STREAM FLOW (SNOWMELT RUNOFF) MODELLING IN HIMALAYAN BASINS

Dr. SANJAY K JAIN
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE

Workshop on "Modern tools and techniques for water resources planning and management"
September 16-17, 2014

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 in which more than 5000 glaciers covering about 38000 km^2 area.

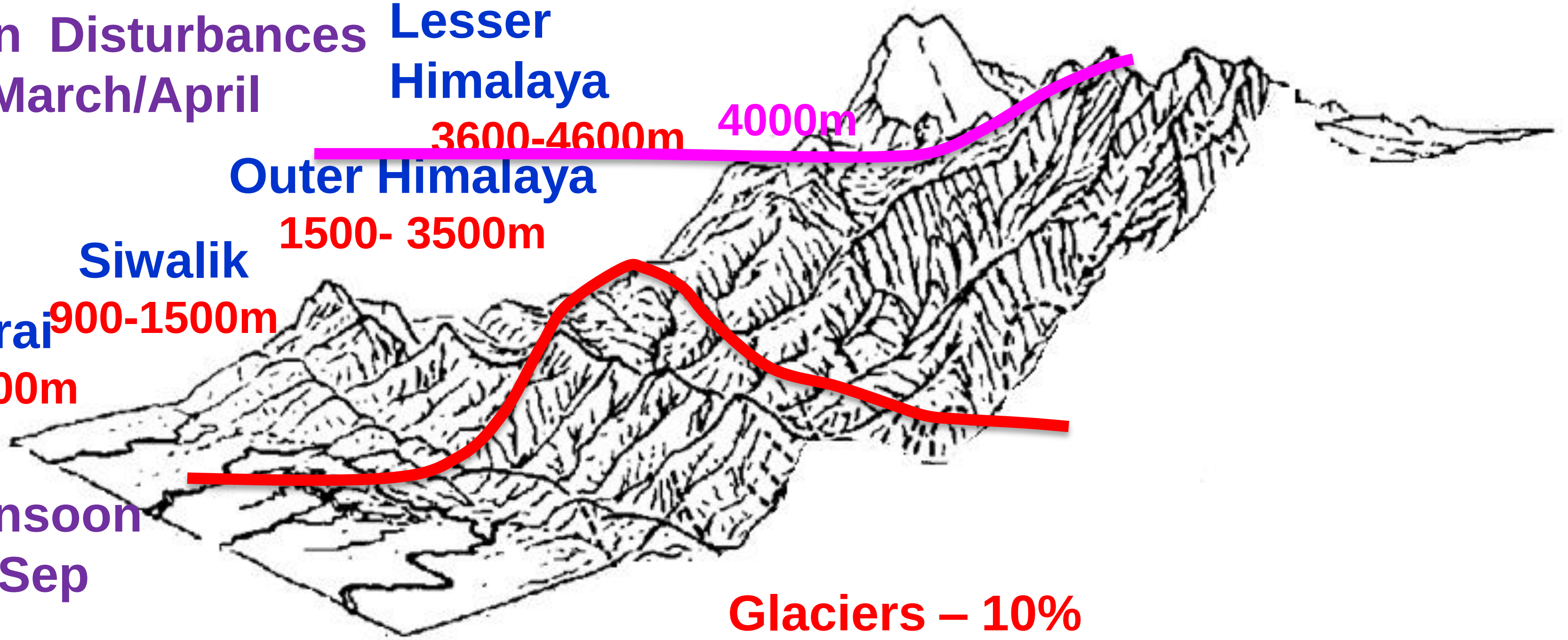
- There are 22 major river systems with about 1 million km^2 catchment area lying in the Himalayas, with snow and glacier melt runoff of more than 50%.

- The seasonal snow and glacier melt coming from the Himalayan Rivers is a dependable source of water for irrigation, hydroelectric power and drinking water supply.

- The hydropower generation contributes about 26% of total installed capacity in India in which Himalayan river systems contribute 78% of the total Indian hydropower potential.

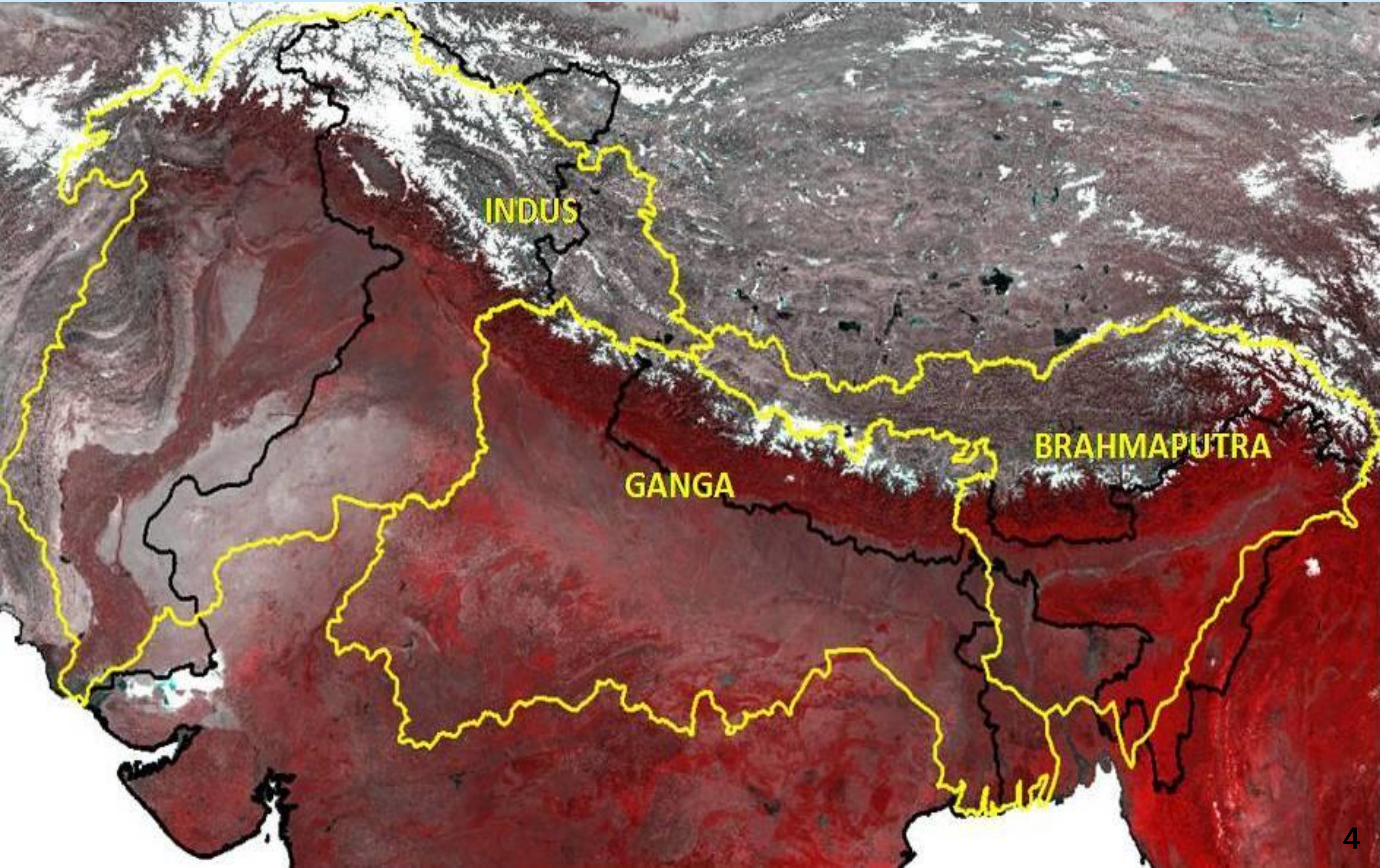
- Snow melt modelling is a crucial element to predict runoff from snow-covered or glacierised areas, as well as to assess changes in the cryosphere associated with climate change.

The Himalayan System



Glaciers – 10%
Winter snow cover 35-50 %
Maximum monsoon precipitation at 1500 – 3000 m asl

INDUS, GANGA, BRAHMAPUTRA BASINS



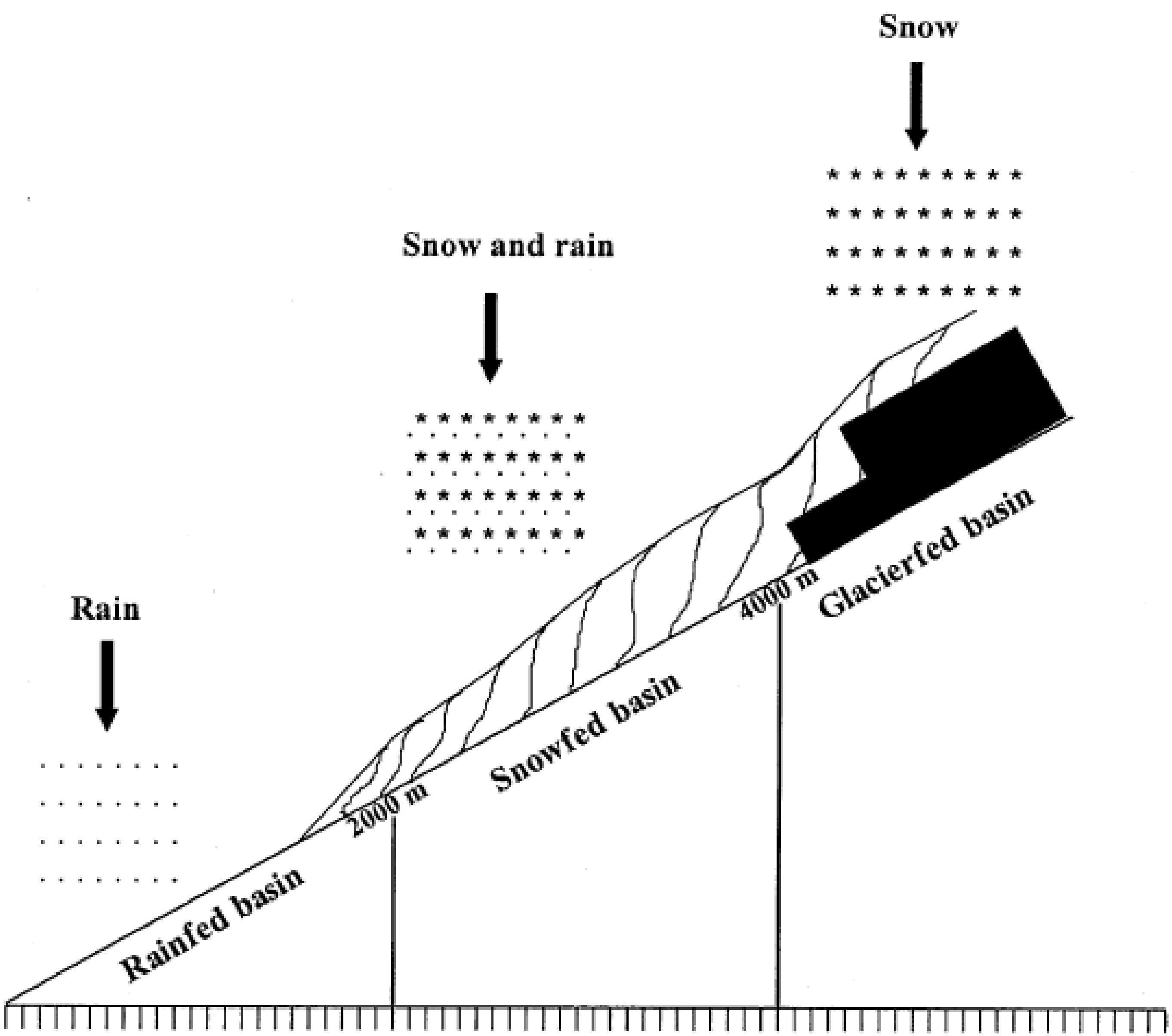
Basins of all major Himalayan rivers have combination of both glacial and nonglacial watersheds.

- **Glacial watershed is characterized as**
  - **High energy and characteristic landforms (Hewitt, 1972)**
  - **High elevation and steep slope**
  - **Rocky terrain**
  - **Presence of ice and snow**
  - **Less biotic activities**

- **Non-glacial (spring fed) watersheds generally have**
  - **Lower elevations and gentle slopes**
  - **Medium to good soil depth**
  - **Intensive biotic activities**

More regional significance

More local significance


Snow
Snow and rain
Rain
Rainfed basin
2000 m
Snowfed basin
4000 m
Glacierfed basin

STREAM FLOW MODELLING (SNOWMELT RUNOFF)

Main steps in modelling are as follows:

Division of Basin Into Elevation Bands

Processing of Meteorological Data

- **Temperature Distribution**
- **Precipitation Distribution**

Variability of Snow Covered Area

Form of Precipitation

Melt due to rain

Degree Day Factor for Snow and Ice

Routing of Surface and Sub Surface Flow

Snow Cover Mapping from Satellite data

Problems in remote sensing of snow in visible band

- Cloud and snow have same reflectance
- Mountain shadow behaves as non-snow area

Snow Mapping methods

- Training sites supervised classification (SC)
- Reflectance Statistics
- Normalized Difference Snow Index (NDSI)

$$\mathrm{NDSI} = \frac{\text{Visible Band} - \text{SWIR Band}}{\text{Visible Band} + \text{SWIR Band}}$$

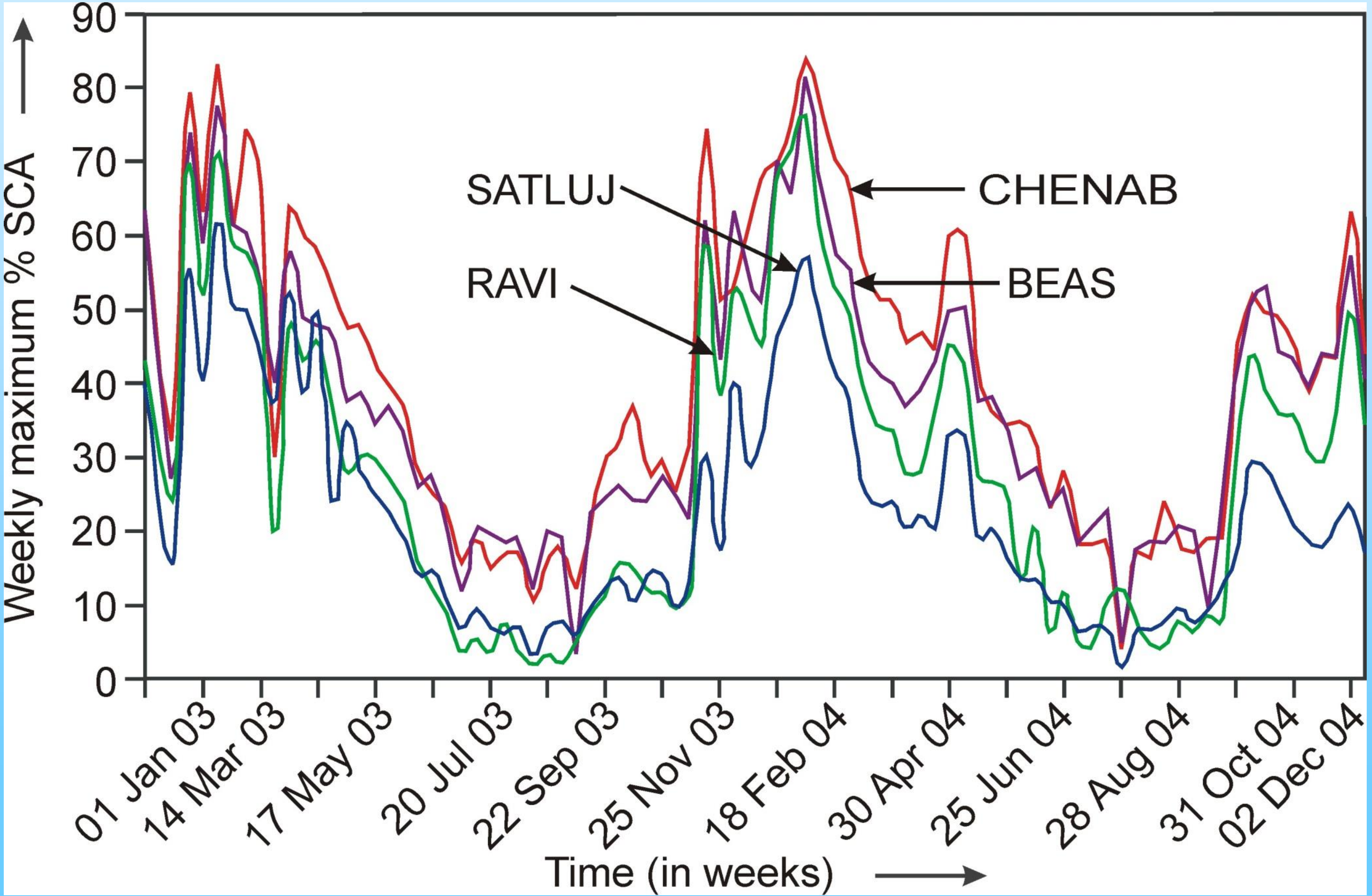
(Snow exhibits high reflectance in visible band and strong absorption in SWIR band Cloud on the other hand shows uniform reflectance due to non-selective scattering)

Snow Cover Mapping from LANDSAT, IRS, NOAA and MODIS data have been carried out for all the basins.

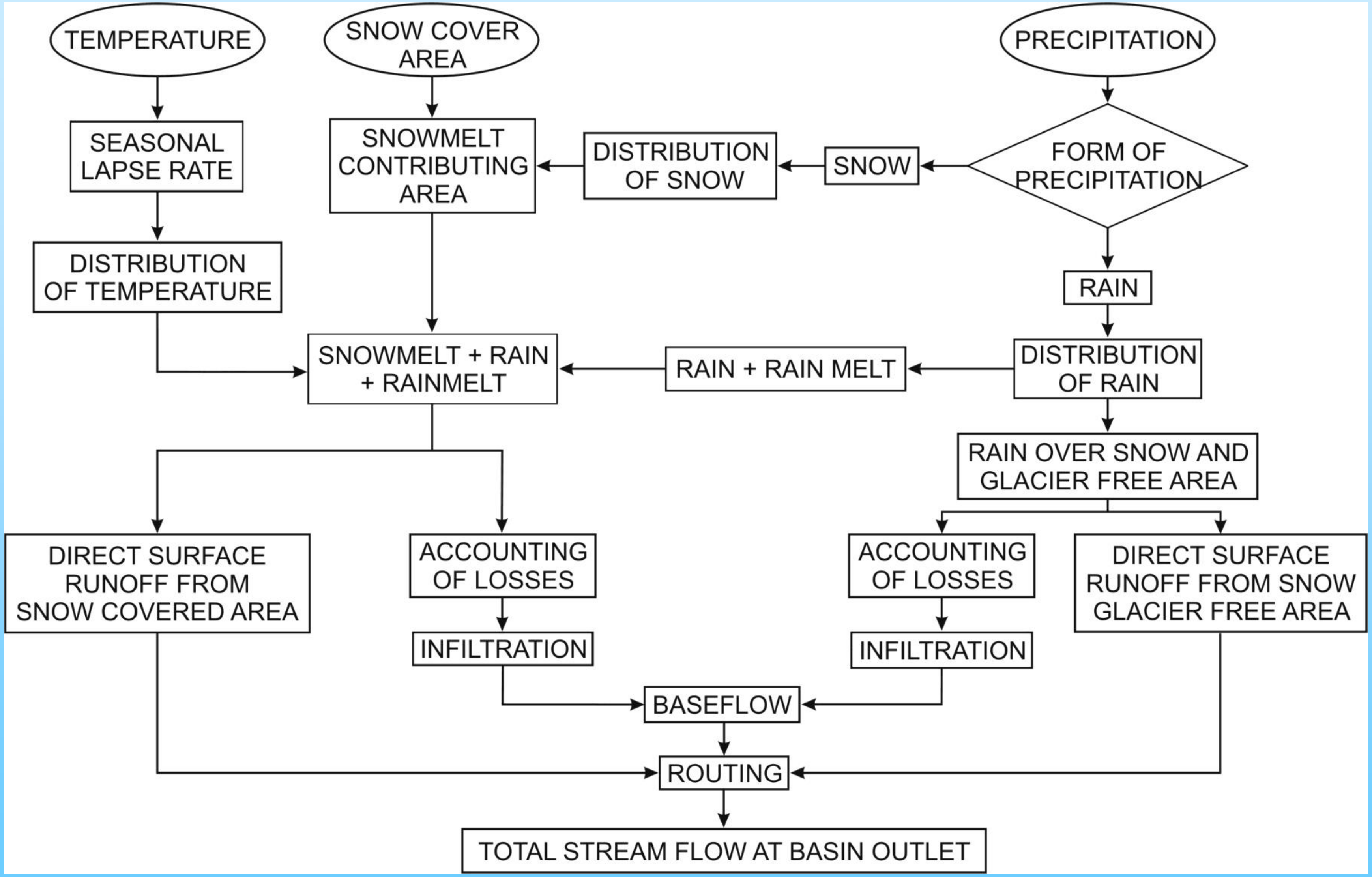
SNOW COVERED AREA

Basin	Site	Total Area (km^2)	Max. SCA (km^2)	Min. SCA (km^2)
Chenab Basin	Akhnoor	22,200	15,590 (70%)	5,400 (24%)
Satluj Basin (Indian part)	Bhakra Dam	22,275	14,498 (65%)	4,528 (20%)
Beas Basin	Pandoh Dam	5,278	2,700 (51%)	780 (14%)
Ganga Basin	Devprayag	19,700	9,080 (46%)	3,800 (19%)

