Snow and Glacial Influences on Water Resources and Stream flow

Dr. SANJAY K JAIN
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE

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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.

“Snow and Glaciers of the Himalayas: Inventory and Monitoring” Released by MOEF in 2011

Snow cover and glacier extent has been monitored regularly for the entire Indian Himalaya, from 2004-05 to 2007-08. An extensive inventory, using satellite-based mapping was conducted across glaciated regions across the Indus, Ganga and Bramhaputra river basins.

A total of 32392 glaciers were mapped in the three basins
Total glaciated area is estimated at 71182.08 km2
India alone has 16,627 glaciers covering an area of 40, 563 km2 .

Over 2700 glaciers monitored of 2767 glaciers, 2184 are retreating, 435 are advancing and 148 glaciers show no change.

In December 2011 , ICIMOD released reports on the occasion of Mountain Day. As per the report,

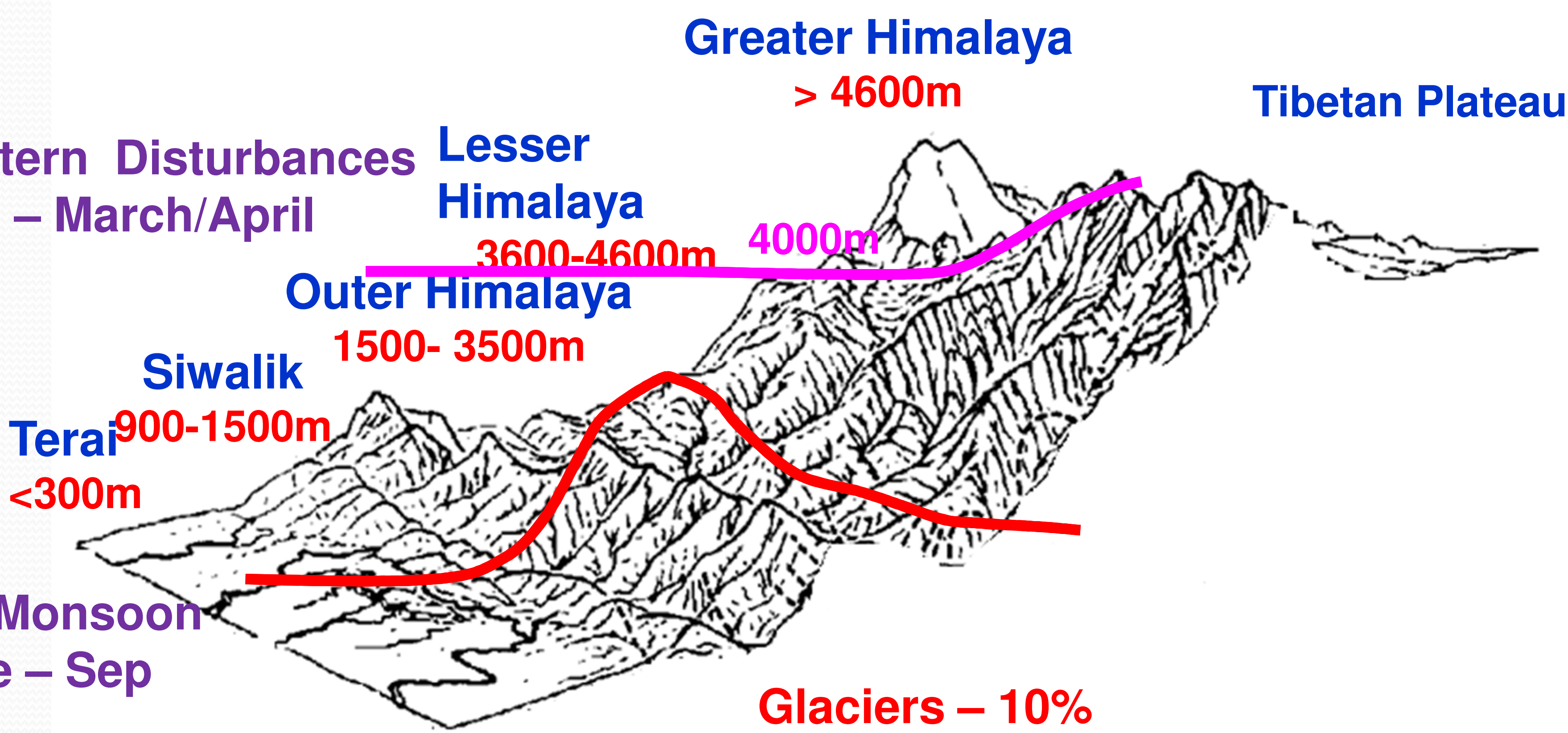
The HKH region, home to 30% Of the world's glaciers has been called the Third Pole.

The rise in temperature has been greater at higher altitudes and more pronounced during the cooler months than in the warmer months. warming across the region is greater than the global average of 0.74 C over the past 100 years.

Of the 54000 Glaciers, only ten have been studied regularly for mass balance. This shows a loss of mass balance, with the rate doubling between 1980 and 2000 and 1996 and 2005. Glaciers appear to be shrinking in both the central and eastern Himalayas.

The Himalayan System

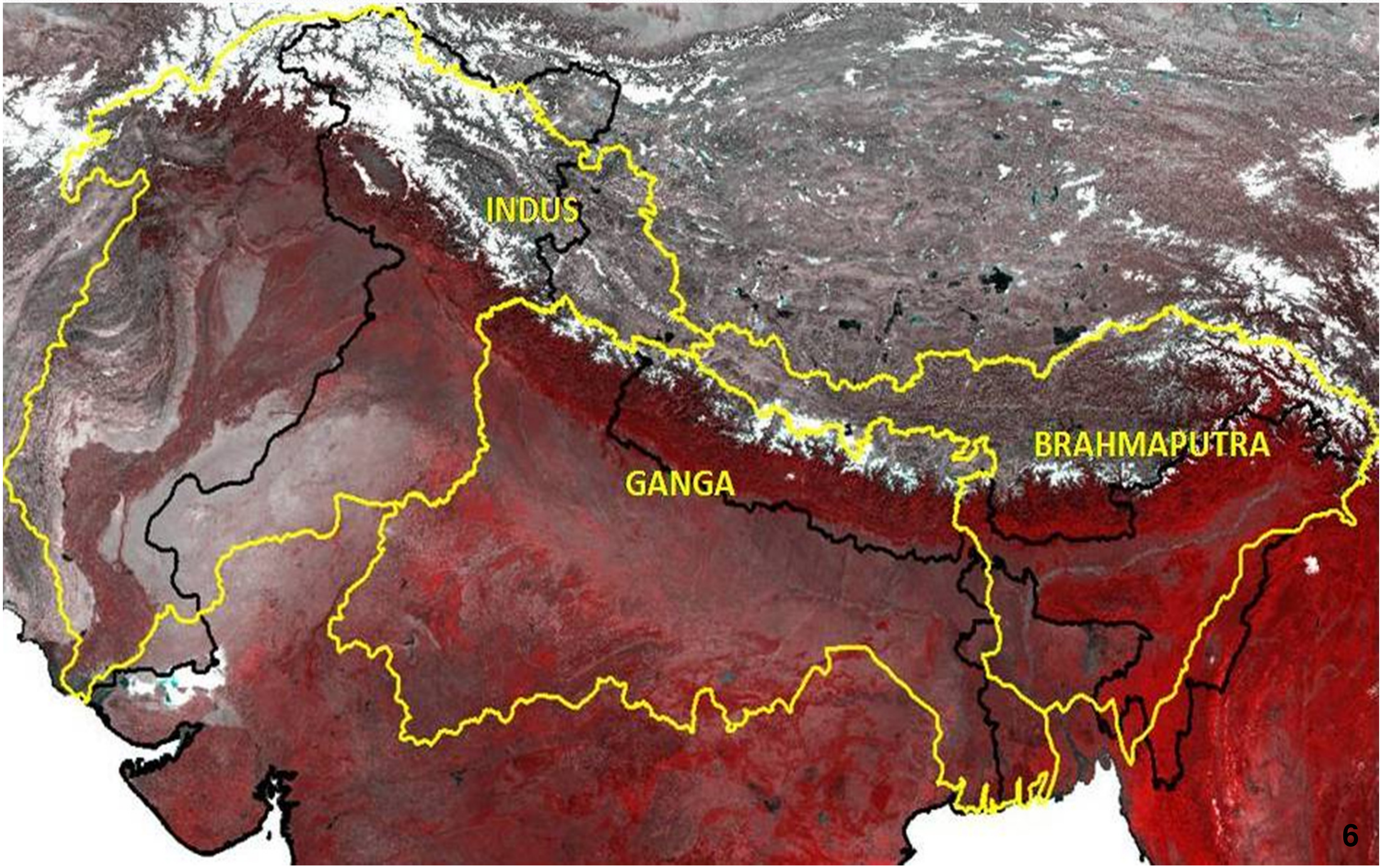
Western Disturbances
Nov. – March/April



SW Monsoon
June – Sep

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

INDUS, GANGA, BRAHMAPUTRA BASINS




SNOW AND GLACIER MELT
SATLUJ BASIN, CHENAB BASIN, BEAS BASIN AND GANGES BASIN

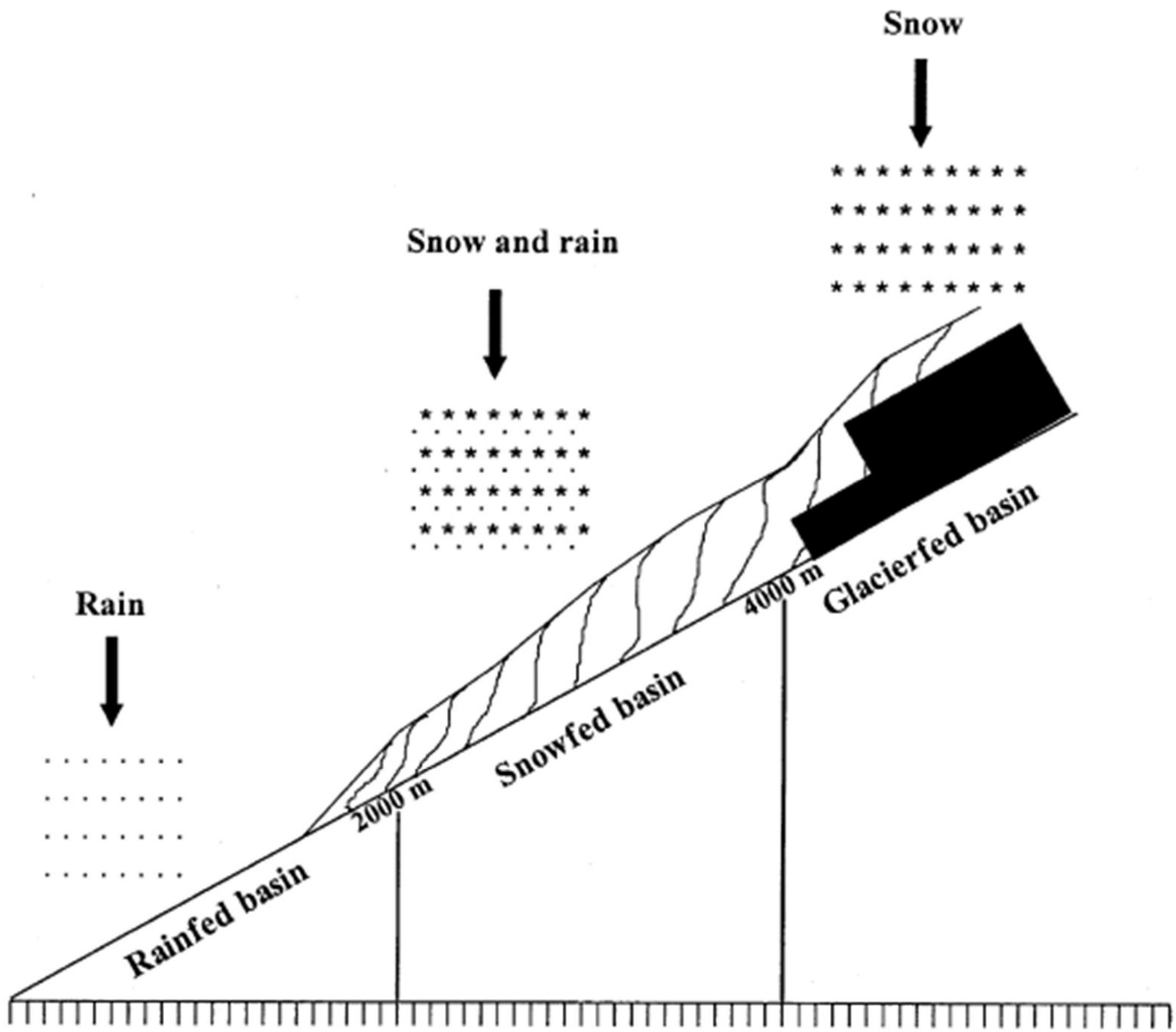
Basins of all major Himalayan rivers have combination of both glacial and nonglacial watersheds.

- **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**

More regional significance

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

More local significance


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

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)

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

(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.

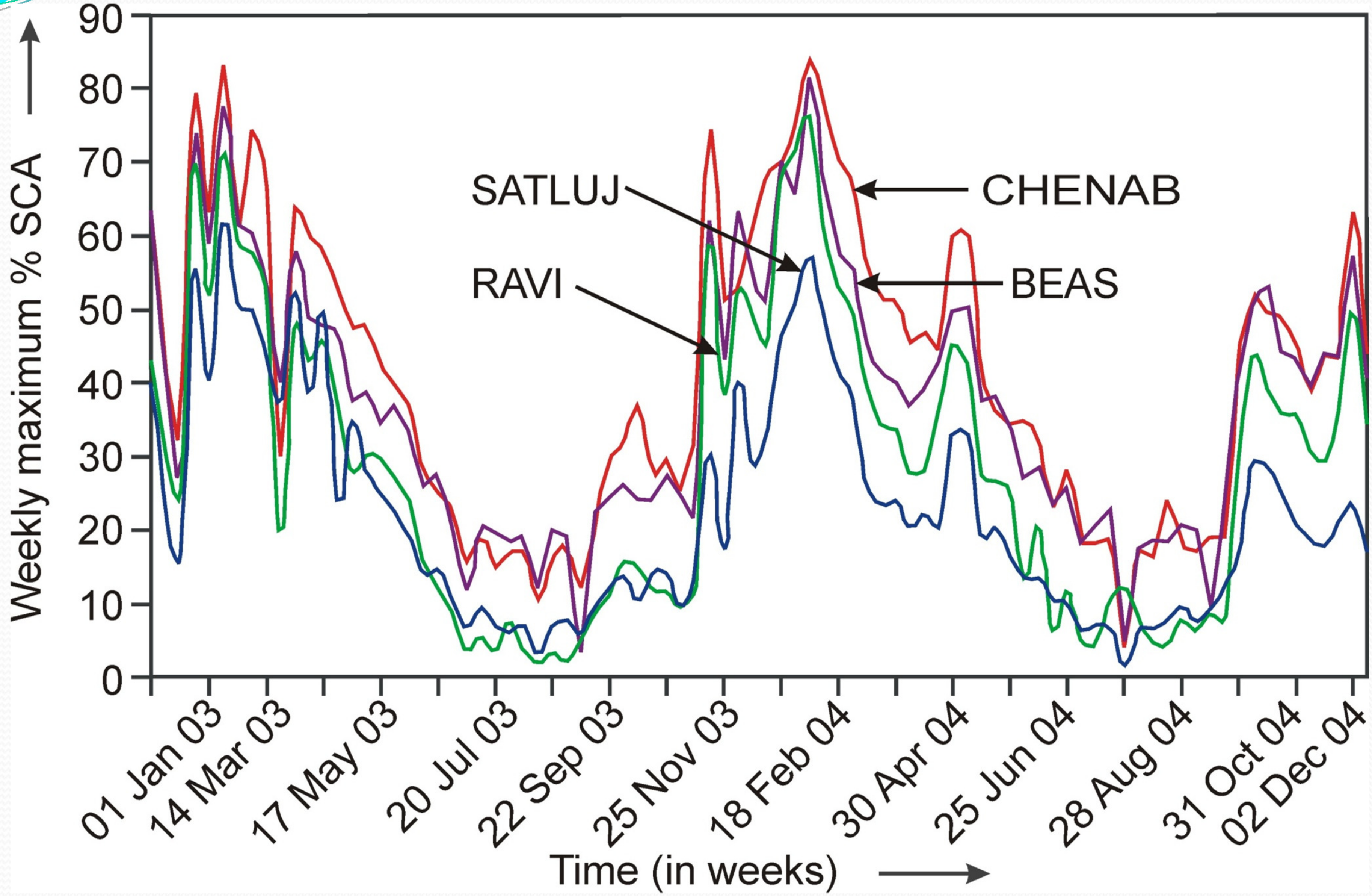
SNOW COVERED AREA

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%)

