RECENT TRENDS IN HIMALAYAN HYDROLOGY

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Abstract *Snow and glaciers contribute substantially to the perennial water resource of Himalayan river basins. Systematic studies on snow precipitation, seasonal snow cover and glaciers in India have been undertaken only in the last three decades. The Himalaya are the largest storehouse of fresh water and sources of mighty rivers such as Indus, Ganga and Brahmaputra. The mean annual rainfall over Himalayan region varies from 50 to 250 cm with lesser rainfall occurring around the foot hills of Himalaya. The mountainous area covered by snow is about 80% of the total area of Himalaya. The snowmelt runoff problem is complex, involving the interaction of many aspects of the watershed system. To analyse such complexity, it is necessary to represent the various aspects of behaviour of watershed in a computer model. Much research effort has gone into developing snowmelt models over the years. Glaciers are essentially reservoirs of both liquid and solid precipitation retaining winter snow and releasing it gradually. For proper management of high mountain water resources, it is necessary to known the amount and location of water stored in a frozen form, the pattern of its release due to melting and how the melt rates are affected by short term weather changes and long term climatic changes. Information of hydrological and meteorological parameters, especially, from altitudes above 3000 m is essential for a realistic assessment of water resources from snow and glaciers. During the last fifteen years techniques for application of remoter sensing to hydrology in general and snow and glaciers in particular have been developed and perfected in the country. A number of isotope techniques areal so in use for the study of snow and ice. A long-term perspective programme for glaciological studies in the countries of the region has to be evolved and intensive studies are to be carried on a few selected glaciers with greater water resources potential.*

INTRODUCTION

Snow, ice and glaciers have been attracting scientists for long. Snow and glaciers contribute substantially to the perennial water resource of Himalayan river basins. Systematic studies on snow precipitation, seasonal snowcover and glaciers in India have been undertaken only in the last three decades.

The history of Himalaya is inextricably interwoven with the history of Indian culture and civilization. The Himalaya are the mightiest mountain system in the world. Extending over a length of 2500 km these mountains run in three parallel ranges. They occupy 51.43 million hectares of geographical area in the country.

The Himalaya are the largest storehouse of fresh water and sources of mighty rivers such as Indus, Ganga and Brahmaputra. The Himalaya have a complex biophysical environment produced by local differences in geology, altitude, aspect, slope angle, and the resulting differences in climate, soils and water budgets. The unique combination of intense seasonal precipitation and steep topography makes hydrology of the region typical. Despite the vast regional potential for development of water resources for multifarious uses, scientific studies of natural forces and human impact on the hydrologic regimes in Himalaya are far from adequate.

The fragile ecosystem of the Himalaya covering varied altitudinal and climatic regions with contrasting ecologic conditions requires a detailed knowledge of the natural and human resources.

THE HIMALAYA

Himalaya is the world's highest mountain system having 14 mountain peaks over 8000 m (asl) and hundreds over 700m (asl). In the east-west direction it is spread over a length of about 2500 km and a width varying from 200 to 400 km in the north-south direction. The Himalayan region covers an area of 51.43 mha out of 96.06 mha mountainous area in the country. The area of Himalaya above various contour heights is given in Table 1.

Table 1 Himalayan area above various contour height.

Contour Height (m)	Area ($km^2 \times 10^6$)	%
1500	4.60	100
2100	3.90	85
3000	3.20	69
3600 and 4500	2.10	45
5400 and 6000	0.56	12

TOPOGRAPHY

Topography is primary factor in determining local patterns of water and energy exchange in mountain watersheds. In the Himalaya, both altitude and relief are at a maximum for the earth as a whole. Himalaya are not a single chain of mountains. They consist of three west-to east running parallel ranges and between these ranges, there are numerous narrow valleys. Three parallel ranges or geographical zones, namely outer Himalaya, middle Himalaya and greater Himalaya, are described below.

Outer Himalaya is the southernmost range of Himalaya and is known as Siwalik Ranges also. Their average height varies from 900 to 1200 m asl and average width varies from 10 to 50 km. The elevation of outer hills rarely exceeds 1200 m.

The ranges representing middle Himalaya consist of higher mountains. These are a series of broken mountain ranges whose mean elevation varies from 2000 to 3300 m (asl). Their width varies from 60 to 80 km. These ranges have different names in the different sections of the Himalaya, such as Lesser Himalaya or Pir Panjal Ranges in the western Himalaya. The middle Himalaya lies between the outer Himalaya and the perpetual snow-covered ranges of greater Himalaya. It is characterized by deeply cut valleys. The ridges extending in irregular direction appear to branch again and again.

The greater Himalaya is the northern most range of the Himalaya. It is a lofty, rugged chain reaching high above the perpetual snowline. The average height of this range is about 6000m asl. In this great Himalayan range as many as 13 peaks exceed 6000m elevation. A still large number of peaks range from 4500 to 6000 m. Beyond the main ranges of Himalaya, there is a continual series of somewhat lower Trans-Himalayan zone (average altitude varying between 5000 and 6000 m) adjoining the Tibetan plateau. Physiographically the region has been divided into five parallel zones:

Warm tropical (below 800m)
Warm subtropical (800 – 1200m)
Cool temperate (1200 – 2400m)
Alpine (2400 – 3600m)
Arctic (Above 3600m)

Slopes and the processes that form them in the Himalaya vary. Aspect is another important factor from the view of not only the rainfall or snowfall received but also the energy available for snow melting through the sunlight received.

In the Himalayan region, the windward and leeward relationships will be most important in the eastern portion of the region while orientation with respect to solar angle will be more important in the western portion of the region.

CLIMATE

The Himalayan ranges have large variations in topography, elevation and location, resulting in great contrasting climates from region to region. The entire Himalaya experience the monsoons during summer. The monsoons starts over the eastern parts of the Himalaya in the first week of June and are deflected westwards. They are active up to the end of September. The western Himalaya are also benefited by rain and snow during the winter months under the influence of western disturbances. The eastern Himalaya on the other hand receive less than 10% of the annual rainfall during the winter months.

WATER RESOURCES

All the mountainous regions are responsible for our perennial stream flows, springs and groundwater. By virtue of high altitudes and geographical placement, the Himalaya are a great reservoir of ice, snow fields and glaciers. They are thus a source of large river systems which flow to the plains of the Indian subcontinent to the south. The rivers that originate and drain through Himalaya are given in Table 2. Rivers of the Himalaya and their drainage basin systems are given in Fig. 1.