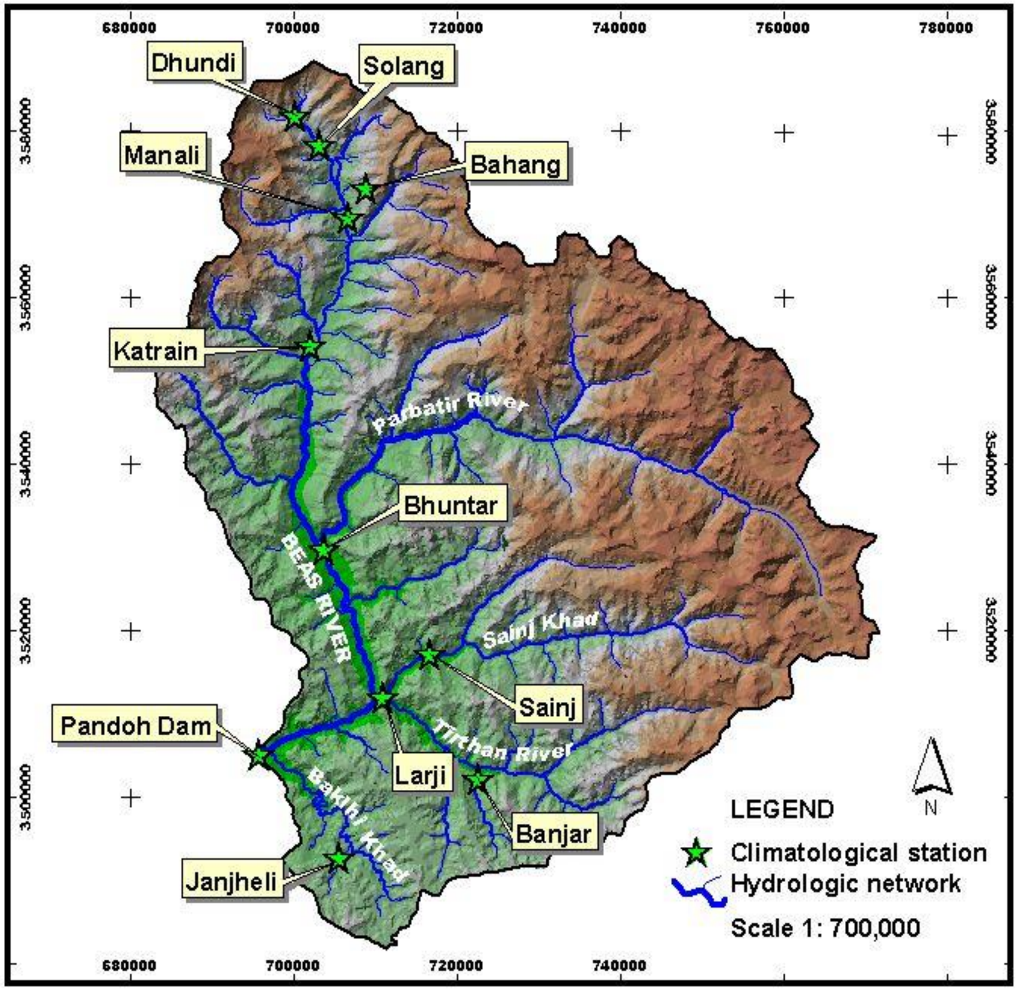
Snow Cover Depletion Curve



STREAM FLOW MODELLING (SNOWMOD)

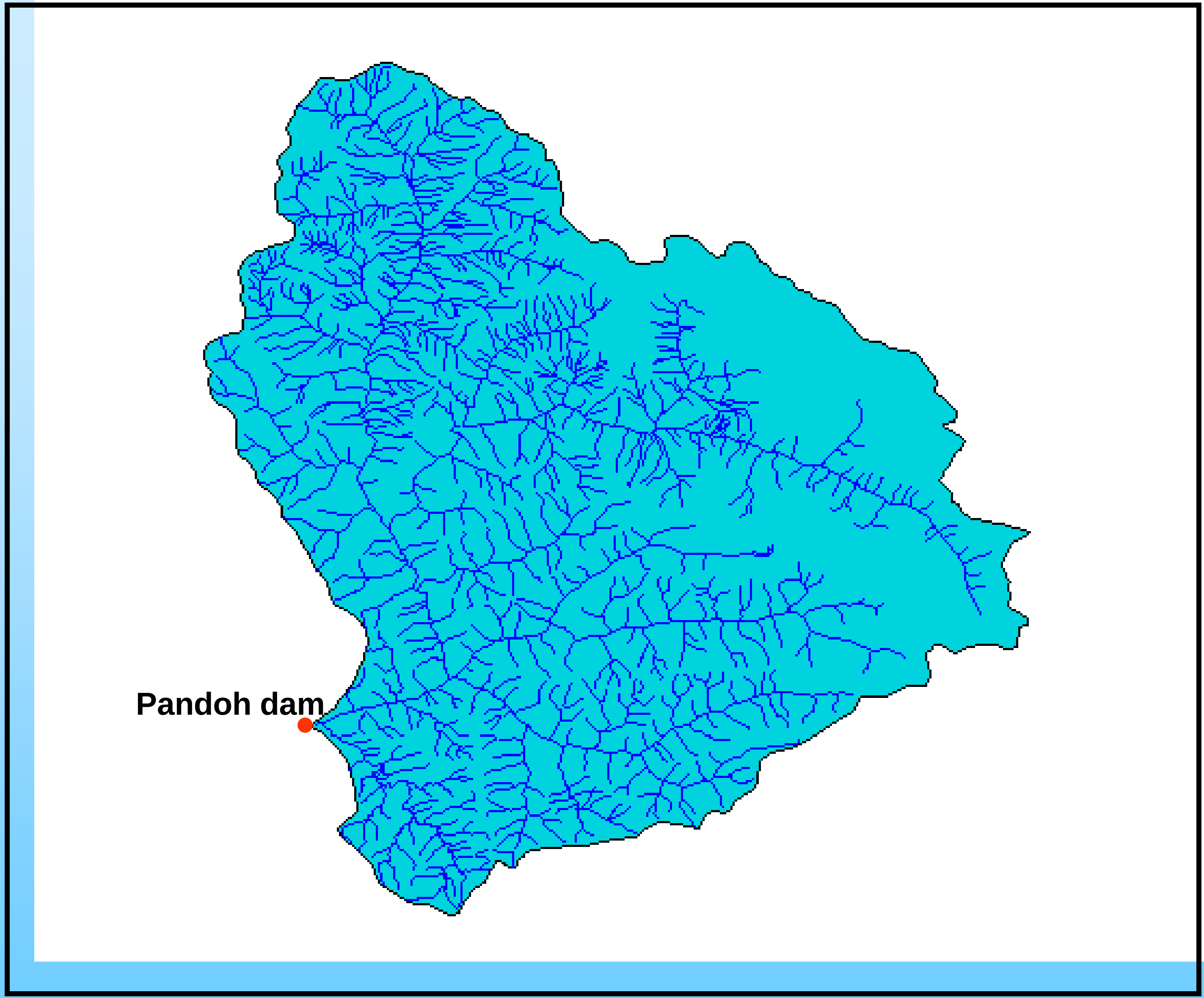


BEAS BASIN up to PANDOH DAM

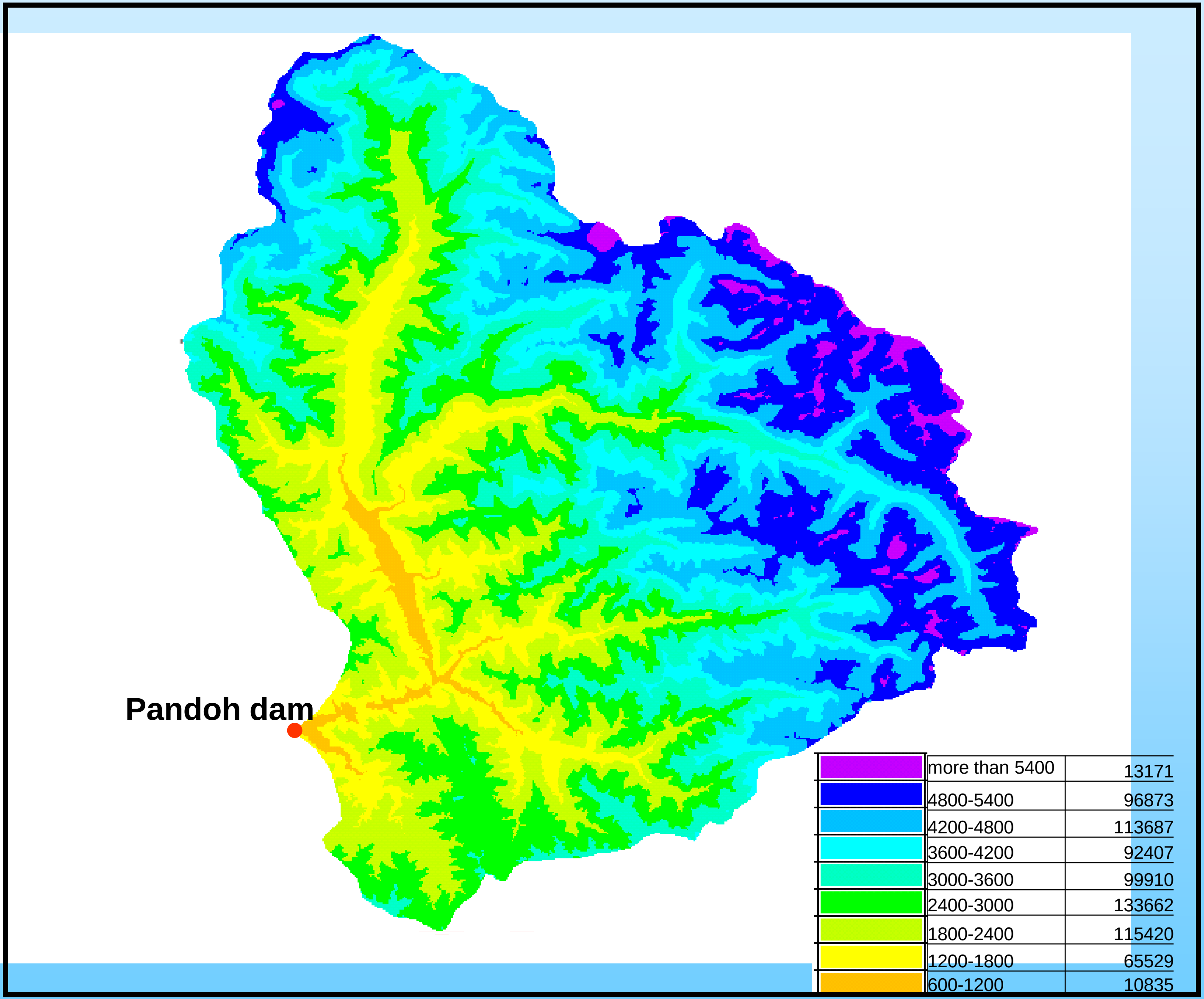


AREA = 5728 km2

ALTITUDE = 600 to 5400 meter

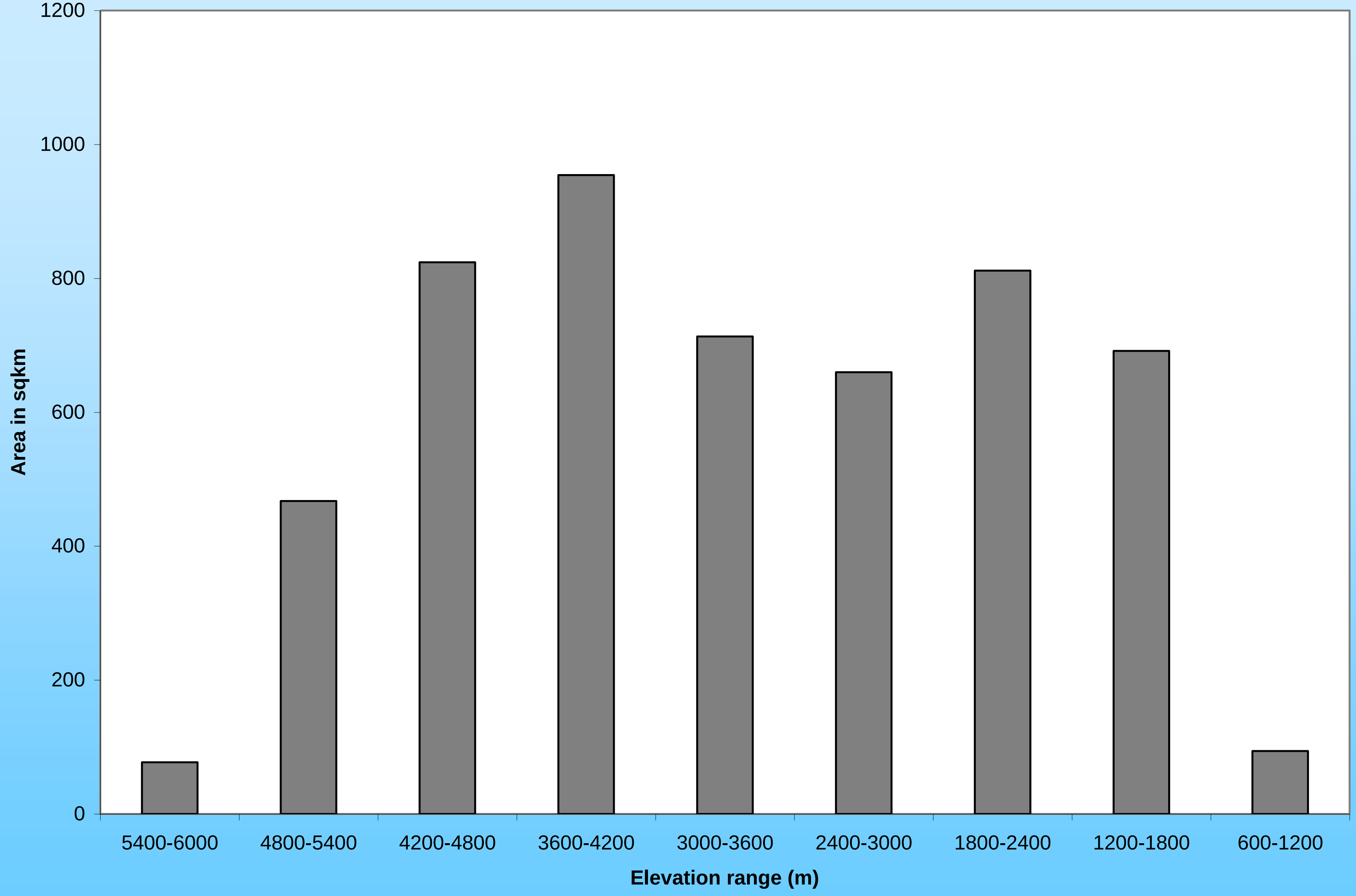


Drainage Network of Beas



DEM of Beas Basin

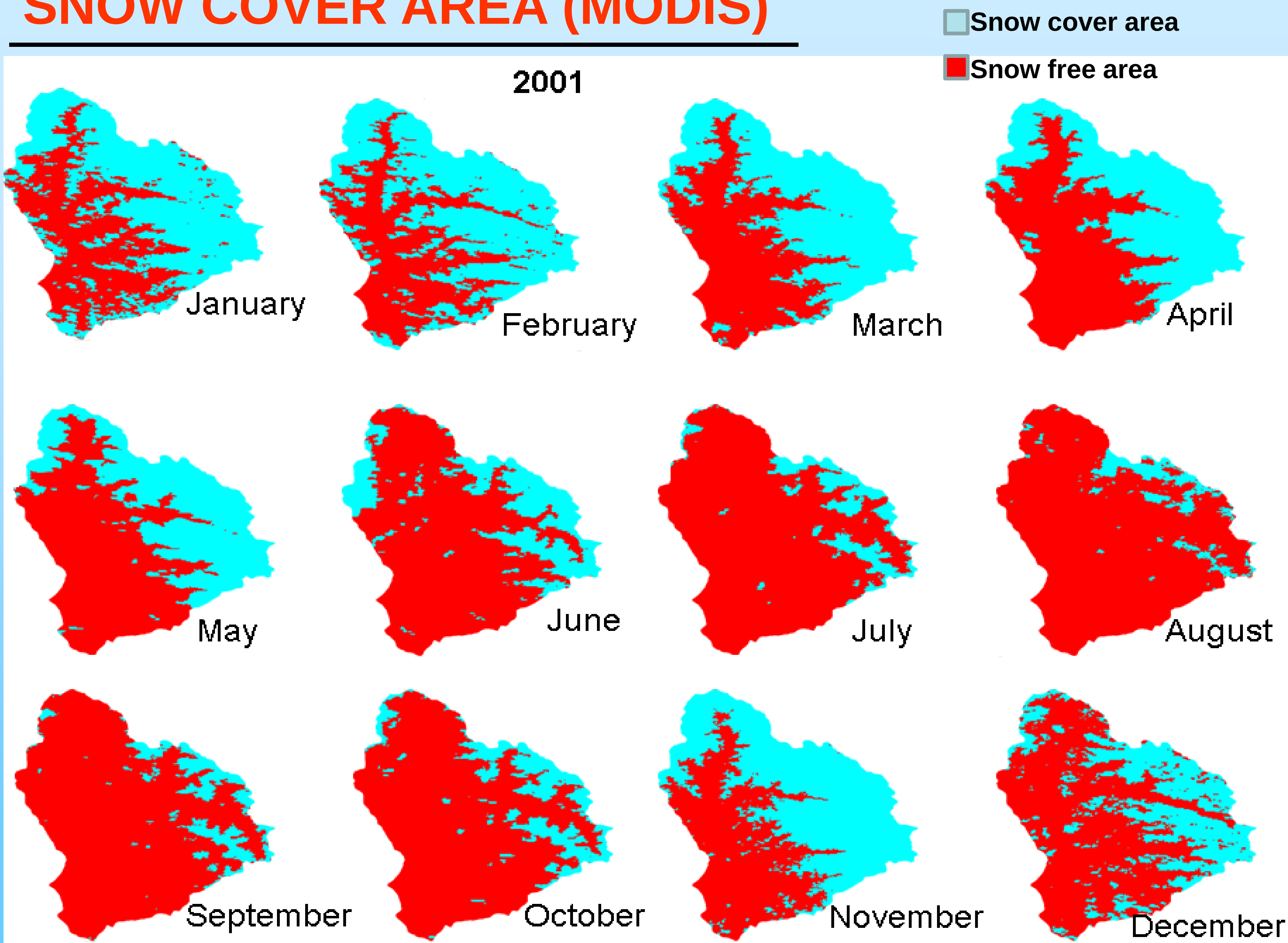
ELEVATION AREA CURVE



ELEVATION ZONE AND STATIONS USED

Zones	Elevation range (m)	Area (km^2)	Percentage	Raingauge station	Temperature station
1	600-1200	77.34	1.46	Pandoh	Pandoh
2	1200-1800	467.56	8.84	Largi	Bhunter
3	1800-2400	823.90	15.57	Manali	Largi
4	2400-3000	954.12	18.03	Manali	Manali
5	3000-3600	713.2	13.47	Manali	Manali
6	3600-4200	659.63	12.46	Sainj	Manali
7	4200-4800	811.53	15.33	Sainj	Manali
8	4800-5400	691.51	13.06	Sainj	Manali
9	>5400	94.10	1.78	Sainj	Manali