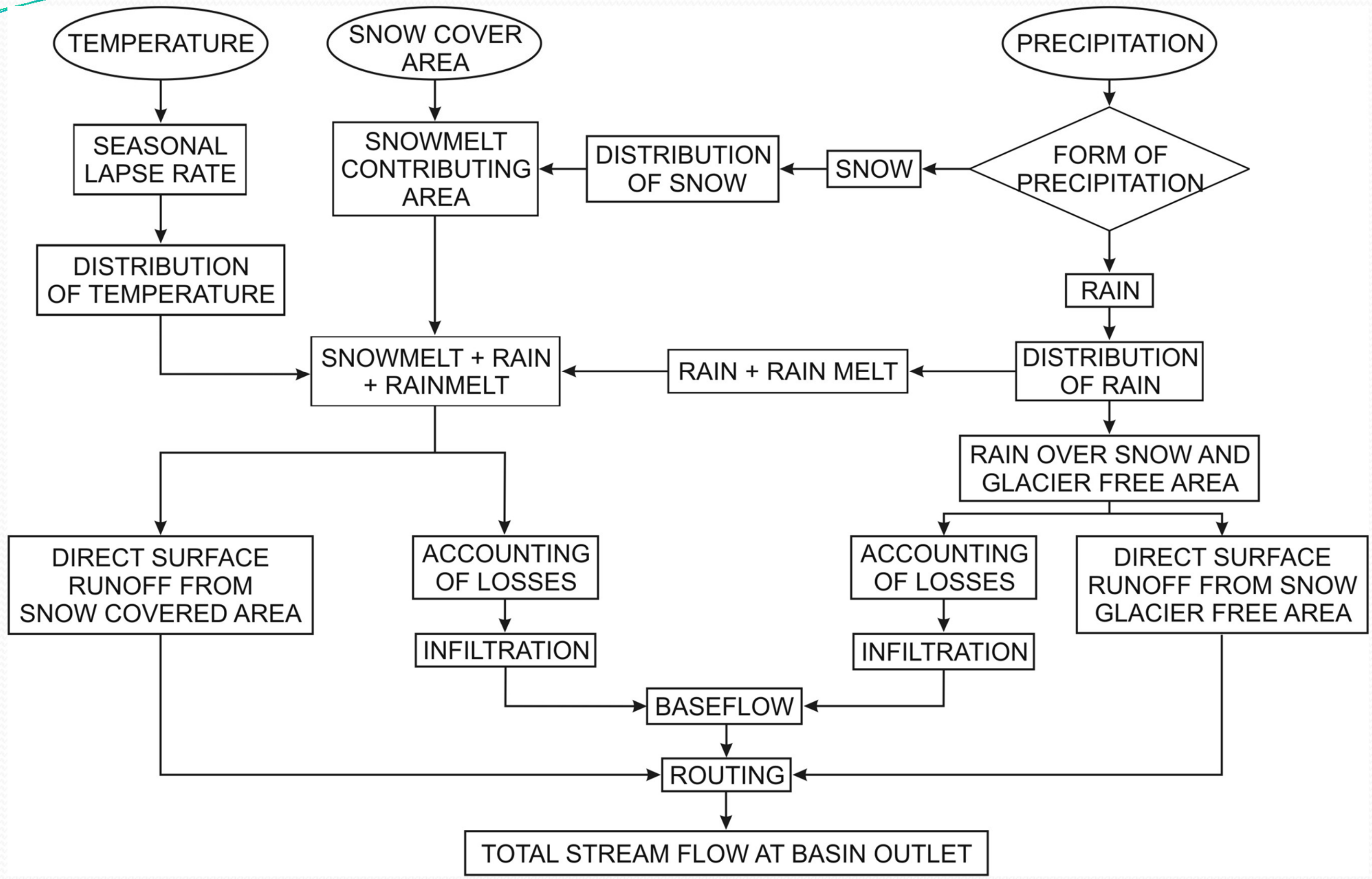
SNOW AND GLACIER MELT CONTRIBUTION

River	Site	Av. snow & glaciers melt contribution to annual flows
Chenab River	Akhnoor	49%
Satluj River (Indian part)	Bhakra Dam	60%
Beas River	Pandoh Dam	35%
Ganga River	Devprayag	28%

Snow Cover Depletion Curve



STREAM FLOW MODELLING



STREAM FLOW MODELLING

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

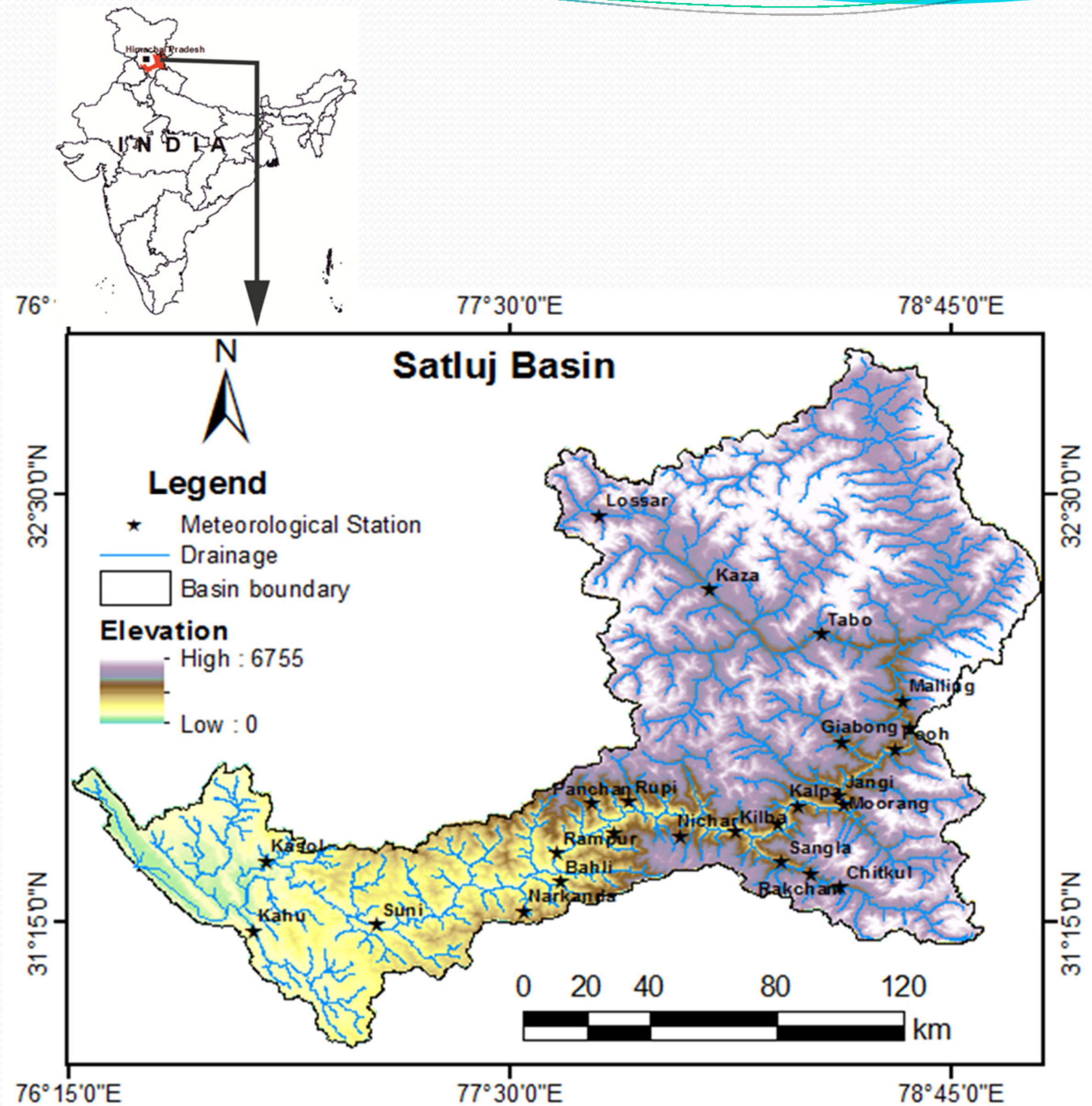
Form of Precipitation

Melt due to rain

Degree Day Factor for Snow and Ice

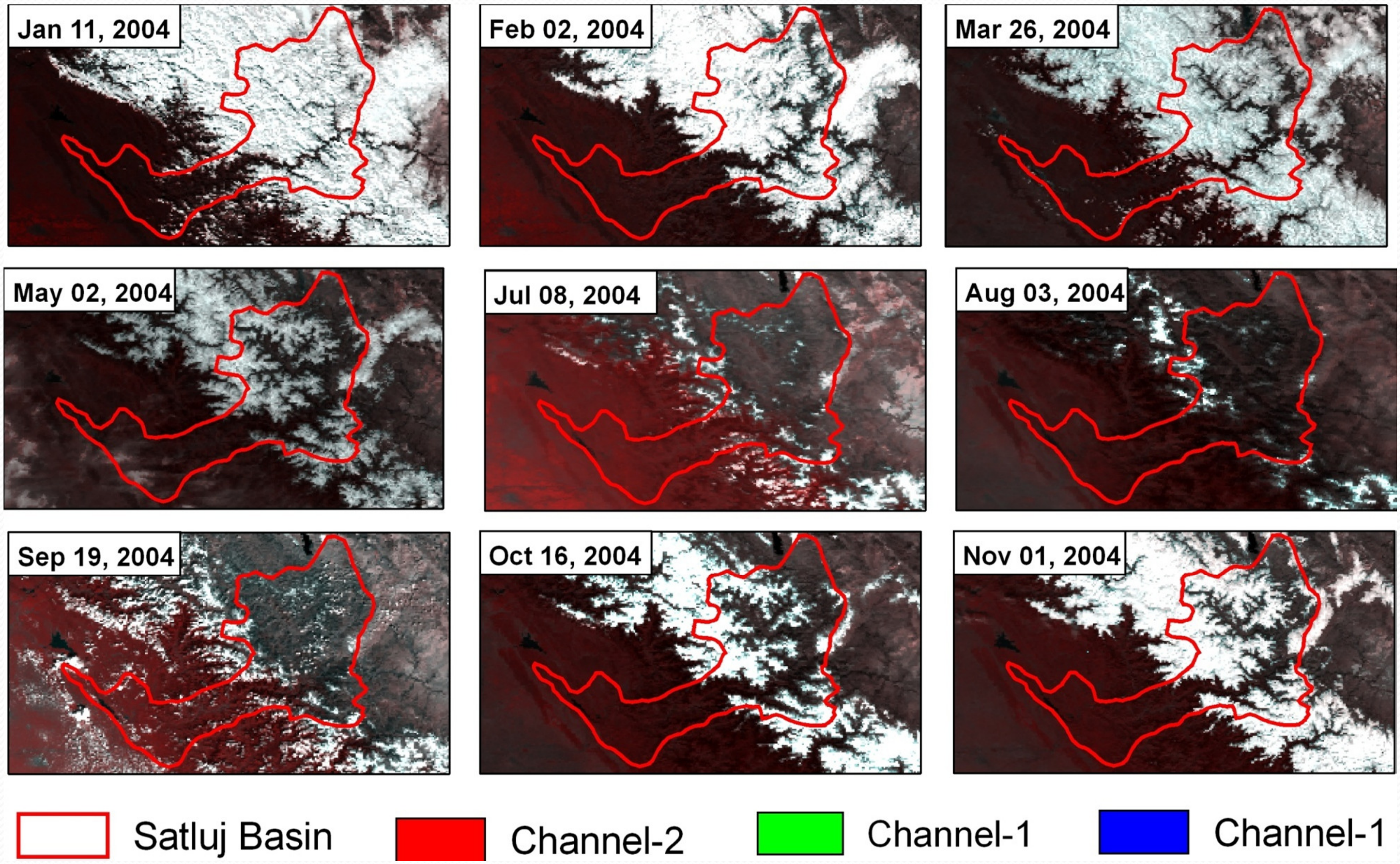
Routing of Surface and Sub Surface Flow

STREAM FLOW MODELLING IN SATLUJ BASIN

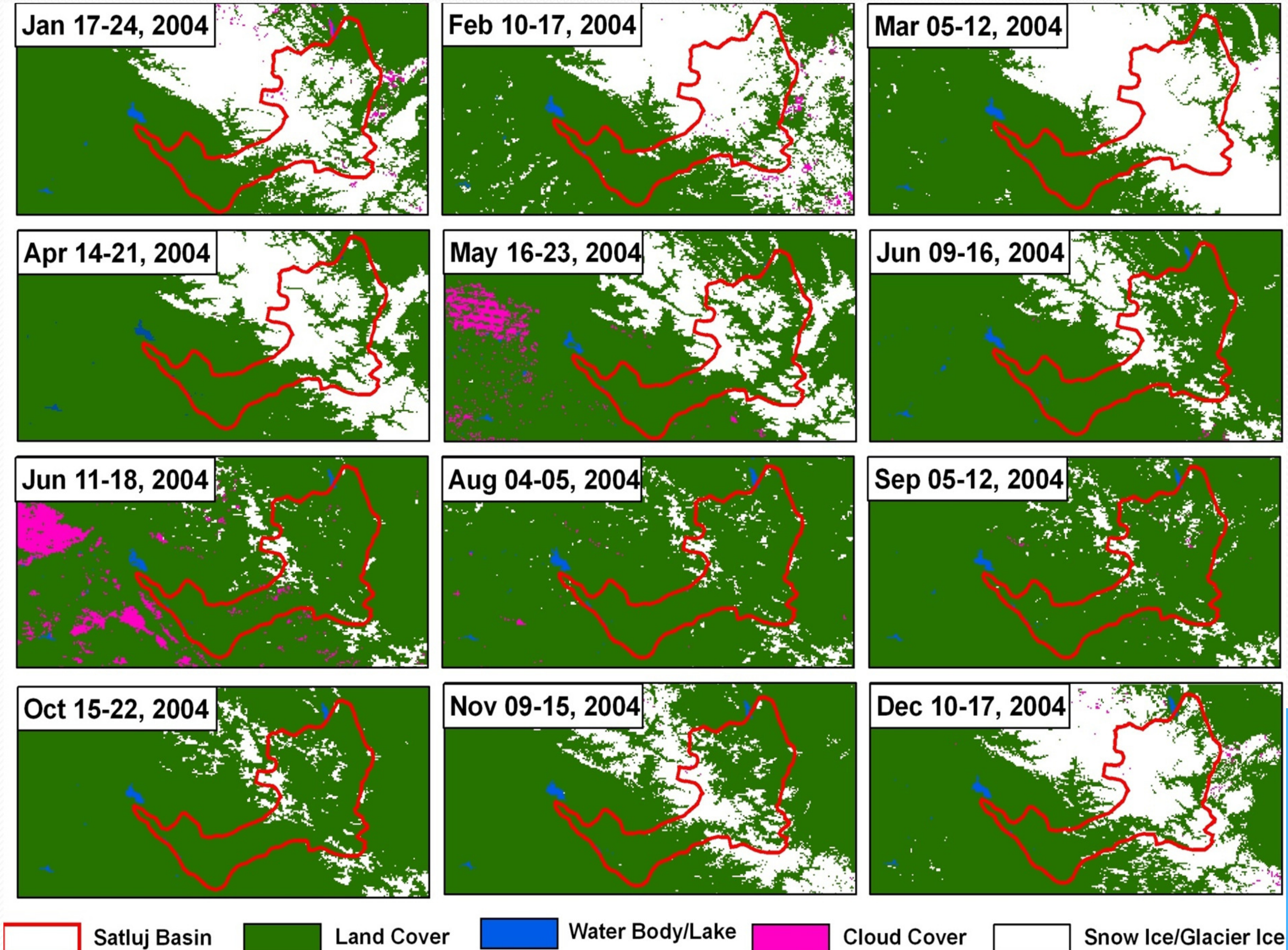


Location of the study area and meteorological stations in the Satluj basin

NOAA-AVHRR Images (2004)