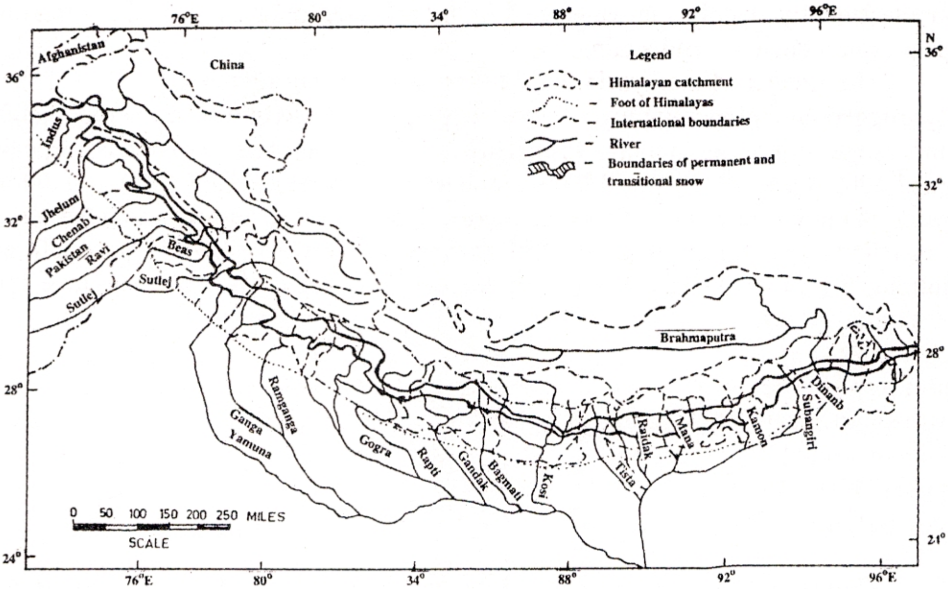

Fig. 1 Catchment of major Himlayan rivers and permanent snow covered areas.

Table 2 The Himalayan river systems and catchment areas.

Sr. No.	River	Catchment Area in Himalayas (sq km)
	A. Indus System	
1.	Indus	265700
2.	Jhelum	33300
3.	Chenab	26900
4.	Ravi	79000
5.	Beas	13800
6.	Sutlej	47400
	B. Ganga System	
7.	Yamuna	11500
8.	Ganga	22800
9.	Ramganga	6700
10.	Kali	14300
11.	Karnal	52700
12.	Rapti	7700
13.	Gandak	35000
14.	Baghmati	3800
15.	Kosi	61200
	C. Brahmaputra System	
16.	Teesta	12300
17.	Raidak	21600
18.	Manas	30700
19.	Subansiri	16100
20.	Luhit	17900
21.	Brahmaputra	250000

The northern and eastern parts of Himalaya in the country have a tremendous potential of water resources and hydropower. The total volume of water from the Himalaya flowing down the plains was estimated at about 8634 million cubic metres of water per year.

The Himalaya has given rise to a drainage system which can be broadly grouped into three main river system; the Indus, the Ganga and the Brahmaputra. The total surface water runoff of these three major systems was estimated at 1009 million cubic meters. It has been observed that the discharge of Himalayan snow fed rivers per unit area is roughly twice that of peninsular rivers of south India. The flows during monsoon season in the Himalaya are the combined effect of rainfall, snowmelt and glacier melt. The contribution from melting of seasonal snow to the rivers in the Himalayan regions varies on average from 25 to 30%, and in some cases even 40%. However, very few studies have been made to determine exact contribution of runoff from each of these sources. The hydropower potential of the Himalayan River Systems is given in Table 3.

Table 3 Hydropower potential of Himalayan river system.

River System	Potential at 60% Load Factor (MW)
Indus	19,998
Ganga	10,715
Brahmaputra	34,920

Source: Central Electricity Authority, 1988

During the monsoon months, June to September, these river systems experience floods, drainage congestion and erosion. It has been estimated that 15 million hectares of land in north India are prone to floods by the river originating in the Himalaya.

The mountainous catchments of Himalaya differ from the plains in the following ways:

(1) More frequent precipitation with longer durations.
(2) Characterised with steep slopes and well-defined boundaries resulting in steep rise in the hydrograph.
(3) Hydraulic gradients and rapid stream responses resulting in flash floods.
(4) Areas in higher elevations experience precipitation in the form of snowfall from November to March. This on melting provides snowmelt stream flow from March to September each year.
(5) The permanent snow line is characterized by glaciers which also contribute melt water from March to September each year. Sometimes breaking of glacier mass blocks the stream channel like a dam, which on breaking causes dam break floods.
(6) Frequent heavy rainfall and low temperature give soil a low moisture deficit resulting in larger stream flow.
(7) Well-defined streams with efficient cross-sections and hardly any flood plain result in a higher magnitude of floods.

(8) Owing to thin soil mantle, most of the rainfall drains off with little or no groundwater storage. This results in steep recession limits.

The average annual stream flow of the three rivers systems is given in Table 4.

Table 4 Average annual stream flows of the three river system.

River system	Av. annual stream flow in km^3/year
Indus	206
Ganga	488
Brahmaputra	510

PRECIPITATION

The mean annual rainfall over Himalayan region varies from 50 to 250 cm with lesser rainfall occurring around the foot hills of Himalaya. As one goes to higher elevations the rainfall has a tendency to increase. Towards east, the rainfall increases in Nepal and Darjeeling Himalaya. Knowledge of precipitation distribution during individual months, seasons and over the year is of vital importance both for planning water resources projects and agriculture operations in a given basin/region. Depending upon broad climatic conditions prevailing over the Himalaya, the following four seasons are well marked in the Himalayan region:

(i) Winter season (December - March)
(ii) Per-monsoon season (April - June)
(iii) Monsoon season (July - September)
(iv) Post-monsoon (October – November)

The source of precipitation and its distribution in each of the seasons are described below.

Winter Season

The precipitation during this season is caused by extratropical weather system of mid-latitude region originating from Caspian Sea and moving eastward. The disturbances approach India from the west through Iran, Afghanistan and Pakistan. With the setting of the winter season these disturbances have a tendency to move along lower latitudes. Normally, these disturbances remain at high latitudes and do not influence the Himalaya. But, as the season advances, they come lower and lower and by the end of December they cover a large part of Himalaya. They recede to their original position beyond the Himalayan mountains after winters.