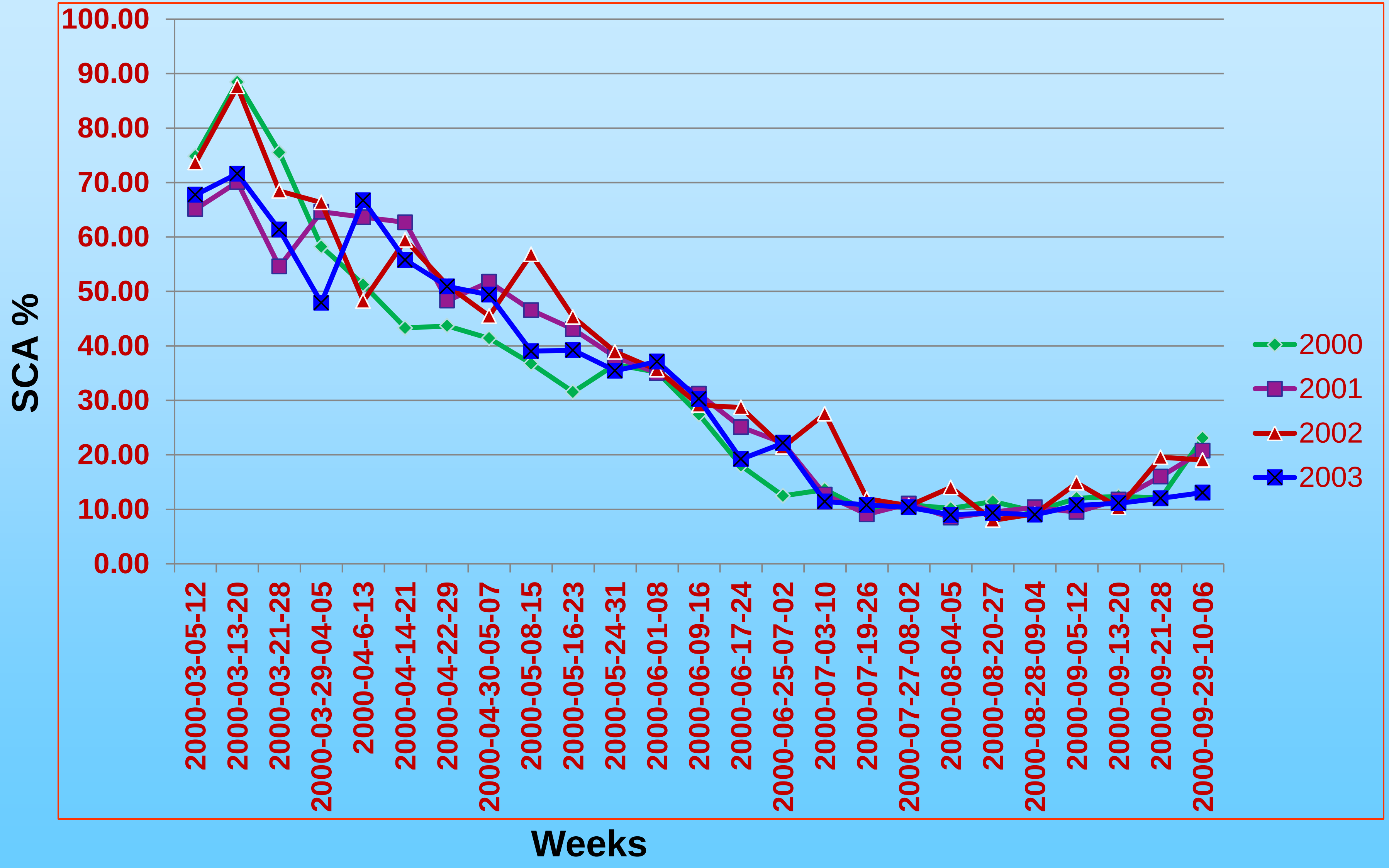
SNOW COVER AREA (MODIS)



SNOW COVER AREA (%)

YEAR	2000	2001	2002	2003	2004
March	74.85	65.11	73.65	67.75	71.13
March	88.47	70.09	87.62	71.61	63.63
March	75.52	54.58	68.44	61.35	55.43
March	58.23	64.62	66.33	47.93	48.28
April	51.23	63.63	48.23	66.69	42.47
April	43.29	62.68	59.45	55.78	39.98
April	43.67	48.31	51.11	50.92	36.76
April	41.42	51.76	45.47	49.40	39.33
May	36.76	46.56	56.81	39.03	45.16
May	31.53	43.06	45.29	39.20	54.70
May	26.90	37.98	38.90	35.45	35.51
June	35.19	34.99	35.59	37.11	37.16
June	24.39	31.19	29.12	30.23	31.80
June	18.02	25.10	28.70	19.21	37.11
June	12.46	22.21	21.42	22.16	21.47
July	13.62	12.66	27.53	11.43	21.84
July	9.67	9.05	11.91	10.77	17.81
July	10.85	11.04	10.68	10.35	9.01
August	10.14	8.45	14.00	8.96	11.56
August	11.42	9.49	8.00	9.34	13.93
August	9.62	10.35	9.16	9.00	10.92
August	12.00	9.48	14.84	10.71	9.39
September	12.37	11.79	10.34	11.12	11.37
September	12.06	16.01	19.55	12.00	10.33
September	23.07	20.74	19.04	13.05	12.84

SNOW COVER DEPLETION CURVES



SNOW COVER MAPS FOR THE YEARS 1990-2000

Snow cover area maps were prepared for the years 2001-2005 using satellite data.

A relationship has been developed between cumulative temperature and snow cover area.

Using this relationship snow cover area for the years 1990-2000 have been prepared.

Snow cover depletion curves for these years have been generated.

Land Surafce Temperature (LST)

In this study, LST maps be used to determine TLR for the Beas river basin which will be inputs in snowmelt runoff modeling.

- **LST generally defined as the Skin temperature of ground.**
- **LST data is derived from satellite data are continuous datasets with better spatial and temporal resolution.**
- **Estimated from satellite data are the energy thermal sensors received in 10.5-12.5 µm wavelength region emitted by land surface.**
- **It depends on latitude of the location and surface properties, specially surface albedo and specific heat of the surface .**

MODIS LST Database for Beas Basin

The MODIS LST products are archived in Hierarchical Data Format - Earth Observing System (HDF-EOS) format files.

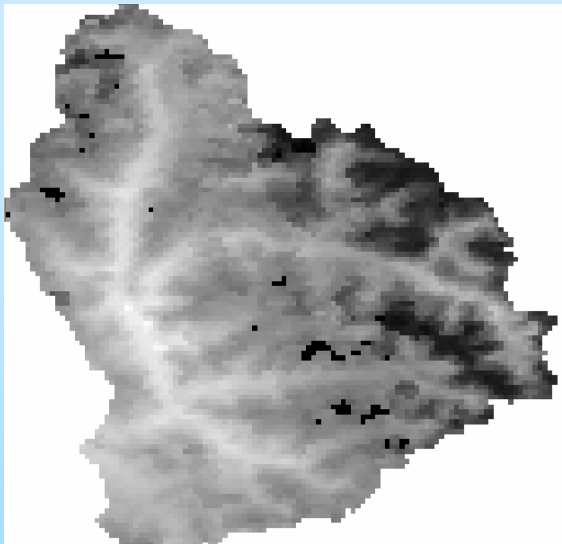
MODIS/Terra Land Surface Temperature data - produced using the split window algorithm developed by Wan and Dozier (1996).

Temperatures are extracted in Kelvin with a view-angle dependent algorithm applied to direct observations.

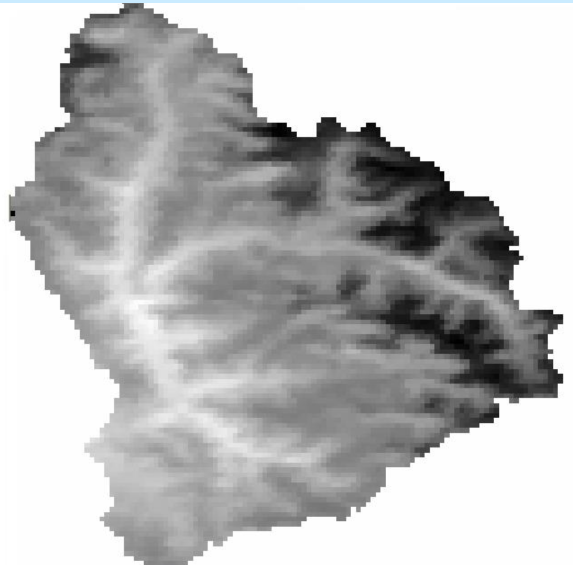
The LST algorithm uses MODIS data in bands 31 and 32 in the split-window (at 11 and 12 microns, respectively).

Earth Science Data Type (ESDT)	Spatial Resolution	Temporal Resolution	Period
MOD11A2	1km (actual 0.927km)	eight days	2000 to 2009

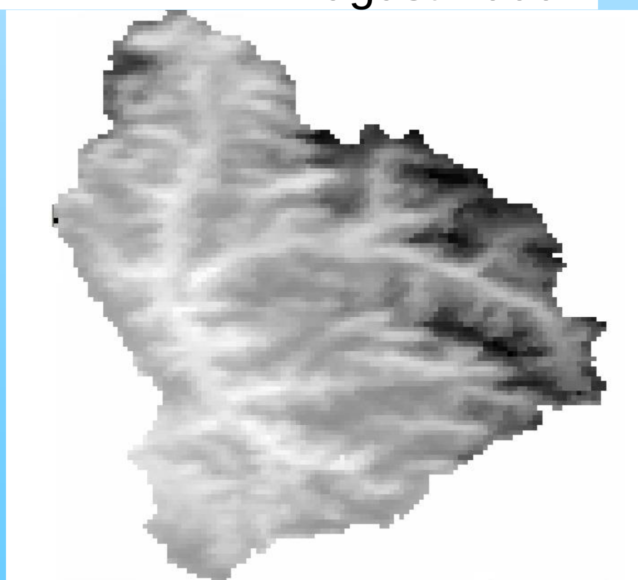
MODIS LST Maps for Beas basin



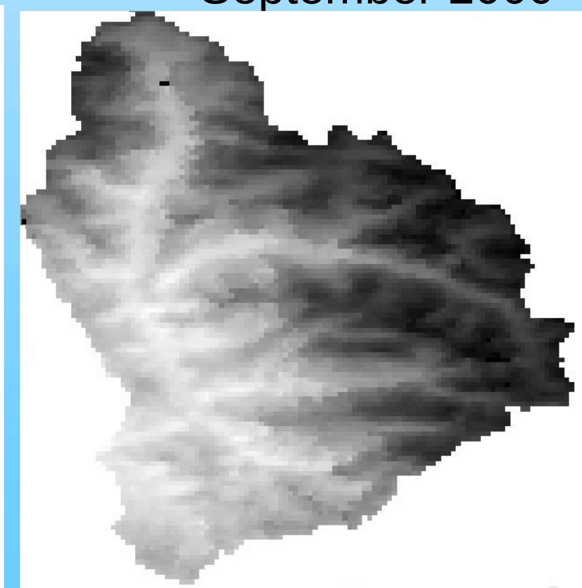
August 2000



September 2000



October 2000

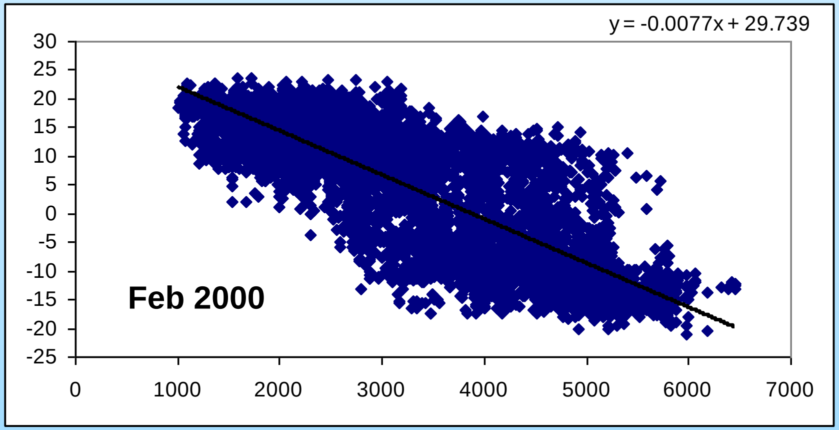


November 2000

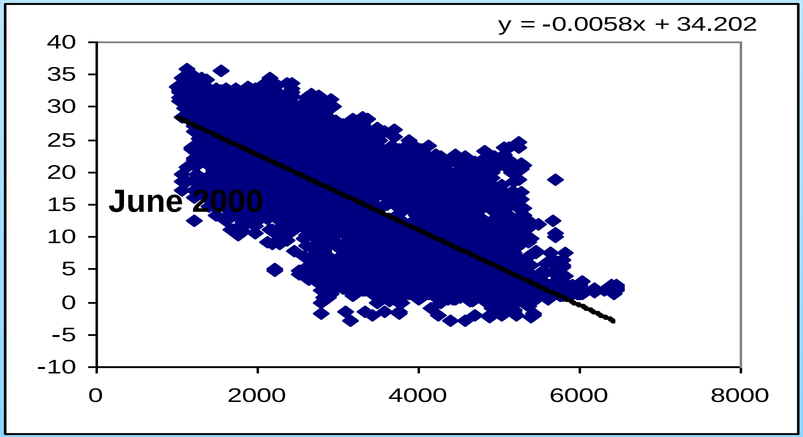
Temperature	Max	Min
AUGUST	32.06	-1.18
SEPTEMBER	32.6	-3.22
OCTOBER	28.24	-5.1
NOVEMBER	19.34	-22.76

Temperature Range

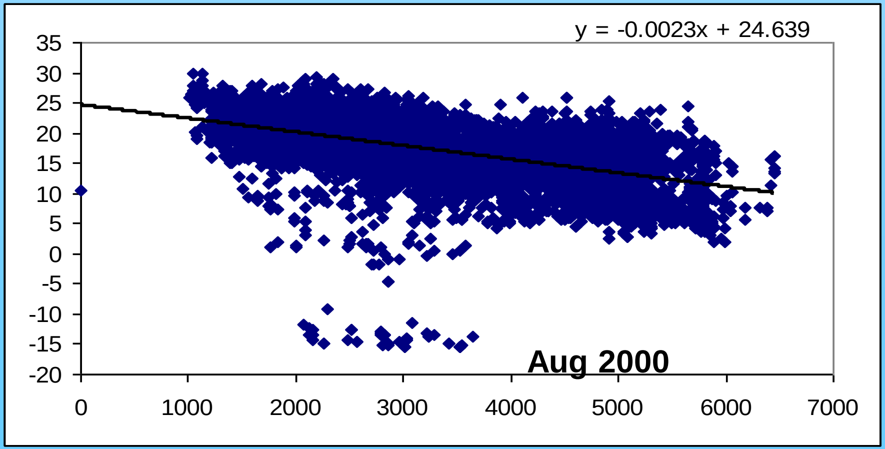
Scatter plots showing the relationship between Elevation and MODIS LST



TLR = 0.7



TLR = 0.6



TLR = 0.3

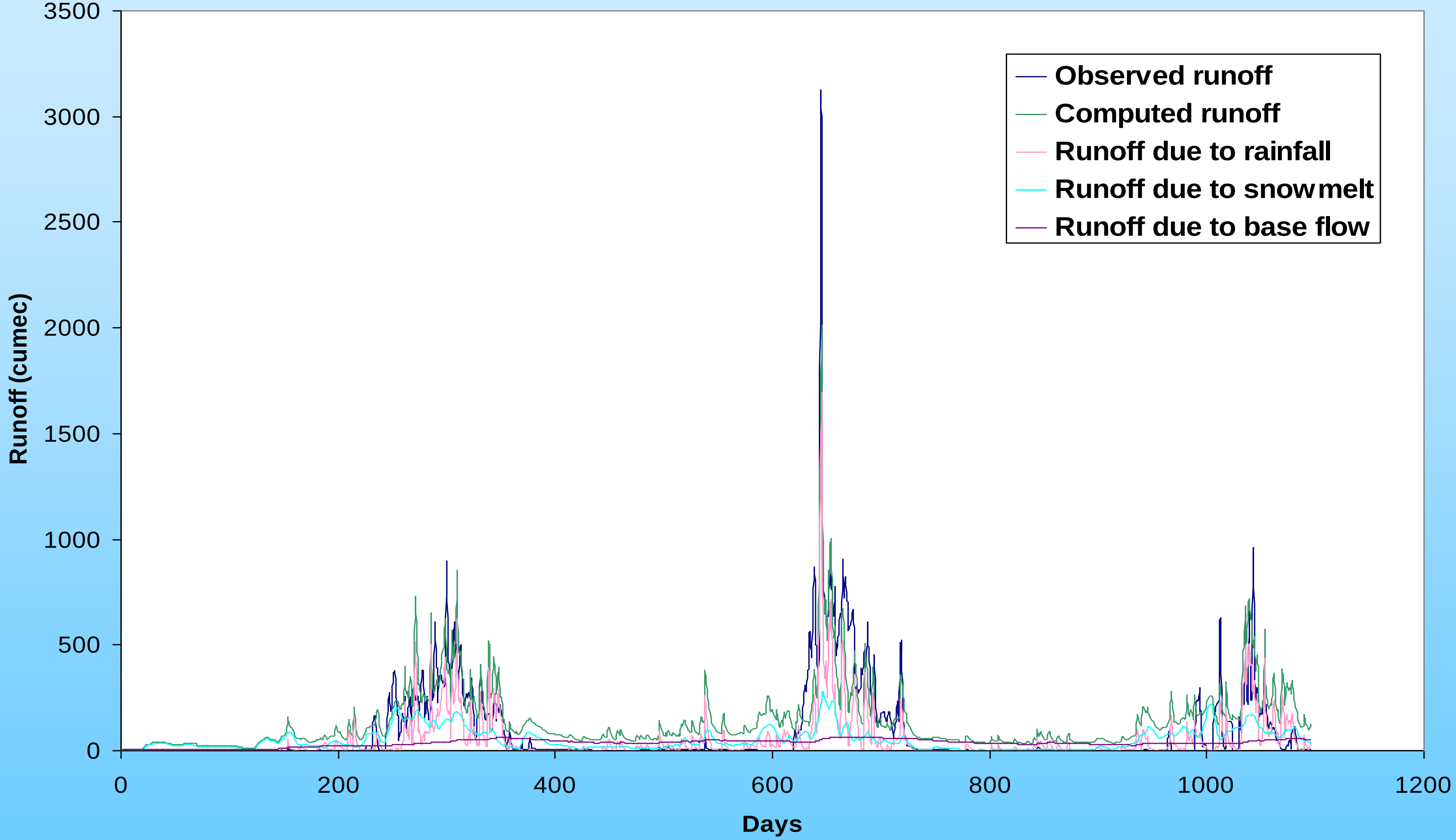
SIMULATION OF STREAM FLOW

The model developed was calibrated for the study basin using data of 3 years (2002-2005).