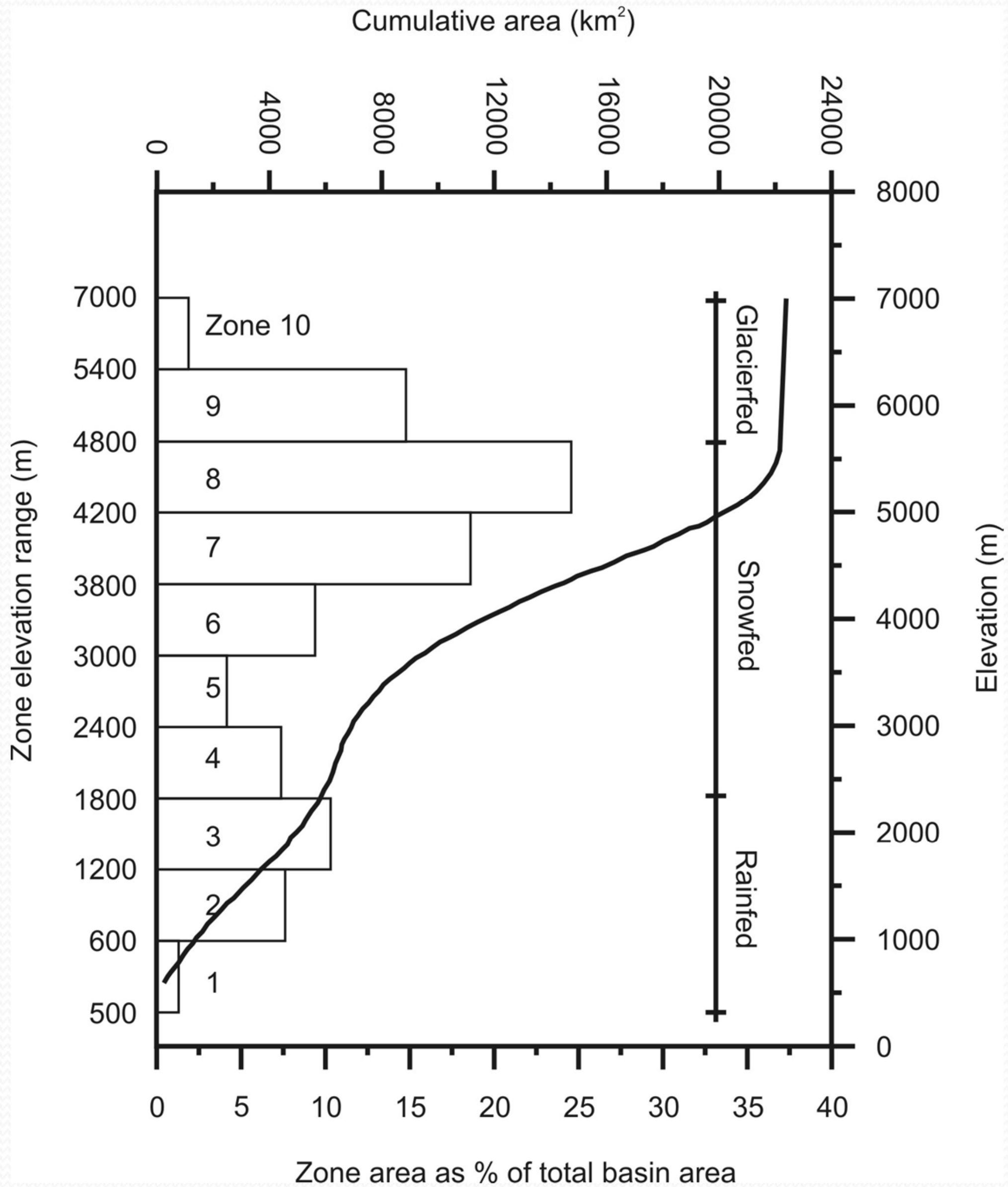


MODIS SNOW Data Product (2004)

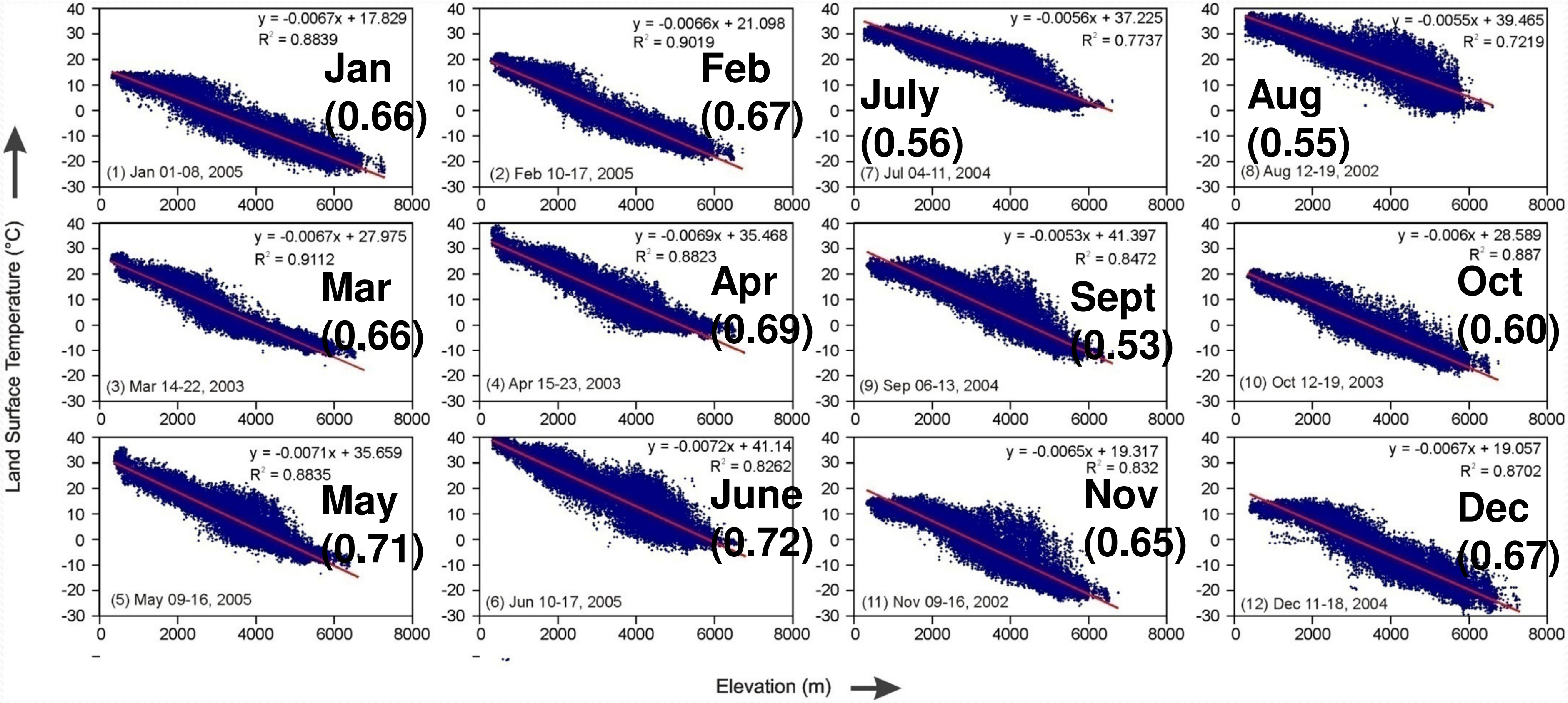


Division of the basin into elevation bands

- 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)

Climate variability analysis for Satluj Basin

- Basin Area (Indian part) : 22,275 km^2
- Elevation Range: 500-7000 m.
- Snow covered area : About 65% after winter
- Glacierized area : About 10%
- Important hydropower scheme: Bhakra Dam

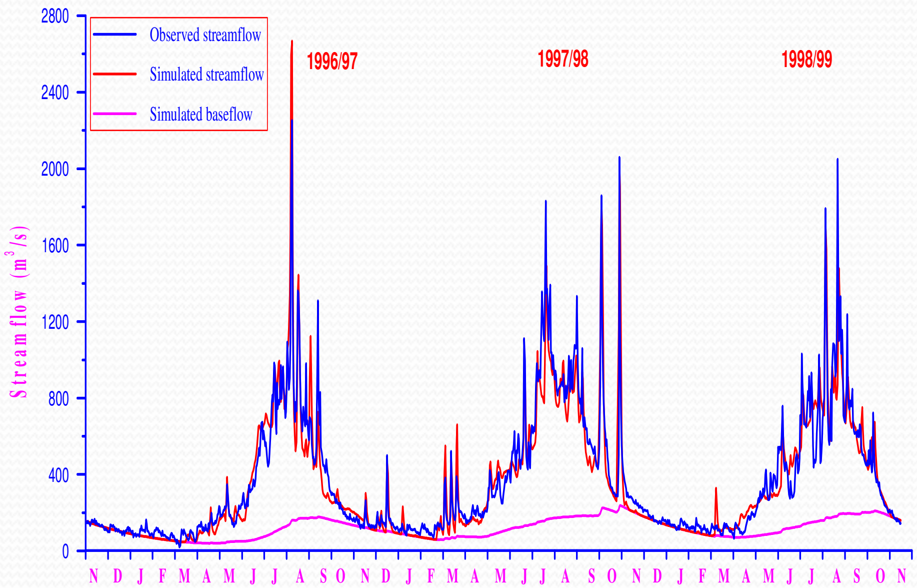
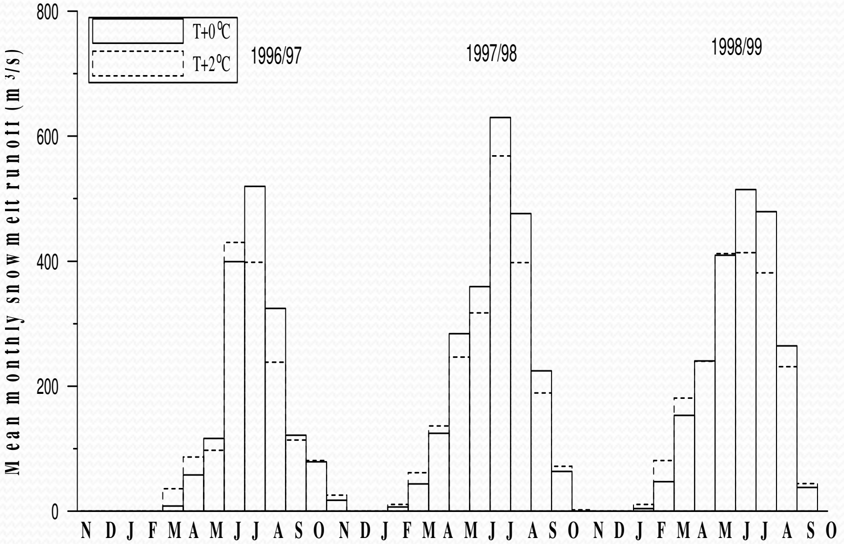


Figure 4: Observed and simulated daily streamflow for the Satluj River at Bhakra for a period of 3 years (1996/97 - 1998/99).



Effect of increase in temperature on mean monthly snow melt runoff for a period of 3 years (1996/97-1998/99) in the Sutlej River Basin.

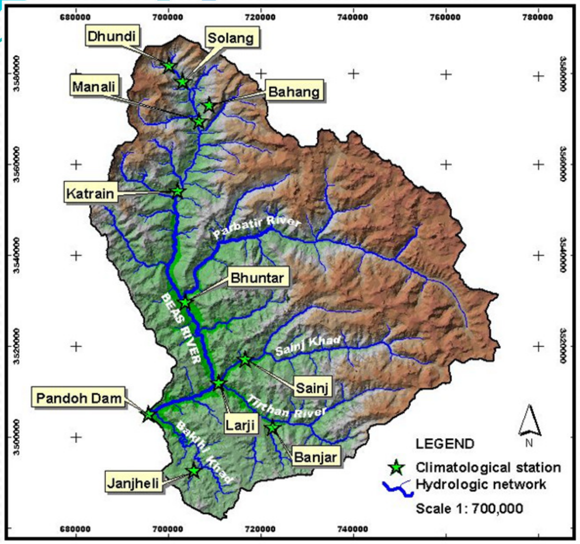
Climate variability analysis for Satluj Basin

Objective: To study the impact of warming on the snowmelt runoff and total streamflow

FINDINGS:

- Changes in distribution of melt runoff were more pronounced in summer showing a decrease of about 10% for a temperature increase by 2 C.
- Considering only the lower and middle part of the basin, where snow disappears in summer, the reduction in snow melt runoff is about 27%.
- High altitude zones containing permanent snowfields/ glaciers throughout the ablation period produce higher melt under warmer climate.
- On basin scale, reduction in melt from lower zones is counterbalanced by the increase in melt from upper zones.