The precipitation during this season is generally in the form of snow in the greater Himalaya, snow and rain in the middle Himalaya, and only rain over the outer Himalaya and the adjoining north Indian plains. Precipitation occurs at intervals throughout the winter season. It is found that average frequency of occurrence of these extratropical disturbances is about 3 to 5 each month, which reduces as the season advances.

The higher precipitation in the western Himalaya during these months is the combined effect of the nearly east-west configuration of the Himalaya and eastward movement of weather systems in winter. The precipitation associated with these weather systems decreases considerably as they move eastwards along the Himalaya because of increasing distance from the source of moisture.

Pre-monsoon Season

Generally this season lasts for about 3 months from April to June and is considered as transit period between winter and southwest monsoon. Light to moderate rain is caused by convective storms. Convective activity increases as the season advances because of increase in temperature over the Himalaya region.

Monsoon Season

Normally precipitation over the Himalaya is caused by the moist air currents from the Bay of Bengal in this season. Sometimes, both branches of monsoon (i.e. the Bay of Bengal and Arabian Sea) arrive simultaneously in this region heralding the onset of monsoon. These moist air currents after striking Burma and eastern Himalaya are deflected westwards and travel along the Himalaya. Rainfall decreases westward because of the increasing distance from the source of moisture, i.e. Bay of Bengal or Arabian Sea, which results in a lesser amount of moisture content in the air currents. Consequently, lesser precipitation is observed as one moves further and further to the west. This is the season of abundant rain and Himalayan rivers are generally flooded. Snow and glaciers at very high altitudes continue melting during this season. The monsoon normally starts withdrawing from this region towards the end of September. While the monsoon currents give copious rainfall over the Indian plains; after crossing the Himalayan ranges and moving over trans-Himalayan regions they become dry as most of the moisture initially carried by them is precipitated during their passage over the plains and mountain ranges of the Himalaya.

Post-monsoon Season

During this season clear autumn weather sets in and there is generally little rainfall. This is the driest season in the entire Himalaya.

The south-west monsoon is the principal source of rainfall contributing 50 to 70% of the annual rainfall in the region. The normal monthly and annual rainfall of some selected stations is given in Table 5. The mean monsoon rainfall of stations in central Himalaya is given in Table 6. The highest point rainfalls observed in the hills range from 200 to 450 mm. The storm of September 1880 would go down as unique in the history of storm rainfall over the region, followed by 1924 storm.

Table 5 Normal and annual rainfall in Himalayas

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Uttar Pradesh													
Mussorie	79.3	89.7	66.8	37.1	54.9	208.3	782.3	800.3	329.4	41.1	12.5	36.1	2537.8
Dehradun	57.9	66.6	37.9	19.6	35.8	184.4	655.6	713.0	304.5	41.9	7.6	24.9	2149.0
Rajpur	69.3	65.8	43.2	24.4	39.4	246.1	968.6	1058.7	392.4	43.9	9.1	25.7	2386.9
Nainital	69.9	73.1	52.6	38.1	84.1	390.9	769.4	750.1	362.7	61.0	12.9	25.4	2690.2
Mukteshwar	56.9	62.0	48.5	36.3	56.4	176.0	316.0	306.3	210.7	43.4	8.9	24.6	1337.0
Almora	42.9	49.3	42.2	27.9	48.3	143.8	264.9	234.2	130.3	32.3	7.4	21.3	1044.8
Pithoragarh	44.2	56.4	40.4	28.3	72.6	182.9	299.7	287.3	149.3	33.3	6.9	21.8	1223.0
Ranikhet	54.1	62.0	46.2	31.0	50.0	144.0	331.5	344.4	165.9	33.5	7.4	22.9	1292.9
Pawi	60.7	66.8	55.1	32.0	51.6	132.3	326.1	359.9	148.3	33.8	8.1	28.2	1302.9
Srinagar	55.1	56.1	36.8	22.1	42.7	118.4	244.1	223.3	97.3	24.9	5.6	21.8	948.2
Joshimath	65.8	92.7	98.5	54.4	35.1	88.9	176.3	184.7	108.5	28.2	12.2	27.4	972.7
Jammu & Kashmir													
Dras	103.9	107.9	146.8	146.8	102.1	56.4	16.5	13.2	15.2	19.6	16.5	57.9	673.0
Kargil	36.8	38.3	59.7	59.7	42.4	24.9	6.6	6.9	9.7	5.8	3.1	20.6	264.5
Leh	10.9	7.6	8.9	8.9	6.1	5.3	4.8	12.7	16.5	3.1	1.8	5.8	92.6
Himchal Pradesh													
Kotgarh	67.9	81.3	86.9	61.5	67.9	105.2	239.3	210.3	107.7	24.9	12.5	35.8	1102.9
Kathkhai	67.1	82.5	67.3	48.3	51.1	92.5	212.1	182.6	105.4	21.9	9.9	31.0	971.4
West Bengal													
Darjeeling	10.9	31.7	54.1	113.0	231.4	597.1	792.2	643.4	445.5	142	24.6	6.3	3092.4
Kalimpong	9.9	23.6	29.2	81.3	144.8	409.2	612.9	504.4	312.2	104	15.5	6.6	2254.0

Table 6 Mean monsoon rainfall of station in the central Himalaya.

Station	Station No.	Approx elevation above mean sea level (m)	Mean monsoon (June-October) rainfall (mm)
Nawalpur	1	1645	2091
Dhulikhel	2	1372	1299
Chautara	3	1676	1669
Dolalghat	4	792	844
Ghumthang	5	2134	3529
Nepalthok	6	579	873
Sindulgarhi	7	1463	2016
Ramechap	8	1219	755
Melung	9	1573	1557
Charikote	10	1981	1907
Kalimate	11	1417	1739
Udaipur Garhi	12	1390	1726
Kurleghat	13	610	766
Manebhanjyang	14	1615	915
Okhaldunga	15	2103	1502
Pekarnas	16	2134	1553
Paphlu	17	2316	1505
Chaurikharkha	18	2438	1955
Namchebazar	19	3200	792
Aisyalukharha	20	2450	2091
Khotang	21	1295	966
Dwarpa	22	1515	1277
Tribeni	23	143	1574
Chatra	24	115	1919
Dharan Bazar	25	500	2117
Barahkshetra	26	146	2185
Machuaghat	27	358	1205
Mulghat	28	341	759
Dhankuta	29	1524	694
Bhojpur	30	1524	954
Munga	31	1317	1050
Leguaghat	32	400	618
Chainpur	33	1329	1039
Dingla	34	1375	1662
Num	35	1676	2332
Chepua	36	2591	1805
Dumuhan	37	914	1398
Teplejung	38	1768	1536
Angbang	39	1219	979
Mameng Ja gat	40	1829	1546
Taplethok	41	1372	1869
Lungthok	42	2438	1880
Walungchung Gola	43	3048	1291
Pangthangdoma	44	3818	1172

As per WMO standard for mountainous areas, one precipitation station has to be established for each 150 sq.km. area. For different elevation ranges of the Himalaya, the number of precipitation stations that have to be located in the Himalayan region below the permanent snowline are given in Table 7. Based on the available information, the status of available gauging sites under different elevation zones are also shown in this table. Most of the gauges maintained by various organisations are below the elevation range of 2100 m. The precipitation gauges are somewhat better below the elevation of 1500 m whereas these stations are quite sparce in the higher elevations.

