mm d^{-1})
$C_{r,i,j}$ = coefficient of runoff for rain on i^{th} day for j^{th} zone
$S_{f,i,j}$ = ratio of SFA to the total area of j^{th} zone on i^{th} day

Total runoff from SFA for all the zones is thus given by

$$Q_{sfa} = \alpha R_{f,i,j}\ A_{sfa,i,j}$$

$A_{sfa,i,j}$ is snow free area in the j^{th} zone on the i^{th} day

Estimation of subsurface runoff

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

$M_{t,i,j} = M_{s,i,j} + M_{r,i,j} + R_{s,i,j.,}$ and β is 0.50

Subsurface runoff was computed by multiplying the depth with conversion factor α and area

$$Q_b = \alpha\,R_{b,i,j}\;A_{i,j}$$

$A_{i,j}$ is the total area (km^2) of zone j on ith day and represents the sum of $A_{sca,i,j}$ and $A_{sfa,i,j.}$

TOTAL STREAMFLOW

$$Q = Q_{sca} + Q_{sfa} + Q_b$$

ROUTING OF DIFFERENT COMPONENTS OF RUNOFF

(i) Routing of surface runoff

$$Q_{n+1,\, j+1} = C_0\, Q_{n\, ,\, j+1} + C_1\, Q_{n\, ,\, j} + C_2\, Q_{n+1\, ,\, j}$$

n and j represent the reservoir number and time index, respectively

For a linear reservoir, $C_0 = C_1$ and therefore, the equation representing the outflow from the n^{th} reservoir is simplified as

$$Q_{n+1,\ j+1} = 2C_1 \overline{Q}_{n,\ j+1} + C_2\, Q_{n+1,\ j}$$

$$\overline{Q}_{n,\ j+1} = (Q_{n,\ j+1} + Q_{n,\ j})/\ 2$$

$$C_0 = (\mathrm{dl}\ t/k)\ /\ (2 + \mathrm{dl}\ t/k)$$
$$C_1 = C_0$$
$$C_2 = (2 - \mathrm{dl}\ t/k)\ /\ (2 + \mathrm{dl}\ t/k)$$

Here C_0, C_1, C_2 are the routing coefficients and the sum of these coefficients equals unity, i.e.

$$C_0 + C_1 + C_2 = 1$$

The storage coefficients were related to SCA and SFA in the nonlinear form

$$k_r = a_r \, (A_{sfa})^{br}$$

$$k_s = a_s \, (A_{esca})^{bs}$$

k_r = storage coefficient for SFA
k_s = storage coefficient for SCA
A_{sfa} = total snow free area in the basin
A_{esca} = total effective snow covered area in the basin
a_r and b_r = model parameters for SFA
a_s and b_s = model parameters for effective SCA

(ii) Routing of subsurface runoff

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

Q_0 is the discharge at time $t = 0$

The parameter k is known as recession constant, or the depletion factor. In the logarithm form this equation can be written as

$$\ln Q = \ln Q_0 - t/k$$

SALIENT FEATURES OF SATLUJ BASIN

Location : Western Himalayas

Basin Area (Indian part) : 22,275 km^2

Elevation Range: 500-7000 m.

Mean elevation: 3600 m

Snow covered area : About 65% after winter

Glacierized area : About 10%

Important hydropower scheme: Bhakra Dam (1000 MW)

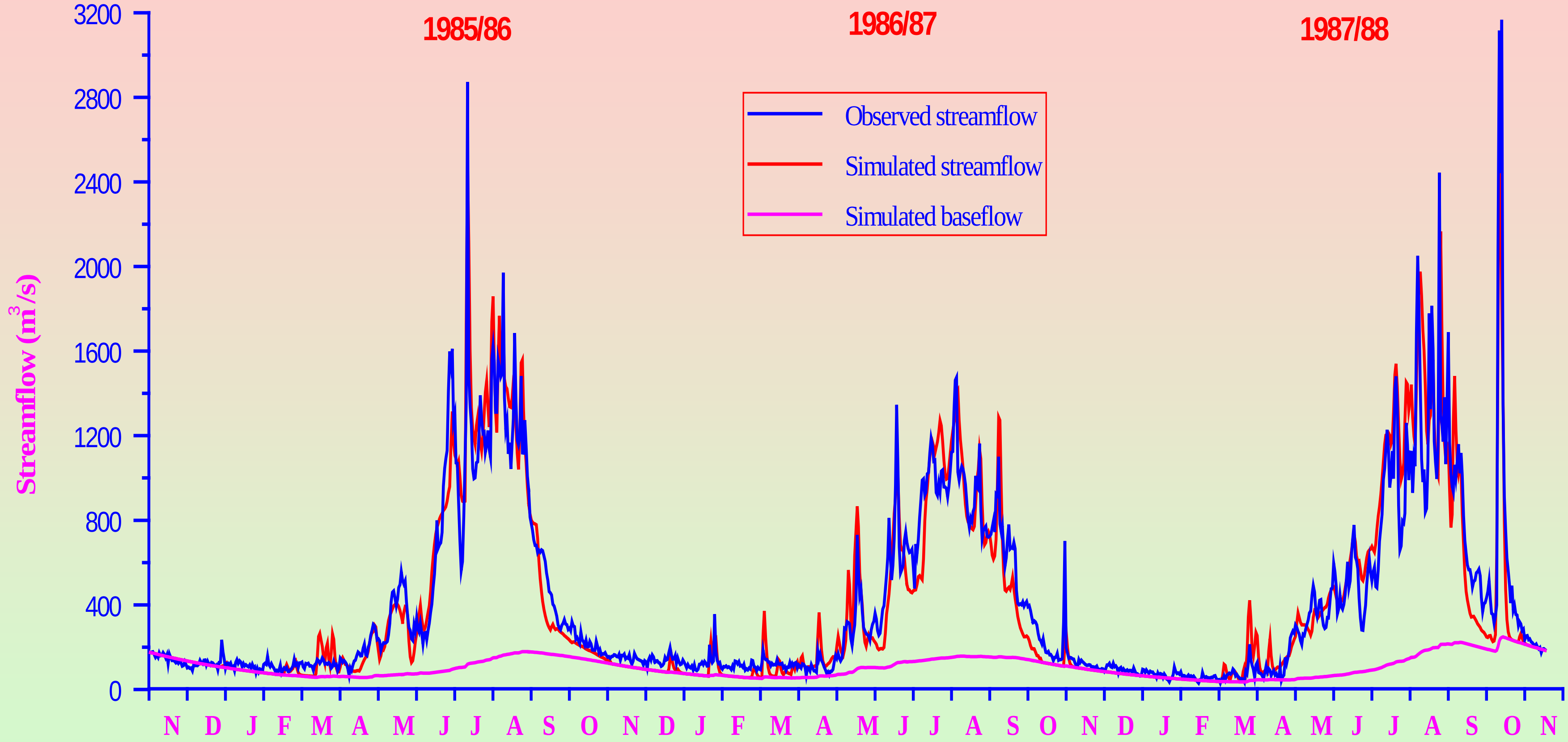


Figure 1: Observed and simulated daily streamflow for the Satluj River at Bhakra for a period of 3 years (1985/86 - 1987/88)

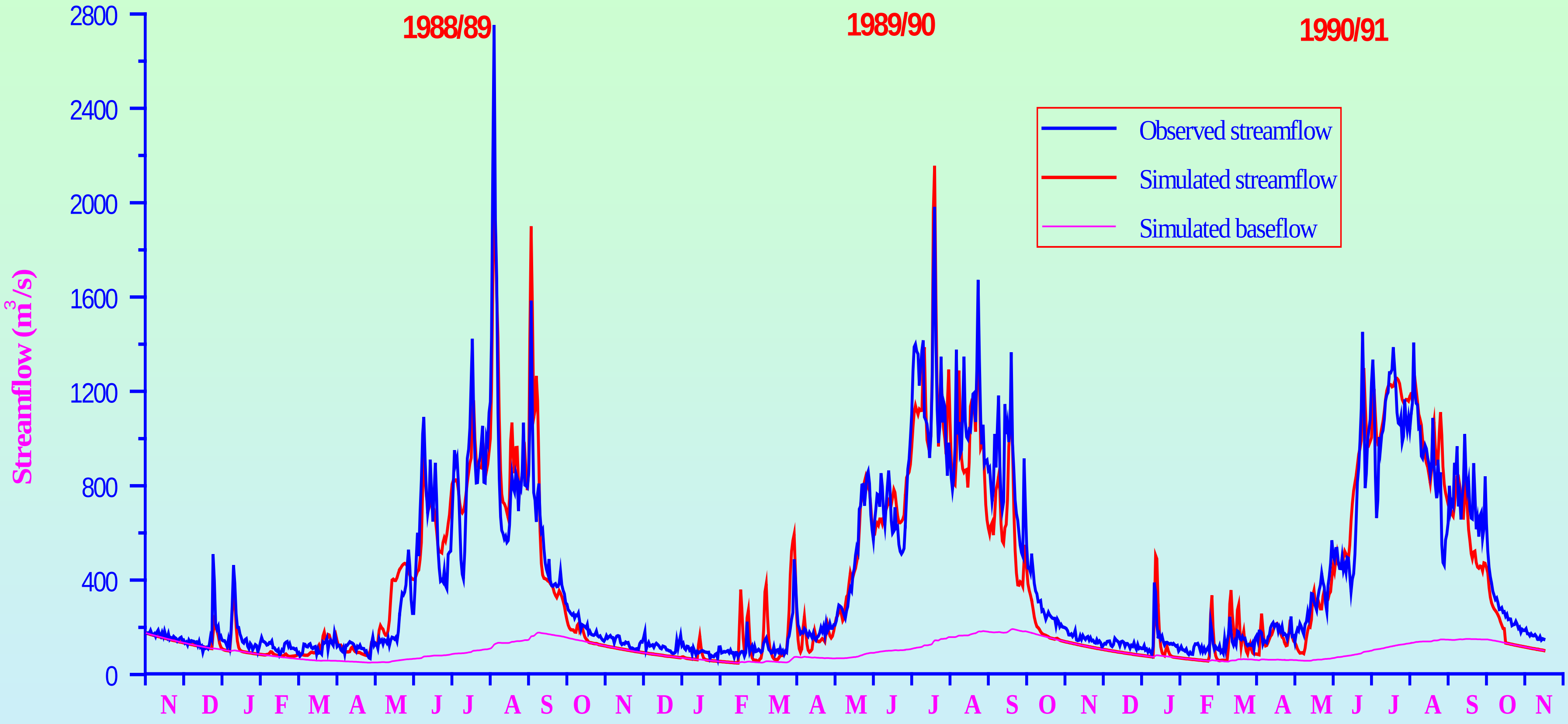


Figure 1: Observed and simulated daily streamflow for the Satluj river at Bhakra for a period of 3 years (1988/89 - 1990/91)