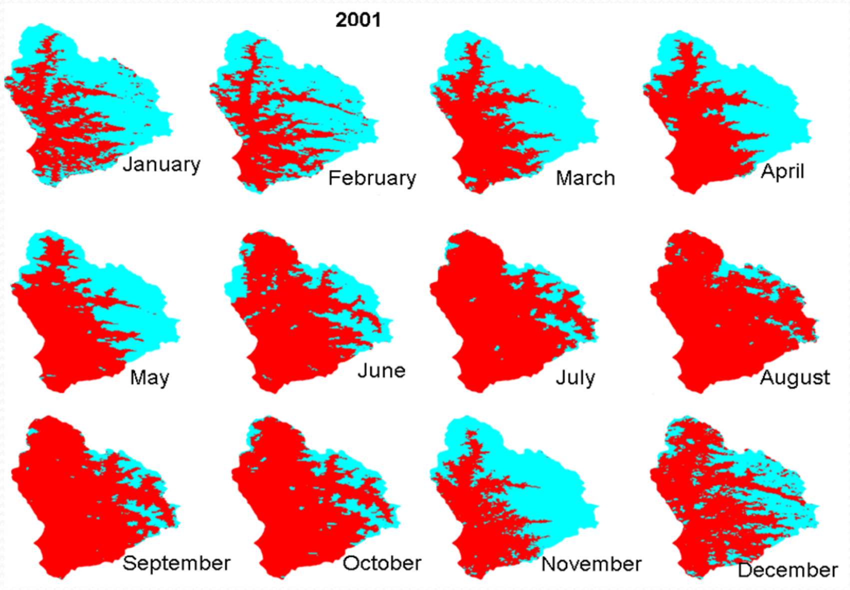
Climate variability analysis for Beas Basin

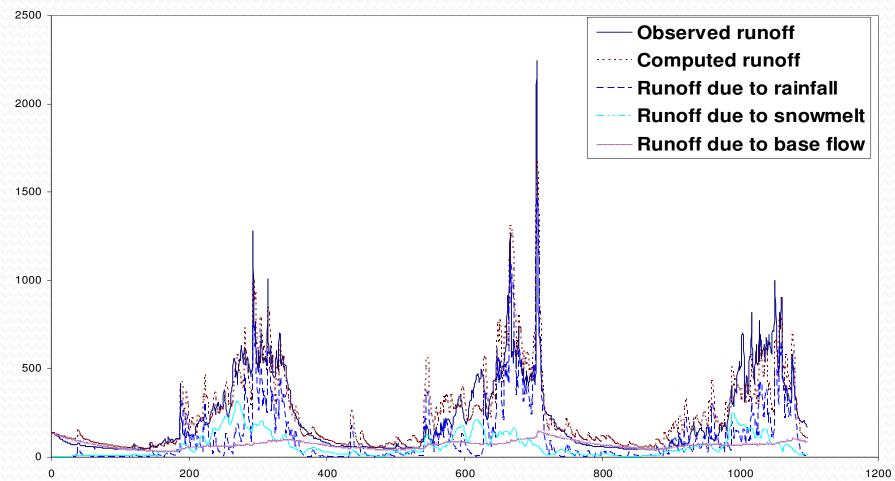


Beas basin up to Pandoh dam

Area = 5728 km^2

Altitude = 600 to 5400m





FINDINGS

- Stream flow is more sensitive to temperature change rather than precipitation change.
- Stream flow and snowmelt runoff increase with the application of different future scenarios with respect to reference scenario.
- It has been observed that for 1 C and 2 C increase in temperature the mean annual stream flow increases about 9% and 8.69% respectively.
- Maximum % increase in mean annual stream flow is 12.12% for T+2 C and P+10%.
- Minimum % increase in mean annual stream flow is 0.37% for T+1 C and P-10%.
- Increase in rainfall by 10% increases mean annual runoff by approx. 3%, while decrease in rainfall by 10% will reduces mean annual runoff by 8%.

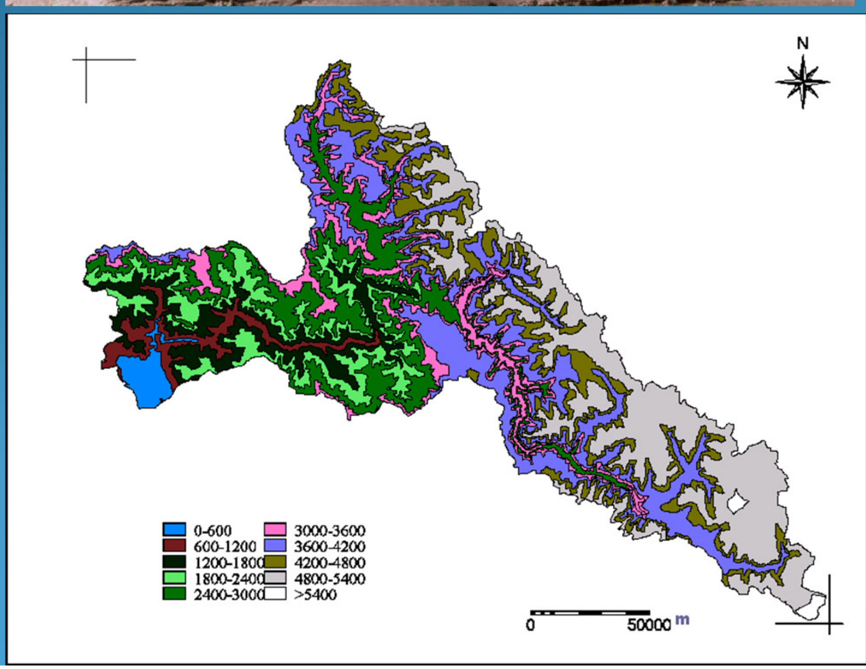
Climate variability analysis for Chenab Basin

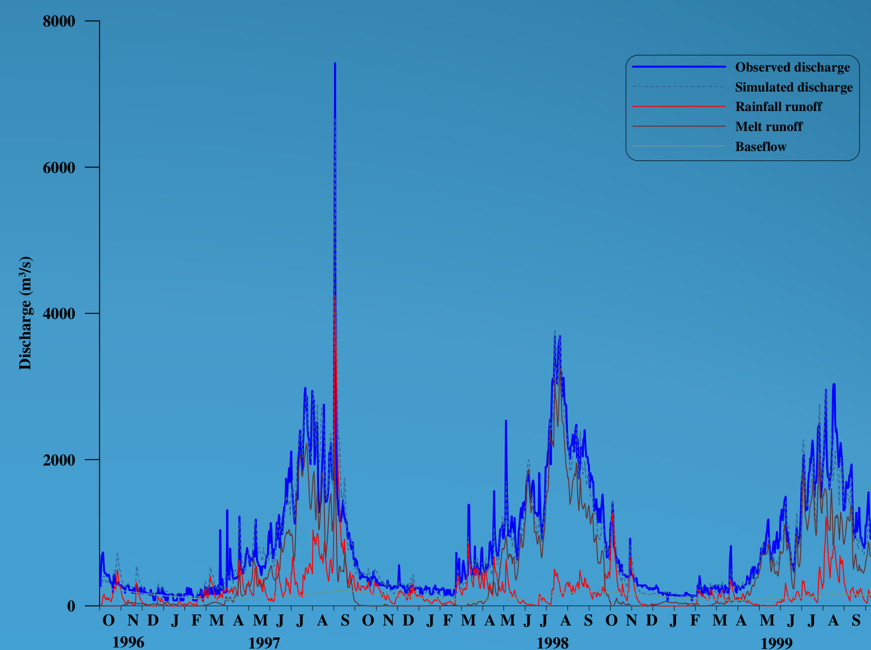
Elevation of the study area varies from ~ 305 m to 7500 m.

Total catchment area up to Akhnoor is 22,200 km^2.

Total Number of Glaciers is 989.

Glacierized Area is 2280 sq km.





Climate variability analysis for Chenab Basin

Objective: To study effect of climate variation on runoff regime of River Chenab

FINDINGS:

- An early response for snowmelt runoff is noticed under the warmer climate. Simulated results under warmer climate show that the peak runoff is increased for whole water year for all the years

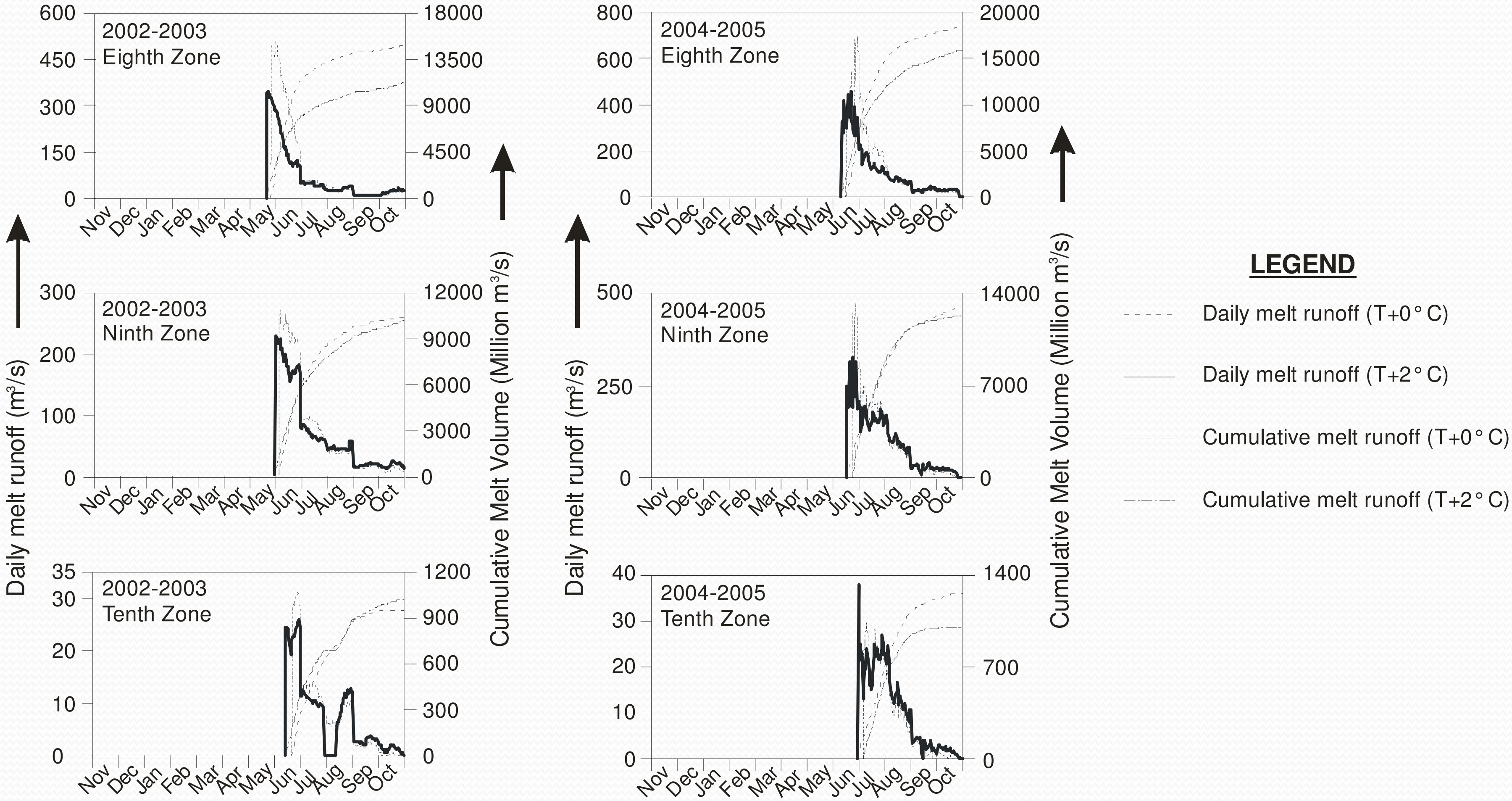
- The average increase in snowmelt runoff for T+1°C and T+2°C scenarios are estimated as 10% and 28% respectively

- The average increase in total streamflow runoff for T+1°C and T+2°C are estimated as 7% and 19%

- No significant change in the winter streamflow was observed

- Changes in rainfall by ±10% resulted in increase in streamflow by ≤ 10%.

Daily and Cumulative snowmelt runoff for the changed climatic scenario for different zones of the study area for the years 2002-2003, and 2004-2005




GLACIER RETREAT

Retreat of the Himalayan Glaciers: General Observations

Like many worldwide glaciers, the Himalayan glaciers also show general state of decline in the last couple of decades.

Due to large geographical extend and climatic variability the retreat rates are not uniform

Rates of glacier retreat vary considerably; 5 to 20 m a^{-1} during the last few decades mostly concerns glacier length & area (Snout retreat)

It has also reported that several glaciers in central Karakoram have advanced and/or thickened at their tongues probably due to enhanced precipitation.

Most of the glaciers are covered by debris and strongly affect the melting/ retreat

Studies based on remote sensing show surface area loss of glaciers by 21% in Himachal (Kulkarni et al.,2005) and 19.4% in Uttarakhand (Bhamari et at., 2011)

Recession also leads to volume loss in single glaciers, for example Dokriani glacier has registered 18% volume loss over a period of 33 years (1962-95) (Dobhal el al.,2004)

Himalayas are believed to have grown warmer with an estimated increase of about 2.2°C in the last two decades (SASE report)

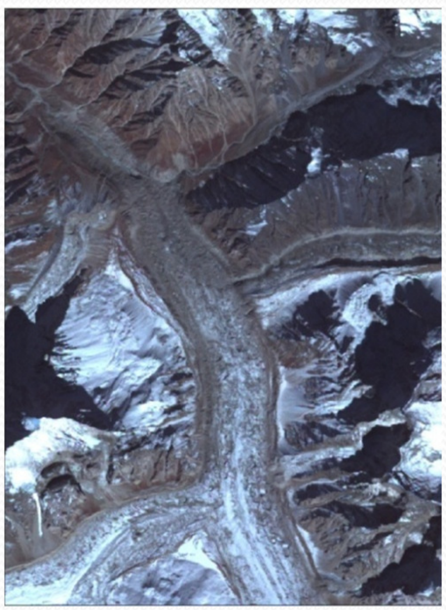
All the glaciers under observation, during the last three decades of 20th century shows negative mass balance.