Table 7 Raingauge stations in Himalayan region

Altitude Range (m)	Density Network density	Actual Density			
		Total	Indus	Ganga	Brahmaputra
< 1500	370	86	33	43	10
1500-2100	460	57	20	28	9
2100-3000	470	35	4	18	13
3000-5000	730	28	3	17	8

The mountainous area covered by snow is about 80% of the total area of Himalaya. The western part of Himalaya gets more snowfall because the western disturbances are more active there than in the eastern part which gets snowfall later. The snowline during winter months of December to March can descend to altitudes as low as 2100 to 3000 m and by June end recedes to about 5000 m. Above 5000 m is the permanent snowline being glaciated area. There are about 1500 glaciers forming a unique water storage system covering an area of about 30,000 sq.km. The glacier and percentage glaciation of main glacier-fed river system of Himalaya are given in Table 8.

Table 8 Principal snow and glacier fed river systems of Himalaya.

No.	Name of River	Major river system	Mountain area (km^2)	Glacier area (km^2)	% age glaciation
1	Indus	Indus	268,842	8790	3.3
2	Jhelum		33,670	170	5.0
3	Chenab		27,195	2944	10.0
4	Ravi		8,029	206	2.5
5	Satluj		47,915	1295	2.7
6	Beas		14,500	638	4.4
7	Yamuna	Ganga	11,655	125	1.1
8	Ganga		23,015	2312	10.0
9	Ramganga		6,734	3	0.04
10	Kali		16,371	997	6.01
11	Karnali		53,354	1543	2.9
12	Gandak		37,814	1845	4.9
13	Kosi	Brahmaputra	61,901	1318	2.1
14	Tista		12,432	495	4.0
15	Raidak		26,418	195	0.7
16	Manas		31,080	528	1.7
17	Subansiri		18,130	725	4.0
18	Brahamputra		256,928	1080	0.4
19	Dibang		12,950	90	0.7
20	Luhit		20,720	425	2.01
	Total		1,001,29	25724	2.6

The average seasonal snowcover spreads over an area of 8.4 mha. A year-to-year study spread over a few years will enable the understanding of the behaviour of snow and glacier melt by identifying the parameters that control the flow, as sufficient information is not available at present. The density of snow and albedo for various types of snow are given in Table 9.

Table 9 Density of snow and albedo for various types of snow.

Sr. No.	Type of snow	Density (g/cc)	Albedo %
1	Freshly fallen snow	0.10-0.17	95-85
2	Dry crystalline snow	0.25-0.28	85-75
3	Fine grained moist snow	0.28-0.30	75-65
4	Coarse grained melting	0.30-0.35	65-55
5	Melting snow/firn	0.35-0.85	55-45
6	Clean glacier ice	0.85-0.91	30-46

The precipitation over mountainous areas are governed by (i) direct uplift of the air, (ii) stimulation of convection, (iii) general storm precipitation, and (iv) spillover.

The lifting of air in the mountain leads to adiabatic cooling which produces rain. In the case of stimulation, conditionally unstable air, on encountering a mountain slope, gets lifted up beyond its instability level and causes convective precipitation. The orographic effects on precipitation can be described in three ways as follows:

(i) The quantity of precipitation increases with altitude up.to a certain level and decreases thereafter. The level of maximum precipitation varies greatly from place to place depending on local topography. It is generally observed between altitudes of 1.5 to 2.5 km (asl).
(ii) Average variability of precipitation generally increases with altitude.
(iii) On higher altitude, the maximum precipitation occur generally earlier than in the foot hills.

The approximate increase in precipitation as has been experienced in different parts of the Himalaya is given in Table 10. The variation of precipitation with altitude for some stations in Western Himalaya is given in Table 11.

Table 10 Approximate increase in precipitation with altitude.

Sr No.	Location	Elevation range	Increase in precipitation (mm/100 m)
1	Western Himalaya	400-3200	3-200
2	Central Himalaya	700-2000	30-300
3	Eastern Himalaya	400-2000	80
4	Western Ghats	400-2000	60-100

Table 11 Variation of precipitation with altitude.

Station	Latitude (N)	Longitude (S)	Height (m)	Annual precipitation (cm)
Kangra Valley				
Dehra	31°50'	76°13'	436	131.8
Kangra	32°06'	76°15'	733	196.6
Palampur	32°07'	76°32'	1250	263.7
Dharmsala	32°15'	76°19'	1387	300.9
Doon Valley				
Ambari	30°30'	77°49'	489	183.7
Dehradun	30°19'	78°02'	679	207.5
Raipur	30°18'	78°05'	750	209.7
Rajpur	30°24'	78°05'	914	300.7
Mussouree	30°27'	78°05'	2042	247.0
Almora Hills				
Alora	29°36'	79°40'	1572	105.4
Ranikhet	29°38'	79°26'	1810	133.7
Kukteshwar	29°28'	79°39'	2311	132.5
Nainital				
Haldwani	29°13'	79°31'	440	199.5
Kathgodam	29°17'	79°32'	513	209.2
Nainital	29°23'	79°27'	1934	253.9
Joshimath				
Karanoparyag	30°16'	79°15'	769	142.3
Ukhimath	30°30'	79°15'	1220	201.1
Biranghol	30°15'	79°15'	1520	122.8
Joshimath	30°33'	79°35'	1840	95.4
Kullu and Leheul Valley				
Kullu	31°57'	77°07'	1215	100.6
Banjar	31°38'	77°20'	1524	110.6
Kathoi	31°18'	77°32'	1608	101.2
Kasauli	31°53'	77°58'	1844	163.2
Kotgarh	31°18'	77°29'	1949	115.3
Simla	31°06'	77°10'	2202	159.0
Keylong	31°35'	77°04'	3166	61.4

Another study indicates that precipitation increases in the lower ranges of Shiwaliks up to maximum of 1200 m and then decreases. Precipitation again increases northward up to elevation of 2000 m to 2400m. Thereafter, the precipitation decreases on the leeward side of these ranges and probably a third maximum occurs on the windward side of greater Himalayan ranges up to an elevation of 6100m. The heavy precipitation of this region is attested by the physical presence of multitude of glaciers.