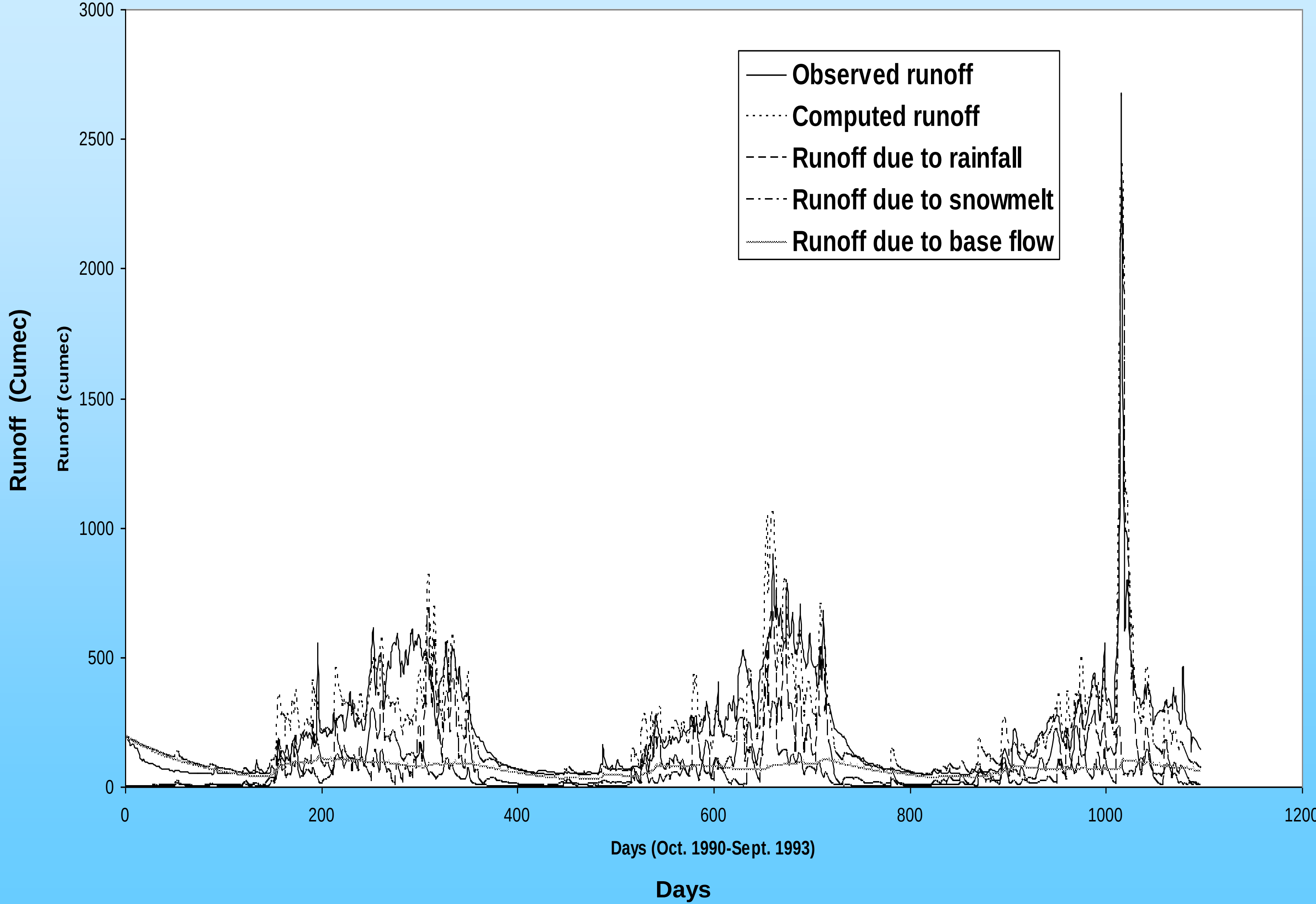
After calibration of the model, the model was used to simulate daily stream flow using impendent data of 12 years (1990-1993, 1993-1996,1996-1999 and 1999-2002).

The different components obtained after simulation are :
Total stream flow, snowmelt runoff, rainfall runoff and base flow

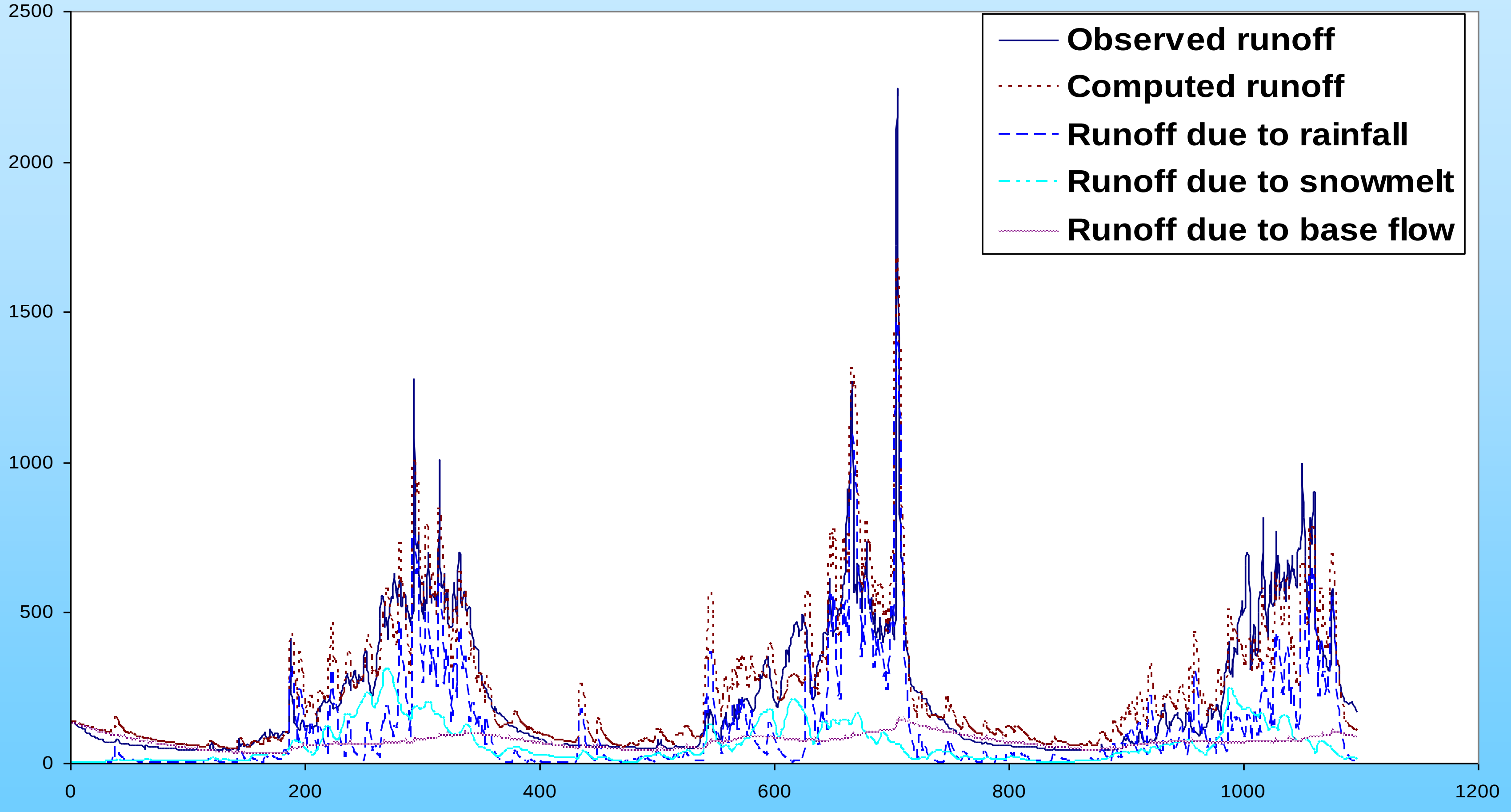
Calibration result of stream flow for 2002-2005



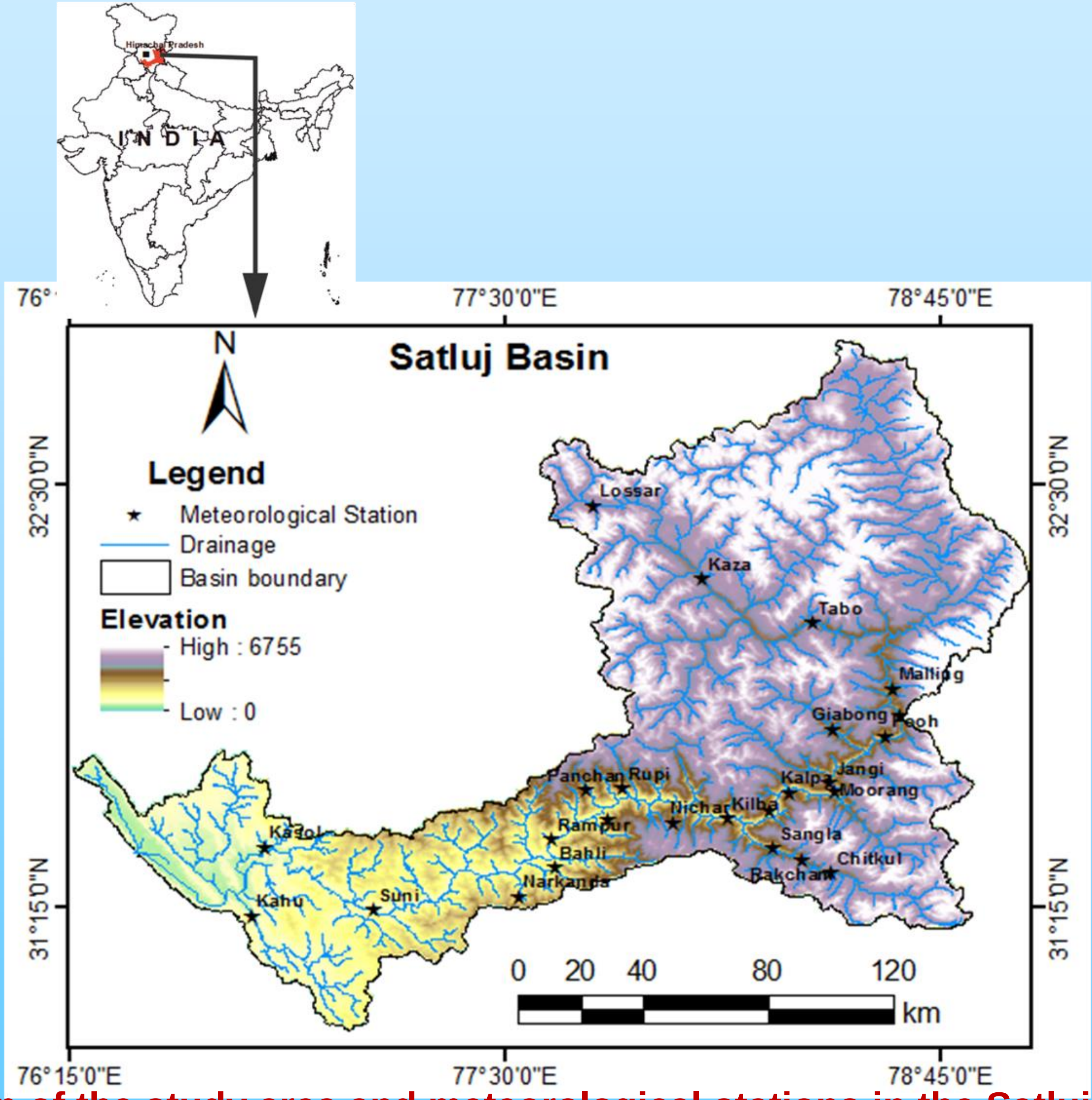
Validation result for 1990-1993



Validation result for 1993-1996

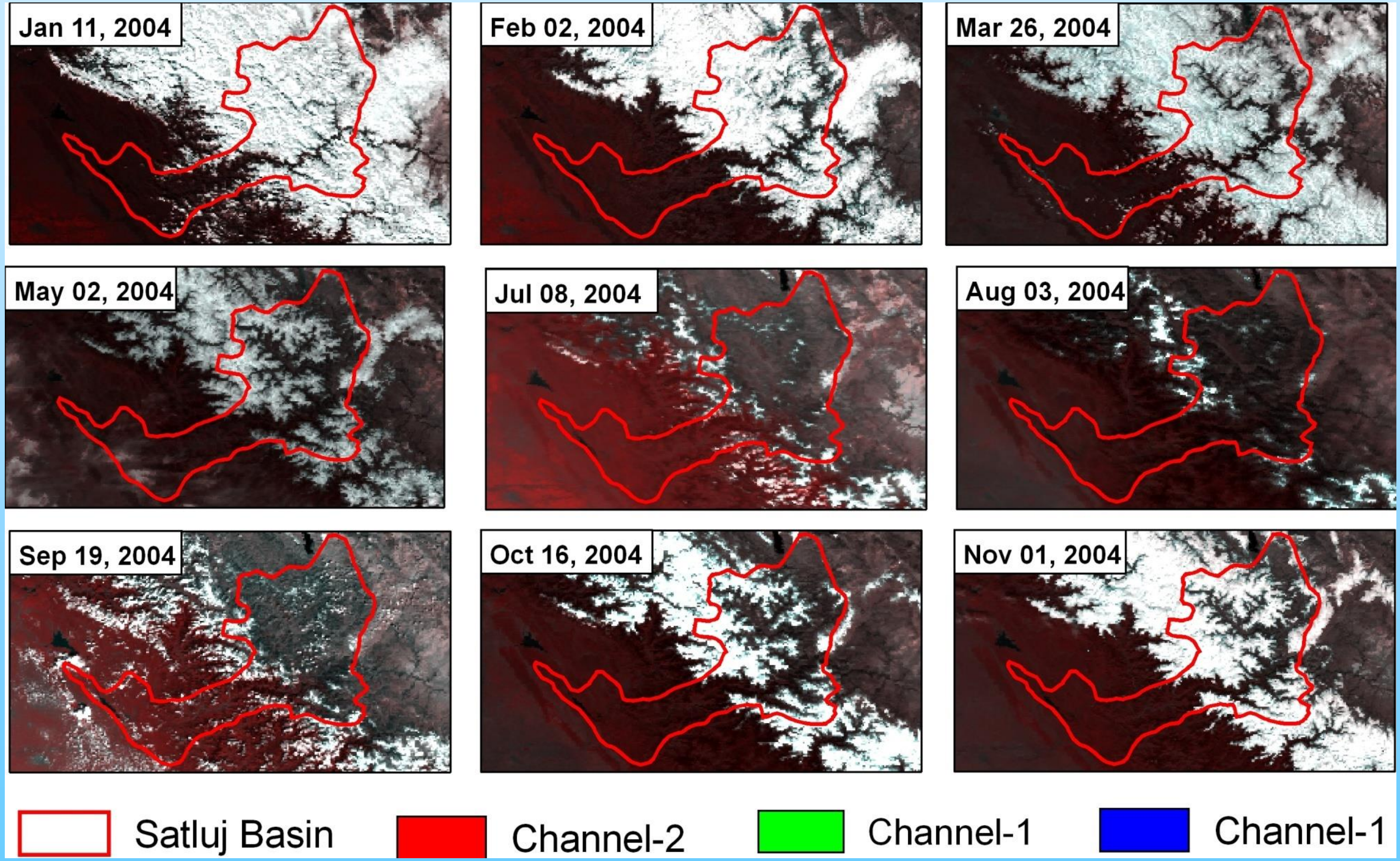


STREAM FLOW MODELLING IN SATLUJ BASIN

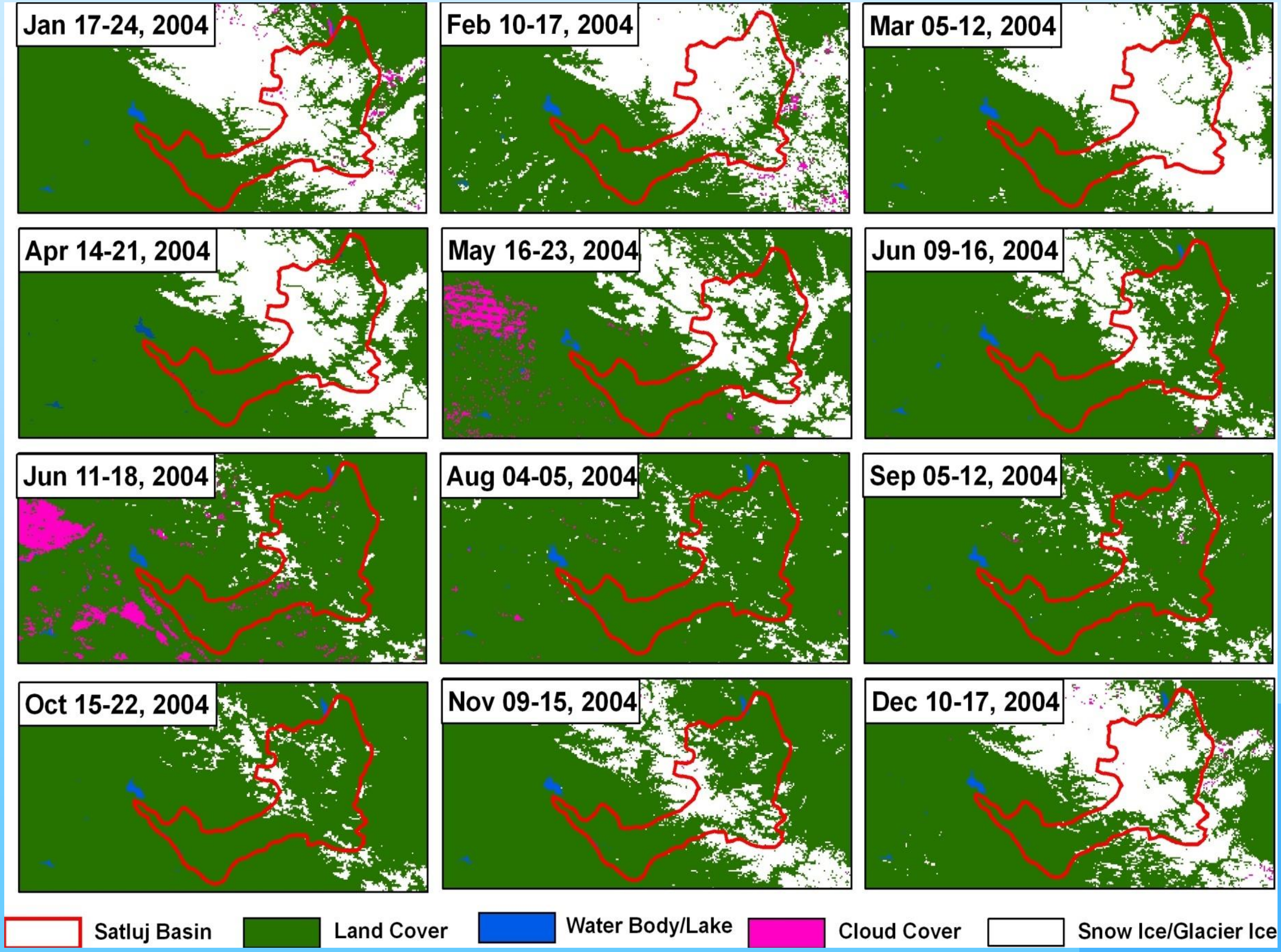


Location of the study area and meteorological stations in the Satluj basin

NOAA-AVHRR Images (2004)

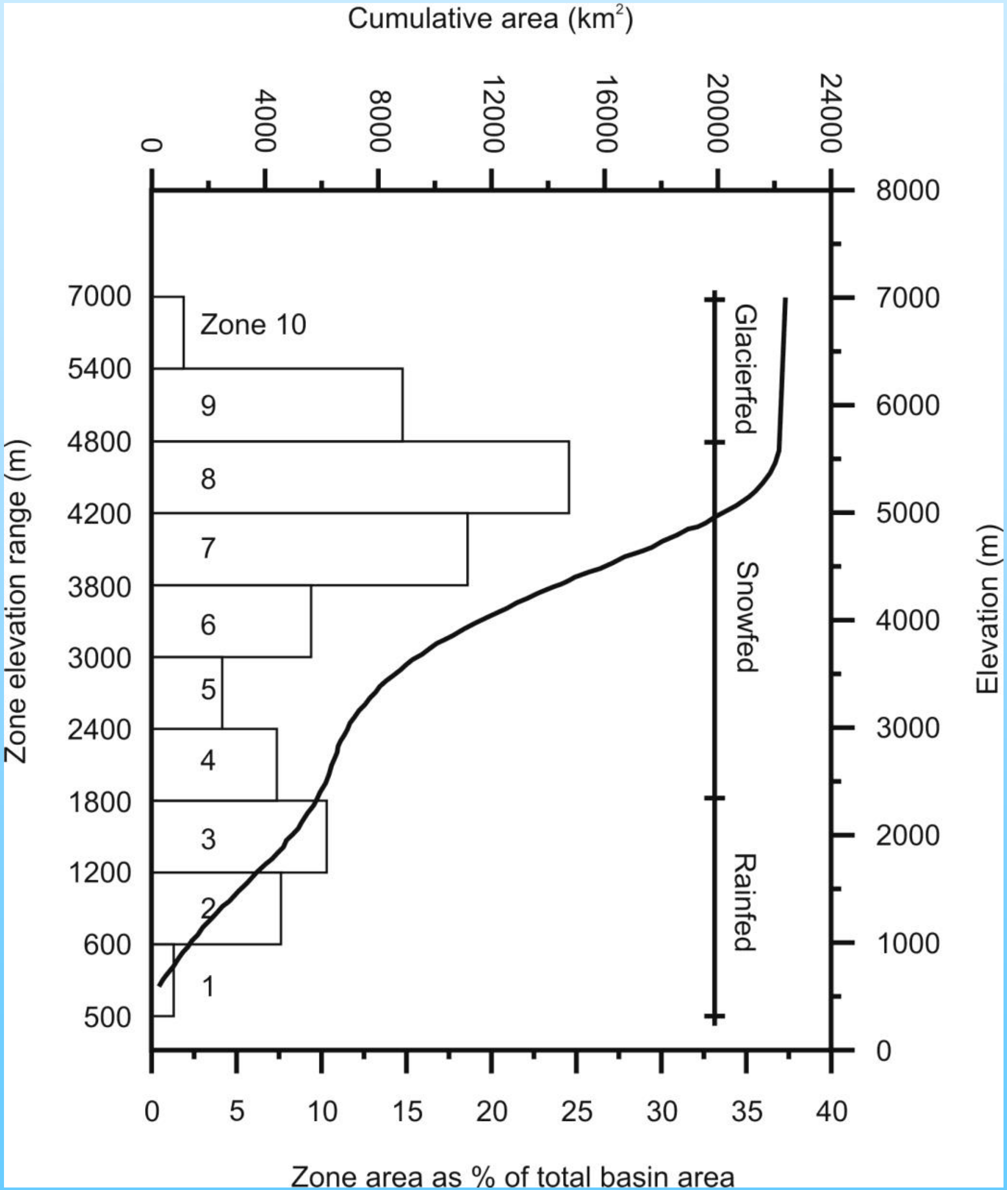


MODIS SNOW Data Product (2004)