GANGOTRI GLACIER

1976

2000

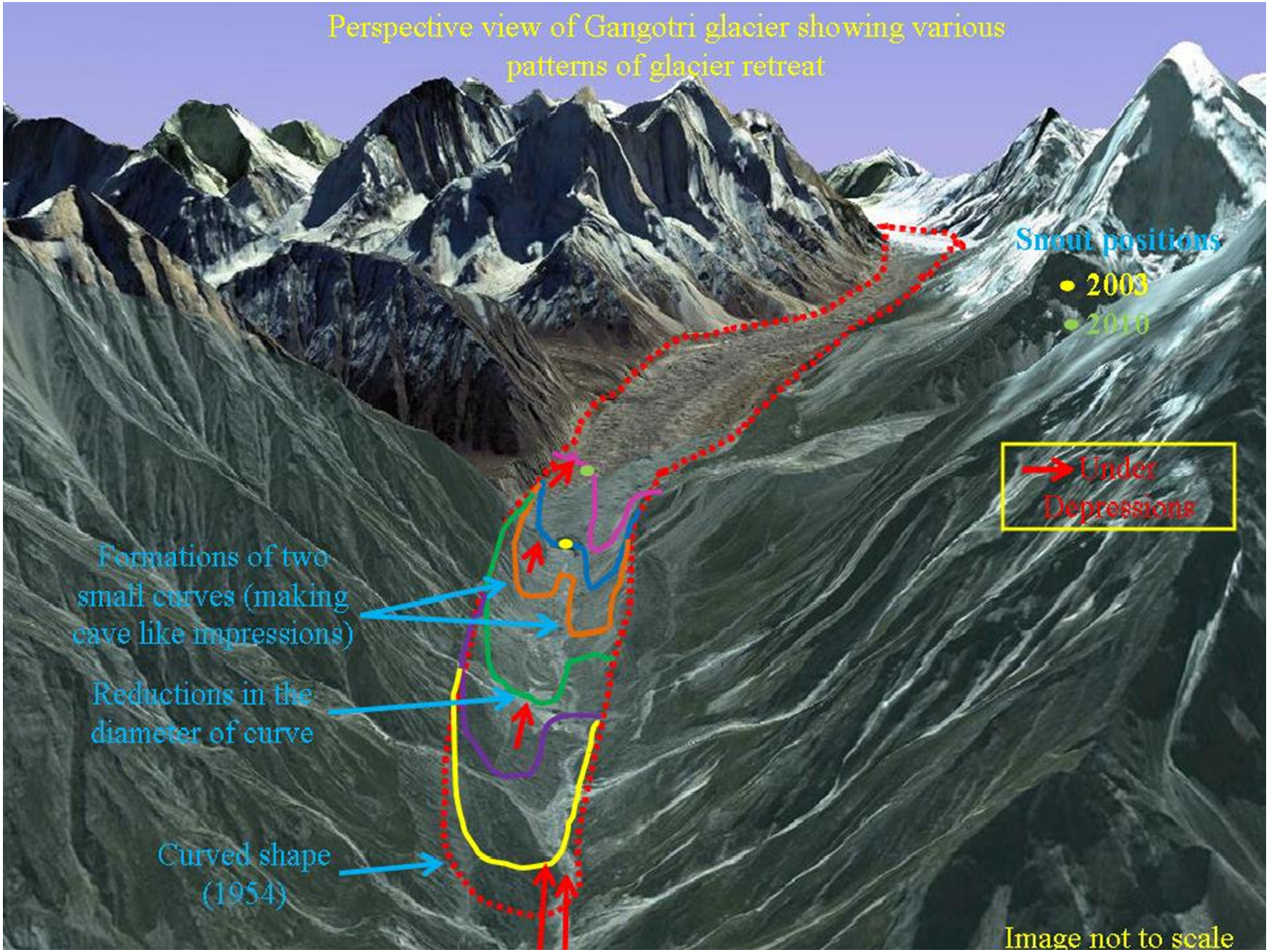
2006



2007

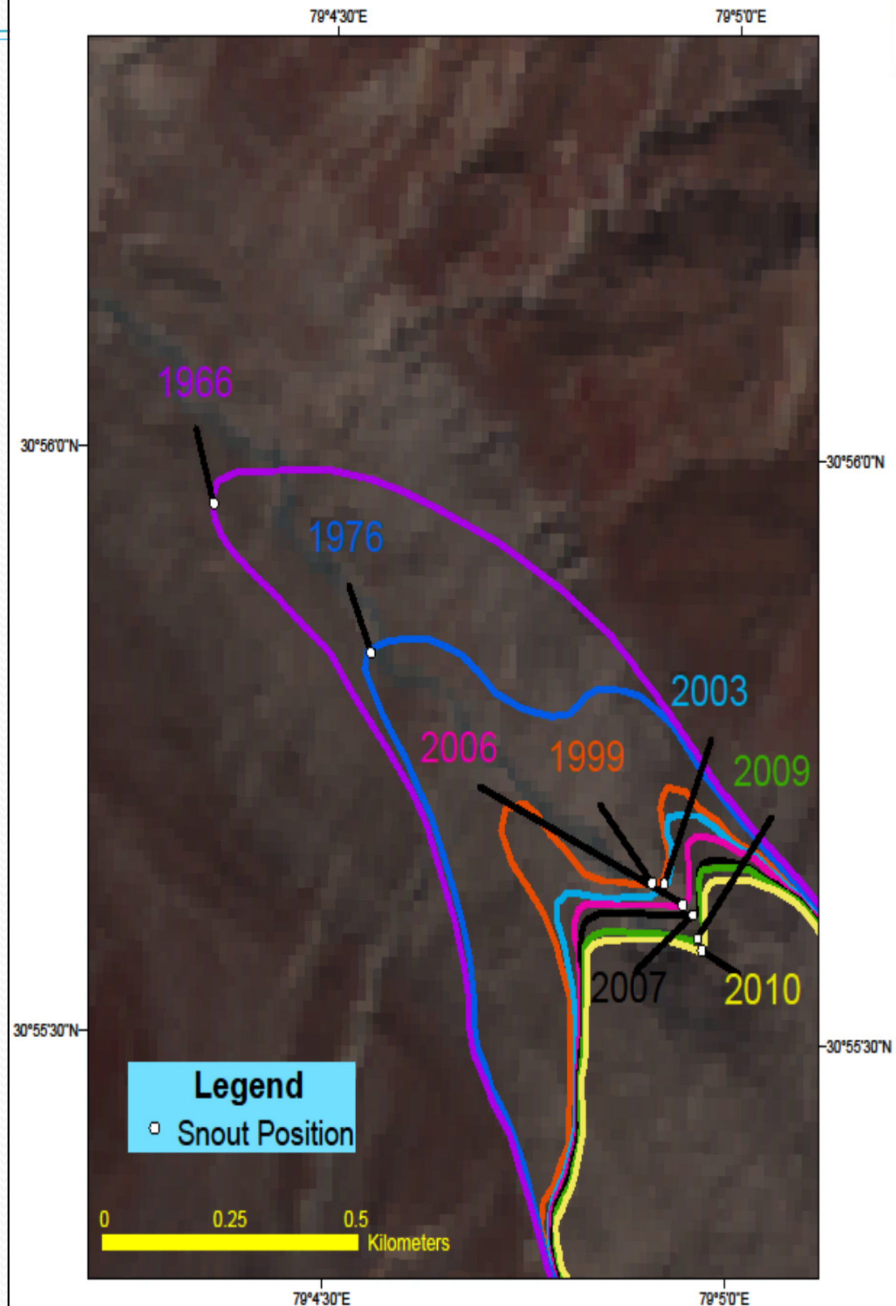
2009

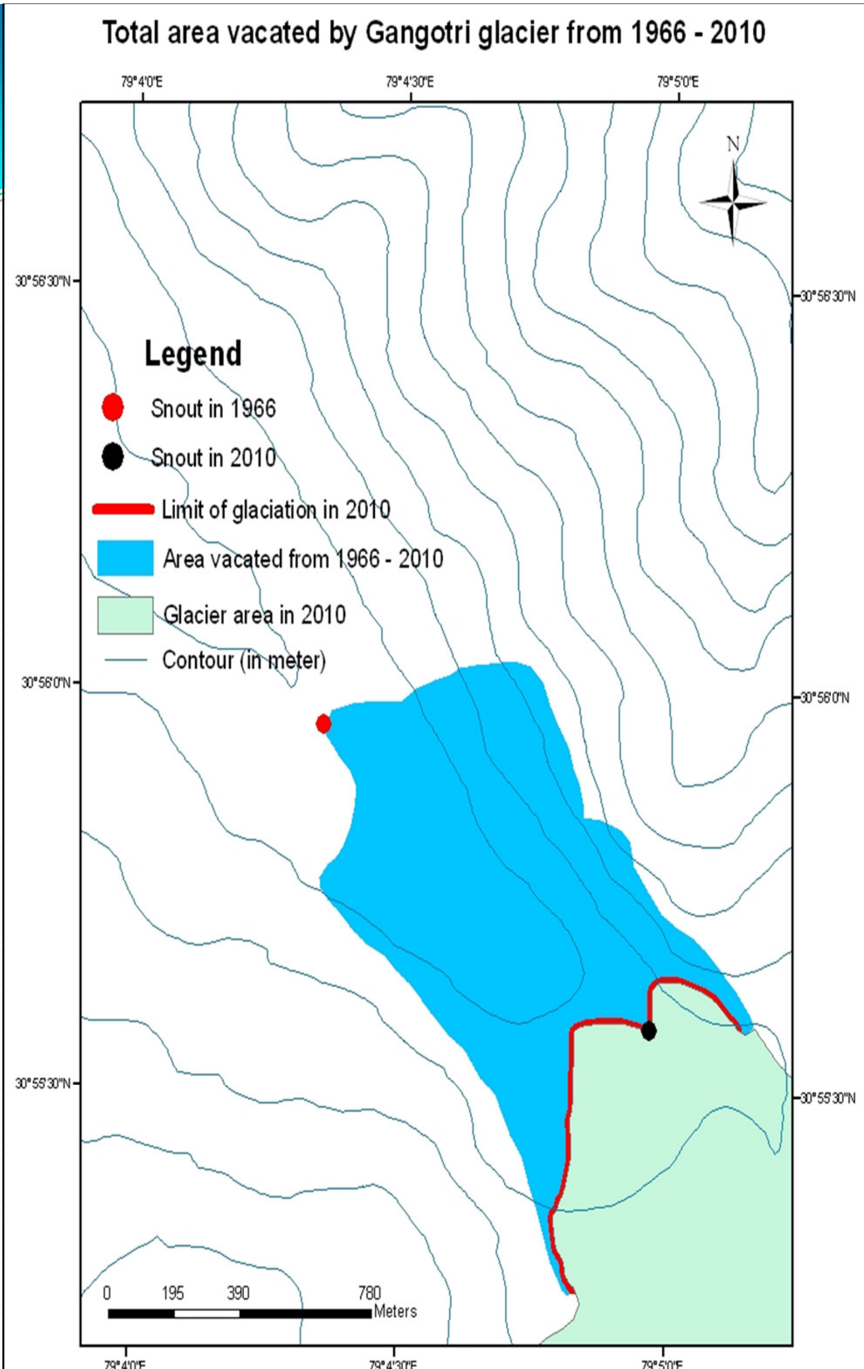
2010

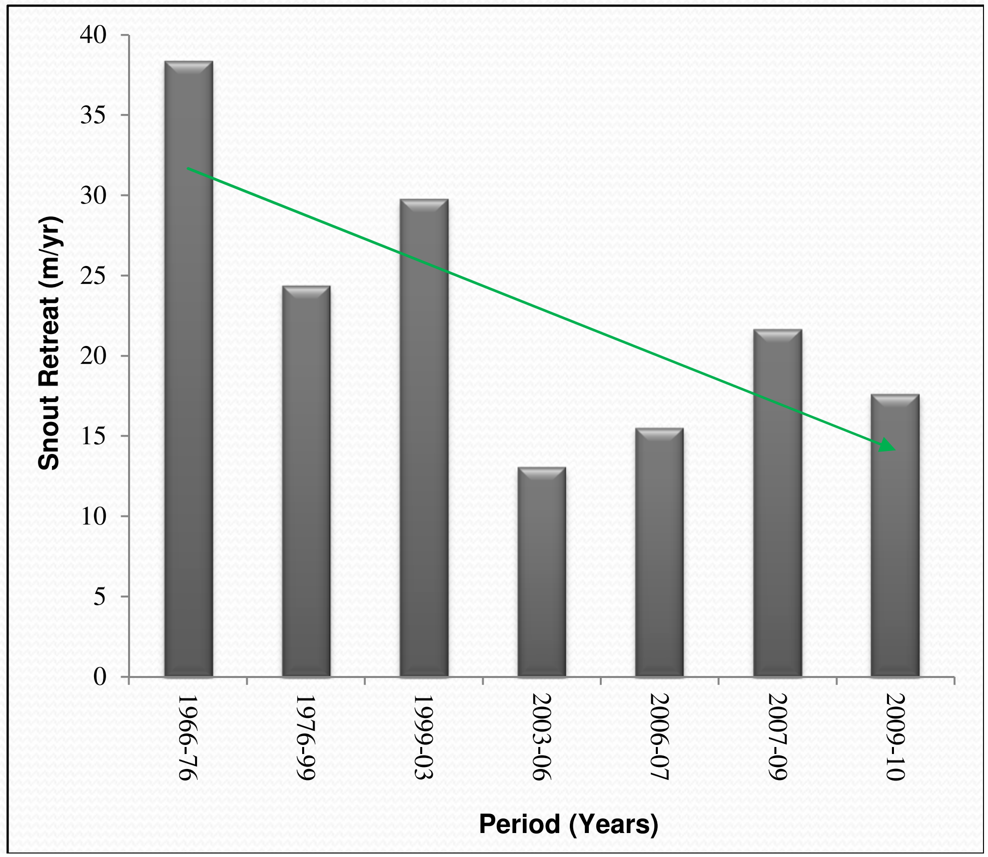


Perspective view of Gangotri glacier showing various patterns of glacier retreat
Snout positions
2003
2010
Under Depressions
Formations of two small curves (making cave like impressions)
Reductions in the diameter of curve
Curved shape (1954)
Image not to scale

Change in snout position from 1966 - 2010

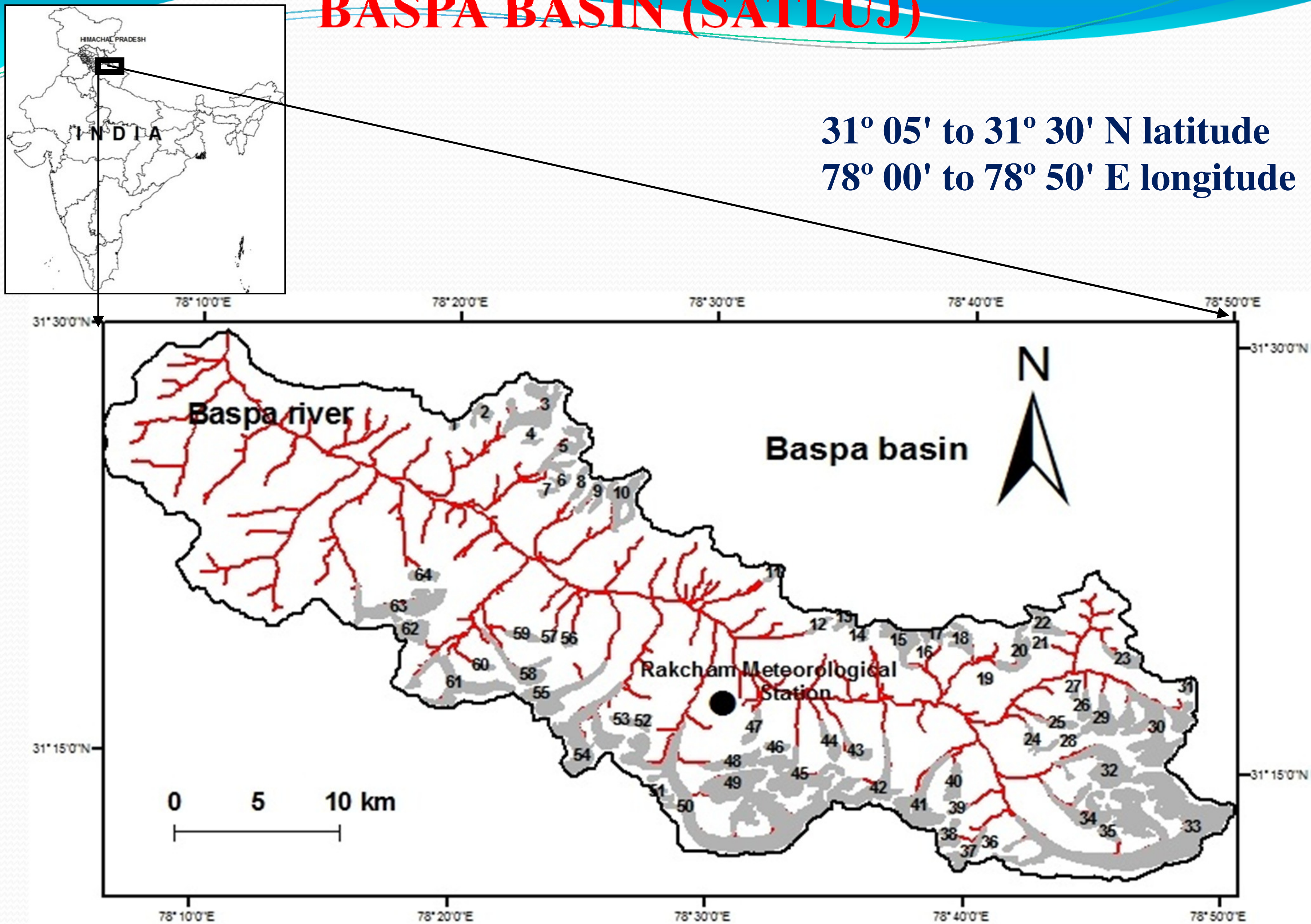



Total area vacated by Gangotri glacier from 1966 - 2010
79°4'0"E
79°4'30"E
79°5'0"E
30°56'30"N
30°56'0"N
30°55'30"N
N
Legend
Snout in 1966
Snout in 2010
Limit of glaciation in 2010
Area vacated from 1966 - 2010
Glacier area in 2010
Contour (in meter)
0 195 390 780
Meters