The upper elevation receives precipitation in the form of snow. The spatial variability of snowfall has a similar mechanism as the distribution of snow. The snowfall is affected by wind and drifting of snow. During the snowmelt process, it has been observed that the snow line generally follows the elevation contour. The assessment of snowfall and snow quality require the data of observation of snowline to delineate the area which will contribute to snowmelt. In the absence of adequate data of snow measurements, the assessment of snow depth or water equivalent still remains a difficult problem which can only be answered by a dense network of point measurements along with the snow survey of representative areas.

Studies carried out in National Institute of Hydrology have shown that rainfall increases linearly with elevation in outer Himalaya and middle Himalaya on both windward and leeward sides. In the greater Himalaya it is insignificant beyond 4500 m.

SEASONAL SNOWCOVER

Seasonal snowcover is a major environmental factor over much of the northern hemisphere. It is highly variable in time and space and to gain an appreciation of its significance on a global scale it is necessary to consider its duration and maximum depth on the ground. Such factors as the rate of accumulation and variation of depth during the winter season are also important.

Seasonal snowcover develops as a result of a series of winter storms and is constantly modified by the action of freezing rain, the formation of wind crusts and diurnal melting and refreezing at the surface. The snowcover depth exhibits considerable fluctuations with passage of time. Major factors influencing the fluctuation of snowcover are deposition, settlement and loss of mass due to melting, evaporation, erosion and sublimation. During each snowfall, the type of snow deposited and the wind direction may change resulting in a stratification that is highly variable.

SNOW SURVEYS IN THE HIMALAYA

During the period 1947 to 1949, snow surveys were initiated in the Himalaya by Central Water, Irrigation & Navigation Commission (CWINC) in collaboration with IMD with a view to knowing how much of water comes in the Himalayan rivers from the seasonal snows in the lean months, April to June, before the onset of monsoon. A number of expeditions were sent to eastern Nepal and Sikkim in the Tamur basin (a sub-basin of the Kosi river), under the technical guidance of Dr. J. E. Church, then President of International Commission of Snow and Glaciers, during March-May 1947. Subsequently trained snow surveyors carried out several expeditions during the winter and spring months of 1948 and 1949 to measure the snow depth and density in snow fields of the Tamur basin. The observations of snow depth and density made by these snow surveyors are given in Table 12. As can be seen from Table 12 and as also stated by snow surveyors in their reports, in the eastern Nepal and Sikkim, winter precipitation is very little and snow does not at all accumulate on the ground as it melts quite rapidly, up to heights as high as 6000 m (asl) or so.

SNOWMELT

In the Himalaya, it is observed that snowfall is fairly high during the month of December to February/March, but daily discharge values in these months are low and reach a minimum during this period. Snowcover usually reaches its maximum accumulation by March. During March-April-May, there is hardly any solid precipitation, and the hydrograph shows a steady increase in discharge indicating that the snow which had accumulated in preceeding months is undergoing melting.

Table 12 Snow survey observation in the Tamur sub basin of the Kosi Catchment (East Nepal) taken during March and April months of 1947, 1948 and 1949.

Date of observation	Name of the snow course	Approx. height a.s.l. (m)	Average depth of snow (cm)	Average water equivalent (cm)	Average Density (%)	Remarks
3-4-1947	Mowna	3993	46.3	8.1	17.4	Snow survey
7-4-1947	Pubuktar	4603	37.1	8.1	21.9	Observations
11-4-1947	Ghunsapan	4115	46.0	8.9	19.3	Under taken in 1947
13-4-1947	Kangla	4938	77.5	16.1	21.6	Under the leadership of J. Banerjee.
20-3-1948	Mowna	3993	14.0	-	-	Snow survey
30-3-1948	Tipthala	4938	34.5	6.9	20.0	Observations
3-4-1948	Bhanjung	4603	19.8	7.6	38.0	Under taken in 1948
12-4-1948	Pubuktar	4938	29.0	8.1	28.0	Under the leader ship of O.N. Dhar.
	Tipthala					
	Bhanjung					
1-3-1949	Mowna	3993	0.0	-		Snow survey
1-3-1949	Tipthala	4420	48.5	7.4	15.0	Observations
2-3-1949	Bhanjung	4724	81.8	11.4	14.0	Under taken in 1949
3-3-1949	(Stage-I)	4938	134.9	26.7	20.0	Under the leader ship of
11-3-1949	Tipthala	4603	46.5	13.0	28.0	O.N. Dhar.
	Bhanjung					
	(Stage-II)					
	Tipthala					
	Bhanjung					
	(Stage-II)					
	Pubuktar					

The amount of meltwater produced depends on net heat exchange between the snowpack and its environment. The main components of snowpack energy budget which are responsible for snowmelt process are

(1) Absorbed shortwave radiation
(2) Net longwave radiation
(3) Condensation from overlying area
(4) Convective or turbulent heat transfer from air
(5) Heat content of falling rain
(6) Conduction of heat from ground beneath

Apart from its temperature, the main snow-pack characteristic to affect the energy is albedo. Albedo changes with time decreasing from 0.8 or 0.9 for freshly fallen snow to 0.4 or so after several weeks of atmospheric and biotic contamination. The snowmelt occurs in areas where the temperature rises after a long cold period and stays high for several days or due to continuous process in which climatological, drainage basin and snowpack characteristics combine to produce snowmelt water outputs. The snowcover estimation and the observed runoff of some river basins are given in Table 13.