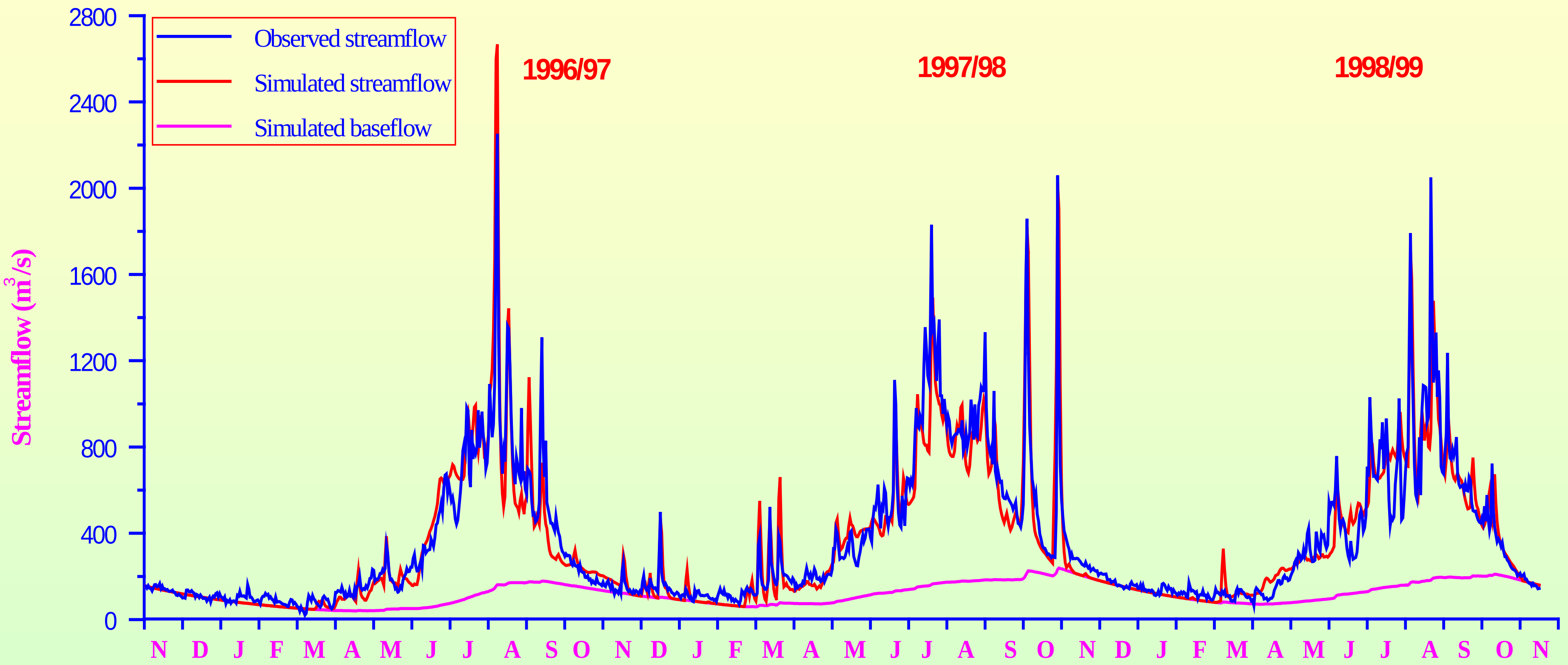


Figure 4: Observed and simulated daily streamflow for the Satluj River at Bhakra for a period of 3 years (1996/97 - 1998/99).

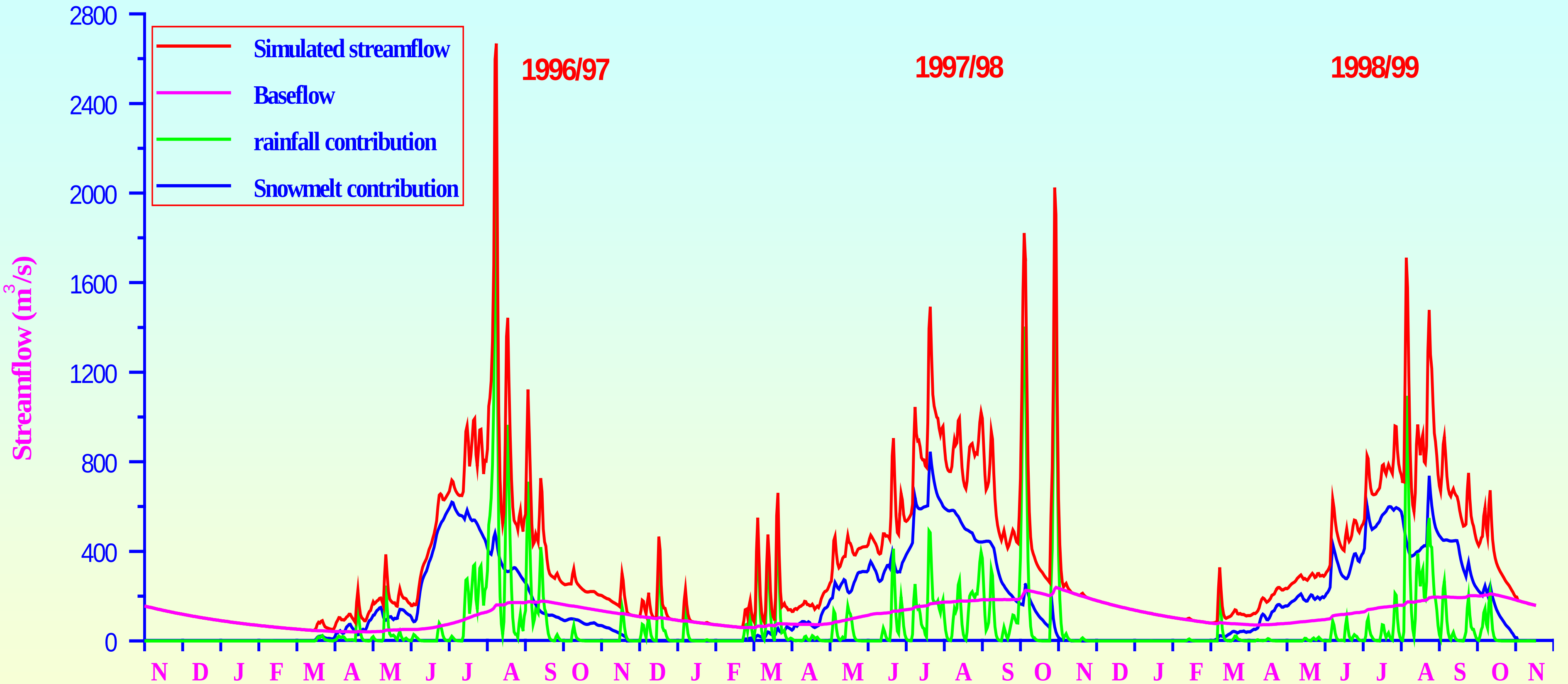
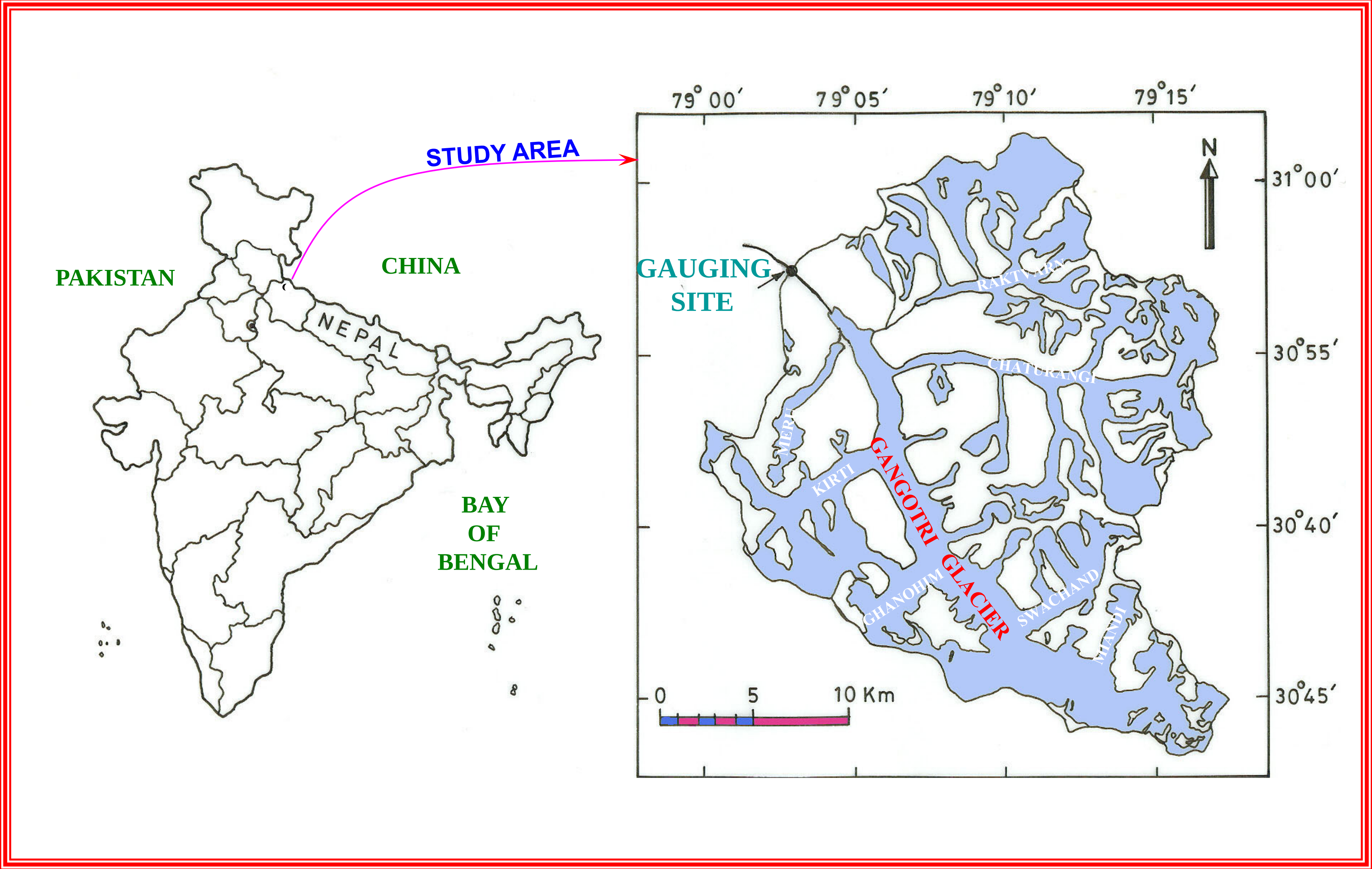


Figure 5: Different components of simulated daily streamflow for the Satluj River at Bhakra for a period of 3 years (1996/97 - 1998/99).