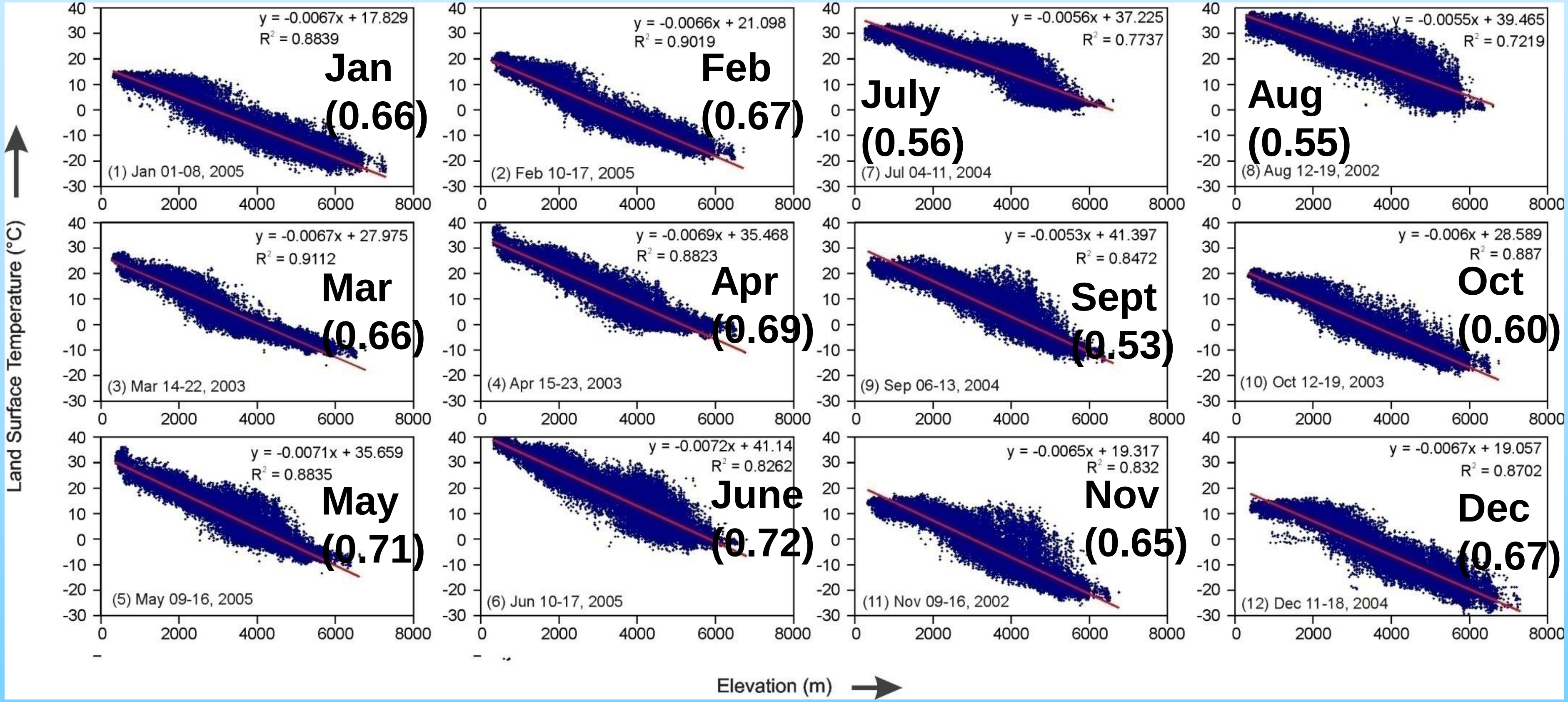


Division of the basin into elevation bands

- The basin is divided into 10 elevation bands with an altitude difference of 600 m
- About 55% of the area lies between 3600 to 5400 m

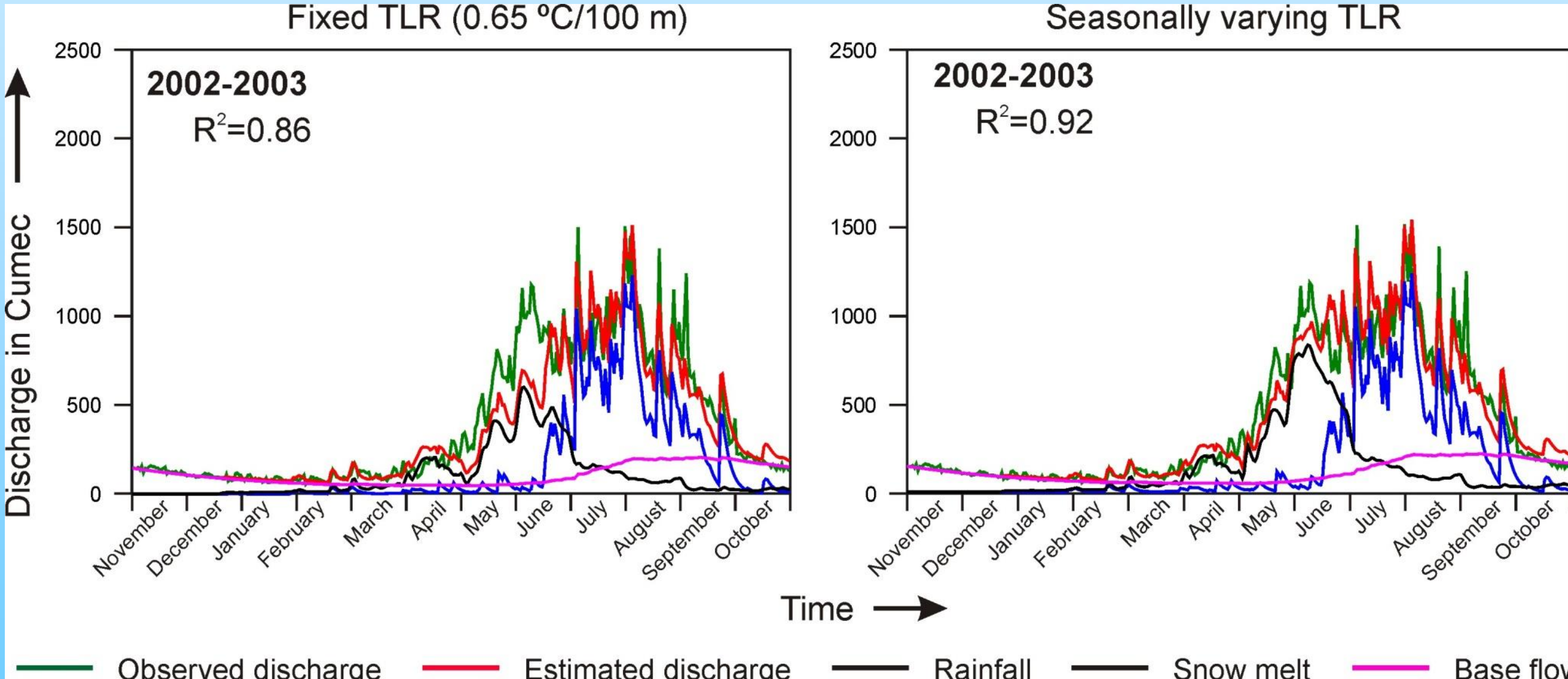


Seasonal Lapse Rate estimation from MODIS LST maps

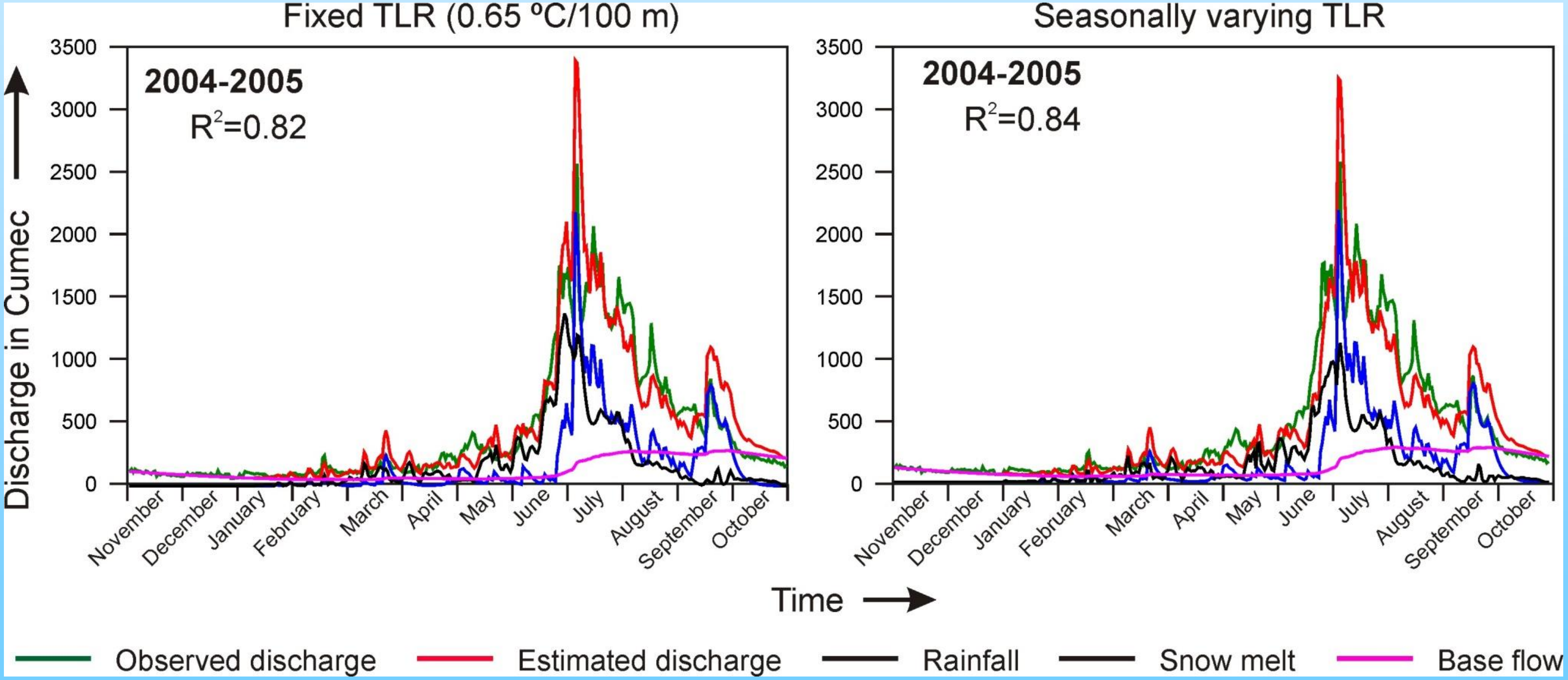


(the slope of the equation is the temperature lapse rate)

Simulation of Runoff (2002-2003)



Simulation of Runoff (2004-2005)



Arc SWAT

SWAT stands for Soil and Water Assessment Tool

physically based, spatially distributed, continuous model - daily time step

Allows a basin to be subdivided into sub-basins or W/S

Each sub-basin are further grouped into hydrologic response units (HRUs) based on land use and type of soil.

ArcSWAT requires input data on weather, soil properties, topography, vegetation, & land management practices

ArcSWAT allows data input via GIS

Model outputs all water balance components (surface runoff, evaporation, lateral flow, recharge, percolation, sediment yield, etc.) at each w/s at daily, monthly or annual time steps.

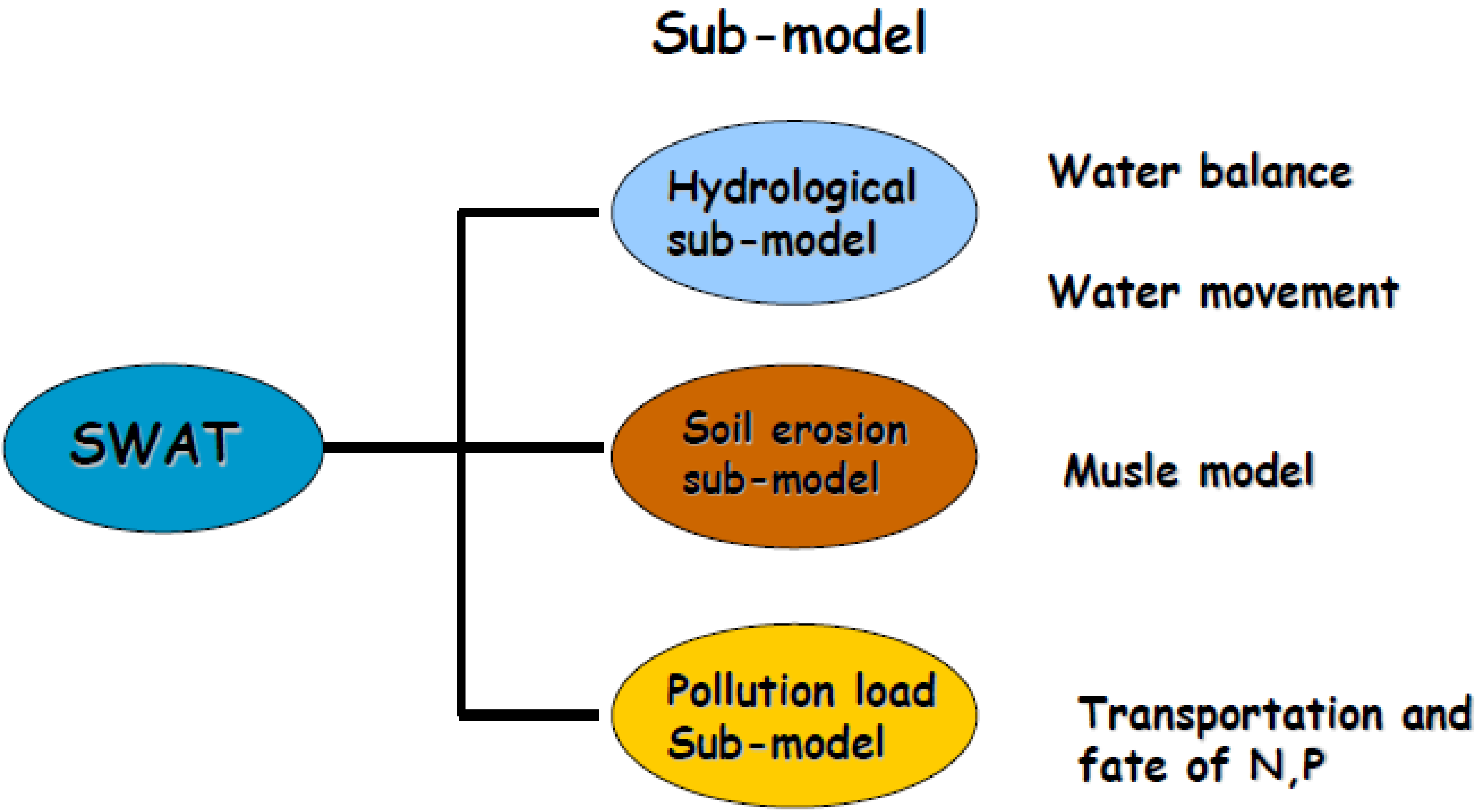
MODEL INPUT

- GIS input files needed for the SWAT model include
  - the digital elevation model (DEM),
  - land cover, and
  - soil layers
- The DEM can be utilized by ArcSWAT to delineate basin and subbasin boundaries, calculate subbasin average slopes and delineate the stream network.
- The land use, soil and Slope layers are used to creat and define Hydrological response units (HRU’s).

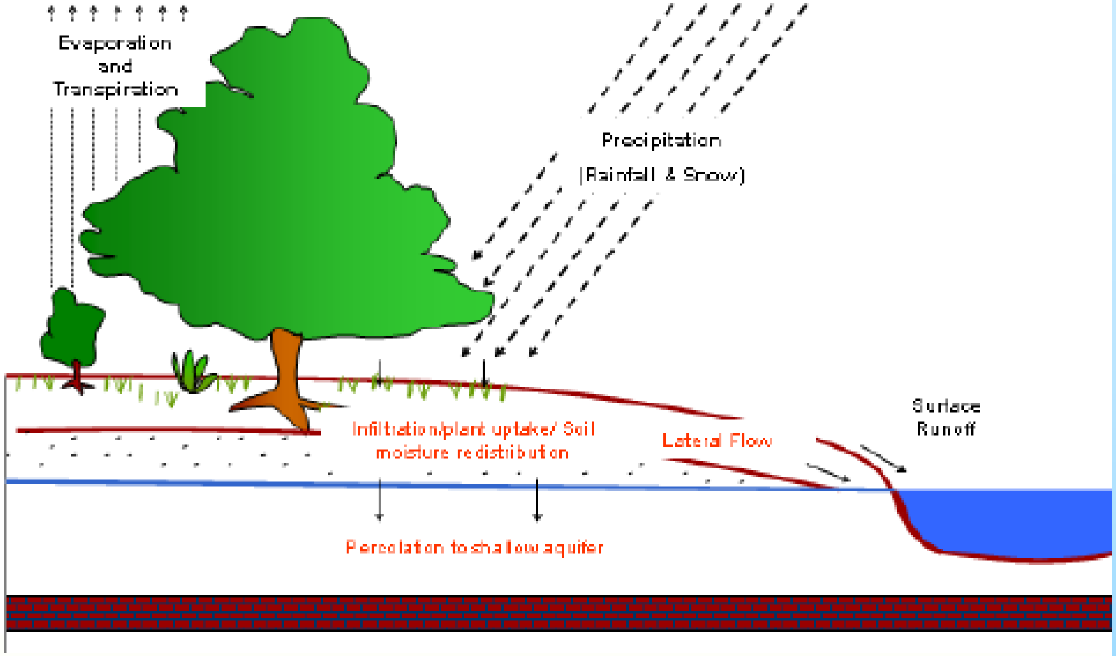
METROLOGICAL DATA

- The weather variables for driving the hydrological balance are
  - precipitation,
  - air temperature,
  - solar radiation,
  - wind speed and
  - relative humidity.