Table 13 The snowcover estimation and the observed runoff

S. N.	Catchment	Station with elevation (in m)	Date of landsat imagery	Snow cover area in sq. km. within			Catchment area in sq. km. within			Percentage of snowcover area within the confines of			Total volume in melt season Mar. to May.
				Nepal	China	Total	Nepal	China	Total	Nepal	China	Total	in 10^6 : Cum
1	Seti	Banga (328)	22-3-77	1738.00	-	1738.00	7460.00	-	7460.00	23.30	-	23.30	551
2	Karnali	Asara Ghat (629)	22-3-77	11993.00	1642.51	13445.51	16810.00	2450.00	19260.00	70.21	67.04	669.81	1301
3	Beri	Janu (246)	22-3-77	3738.24	-	3738.24	12290.00	-	12290.00	30.42	-	30.42	536
4	Kali Gandaki	Seti Beni (546)	22-3-77	1850.00	-	1850.00	6630.00	-	6630.00	27.90	-	27..90	499
5	Marsvandi	Gopling Ghat (320)	22-3-77	2370.50	-	2370.50	4192.70	-	4192.70	56.54	-	56.54	479
6	Burhi Gandaki	Arughat (485)	22-3-77	1096.81	983.26	2080.07	2828.00	1442.00	4270.00	38.74	68.19	48.71	439
7	Trisuli	Betrawati (840)	22-3-77	460.70	1417.09	1870.09	1382.00	2728.00	4110.00	33.33	51.95	45.69	484
8	Bhote Kosi	Barabise (840)	22-3-77	84.37	1323.16	1407.53	0313.00	2097.00	2410.00	26.96	63.10	58.40	166
9	Sun Kosi	Khurkot (455)	22-3-77	939.64	1697.16	3636.80	6529.00	3471.00	10000.00	14.39	77.70	36.37	764
10	Likhu Khola	Sangutar (543)	22-3-77	84.37	-	84.37	.823.00	-	823.00	10.25	-	10.25	92
11	Dudh Kosi	Rabuwa Bazar (460)	22-3-77	1338.00	-	1383.00	4100.00	-	4100.00	33.73	-	33.73	423
12	Arun	Turkeghat (414)	22-3-77	806.00	10446.47	11252.47	5056.00	23032.89	28088.89	15.94	45.35	40.06	1710
13	Arun	Turkeghat (414)	19-4-84	257.00	10446.47	10703.47	5056.00	23032.89	28088.89	5.08	45.35	38.11	1388
14	Arun	Turkeghat (414)	15-2-85	1335.00	10446.47	11801.47	5056.00	23032.89	28088.89	26.80	45.35	42.01	1184
15	Tamur	Mulghat (276)	22-3-77	1714.00	-	1714.00	5640.00	-	5640.00	30.39	-	30.39	926
16	Tamur	Mulghat (276)	3-75	1775.00	-	1775.00	5640.00	-	5640.00	31.47	-	31.47	682

The Ministry of Water Resources, Government of India had requested the National Institute of Hydrology to take up studies for estimation of the contribution due to snowmelt and glacial melt in the rivers origination from the Himalaya. It was seen that the contribution due to snowmelt and glaciermelt in the annual flow was of the order of 50% in Chenab at Akhnoor and around 40% in Ganga at Deoprayag.

SNOWMELT FLOODS

Floods resulting from snowmelt is a major component of the hydrological regime in high altitude areas. Meltwater floods are essentially seasonal floods in which a substantial increase in river discharge takes place every year, in the same season. Such floods normally occur only once in a year resulting in a single flood wave which may have several peaks.

The two most crucial factors determining the severity of snowmelt floods are the depth of snow accumulation and rate of melting. Deep snow may melt so gradually that sometimes flooding is averted and instead high runoff period is maintained over several weeks. The fluctuation of snowmelt is only the first stage of production of snowmelt floods, because floods will result if substantial quantity of meltwater is routed rapidly into stream channel. The peak flood in mountainous rivers are normally between 2 and 3 times the mean annual flood. The quick flow will be produced only from those areas beneath the snowpack where water is unable to infiltrate the surface layers before moving laterally beneath the ground surface as interflow.

SNOWMELT WITH RAIN OR SNOW

The situation is even more complex in case of rain on snow than the case of floods due to snowmelt without rain. In the case of rainfalls over snow, the snowpack may either temporarily store and detain the rainfall and meltwater generated or the rain and meltwater may pass straight through the snowpack, in which case the meltwater adds an increment to flood runoff generated by rainfall eventually. A considerable quantity of rainfall may be stored within a dry sub-freezing snowpack and even from heavy rain storms, the runoff may be effectively retarded and delayed even by two days. Rain on snow floods may be caused from prolonged low intensity rain falling on moderate depth of snow in low altitude areas during the period of warm weather.

HYDROLOGICAL MODELS

Since the mountainous catchments have a complex hydrological behaviour, the hydrological response would be controlled by a large number of climatic and physiographic factors which vary both in time and space. The catchment behaviour is largely distributed, non-linear, time-varient and stochastic in nature. The complexity of catchment of mountainous regions and its flood producing process makes the modelling difficult even by the most rigorous model. The status of data would require to make adequate approximations and simplification to use them for mountainous catchments.

There are numerous watershed models available and most of these have been developed taking into account the component processes of the runoff formation as the basis of their development. The basic approach in these models uses the precipitation and snowfall input and computes the runoff from rainfall and snwomelt by routing through the channel and after accounting for the input loss, arrives at the hydrograph at the outlet point. Some of these models use the satellite based information of the catchment.

SNOWMELT MODELLING

Snowmelt is a significant component of the hydrologic cycle in a variety of climatic and physiographic regions. Estimation of snowmelt has considerable economic importance for flood forecasting and especially for successful operation of irrigation and hydroelectric schemes. Operational forecasts are usually required for periods longer than one day. Short term forecasts might be for the next ten days and medium range forecasts could be for a month or a season.

The snowmelt runoff problem is complex, involving the interaction of many aspects of the watershed system. To analyse such complexity, it is necessary to represent the various aspects of behaviour of watershed in a computer model. Much research effort has gone into developing snowmelt models over the years.

Snowmelt runoff models in general, consist of two components; a snowmelt model which simulates the process of snow accumulation and melting and a transformation model which takes snowmelt and/or rainfall as input data. The snowmelt models could be classified as lumped or distributed. The distributed models can be further classified as:

i. models distributed by 'elevation zones' and having the option of running as either 'energy balance' or 'index' models and
ii. Models distributed by some 'other' basic characteristics, such as soil type or land use and having the option of running as either 'energy balance' or 'index' models.