MODEL EFFICIENCY

Year	R^2	D_v
1985/86	0.93	-2.1
1986/87	0.85	-10.9
1987/88	0.88	-2.4
1988/89	0.90	-2.6
1989/90	0.89	-4.2
1990/91	0.90	0.3
1996/97	0.87	-9.3
1997/98	0.88	-8.8
1998/99	0.85	-3.3
Over 9 years	0.90	-3.3


STUDY AREA
PAKISTAN
CHINA
NEPAL
BAY OF BENGAL
GAUGING SITE
79° 00′
79° 05′
79° 10′
79° 15′
31° 00′
30° 55′
30° 40′
30° 45′
N
RAKTVARN
CHATURANGI
MERU
KIRTI
GANGOTRI GLACIER
GHANOHIM
SWACHAND
MIANDI
0
5
10 Km

SALIENT FEATURES OF GANGOTRI GLACIER

Location : Garhwal Himalayas

Type : Valley Glacier

Approach : 18 km trekking

Elevation : ~ 4000-7000 m

Length : ~ 30 km

Glacierized Area : ~ 286 km^2

Catchment Area : ~ 556 km^2

A view of snout of the Gangotri Glacier (Gomukh)

Ice wall near at the snout of Gangotri Glacier

October 15, 2004

DATA COLLECTION

Discharge (round the clock) (May-October):

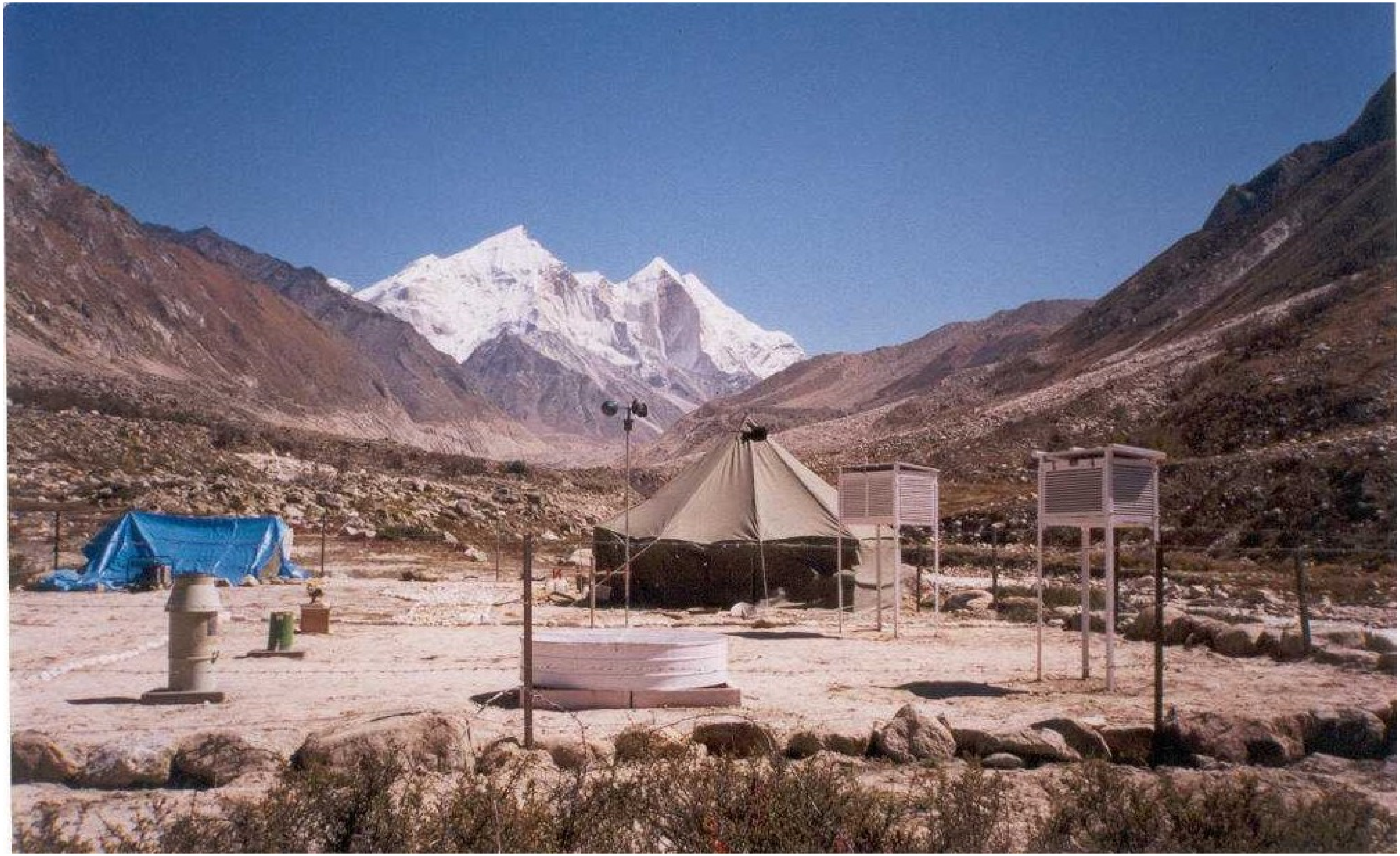
- Establishment of gauging site
- Stilling well, water level recorder

Meteorological parameters

- Rainfall
- Temperature
- Wind speed and direction
- Relative humidity
- Sunshine hours
- Evaporation

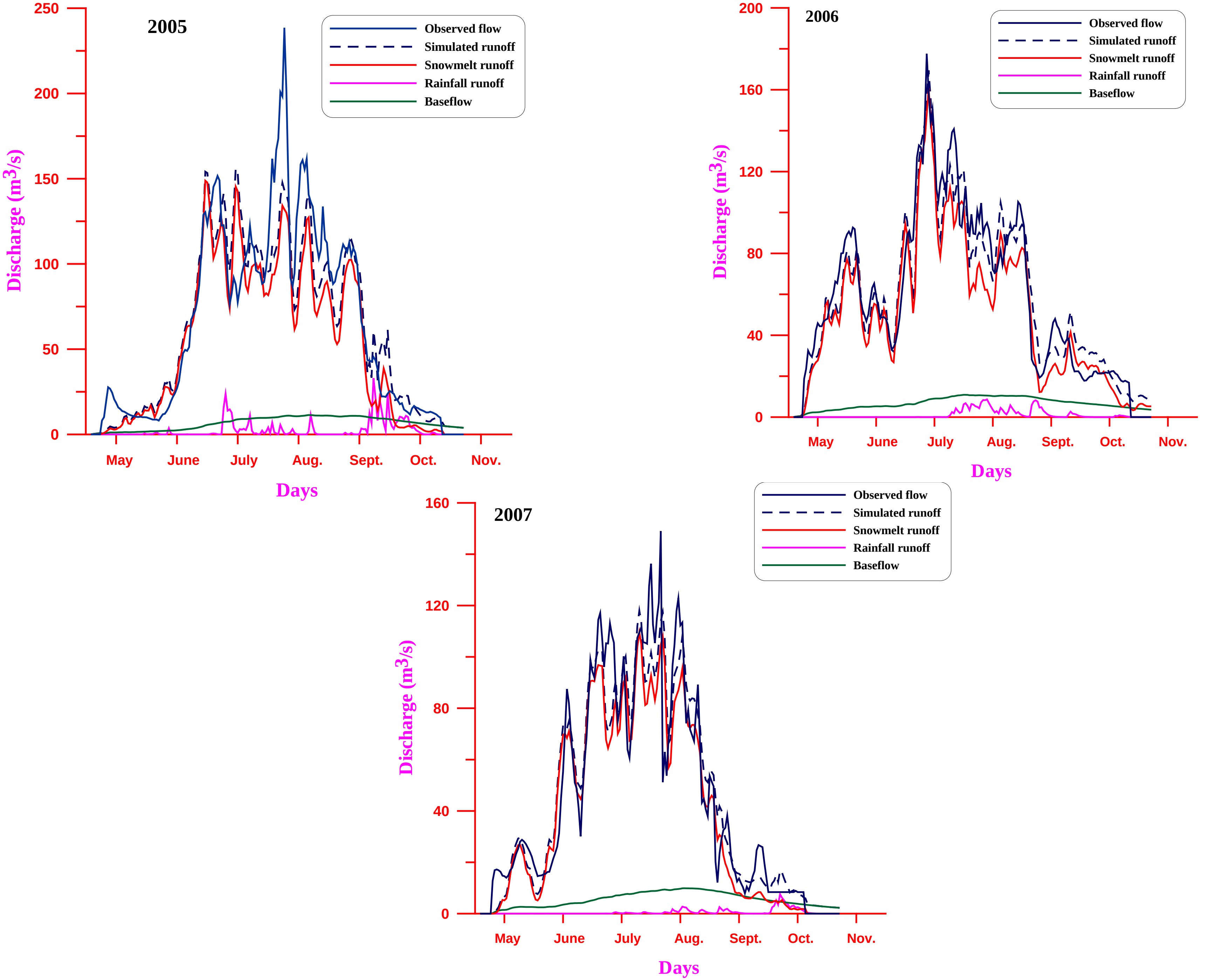
Suspended sediment

- Suspended sediment concentration



Meteorological Observatory near the Gangotri Glacier

A view of gauging site near the Gangotri Glacier



Different components of simulated runoff for summer season (2005-2007) for the Gangotri Glacier.