Snout Retreat (m/yr)
0
5
10
15
20
25
30
35
40
1966-76
1976-99
1999-03
2003-06
2006-07
2007-09
2009-10
Period (Years)

BASPA BASIN (SATLUJ)

31º 05' to 31º 30' N latitude
78º 00' to 78º 50' E longitude

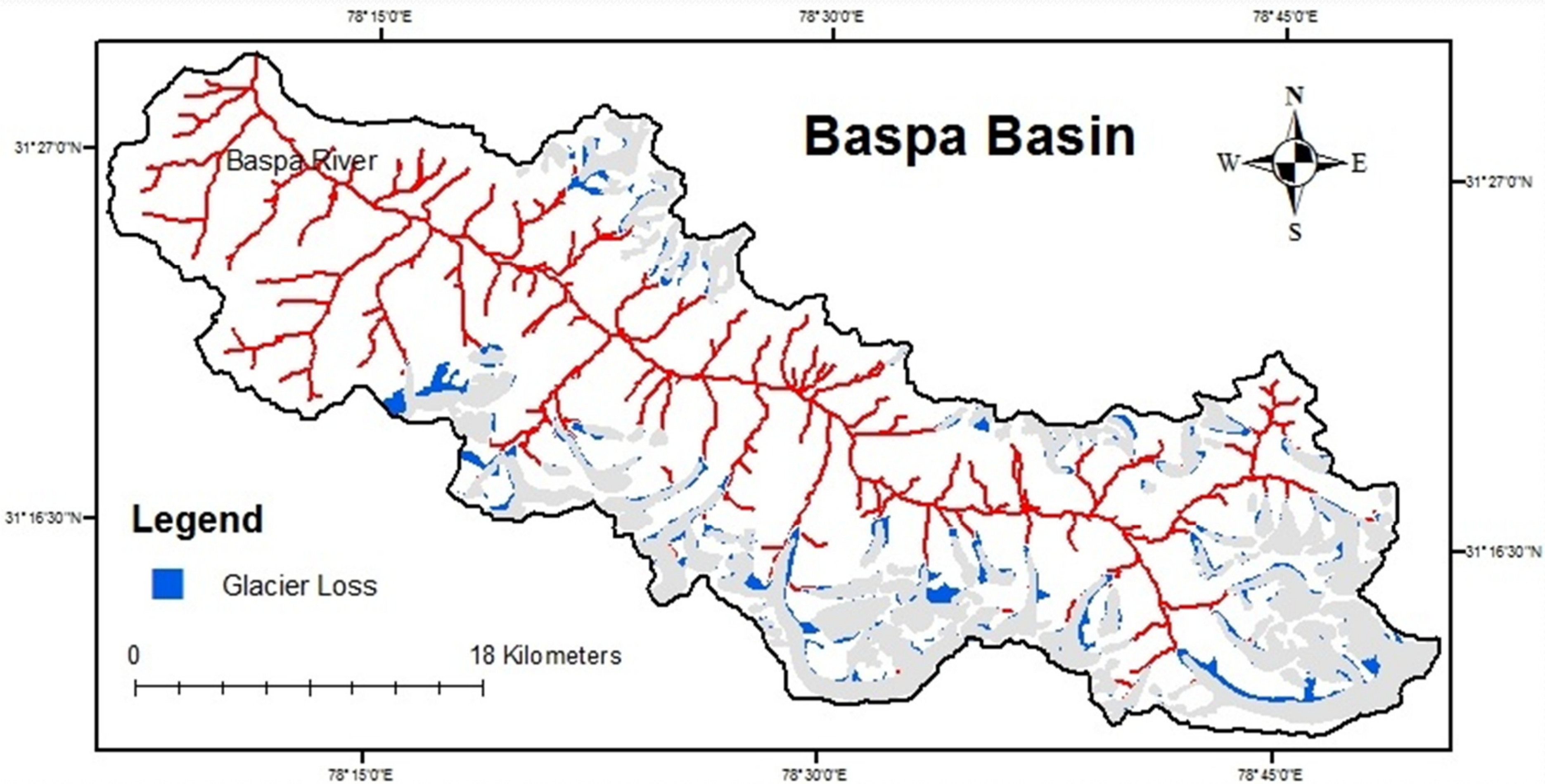


Deglaciation from 1966 to 2006

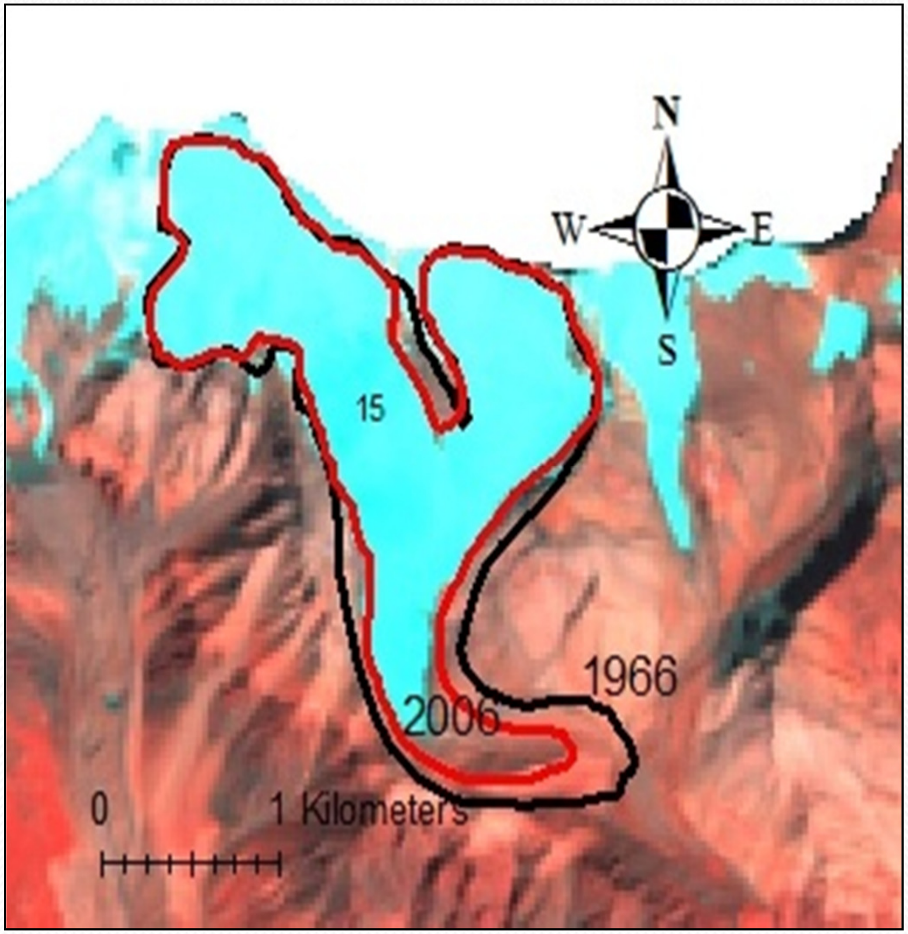
Serial No.	Year	Aggregate area km^2	Loss from 1966 (km^2)	Loss % from 1966	Average Loss % 1966-2006
1	1966	235.1		-	
2	1999	193.0	42.1	17.9	20.7
3	2000	188.5	46.6	19.8	
4	2006	177.7	57.5	24.4	

Serial No.	Year	Aggregate Volume km^3	Loss (km^3) from 1966	Loss (%) from 1966	Average Loss % 1966-2006
1	1966	22.2		-	
2	1999	17.4	4.8	21.7	24.46
3	2000	16.9	5.3	23.8	
4	2006	16.0	6.2	27.9	

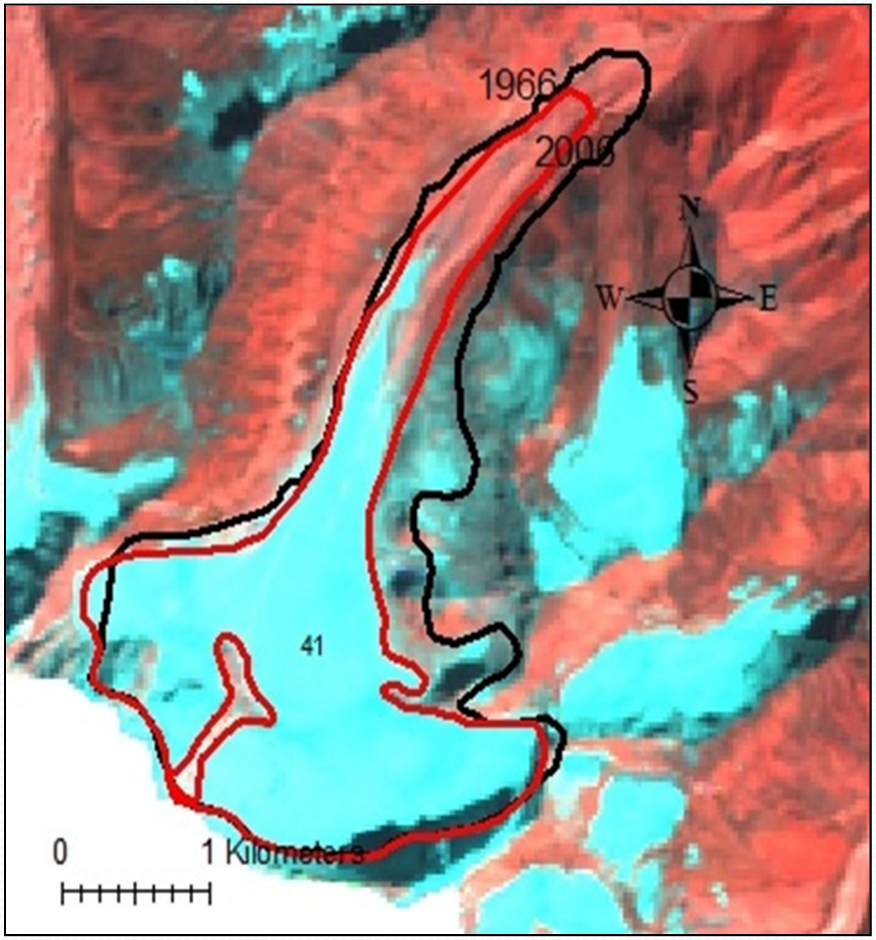
Glacier retreat map (1966 to 2006)