The snowmelt runoff models which are used widely are:

i. The Snowmelt Runoff Model (SRM) of Switzerland
ii. The University of British Columbia (UBC) model used in Canada
iii. The HBV model of the Swedish Meteorological and Hydrological Institute
iv. The Rainfall Runoff model NAM II of the Danish Hydraulics Institute, Denmark
v. The Streamflow Synthesis and Reservoir Regulation (SSARR) model of the Hydrological Engineering Centre, USA.

vi. The National Weather Service River Forecasting Service (NWSRFS) model of the U.S. National Weather Service

These models were among the eleven models used in the WMO intercomparison of snowmelt runoff models projects. Although the models are in general the same, the differences in the procedures used by them can be broadly categorised under the following groups:

A. Handling of meteorological data

(i) method of subdividing catchment
(ii) distribution of temperature lapse rate
(iii) determination of form of precipitation
(iv) distribution of precipitation
(v) distribution of other meteorological inputs.

B. Structure of snowmelt models

(i) accumulation
(ii) areal snow distribution
(iii) surface energy exchange
(iv) internal processes
(v) snow soil interactions.

C. Structure of transformation models

Problems associated with modelling snowmelt runoff in different regions relate to data availability, regional characteristics, modelling approach and model application. Many of these problems are common to all models and regions. The more universal problems are generally associated with data constraints, whereas the more unique problems are associated with model formulation and the climatic and physiographic characteristics of a region. In this context it is worth noting that almost all the models tested in the WMO Snowmelt Intercomparison Project still use a degree day method for computation of snowmelt. This reliance on the degree day method causes concern about the accuracy of the existing forecast methods.

The basic snowmelt processes are well understood but there are various practical and theoretical difficulties in determining the values of the various energy components which are all derived from incoming solar radiation. While the data requirements of the models using the degree day methods are modest, those using the energy budget approach would require data on radiation, wind etc. However, there are advantages in using the energy budget equations for snowmelt estimation. The physical basis of the equation makes it possible to estimate snowmelt for forested and open conditions, for clear or cloudy weather, for various slopes and aspects of mountainous watersheds and for changes in elevation.

In the Indian subcontinent, as in other areas of the world where a large portion of the river flow in low lands may stem from adjacent mountains, several studies have been made to relate seasonal runoff volumes to pre-season extent of snow cover [Pramanik and Rao, 1951; Tarar, 1982 and Ramamoorthi, 1983]. These studies rely on a purely statistical approach and can give reliable predictions only under certain conditions and after long periods of calibration for every new basin of interest. Also, they are based on the assumption that a larger extent of snow cover necessarily produces more runoff. However, if the percentage of glacierised area of a basin is large (e.g more than 20%), a more extensive snowcover would reduce meltwater yield. In the recent studies on snowmelt simulation for Sutlej by National Institute of Hydrology the UBC model has been used [Pratap Singh and Quick, 1992].

ARTIFICIAL MANAGEMENT OF SNOW

Of late several ideas are being floated about artificially manipulating the snowcover for advancing or delaying the melting. Since the snow and glaciers have not only a direct effect on the environment surrounding them but also weather and climate elsewhere any attempts at experimenting with the snowcover would create regional imbalances in terms of weather and water resources. It would be, therefore, prudent to leave the snow and glaciers in the care of nature rather than trying to influence them artificially.

GLACIERS

Glaciers are essentially reservoirs of both liquid and solid precipitation retaining winter snow and releasing it gradually. Low albedo and high temperature encourage melting. Although most glaciers are remote from the principal centres of human habitation, there is a practical need to deal with them as an important dynamic part of the mountain environment. Glaciers provide a dependable source of water for hydropower and irrigation. Both the benefits and hazards from glaciers are becoming of ever increasing importance as a result of the increasing habitation in the mountainous regions and development of nearby areas.

The Great Himalayan range is the permanent abode of glaciers and ice. Glaciers occupy about 43000 sq. km of this magnificient hill range. The Himalayan glaciers numbering around 15000 form a unique system in the Eastern Hemisphere.

GLACIER MELT

For proper management of high mountain water resources, it is necessary to known the amount and location of water stored in a frozen form, the pattern of its release due to melting and how the melt rates are affected by short term weather changes and long term climatic changes. The timing and amount of melt water produced from mountain glaciers is different from that derived from snowpacks on land. The major contribution from the seasonal snow reaches the streams between

March and June (before monsoon). The glaciers starts melting when all the snow accumulated in the last season is melted. The meltwater from the snow and glaciers is delayed before joining a stream or ground water reservoir. This delay is more prominent in the glaciers. Although insolation reaches a peak in June in the northern hemisphere, the average albedo of snow covered glacier surface at this time is relatively higher causing only low or moderate melt rate. In July and August, insolation is slightly reduced but the mean albedo of the glacier surface drops markedly as old dirty ice gets exposed, and the rate of melt is found to be higher than in June. A year of heavy snow accumulation results in a layer of high albedo snow persisting longer into the summer season and curtailing melt. A dry winter or a hot summer results in increased melt. Thus production of meltwater from glaciers tends to compensate for unusually wet or dry, or hot or cold years, thereby naturally regulating the streamflow.

Discharge from a glaciated area is an integrated output of a number of meteorological parameters such as liquid precipitation, air temperature, incoming solar radiation, humidity and wind velocity. Actual glacier runoff volume may vary from ±20% to ±30% of the average annual discharge. Ice melt normally takes place more slowly than snowmelt and by itself is rarely responsible for severe flooding. Floods do occur, however, when the melting of glacier ice suddenly releases large volumes of bonded melt water or when the breakup of ice pack results in an ice jam which may hold back large volumes of water before suddenly giving way.

GLACIER MELT FLOODS

Sudden releases of water from glaciers are known as glacier floods and may represent the outflow either of water which has been held within the ice body or of surface lakes on the ice or dam pack by the ice tributory valleys. This phenomenon has been common in Karakoram Himalaya, where 30 glaciers form substantial dams in the upper Indus river. The 1929 outburst flood of Chong Khundam glácier was monitored for 1500 cum. Some 300,000 cum of ice was carried with the flood. It was completely drained in 48 hours with peak flood discharge of 22650 cumecs. Another example is the glacier flood in August 1959 in Kashmir, which caused a rise in water level of more than 30 m at a distance of over 40 km from the point of outburst.

Major floods occur in some rivers when river ice breaks up into large blocks during the early stages of spring melt and piles up to form ice jam. After a jam develops, the water level behind it rises often quite rapidly, until eventually the obstruction gives way releasing water and debris into the channel. Therefore, the flood hydrograph close to the ice jam is often extremely sharp peaked until the flood wave moves down the channel when its form gets moderated.