Percentage difference in volume, model efficiency and contributions of rainfall, snowmelt and base flow computed by the model.

Year	Model	Percentage Diff. in Vol.	Model efficiency (%)	Rain (%)	Snow (%)	Base flow (%)
2005	Snowmod	-4.01	90	4.00	85.10	10.90
2006	Snowmod	-1.61	95	2.06	86.34	11.60
2007	Snowmod	0.29	93	1.30	86.39	12.31

Chenab Basin Study

- Elevation of the study area varies from ~ 305 m to 7500 m.
- Mean elevation of the basin is about 3600 m.s.l.
- Total catchment area up to Akhnoor is 22,200 km^2.
- Total Number of Glaciers is 989.
- Glacierized Area is 2280 sq km.

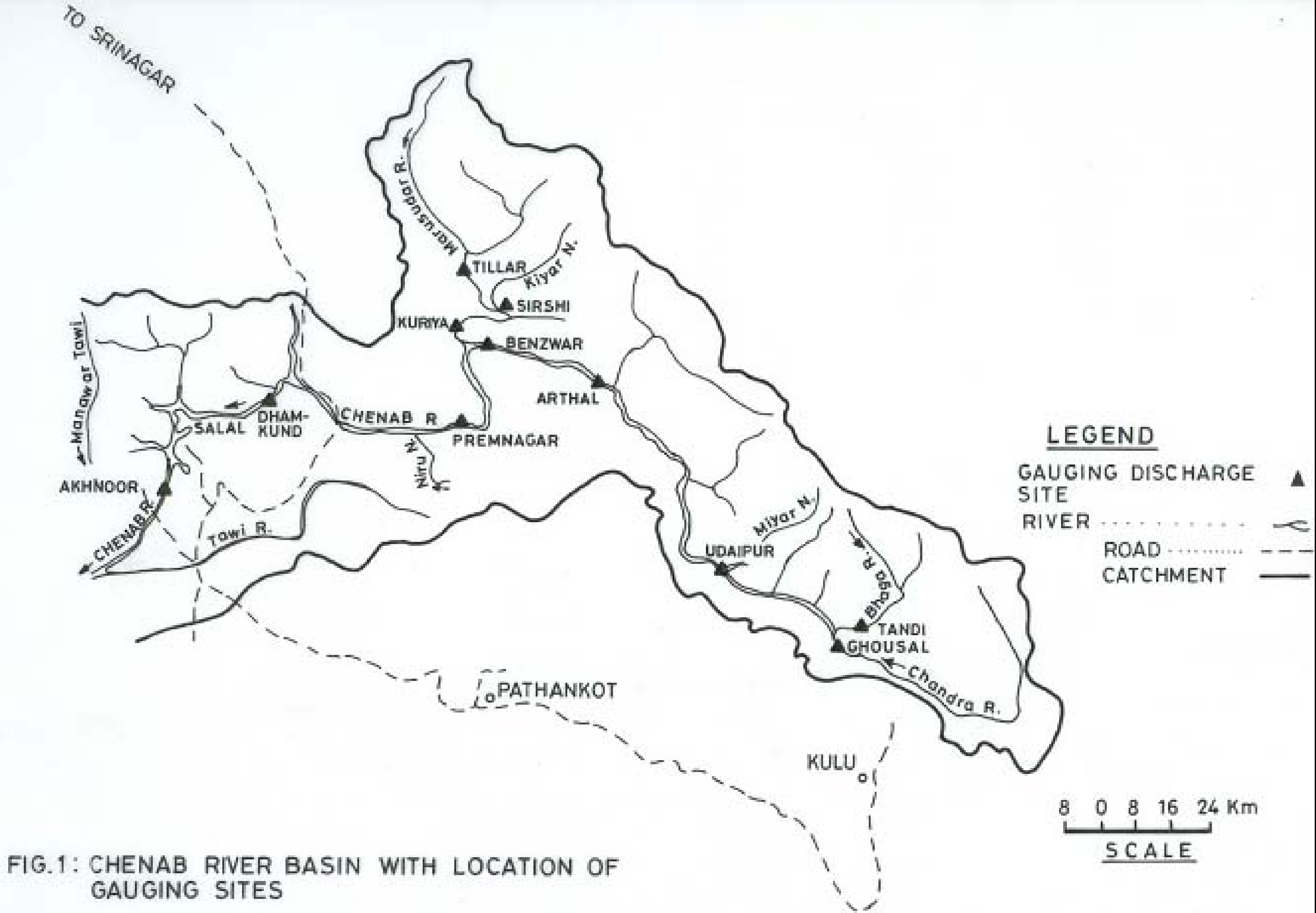
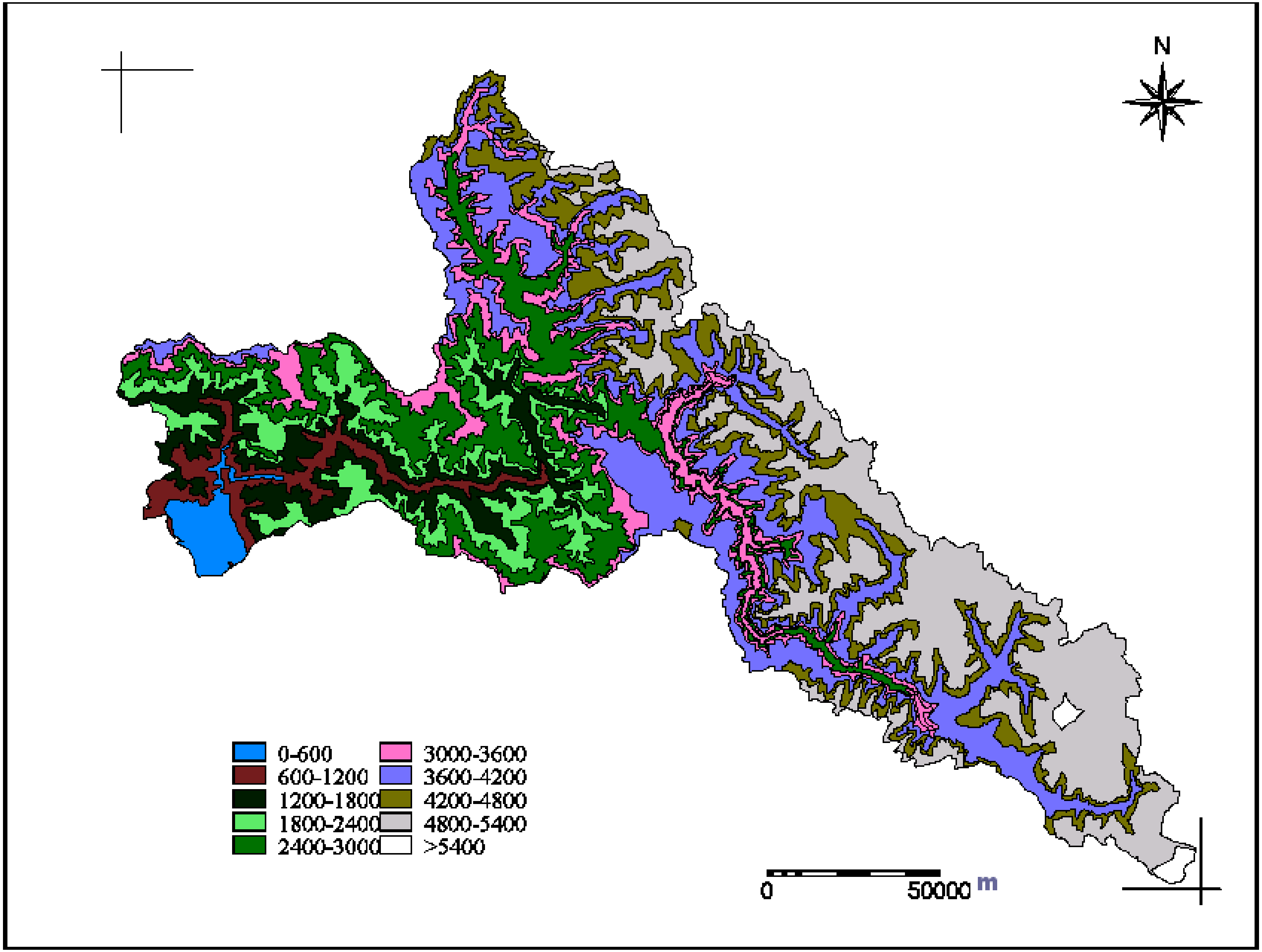
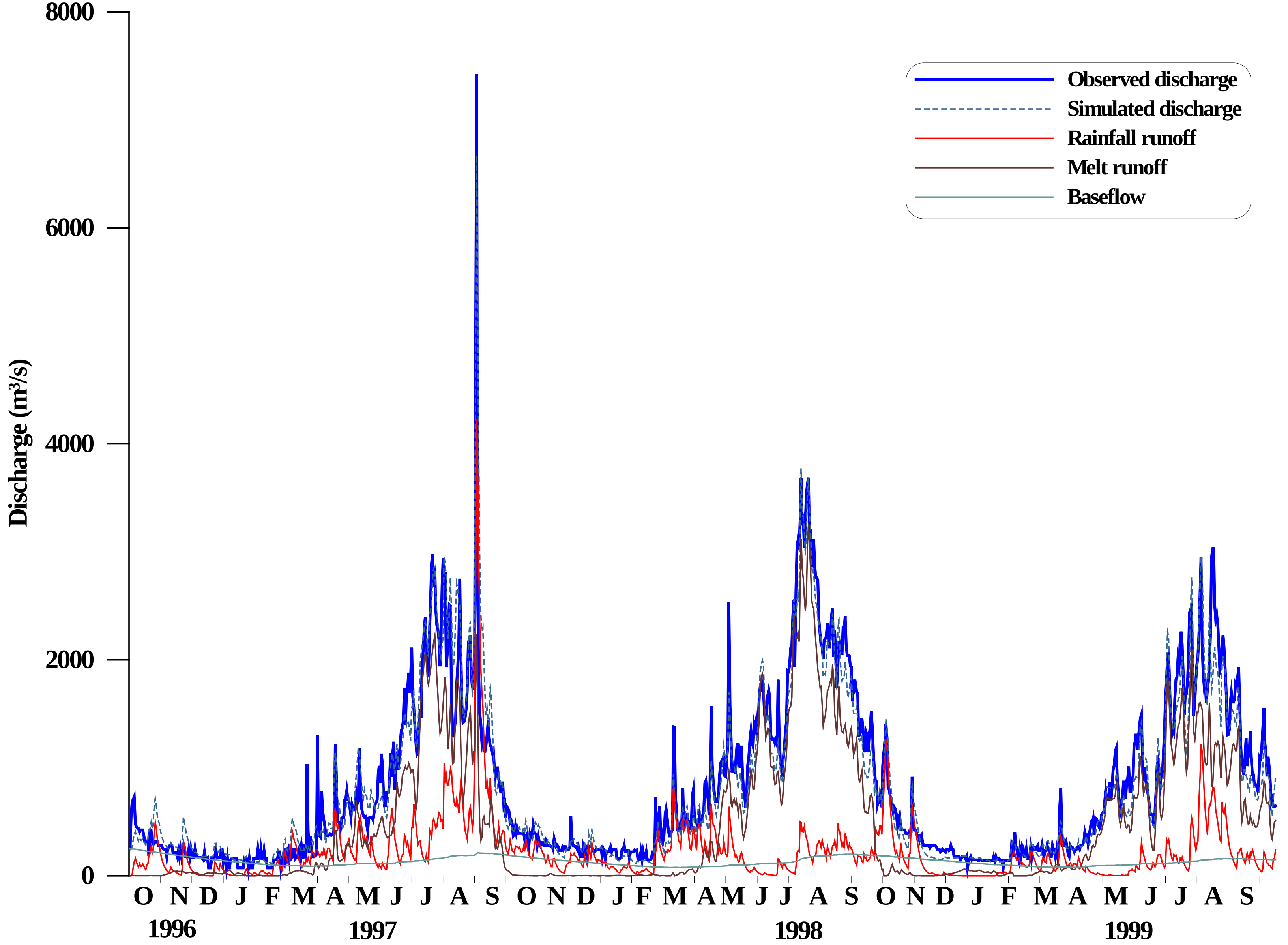