Retreat between 1966 and 2006

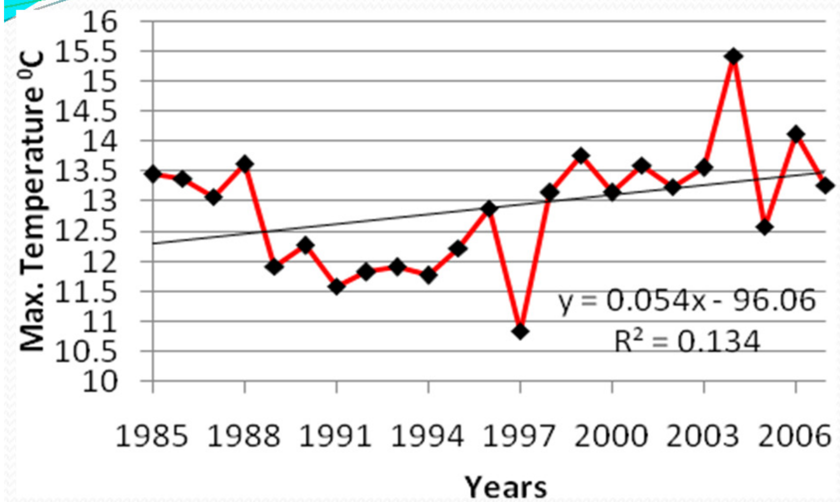


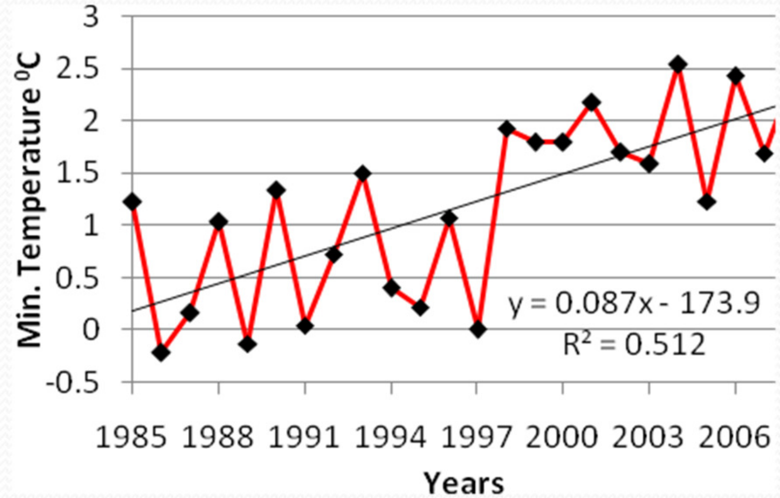
G-15

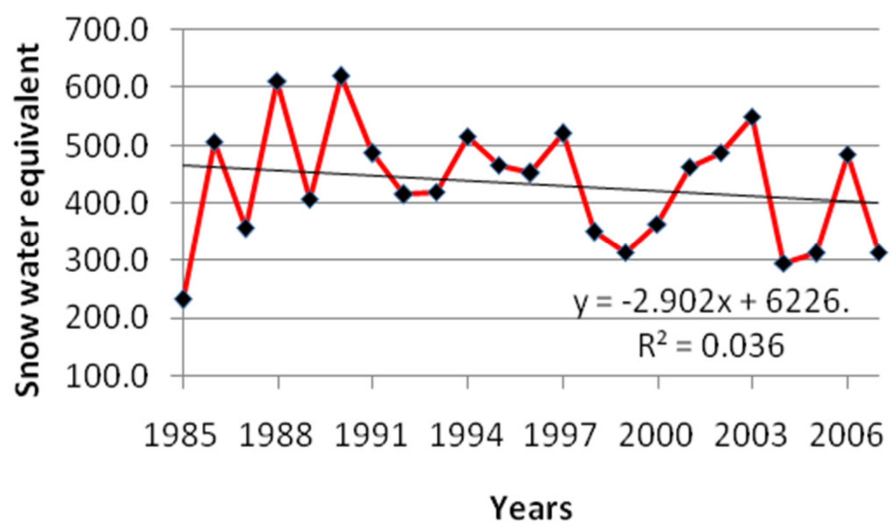


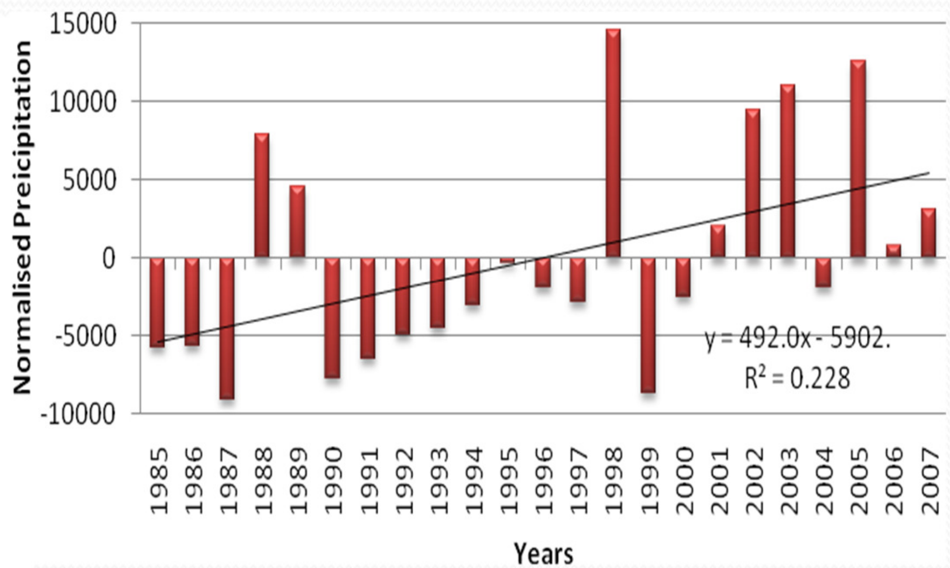
G-41

Meteorological parameters

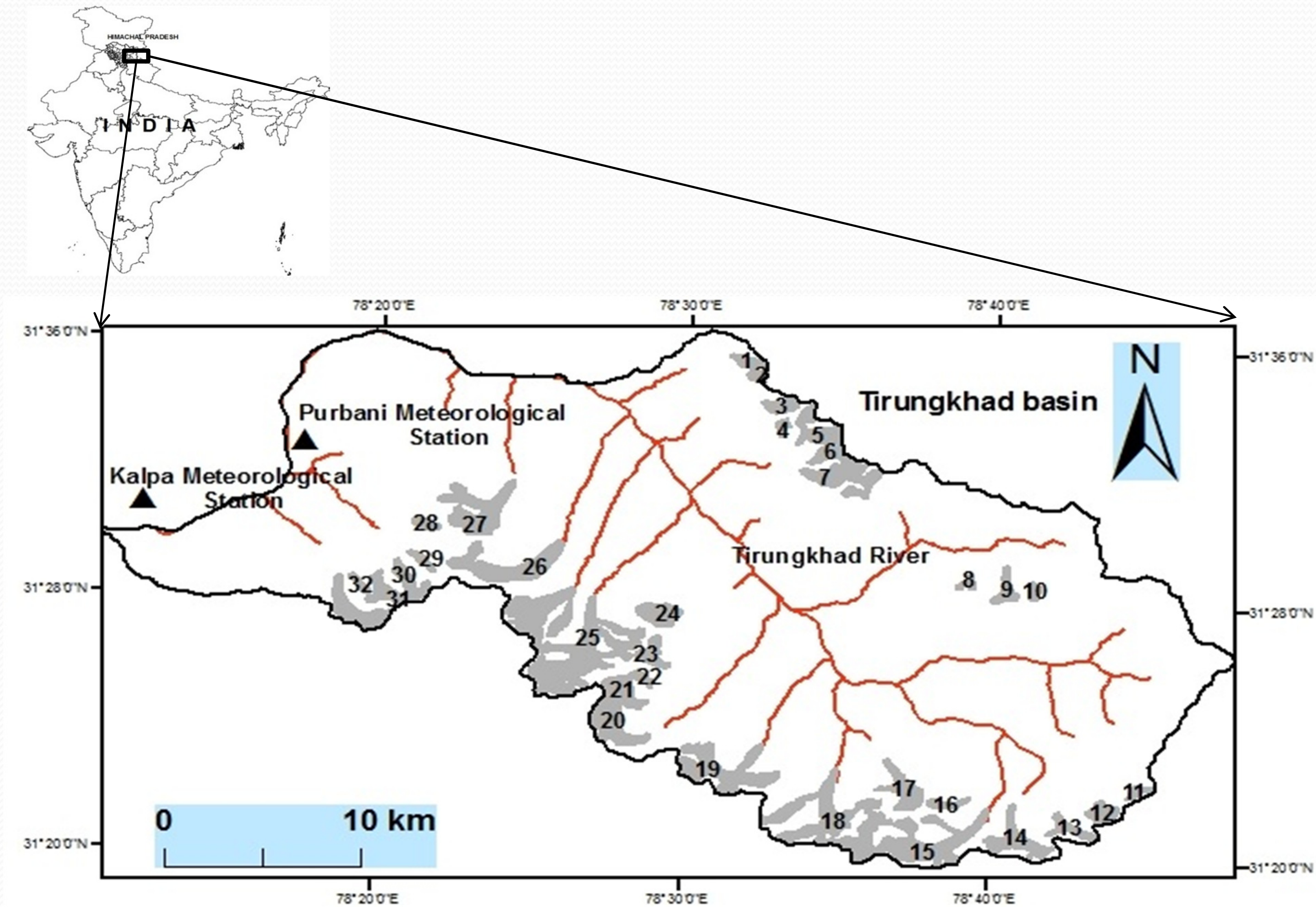




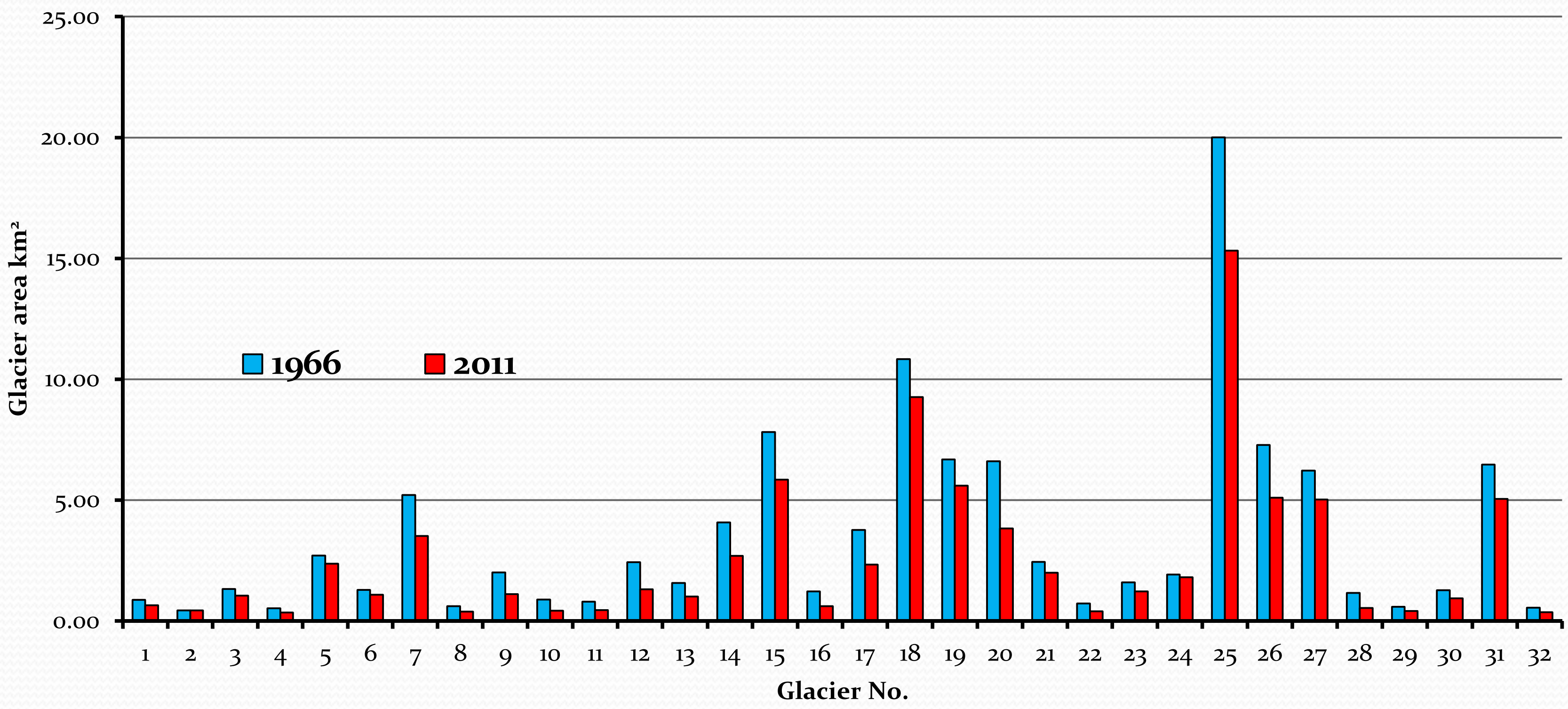




TIRUNGKHAD BASIN (SATLUJ)



Comparison of Glacier area

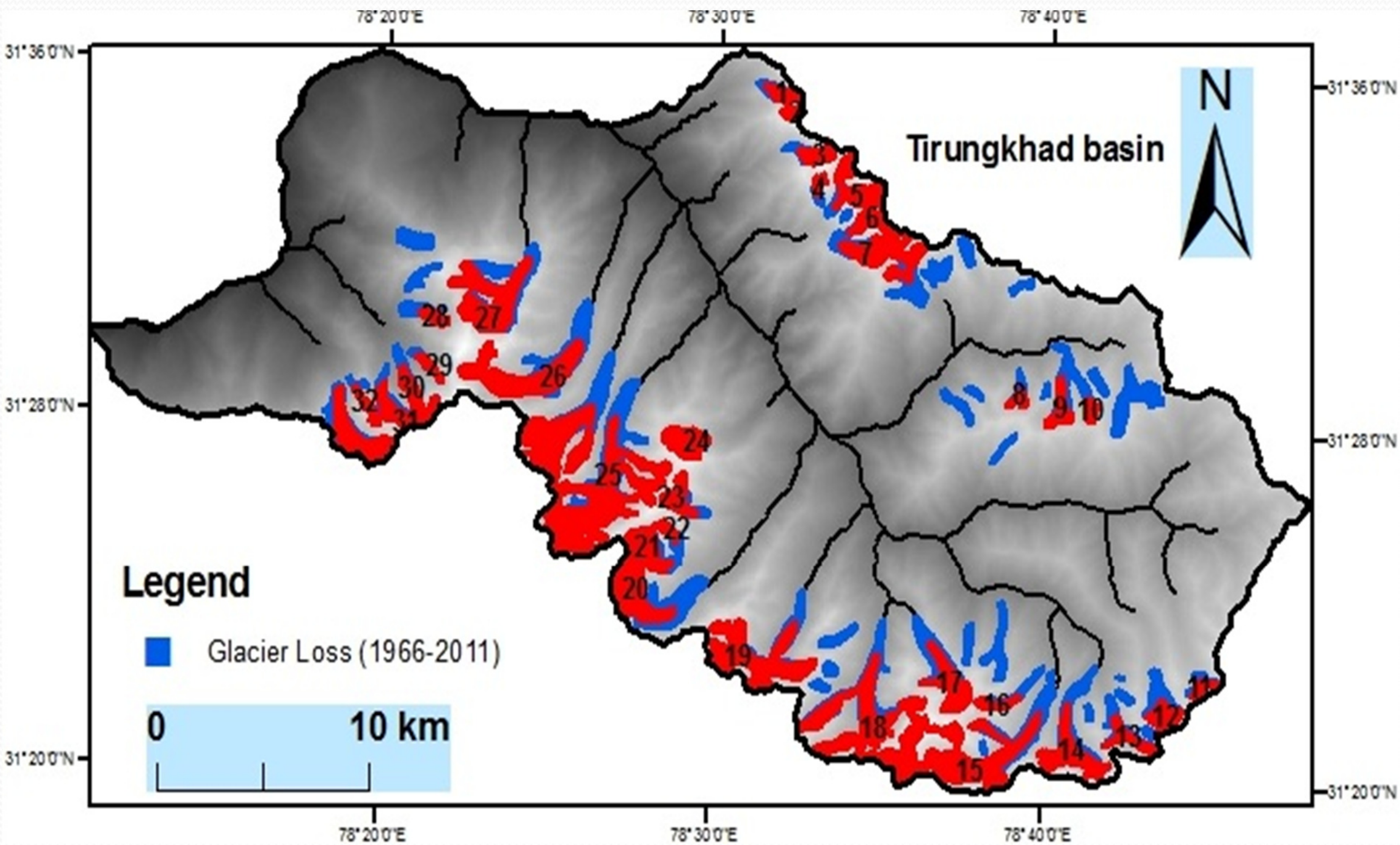


Retreat in percentage of glacier area and volume

S. No	Year	Total area km²	No. of years	Year to year loss km²	Loss from 1966 km²	Loss (%) from 1966	Average loss (%) from 1966-2011
1	1966	112					
2	2000	91	24	20.7	21	18.5	
3	2006	87	6	4.0	25	22.2	22.2
4	2011	82	5	4.3	29	26.0	

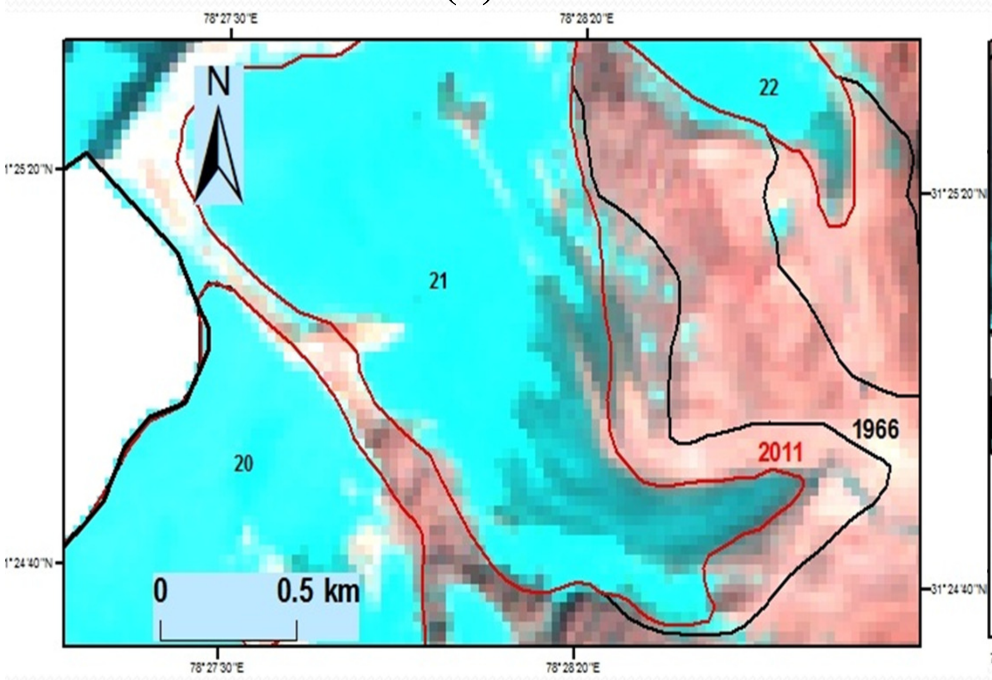
S. No	Year	Total volume km³	No. of years	Year to year loss km³	Loss from 1966 km³	Loss (%) from 1966	Average Loss (%) from 1966-2011
1	1966	9.1					
2	2000	7.0	24	2.1	2.1	23.1	
3	2006	6.6	6	0.4	2.5	27.6	27.6
4	2011	6.2	5	0.4	2.9	32.0	