Model Components



Water balance



$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

SW_t : the final water content (mm)

SW_0: the initial soil water content on day i (mm)

t: the time (days)

R_{day}: the amount of precipitation on day i (mm)

Q_{surf}: the surface runoff on day i (mm)

E_a: the amount of evapotranspiration on day i (mm)

W_{seep} : the amount of water entering the vadose zone from the soil profile on day i (mm)

Q_{gw}: the amount of return flow on day i (mm)

COMPONENTS OF SWAT

Major components can be grouped into two categories

(i) Land phase of the hydrologic cycle

- **- controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin, and,**

(ii) Routing phase of the hydrologic cycle

- **- defines the movement of water, sediments, nutrients etc. through the channel network of the watershed to the outlet.**

BEAS BASIN

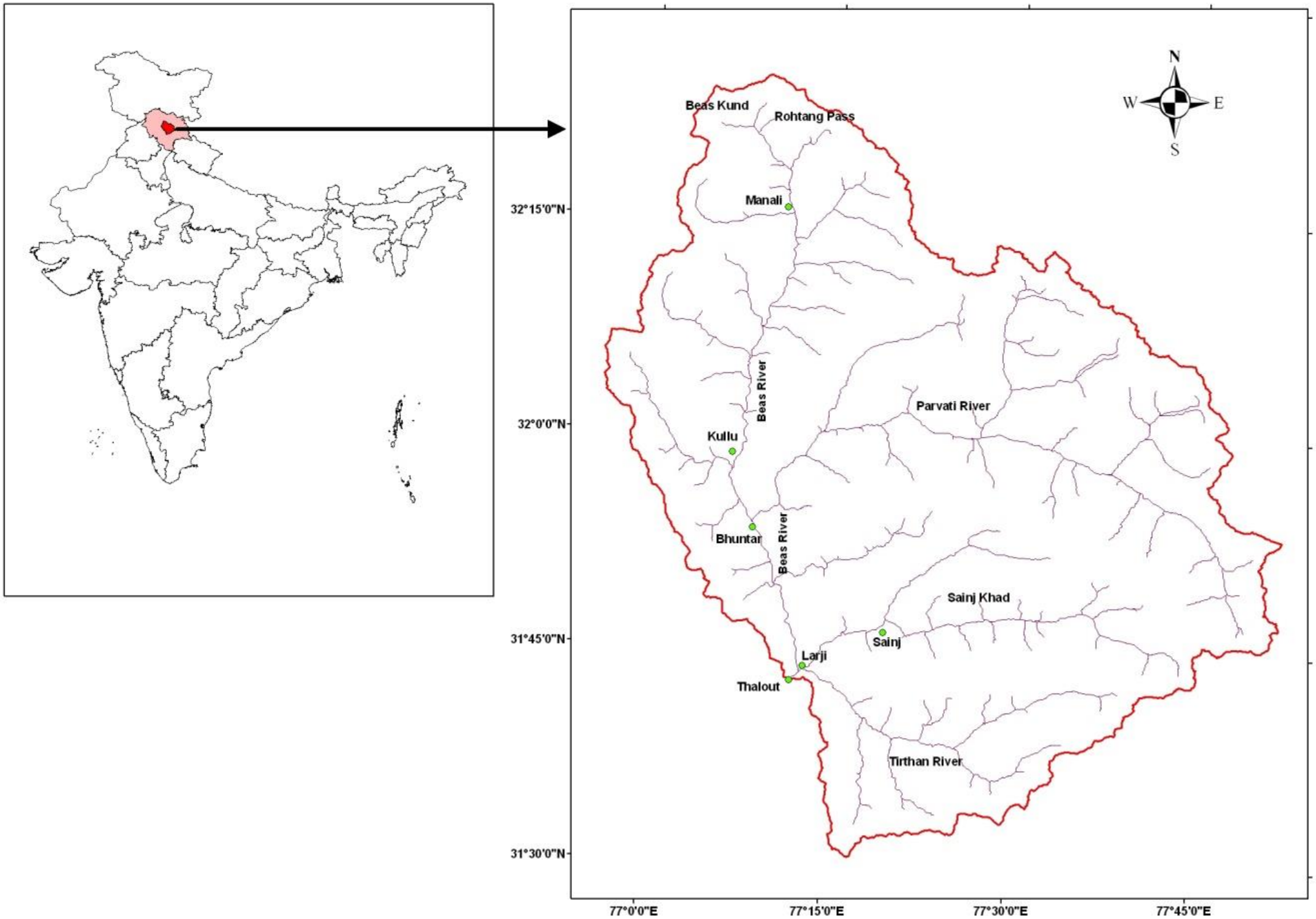
Spatial data base was prepared in raster (grid) format

DEM which is one of the main inputs of SWAT Model was taken from ASTER DEM

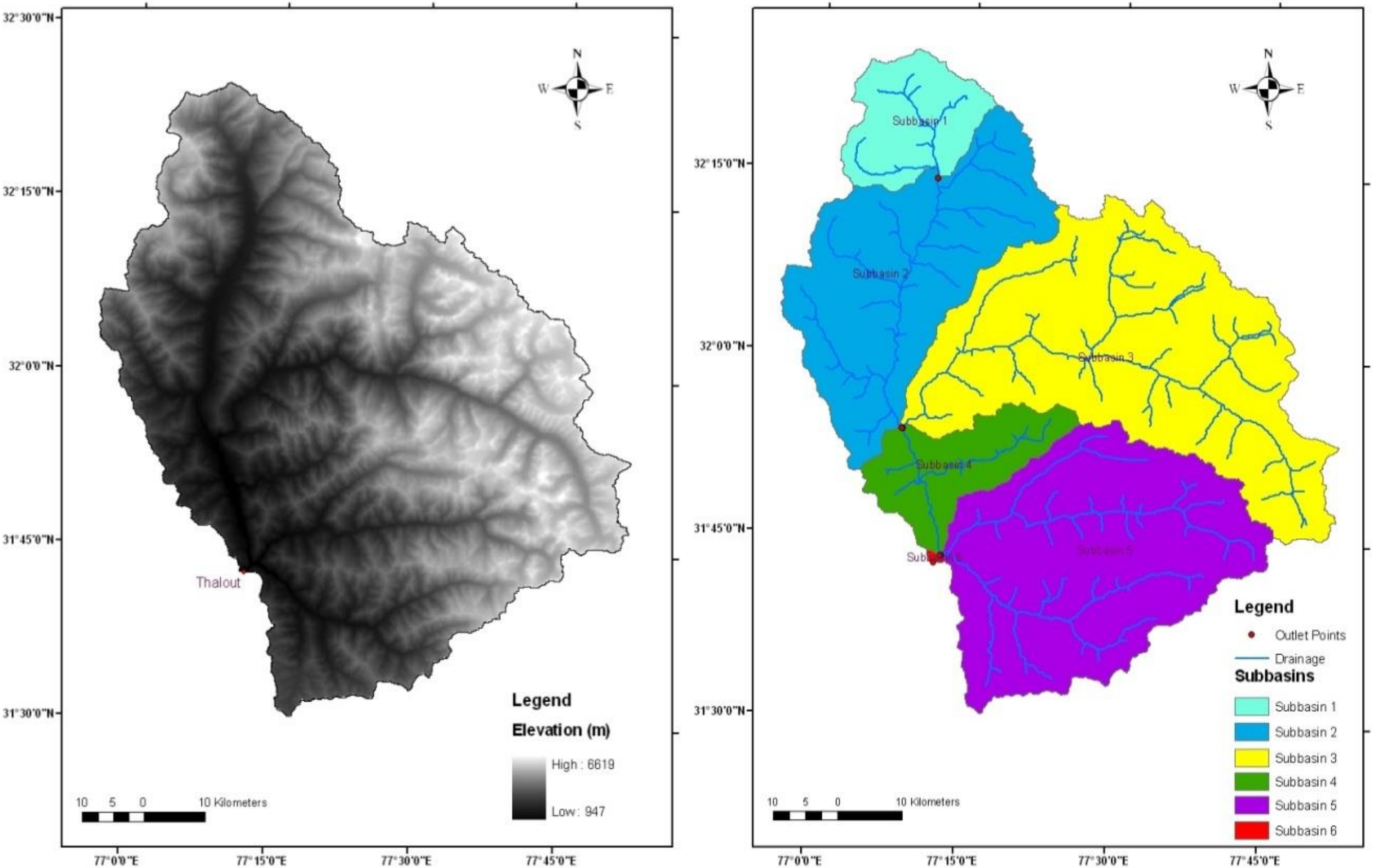
Drainage map was extracted from DEM using channel threshold area of 45 sq km

Land use/land cover map was prepared using remote sensing data of Landsat ETM+.

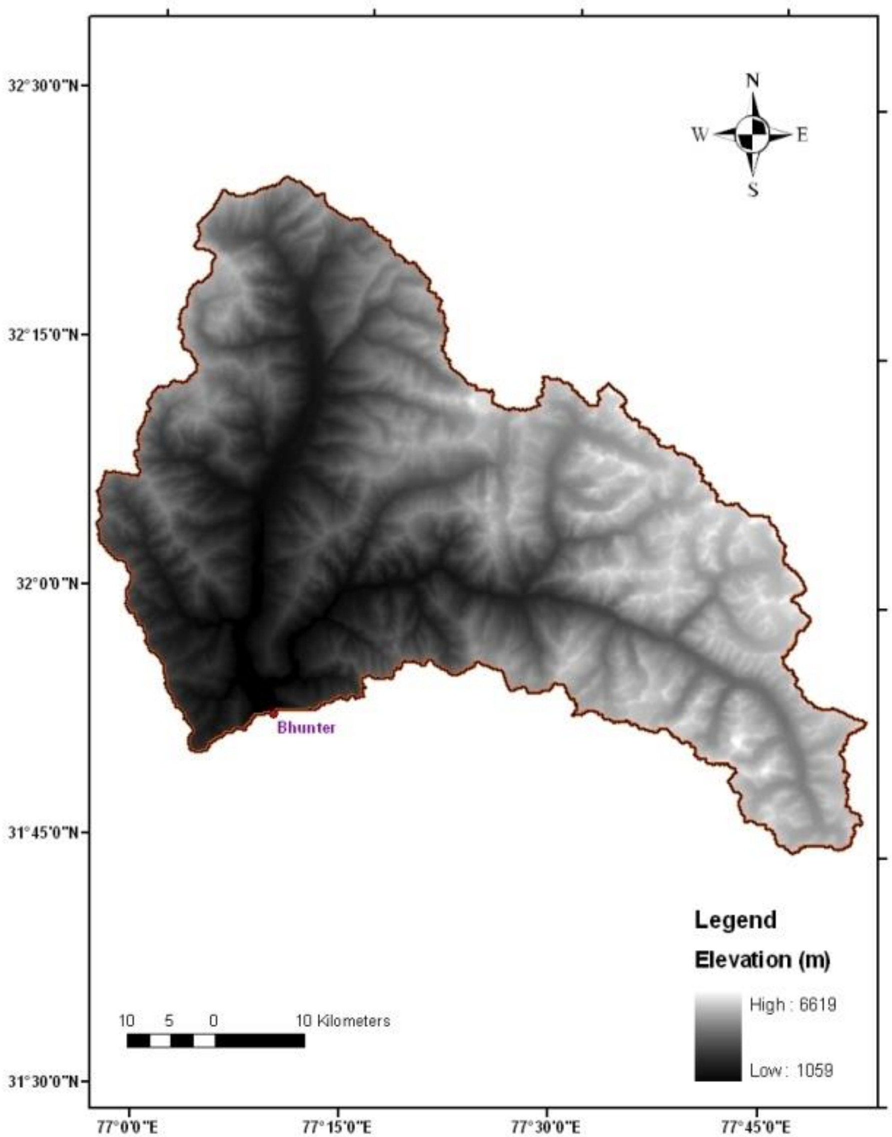
Soil map of the study area was digitized from soil map of NBSS &LUP at a scale of 1:50,000

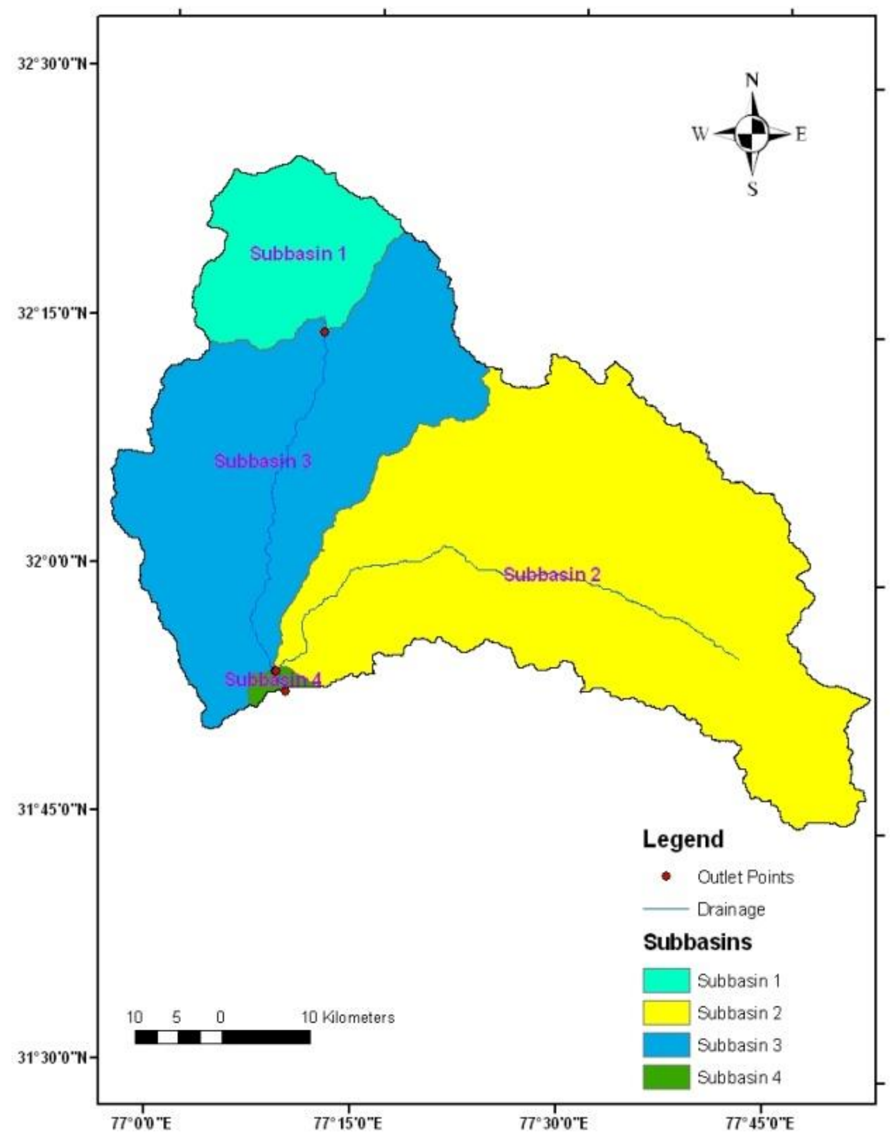


N
W
E
S
Beas Kund
Rohtang Pass
Manali
32°15'0"N
Beas River
Parvati River
32°0'0"N
Kullu
Bhuntar
Beas River
Sainj Khad
31°45'0"N
Sainj
Larji
Thalout
Tirthan River
31°30'0"N
77°0'0"E
77°15'0"E
77°30'0"E
77°45'0"E

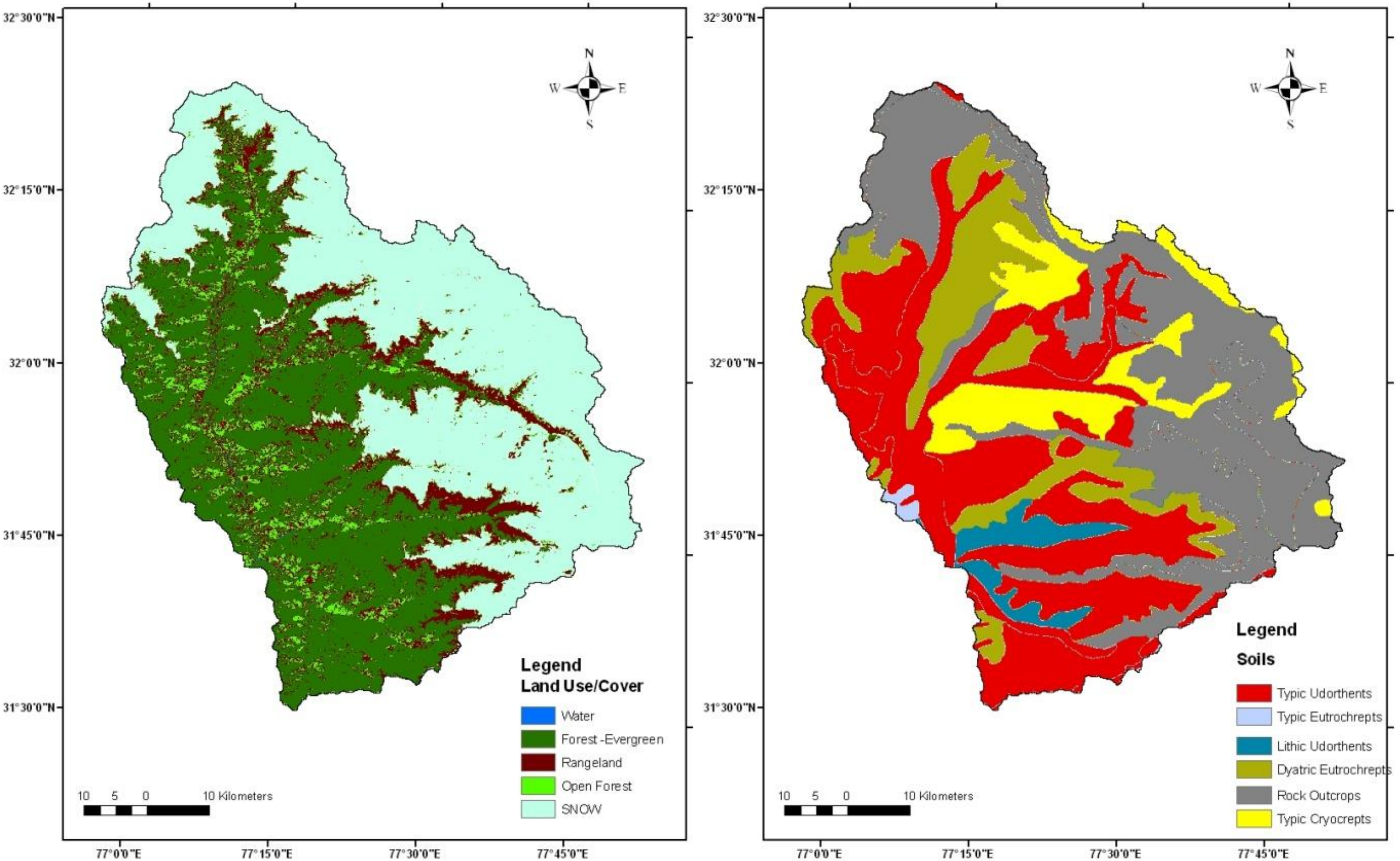


DEM AND SUB BASINS OF BEAS BASIN (THALOUT)