FIG.1: CHENAB RIVER BASIN WITH LOCATION OF GAUGING SITES

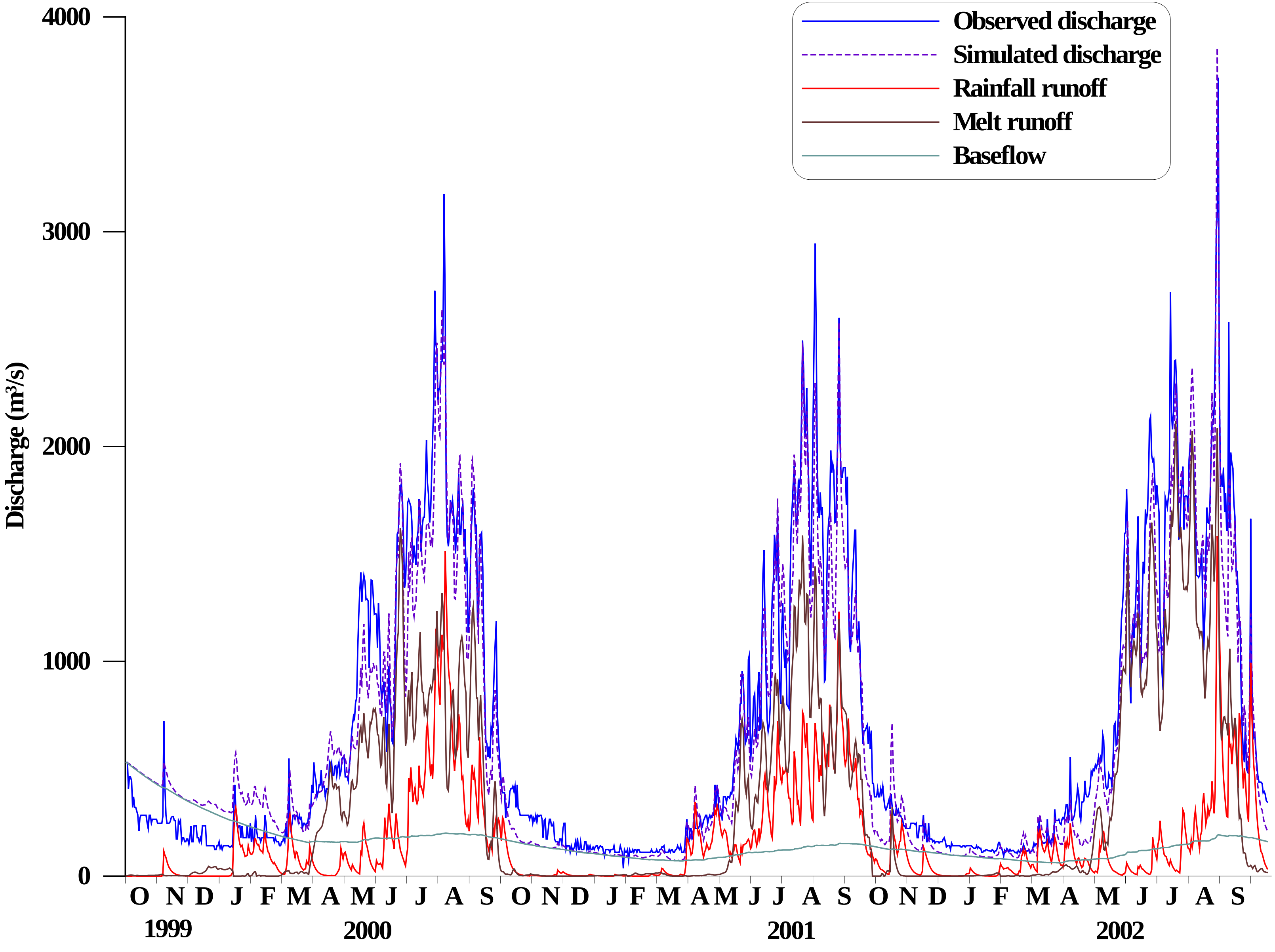

N
0-600
600-1200
1200-1800
1800-2400
2400-3000
3000-3600
3600-4200
4200-4800
4800-5400
>5400
0
50000 m



A comparison of observed and simulated discharge of the Chenab River at Salal Dam for the calibration period (1996/1997 to 1998/1999).

Model efficiency for the calibration period (1996/1997, 1997/1998 and 1998/1999)

Period	R^2	Volume difference (%)
1996/1997	0.87	7.07
1997/1998	0.94	0.98
1998/1999	0.86	9.91
1996/1997 to 1998/1999	0.91	2.48



A comparison of observed and simulated discharge of the Chenab River at Salal Dam for the simulation period (1999/2000 to 2001/2002).

Model efficiency for the simulation period (1999/2000, 2000/2001 and 2001/2002)

Period	R^2	Volume difference(%)
1999/2000	0.91	1.73
2000/2001	0.90	7.97
2001/2002	0.91	3.95
1999/2000 to 2001/2002	0.92	6.6