Retreat of glaciers (1966 to 2011)

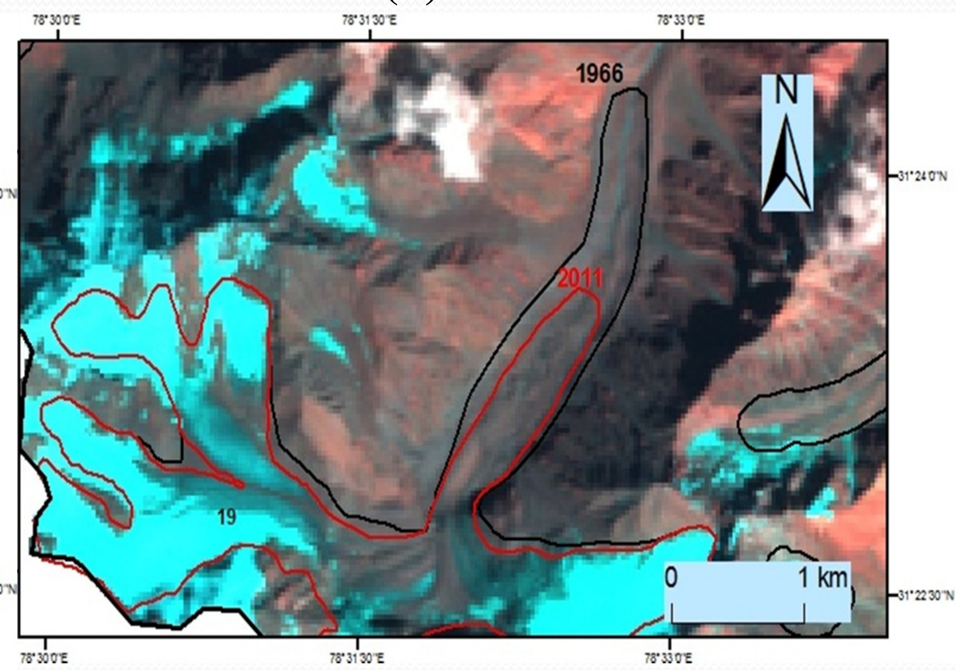


Glaciers (G-19 and G-21) showing the retreat

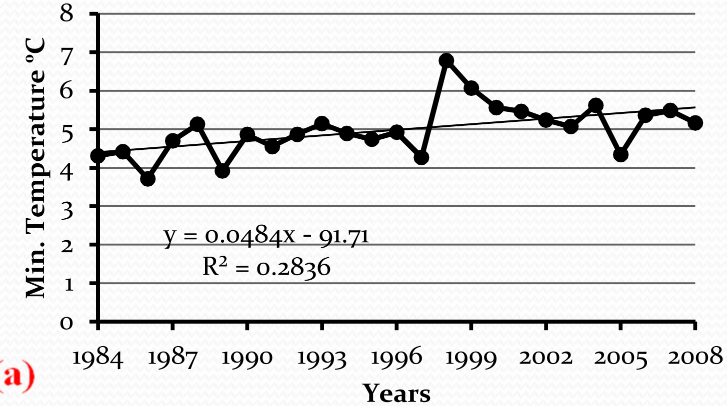
(a)



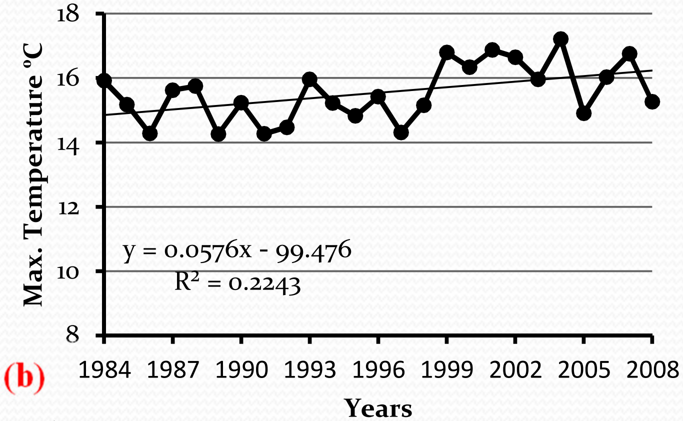
(b)



Interannual variations and trend of (a) annual maximum temperature (b) annual minimum temperature and (c) snow water equivalent (Kalpa station) and (d) snow water equivalent (Purbani station) (e) precipitation mm



(a)



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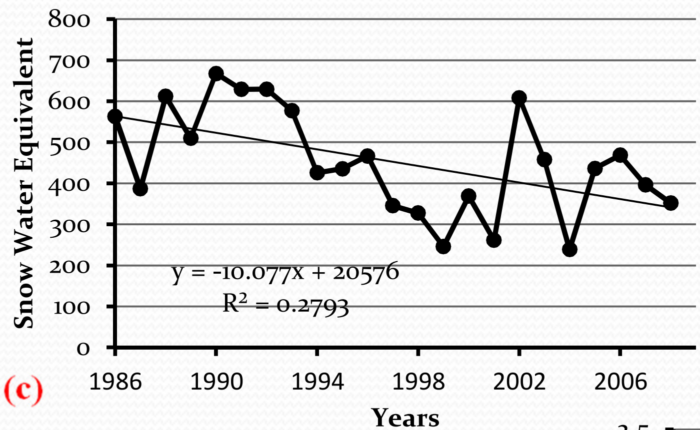
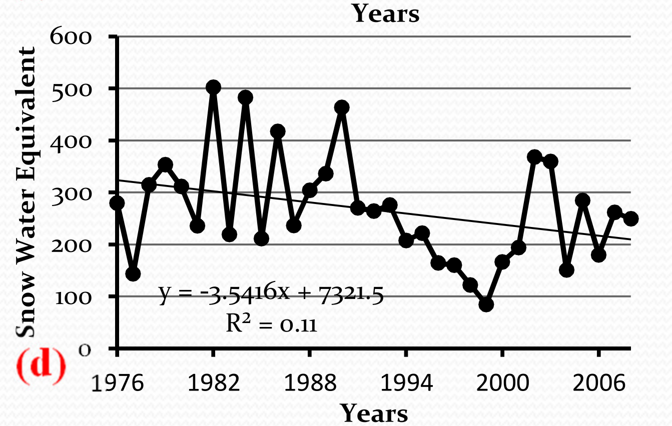
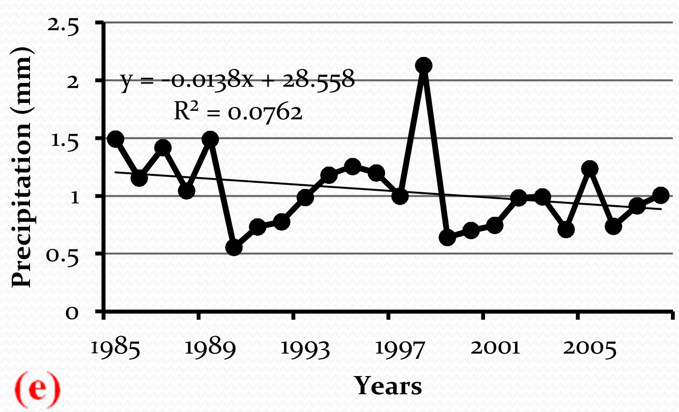


(c)



(d)



(e)

Glacial Lake And Glacial Lake Outburst Flood (GLOF)

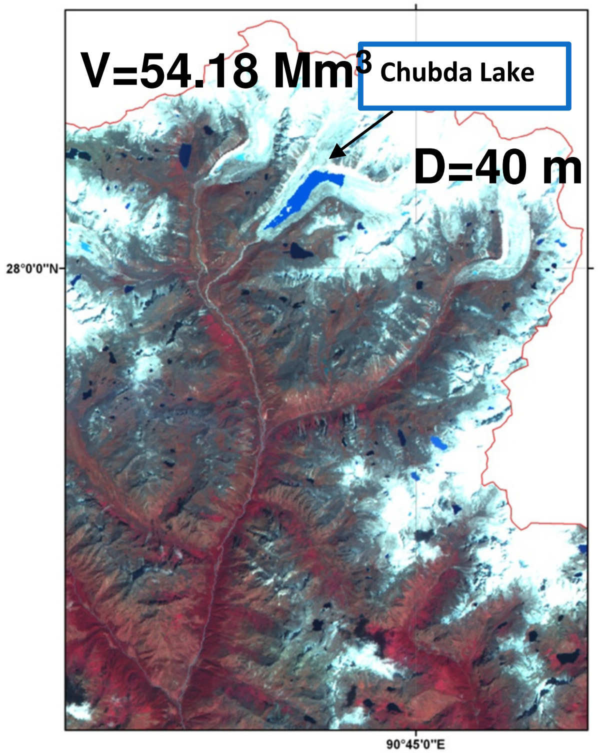
Glacial dammed lakes are formed by accumulation of water from the melting of Snow and Ice cover and by blockage of end moraines.

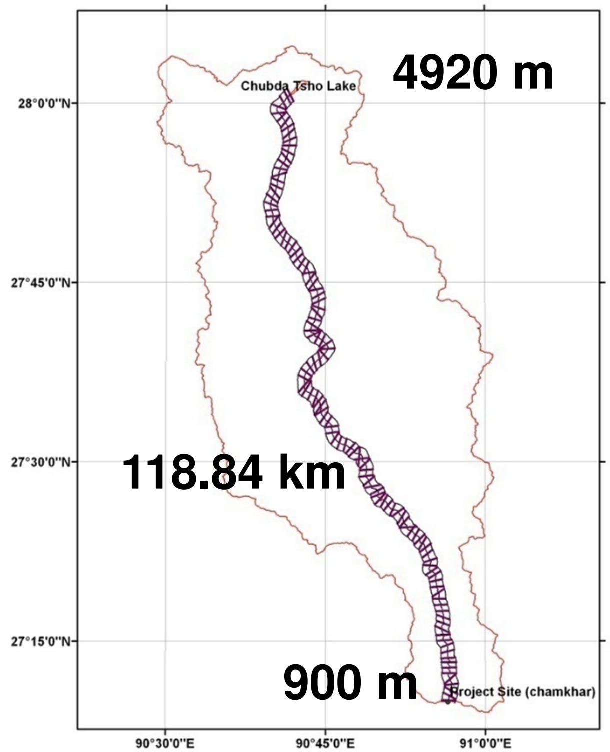
A glacial lake outburst flood (GLOF) can occur when a lake contained by a glacier or a terminal moraine dam fails.

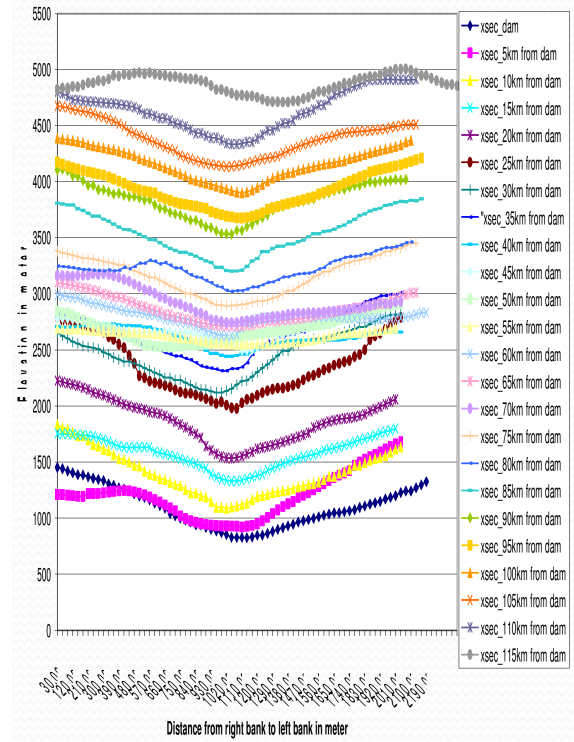
The bursting of moraine-dammed lakes is often due to the breaching of the dam by the erosion of the dam material as a result of overtopping by surging water or piping of dam material

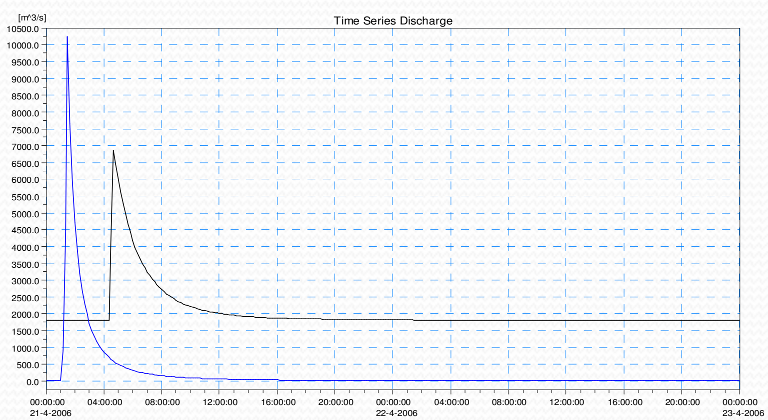
GLOF STUDIES HAVE BEEN CARRIED OUT FOR LAKES IN THE BASINS OF GHARWAL HIMALAYA, EASTERN HIMALAYA AND BHUTAN HIMALAYS

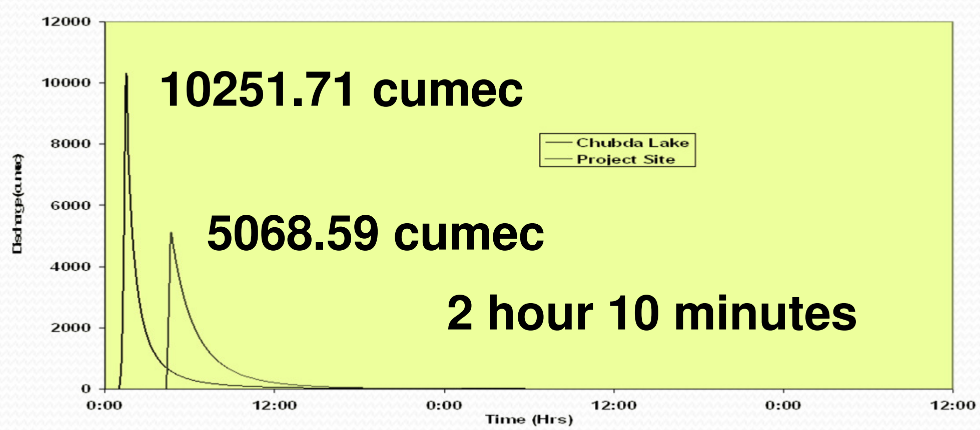
GLOF HYDROGRAPH AT CHAMKHARCHU H.E. PROJECT BHUTAN











Concluding Remarks

- Glacier and snow-melt have major contribution to the river flows in the region. It is necessary to characterize the glaciers in different climatological regions of the basin

- The rate, volume and timing of snow melt are likely to change, therefore, impact of climate change on the snowmelt runoff and total streamflow of the large Himalayan rivers should be investigated using GCMs output as input to the calibrated hydrological models.

Concluding Remarks

- Reduced contribution of snowmelt from lower elevation is counteracted by increased glacier melt from higher elevation

- Streamflow initially increases as glaciers melt, then decreases when glaciers are depleted

- Glaciers retreat rates are not only controlled by changing in climate but, topographic and morphological factors equally play important role to control glacial retreat.

- Studies on the trend of changes in snow cover over the Himalayas/basins along with retreat of glaciers need immediate emphasis.

THANKS