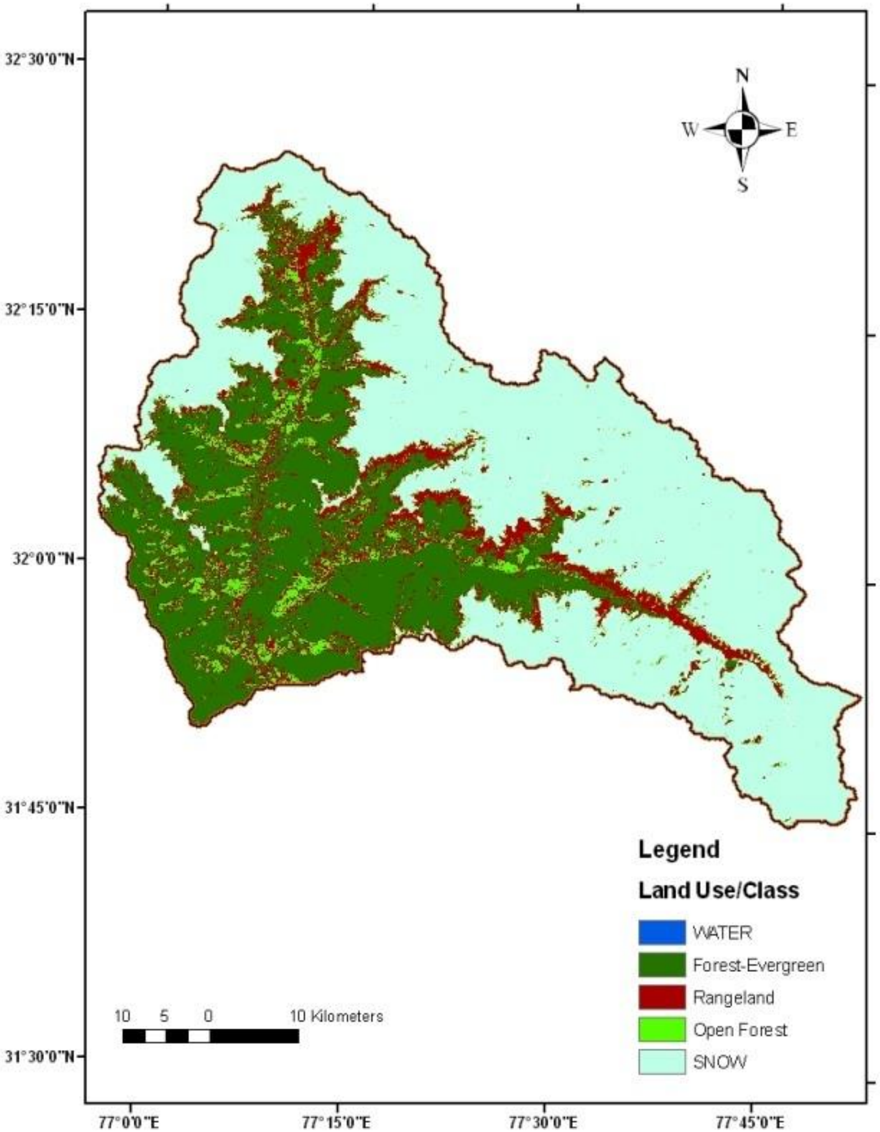


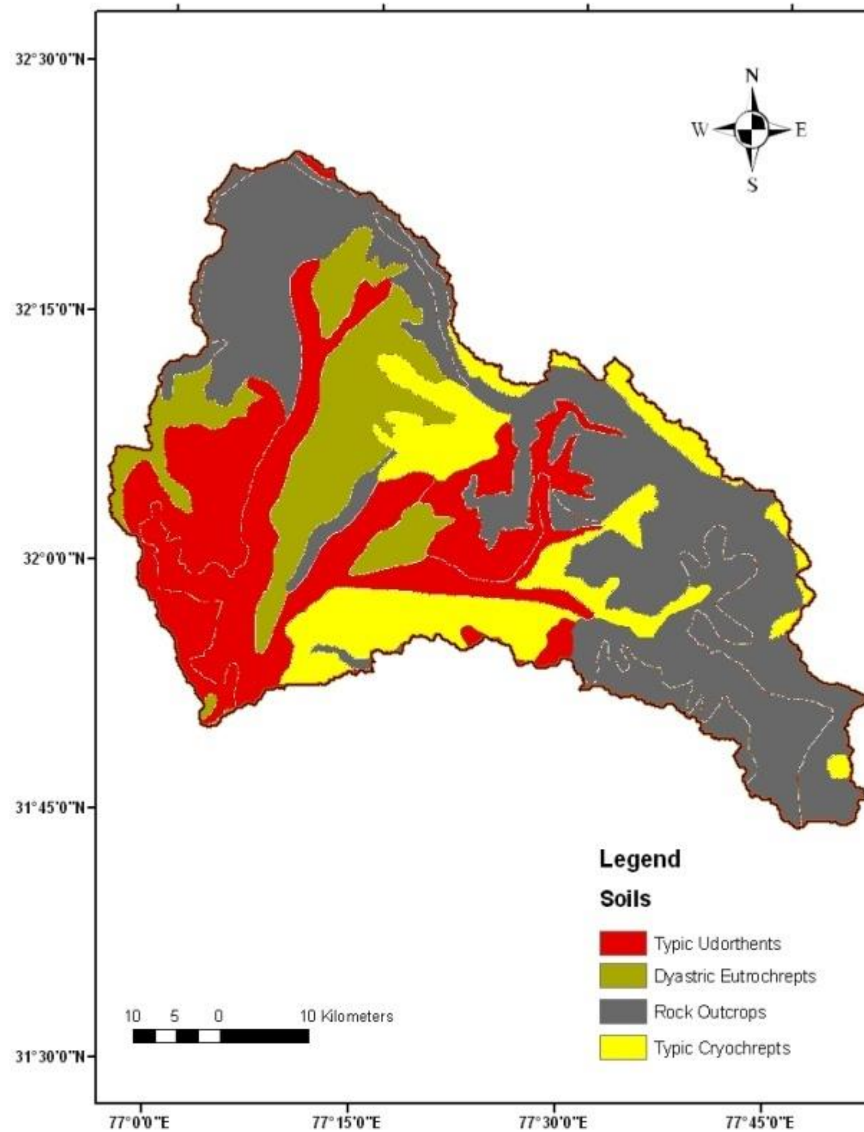


DEM AND SUB BASINS OF BEAS BASIN (BHUNTER)

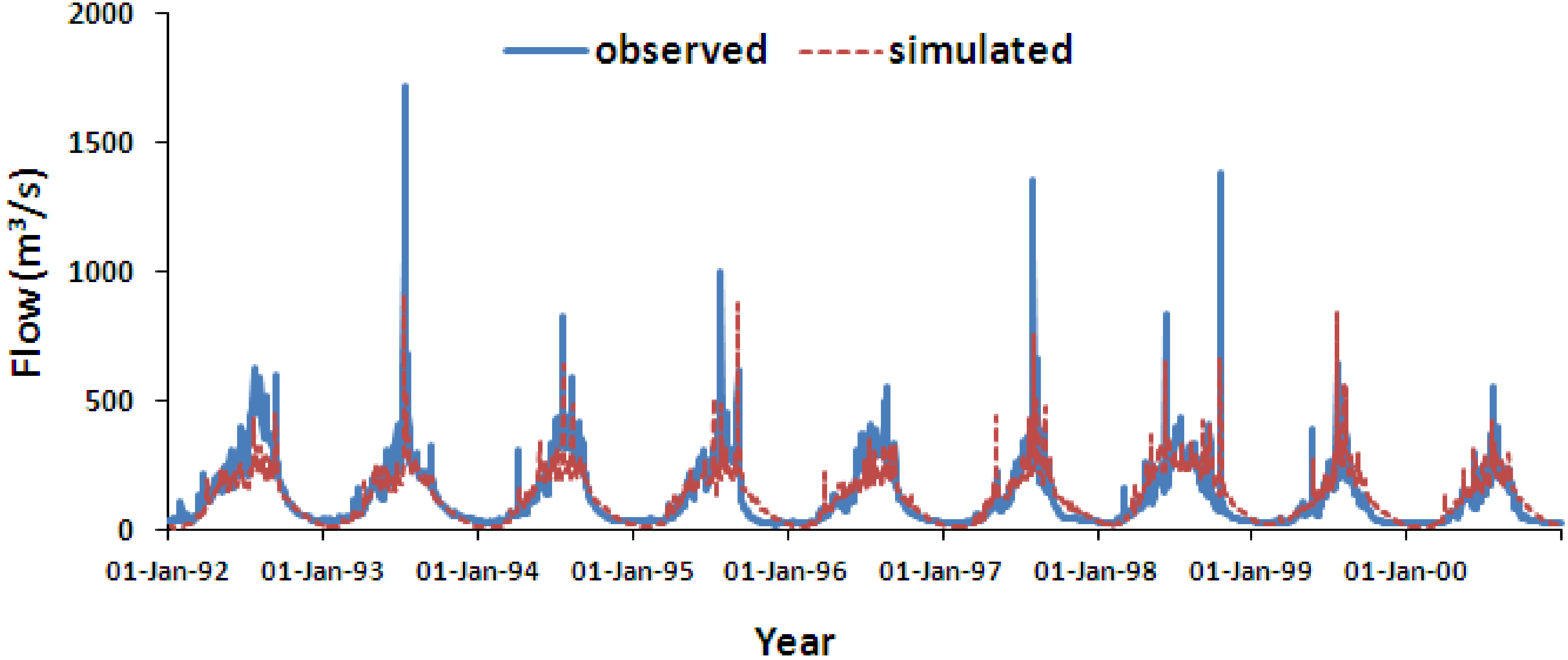


LAND USE AND SOIL MAPS OF BEAS BASIN (THALOUT)

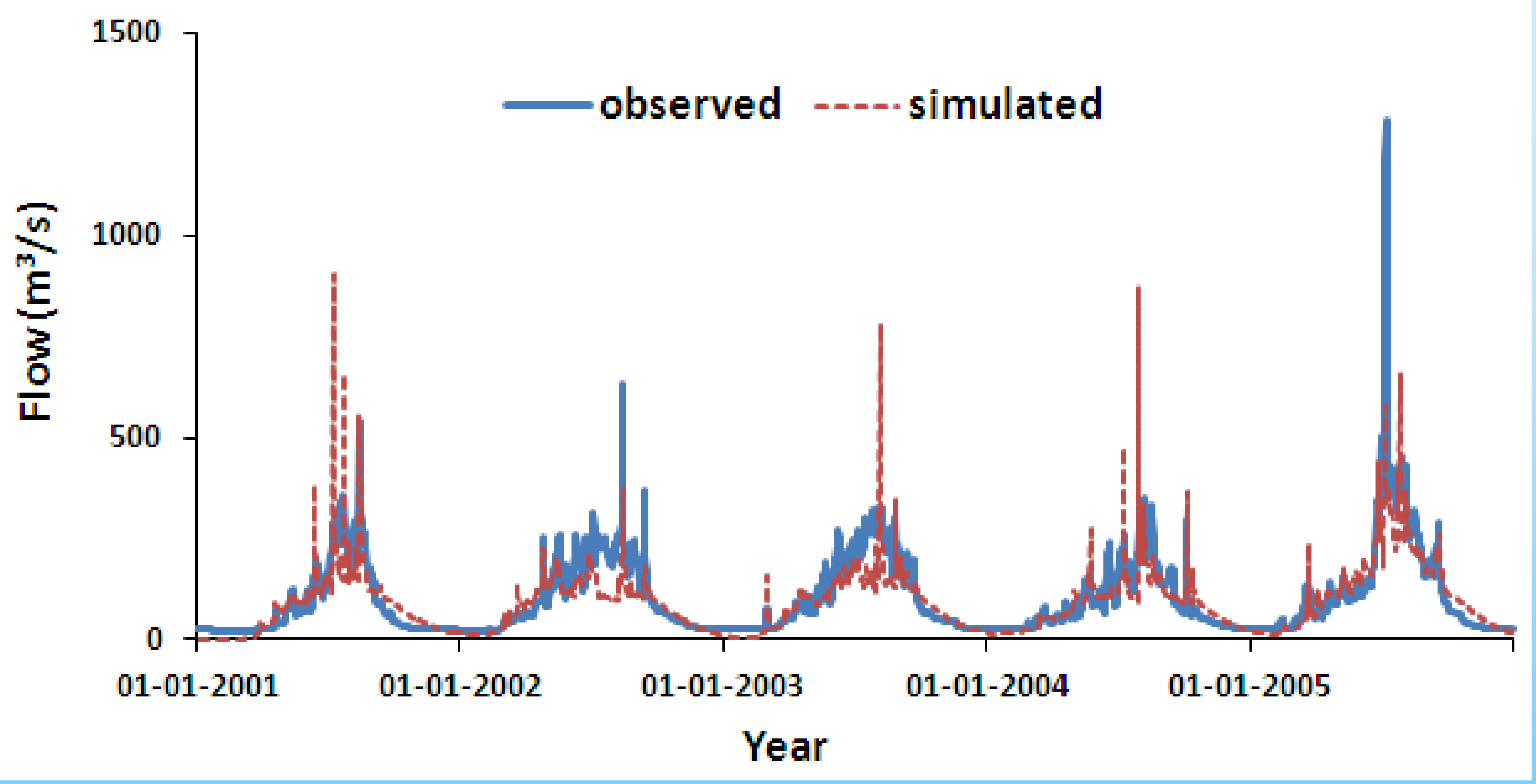




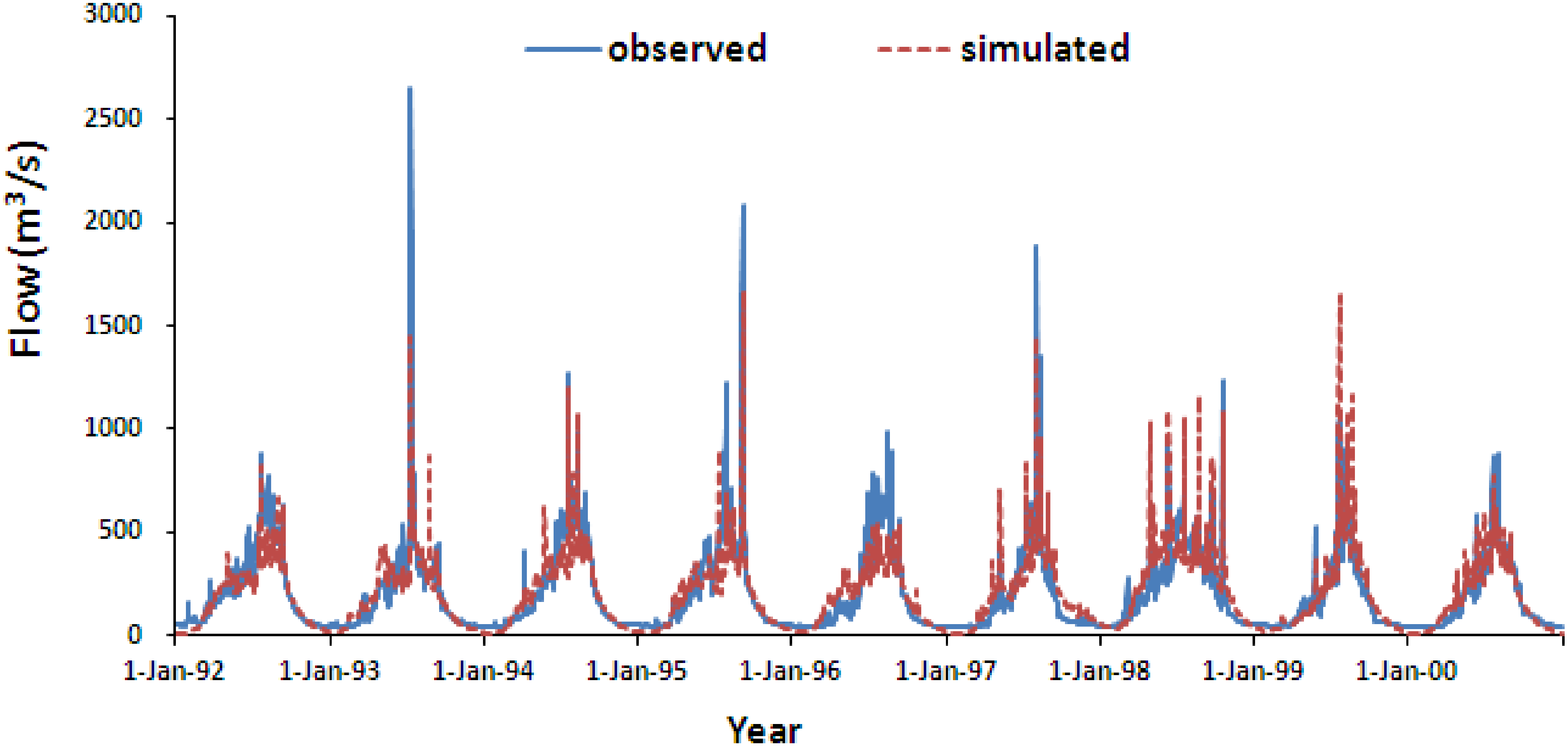
LAND USE AND SOIL MAPS OF BEAS BASIN (BHUNTER)



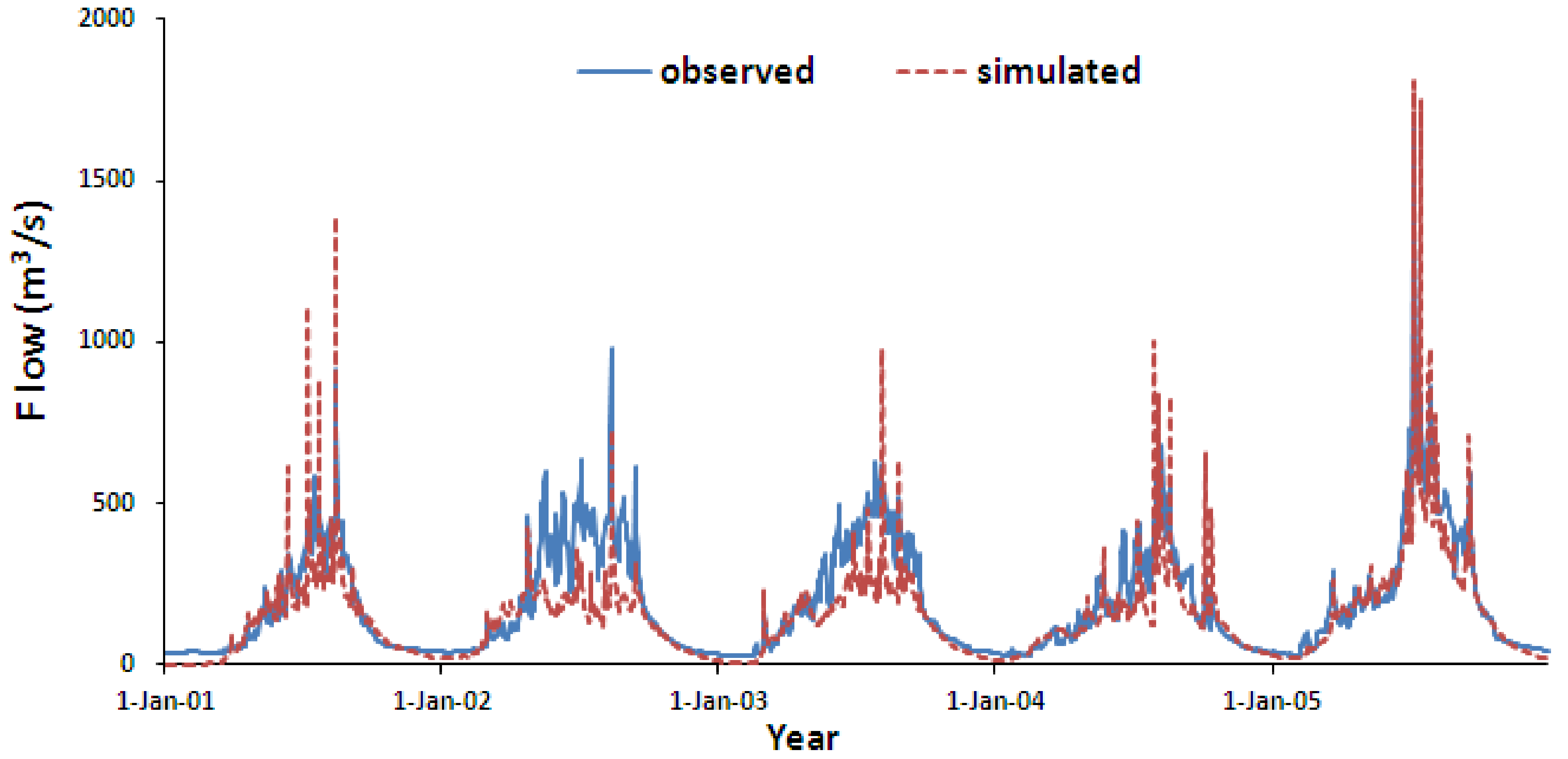
Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Bhunter during calibration period (1992-2000)



Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Bhunter during validation period (2001-2005)



Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Thalout during calibration period (1992-2000),



Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Thalout during validation period (2001-2005),

Daily calibration goodness of fit statistics for Beas river catchment

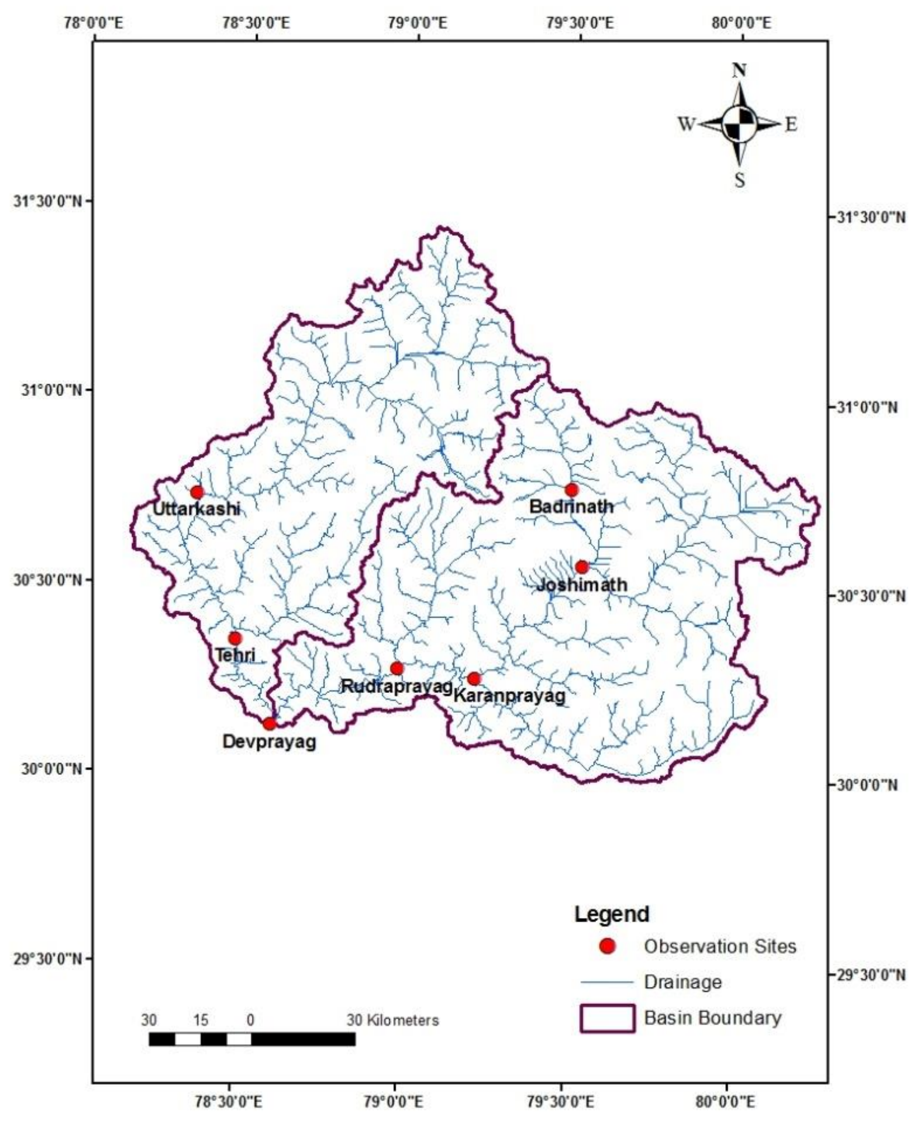
Statistical Indicator	Calibration (years 1992-2000)		Validation (years 2001-2005)	
	Beas basin up to Bhunter	Beas basin up to Thalout	Beas basin up to Bhunter	Beas basin up to Thalout
R^2	0.72	0.75	0.67	0.71
NSE	0.71	0.75	0.66	0.66
PBIAS	5.3 %	3.0 %	10.2 %	21.4 %