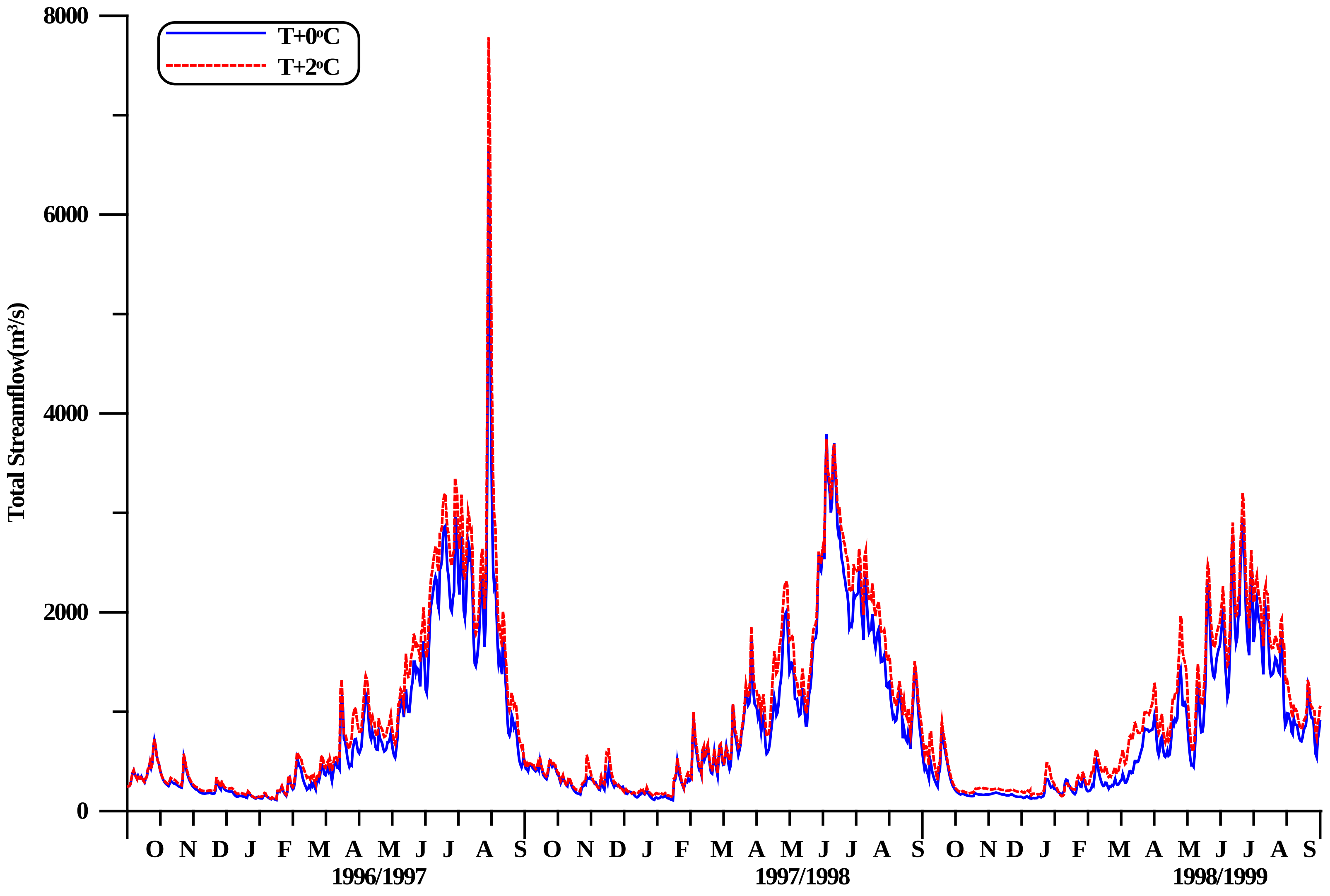


Figure : Effect of increase in temperature by 2°C on daily streamflow for the years 1996/1997, 1997/1998 and 1998/1999.

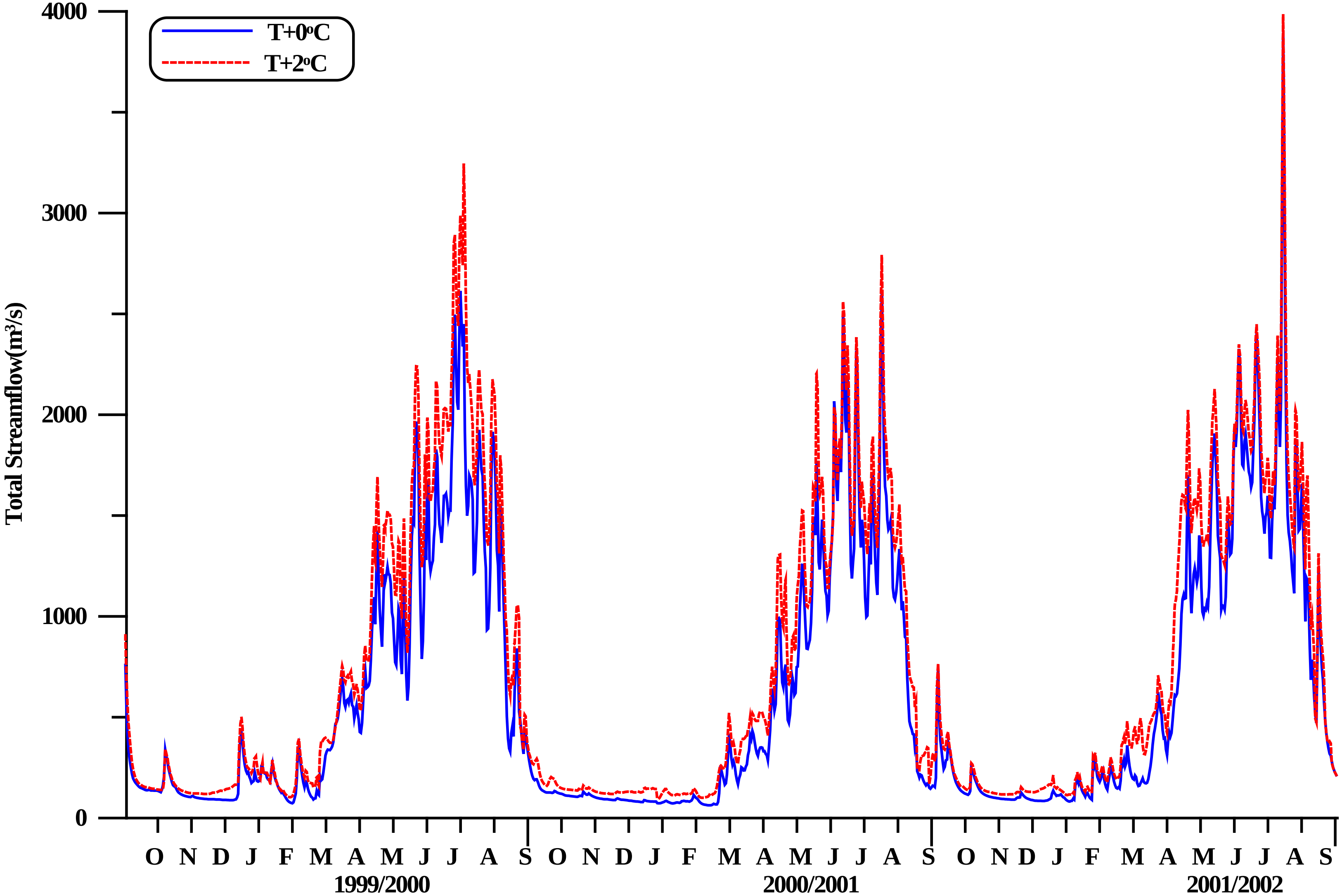


Figure : Effect of increase in temperature by 2ºC on daily streamflow for the years 1999/2000, 2000/2001 and 2001/2002.

- **For a temperature increase of 2°C, the variation in annual streamflow is computed to be 18, 13, 22, 24, 22 and 19% respectively for 1996/1997, 1997/1998, 1998/1999, 1999/2000, 2000/2001 and 2001/2002.**

- **The average value of increase in total streamflow runoff for T+1°C, T+2°C and T+3°C are obtained to be 7%, 19% and 28% respectively.**

The Dokriani Glacier

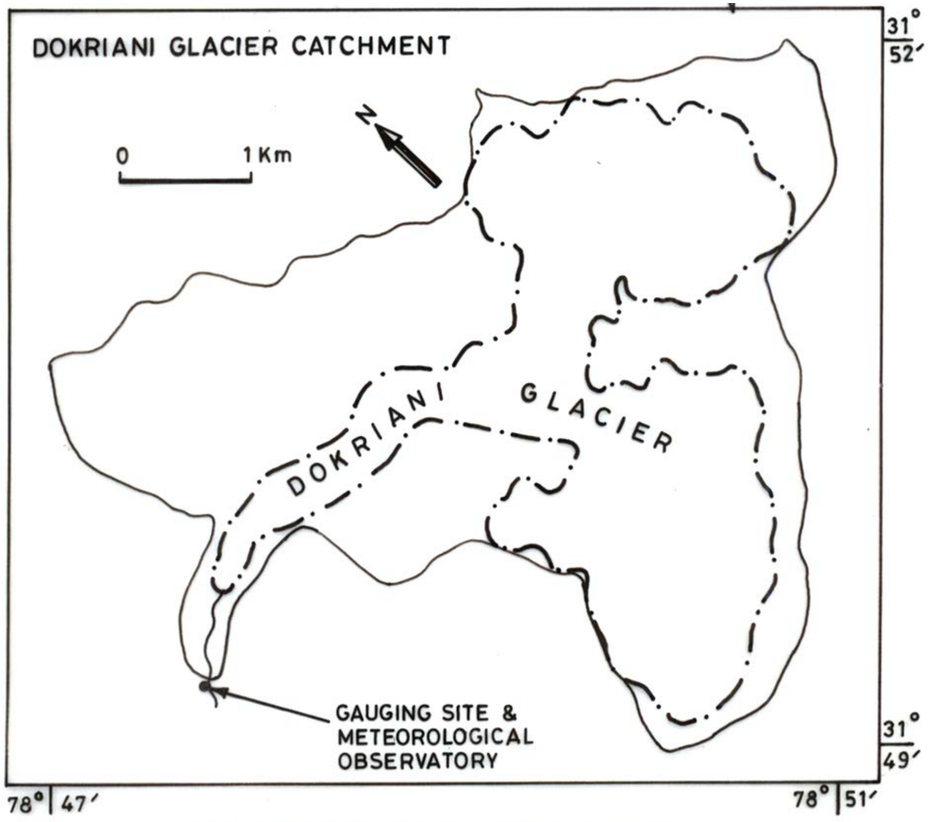
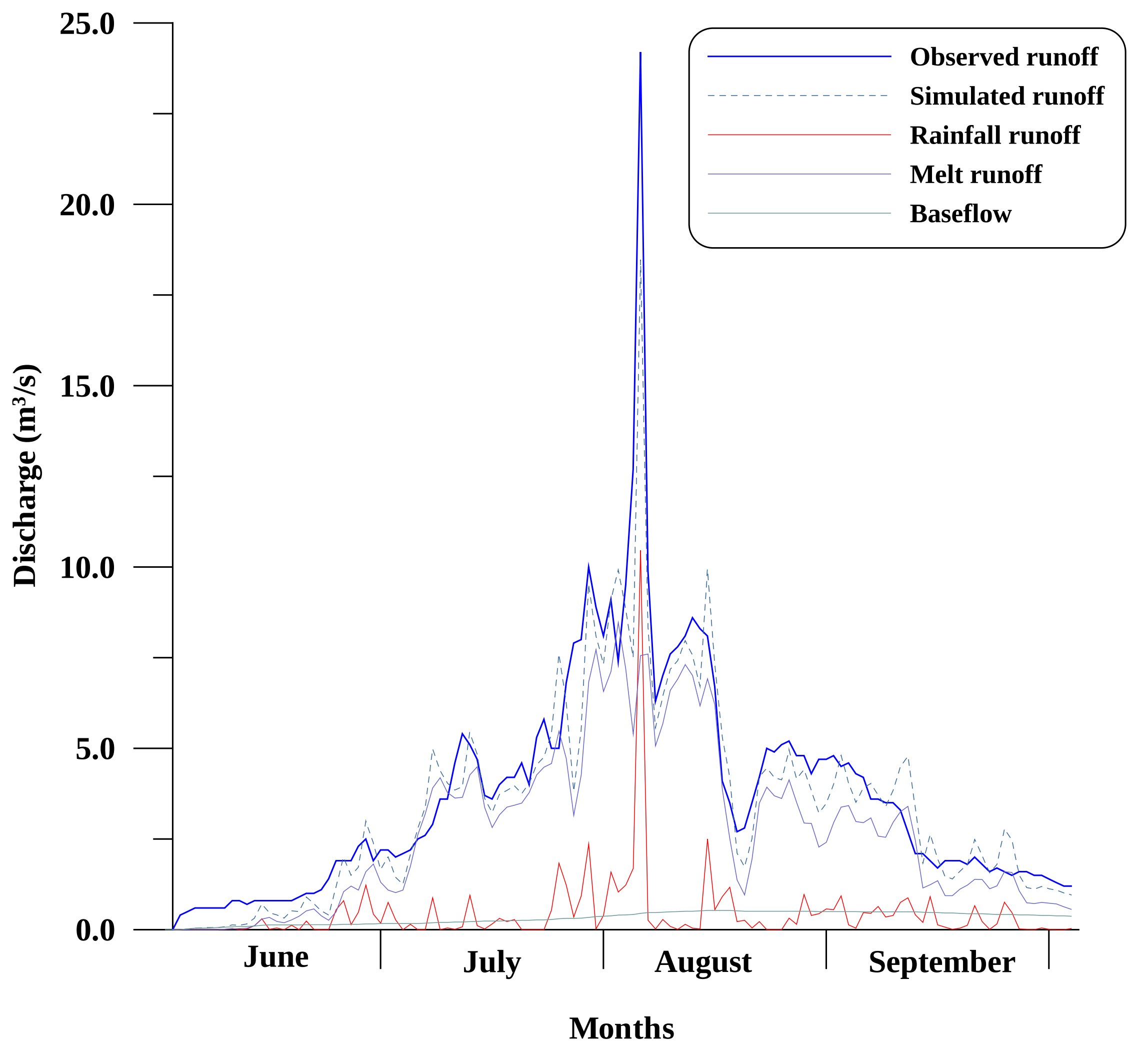
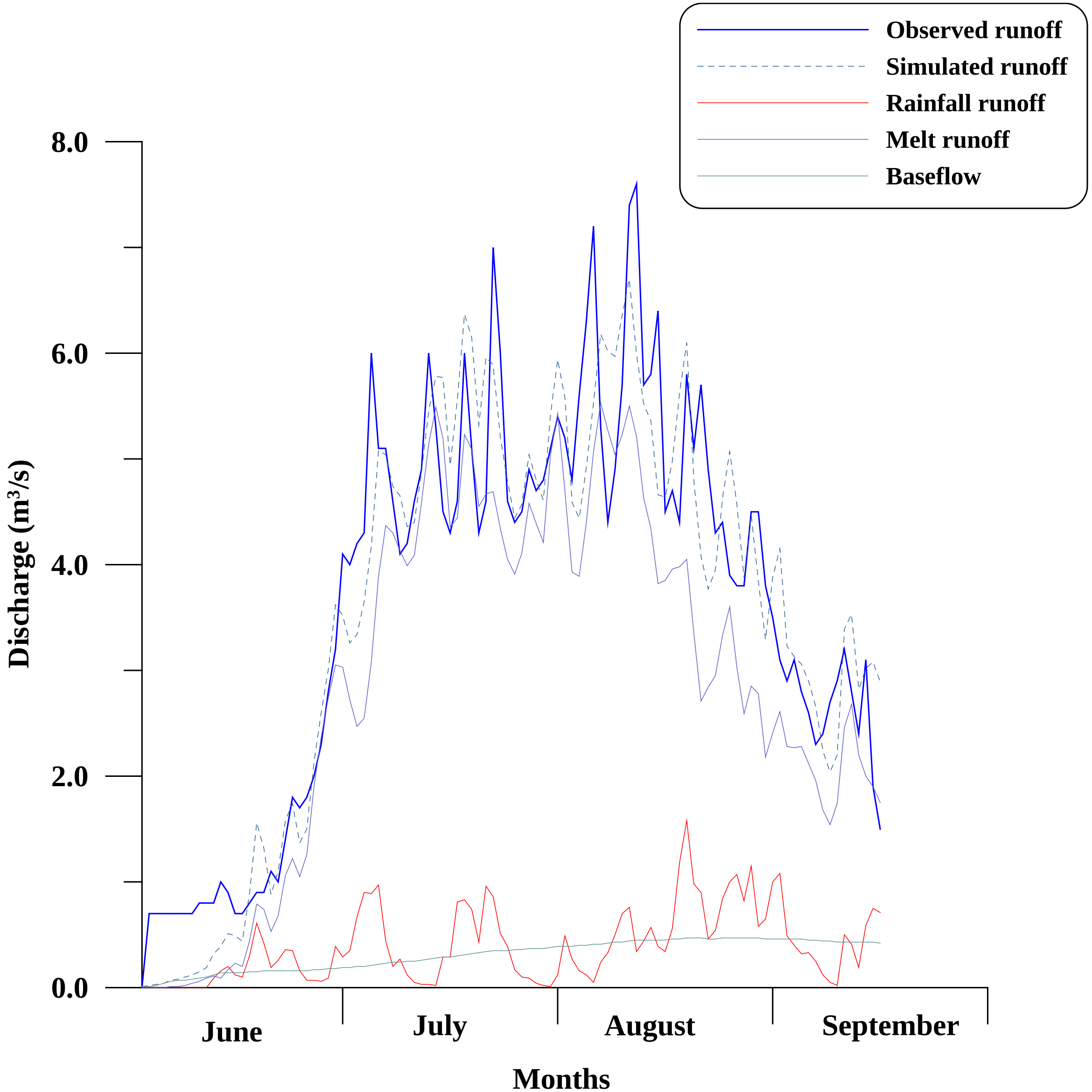


FIG.1 LOCATION OF DOKRIANI GLACIER

- **Total drainage area up to the gauging site ~ 16.13km^2**
- **9.66 km^2 (60%) is covered by snow and ice.**
- **Elevation range - 3950-5800 m.**
- **Length ~ 5.5 km, Width ~ 0.1-2.0 km.**
- **Maximum glacier area (12.86%) lies in 5000-5100m range and 12.44% in the 5100-5200m.**



Observed and simulated daily discharge for the summer 1997 for the Dokriani Glacier in Garhwal Himalayas.



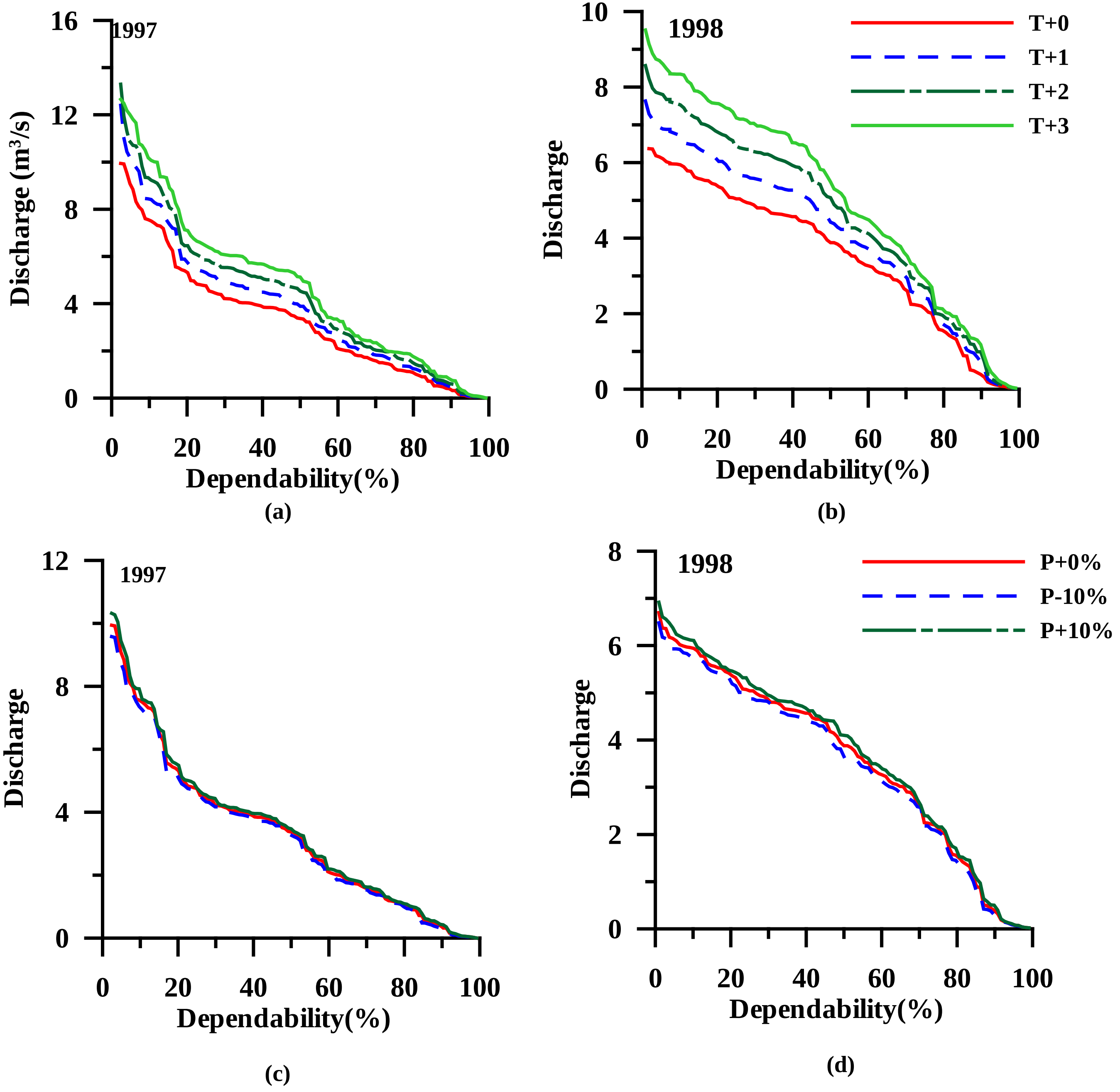
Observed and simulated daily discharge for the summer 1998 for the Dokriani Glacier in Garhwal Himalayas