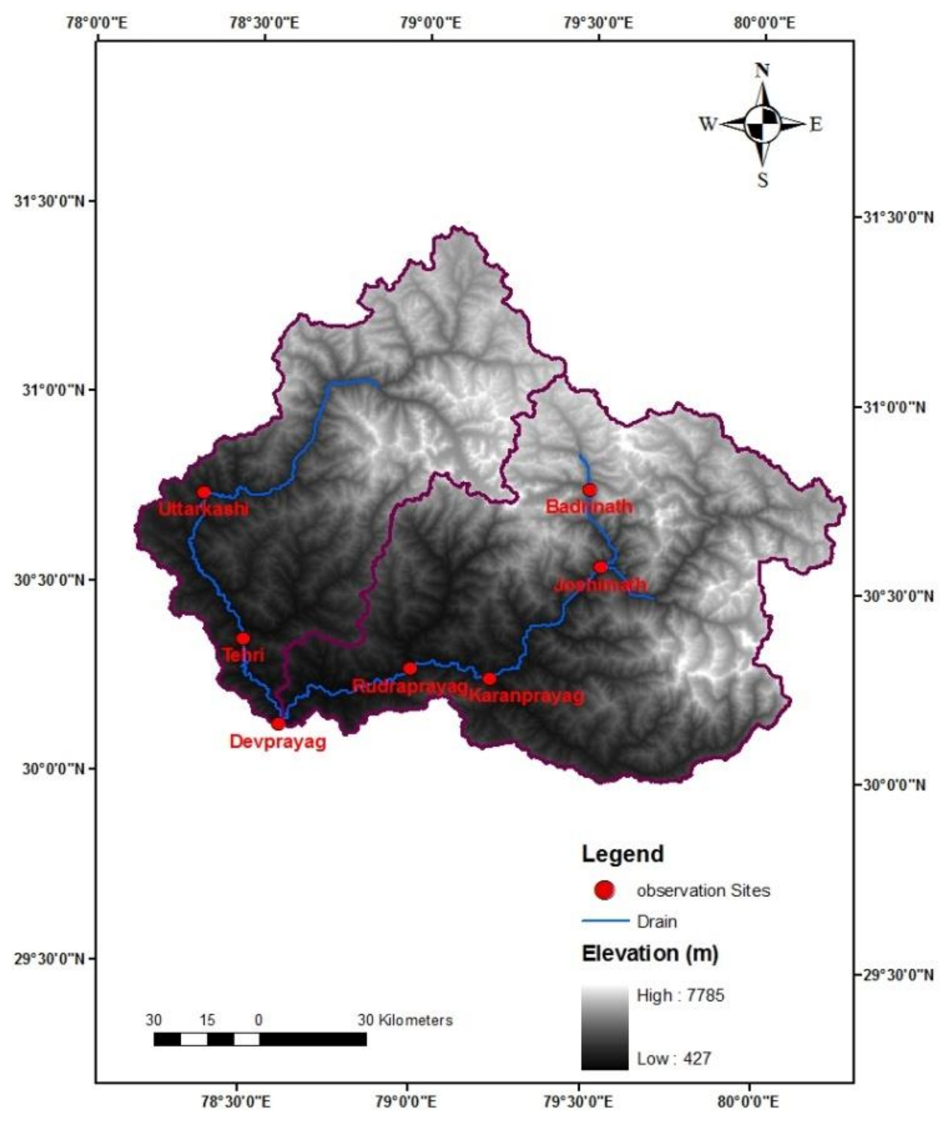
WATER BALANCE (mm)

	P	ET	Sur_Q	LAT_Q	GW_Q	WYLD	Snowfall	Snow melt
Beas basin up to Bhunter								
Calibration	1410.7	770.2	16.94	146.96	272.17	436.03	248.85	192.07
Validation	1106.3	801.4	13.43	110.46	195.29	319.15	181.51	130.56
Beas basin up to Thalout								
Calibration	1427.2	687.7	34.15	213.91	353.94	601.37	274.63	226.22
Validation	11445	719.1	33.35	168.01	265.86	467.18	189.90	148.85

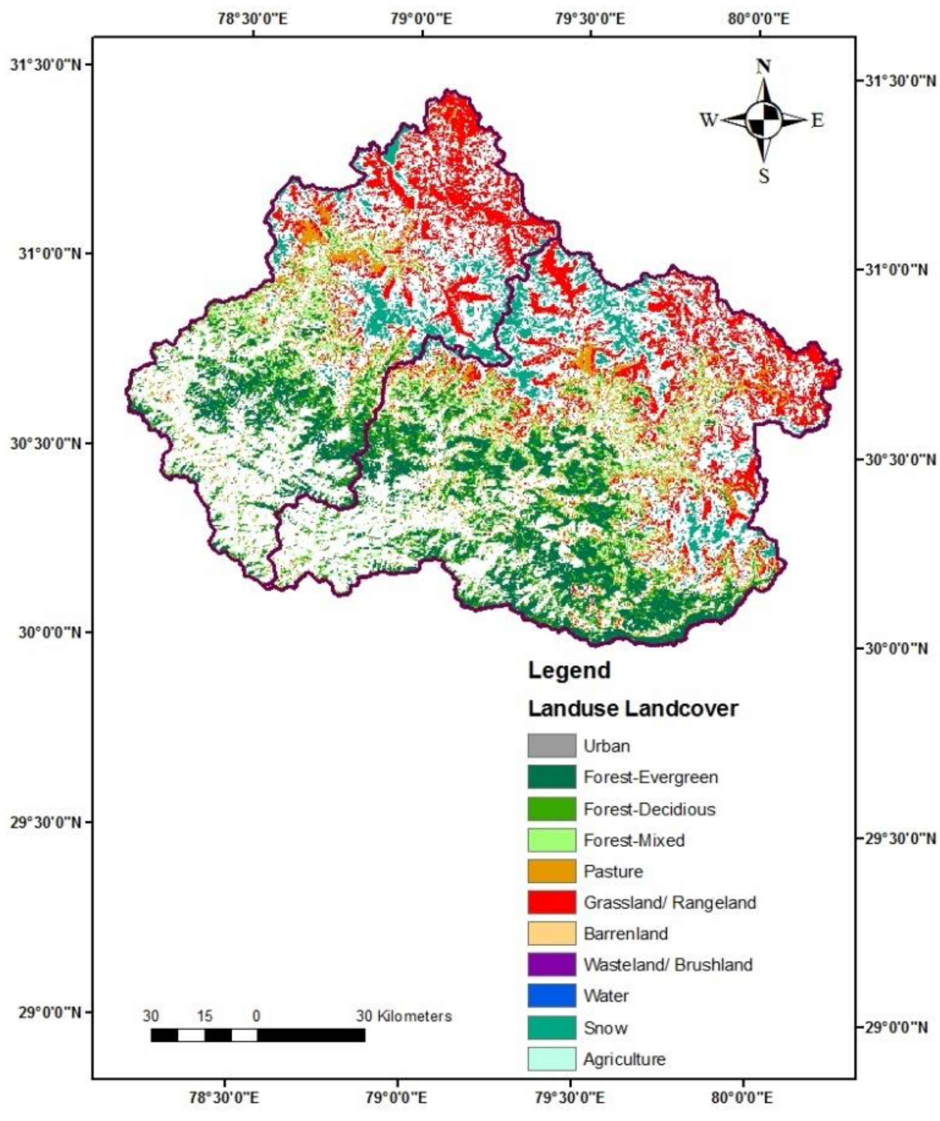
GANGA BASIN UP TO DEOPRAYAG

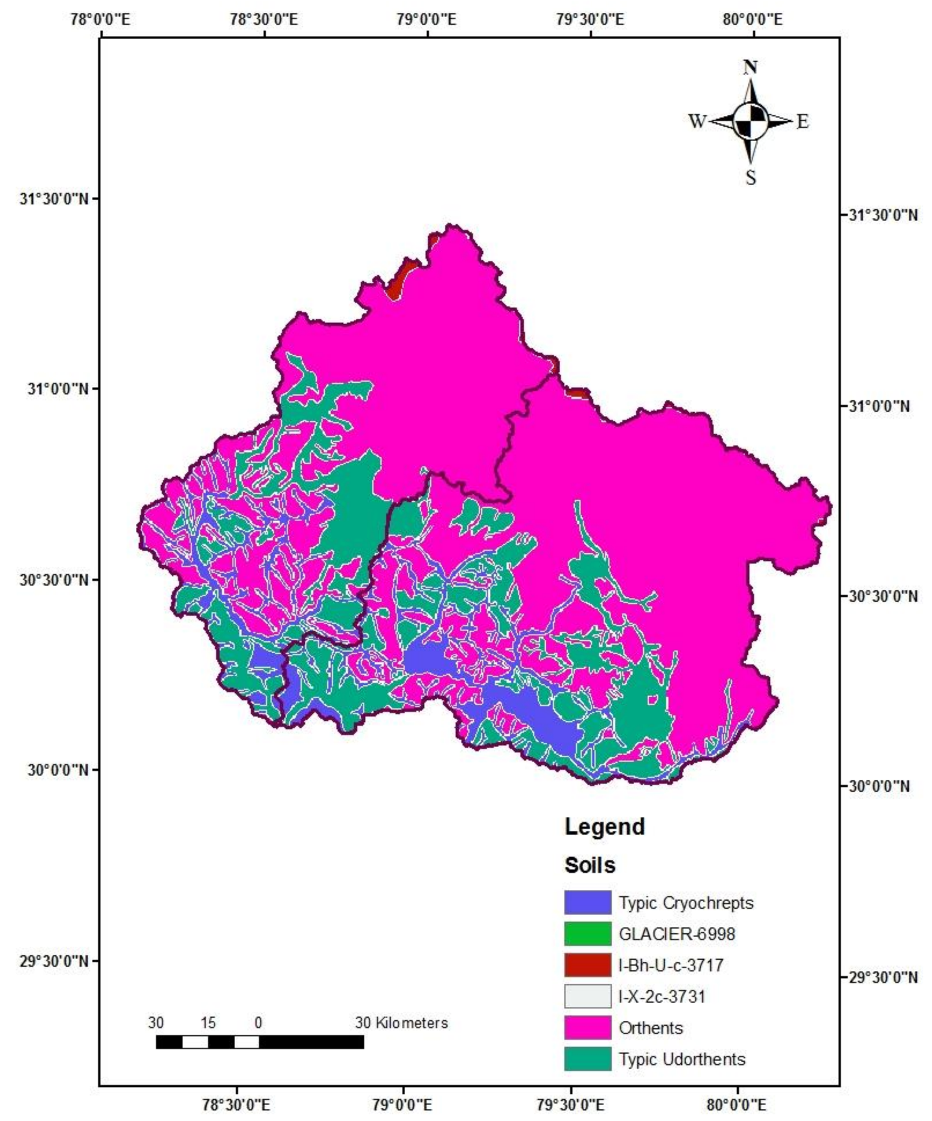
- Spatial data base was prepared in raster format
- DEM which is one of the main inputs of SWAT Model was taken from ASTER DEM
- Drainage map was extracted from DEM
- Land use/land cover map was prepared using remote sensing data of Landsat ETM+.
- Soil map of the study area was digitized from soil map of NBSS &LUP at a scale of 1:50,000



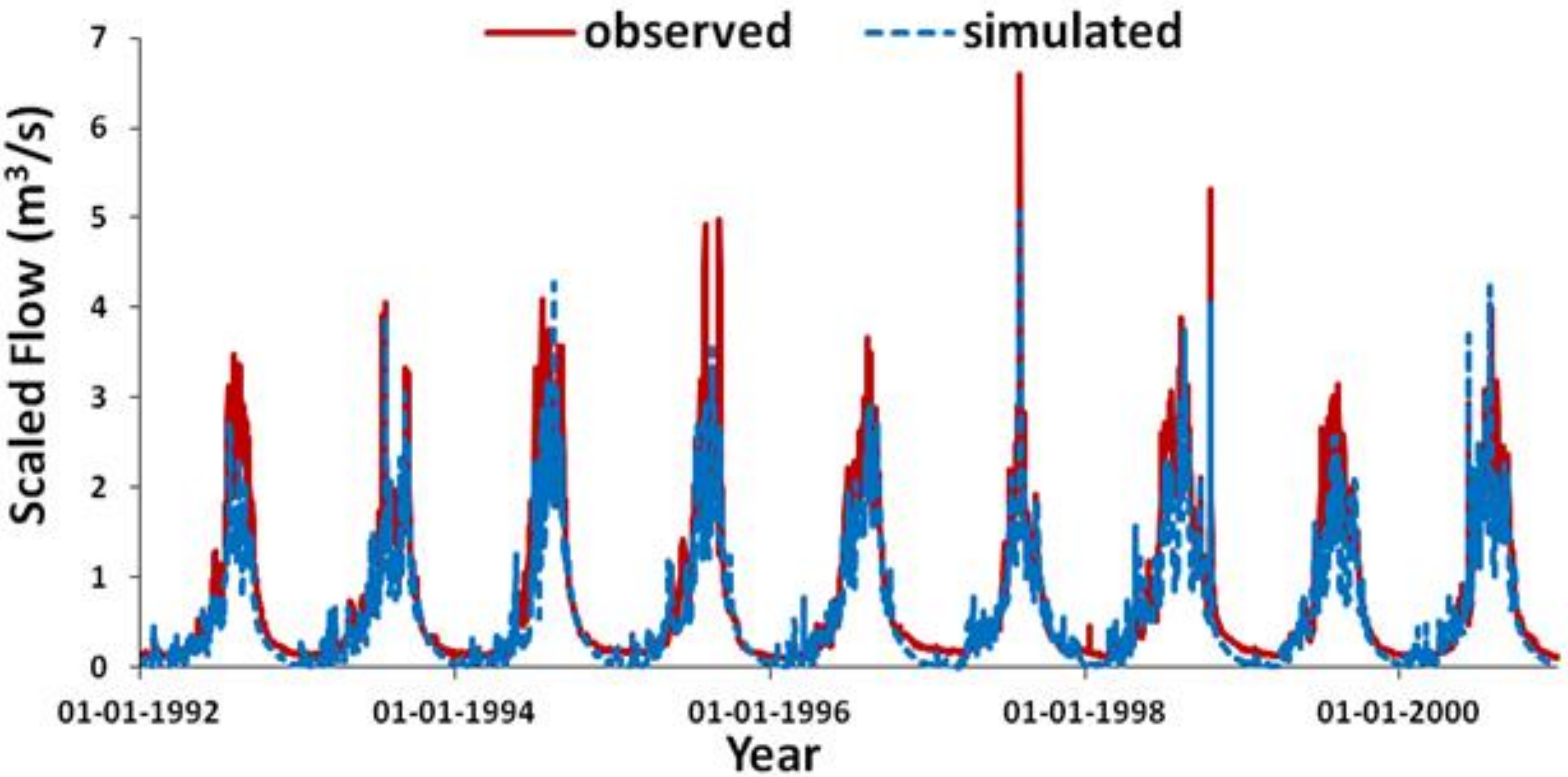


DEM AND SUB BASINS OF GANGA BASIN (DEVPRAYAG)

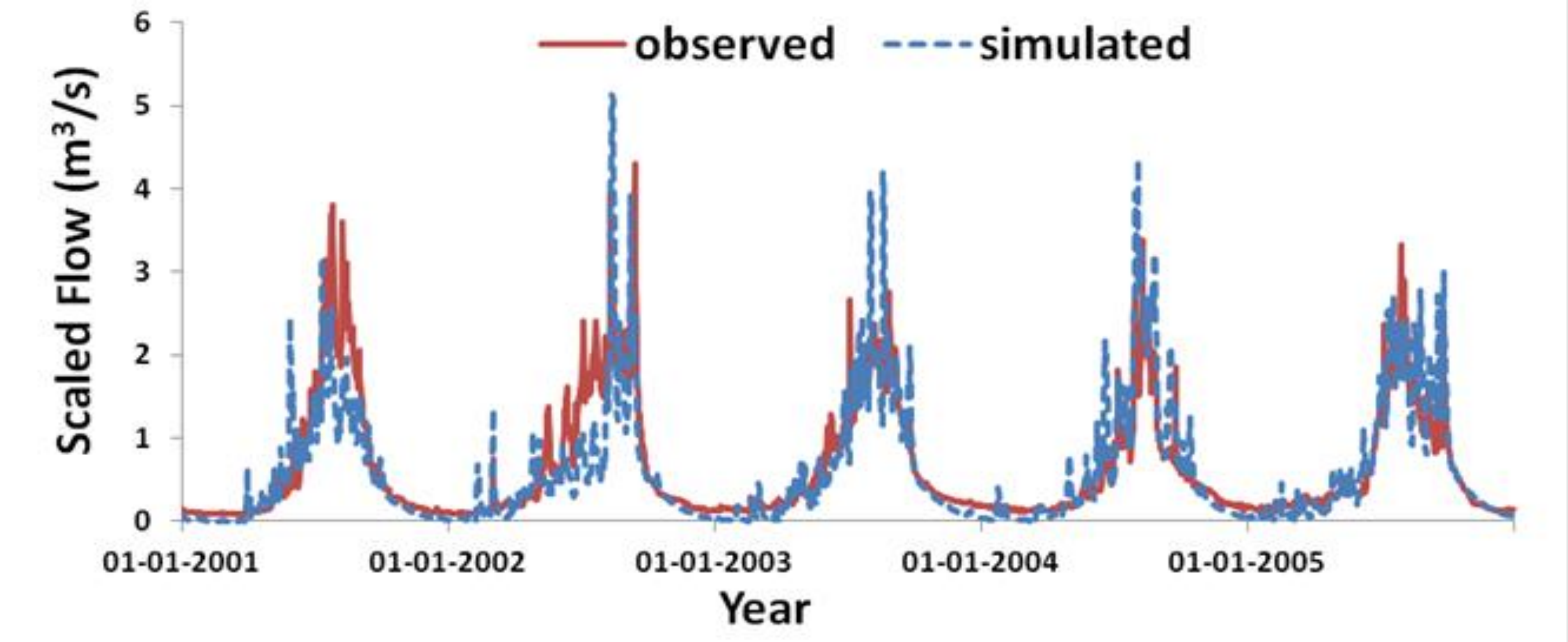




LANDUSE AND SOIL MAP OF GANGA BASIN (DEVPRAYAG)



Comparison of a) scaled daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during calibration period (1992-2000)



Comparison of: a) scaled daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during validation period (2001-2005),

CONCLUDING REMARKS

Mountain river hydrology is critical for downstream drinking water, agricultural irrigation, power generation, and flood management . Simulation and forecast of snowmelt runoff has become a real necessity in Himalayan region.

The increasing availability of remote sensing data facilitates the successful application of the model in the snow-dominated mountainous basins, where measured hydro-meteorological data are limited and/or not available at all.

Due to global climate change and global warming, snowmelt runoff research is considered more essential than ever before to predicting water resources availability, programing water usage and management.

More research should be encouraged on the feasibility of modeling snowmelt runoff in data-sparse mountainous watersheds by utilizing snow and glacier cover remote sensing data, GIS tools, field measurements, and innovative ways of model parameterization.

THANKS