- **The contribution of glacier melt: 87%**

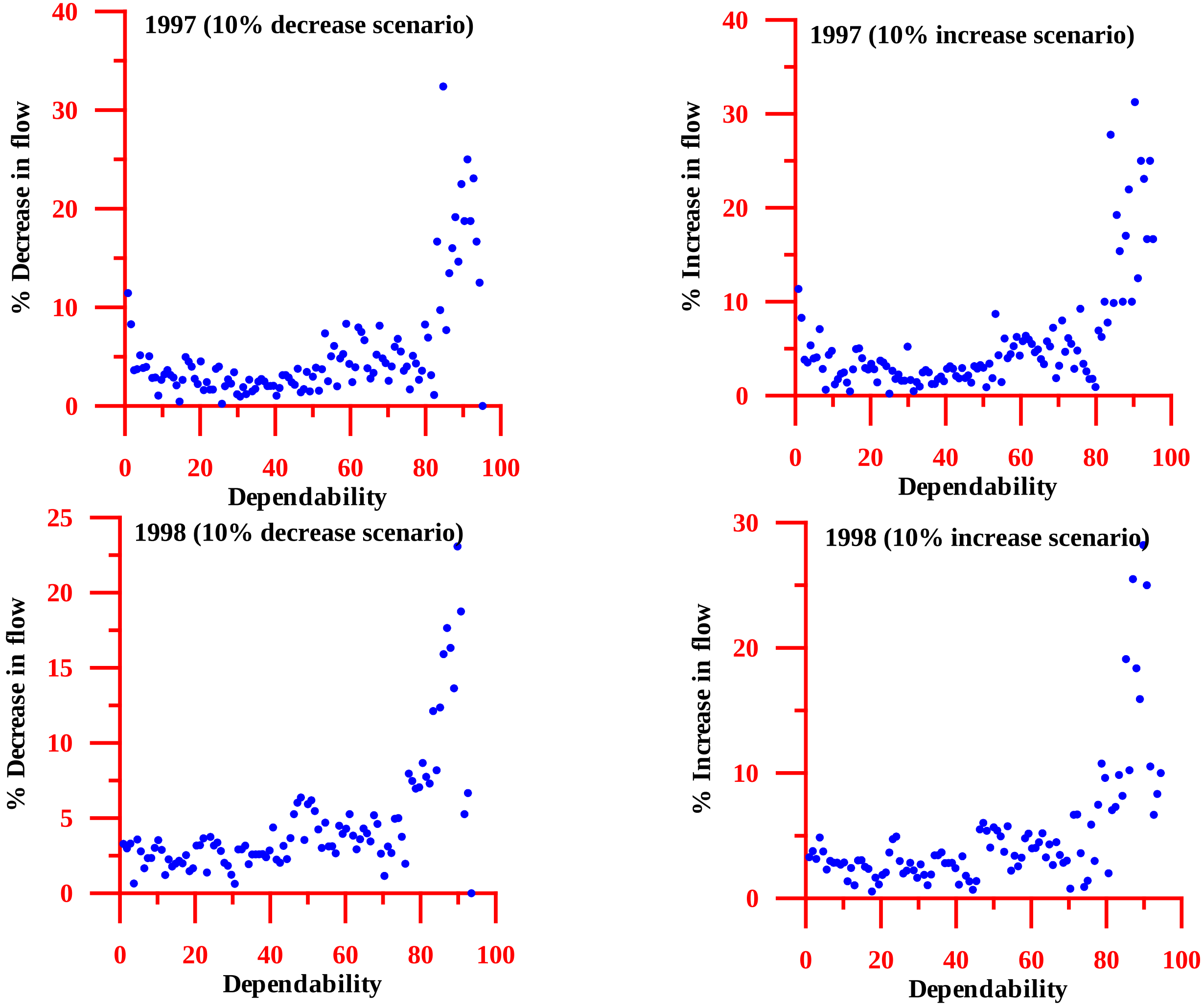
- **The contribution of rainfall: 13%**

- **For a temperature rise of 2°C**

  Increase in summer stream-flow: 28%.



Flow duration curves of the Dokriani Glacier for 1997 and 1998: baseline and other scenarios.



Under different rainfall scenarios: Percent change in flow with different dependabilities

- **Streamflow is fed by direct runoff and there is negligible amount of storage in the basin.**

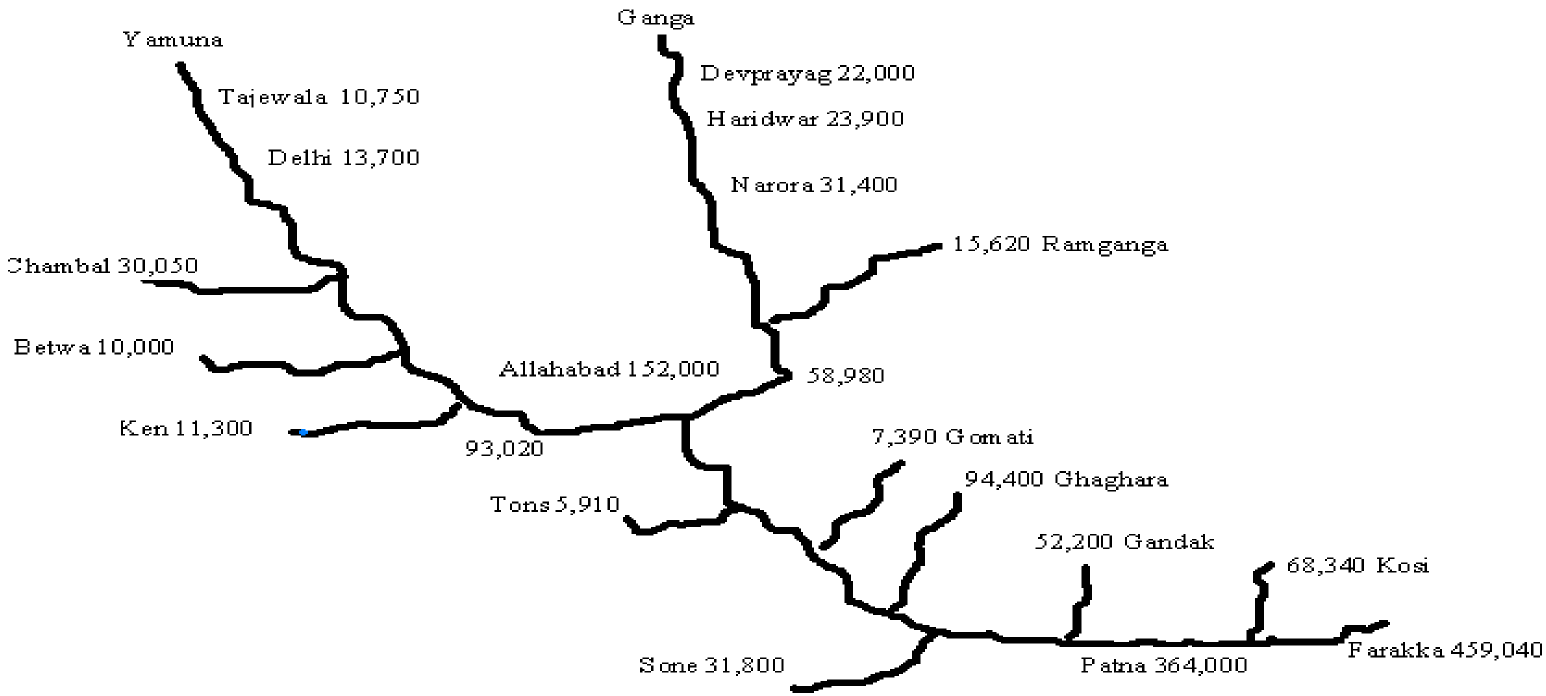
- **Also there is marked variability in flows because of rise in temperature.**

- **The flow historically exceeded 60% of the time (3.2 m^3/s in 1998) would be exceeded 70% of the time under a warming of 2°C.**

- **The flow exceeded 80% of the time would increase by 2% when rainfall is increased by 10% and would decrease by 8% when rainfall is decreased by 10%.**

- **Under different rainfall scenarios - rainfall influences low flows more in comparison to high flows**

Major tributaries of the Ganga and their flow contribution



- **Only about 7% of the basin up to Devprayag is glacier-fed.**
- **Snow and glacier melt contribute only 29% to the annual flow at Devprayag.**
- **At Devprayag, the average annual flow is about 22,000 MCM. This means that the average snow + glacier contribution at Devprayag is about 6380 MCM.**
- **More than 70% of the flow at Haridwar is due to rainfall and the river has significant amount of baseflow downstream of Haridwar.**
- **Possibility of the Ganga becoming a seasonal river downstream of Haridwar in the near future is low.**

- **Among the tributaries of the Ganga, Yamuna River contributes about 61% of the total flow at Allahabad, and just 16% comes from Haridwar.**

- **Four mighty rivers join the Ganga in Bihar: Ghaghara, Gandak, Kosi and Sone. The contribution of these four rivers is 246,740 MCM, which is 1.62 times the flow at Allahabad.**

- **Note that the average annual flow at Patna is about 364,000 MCM, which is nearly 17 times the flow at Devprayag.**

- **Besides Gangotri, other glaciers in the headwaters region of Alaknanda, Yamuna, Ghaghara, Kosi, etc. also contribute to the flow in the Ganga.**

- No doubt Gangotri glacier is shrinking, but it is not going to disappear anytime soon.

- Its retreat will no doubt effect the flow but will not have a drastic influence on the flow of Ganga River as is projected.

- The flow regimes are likely to change; interannual variability in flows will likely increase and reliability of flows in the late summer period will likely decrease due to the lowering of the buffering effect of glacier melt

CONCLUDING REMARKS

- Data collected near the snout used for Modelling
- Model Efficiency would increase if the Radiation Data is used
- Need to correlate the Glacier Retreat with Discharge
- GCM Output need to be Down Scaled and Hydrological Modelling to be carried out for Climate Change

WinSRM


THANK YOU