GLACIER MELT MODELLING

There are two different methods of glacier melt modelling presently in use, a physical model based upon energy exchange at the glacier surface, and a mathematical statistical model based upon actual observations of runoff and meteorological parameters. The meteorological approach considers the mass and heat exchange at the glacier surface and has achieved a fair degree of success in forecasting of snow melting and glacier drainage. Glacier runoff is minimum in the early morning and maximum later afternoon. As the temperature rises, the top snow surface on the glacier begins to melt and meltwater starts to percolate through the snowpack and finds its way to the body of the glacier through crevices; this process also assists in the melting of additional ice. The discrete conduit system changes continuously by melting and plastic flow of the ice. A constant supply of heat from the bedrock adds to the melt contribution of glacier ice.

Mass balance studies on specific glaciers over the years have indicated both positive and negative balance. In general it was seen that the glacier regime over the Himalaya has an inverse relation with the monsoon rainfall in the other parts of the country. Studies on glaciers in India carried out so far include characteristics of ice and ice crystals, isotopic spectrometry, chemical analysis and also drilling of glacier cores and their analyses. Satellite derived data have been used for mapping of glaciers. The studies carried out so far have helped in

(a) Creating a systematic database,
(b) Coordinated laboratory and field researches
(c) Providing avenues to develop trained manpower as core group in different institutions
(d) Creating a general awareness and interest in glacier studies among scientific community.

More important are the efforts made to interrelate the work on glaciers with water resources and the rapport that developed between investigating the user organisations during the last decade.

DATA SYSTEMS

In snow hydrology research, as in other areas, more often attention has been paid to things which are easier to accomplish. That is why we have so many computer models, simulation studies etc., but so few hydrological and meteorological data on snow and glaciers. Information of hydrological and meteorological parameters, especially, from altitudes above 3000 m is essential for a realistic assessment of water resources from snow and glaciers. Since the great mountain ranges of the Himalaya are on a large scale undeveloped, it is, generally, not possible to install in a short time a network of this sort.

One of the important considerations for water resources of Himalaya is the adequate data of land use and vegetal cover, topography, geology and soils, hydrometeorological and hydrological observations, the most important being precipitation and other hydrometeorological parameters and streamflow. For this purpose, an adequate network of observations is required. Normally the density of network is determined by climatic, topographical, geographical, vegetal, population density and economic development. In mountainous region, orography attains special significance in view of the variation of precipitation and other meteorological parameters. The network of observations has to be such that it accounts for adequate assessment of precipitation and water potential of the basins.

The measurement of streamflow pose serious practical problems due to rough boulderly bed, high turbulent velocity and floe taking place through river channel in deep gorges. Not enough attention has yet been paid to the measurement of runoff in mountainous streams. Most of the stream gauging sites have been established recently and have provided limited data of river flows including foods. One of the major problems experienced in measurement of streamflow in mountainous reaches is that the gauges get swept away by the high turbulent torrential flow. In some places sudden short duration and comparatively rare floods accompanied by mud flow rule out the direct measurement of the elements of flood flow. Due to unstable bed of mountainous rivers, the stage discharge relationships are not fixed. It gives erroneous discharge values corresponding to observed stages.

It is, therefore, observed that the data status in respect of precipitation (rainfall and snowfall) and streamflow is highly inadequate for the estimation of water availability or flood hydrograph for water resources estimation and planning.

Various models for short-term seasonal melt runoff forecasting require temporal and spatial variation of snow and meteorological parameters from river catchments as input data. Observation network in the Himalaya especially at the high altitudes is not representative due to logistic problems as well as in inhabited terrains. A part from water equivalent of snow information is needed on temperature, wind, solar radiation and albedo. So far, except SASE no other organisation is able to operate meteorological stations at high altitudes. With the availability of reliable sensors which can operate at low temperature and India's own satellites being functional it should be possible for other national organisations also to collect data continuously from the remote locations at high altitudes. The National Institute of Hydrology has prepared a proposal for the establishment of 156 Automated Weather Stations (AWS) equipped with snow sensors at higher elevations in the various river basins of Himalaya. The proposal envisaged linking up the AWS to an Indian satellite for collection of data from various locations in Himalaya through out the year. Basin-wise list of the stations is given in Table 14.

Table 14 Requirement of automated weather stations in Himalaya.

Sr. No.	Basin	Number of AWS
1	Indus	05
2	Jhelum	16
3	Chenab	39
4	Ravi	19
5	Beas	13
6	Sutluj	18
7	Yamuna	11
8	Ganga	13
9	Ramganga, Sarda	07
10	Teesta	09
11	Brahmaputra	06
	Total	156

Also, efforts are needed to use satellite based active and passive microwave sensors for monitoring snow cover periodically during the melt season.

INSTRUMENTATION FOR HIGH ALTITUDES

The degree of success of achieving the objectives of data observation depends to a great extent on the accuracy of optimum performance of the instruments deployed for measurement as a part of the data collection system. Conventional instruments could not be used at high altitudes owing to their limitations. Advanced instruments are generally not available within the country and need to be imported. However, the fast developments in the field of instrumentation with advanced technology in the country should be taken advantage of for developing appropriate measurement techniques and fabricating the required instruments within the country.

REPRESENTATIVE BASIN STUDIES

There has been a tradition of cooperation in hydrological research within the International Hydrological Programme (IHP) of UNESCO. The countries of Europe have been participating in the FRIEND (Flow Regimes from International Experimental an Network Data). Twelve countries have been participating in this European Network of Experimental and Representative Basin which was established in 1986.

For the countries of the Hindukush Himalayan Region, similar efforts have been made by preparing a Regional Project which envisaged setting up of representative basin in the Himalaya in each country and exchange of information and technology for developing hydrological models for flow forecasting in these catchments.

REMOTE SENSING APPLICATION FOR SNOW AND GLACIERS

During the last fifteen years techniques for application of remoter sensing to hydrology in general and snow and glaciers in particular have been developed and perfected in the country. Based on satellite derived information, Dhanju (1983) reported the permanent snow covered area in the Himalaya to be 1,000,000 sq.km. Satellite derived snow covered area was being used for preparing seasonal snowmelt forecasts by NRSA (Ramamoorthi, 1983).

The Space Application Centre (SAC) has been making inventory of Glaciers in the Himalaya through satellite derived data. Remote sensing based inventory of glaciers was done using Indian Remote Sensing satellite (IRS) Liss II and Landsat TM (Kulkarni, 1989 and 1991). A typical inventory for Gangotri is shown in Fig. 2.

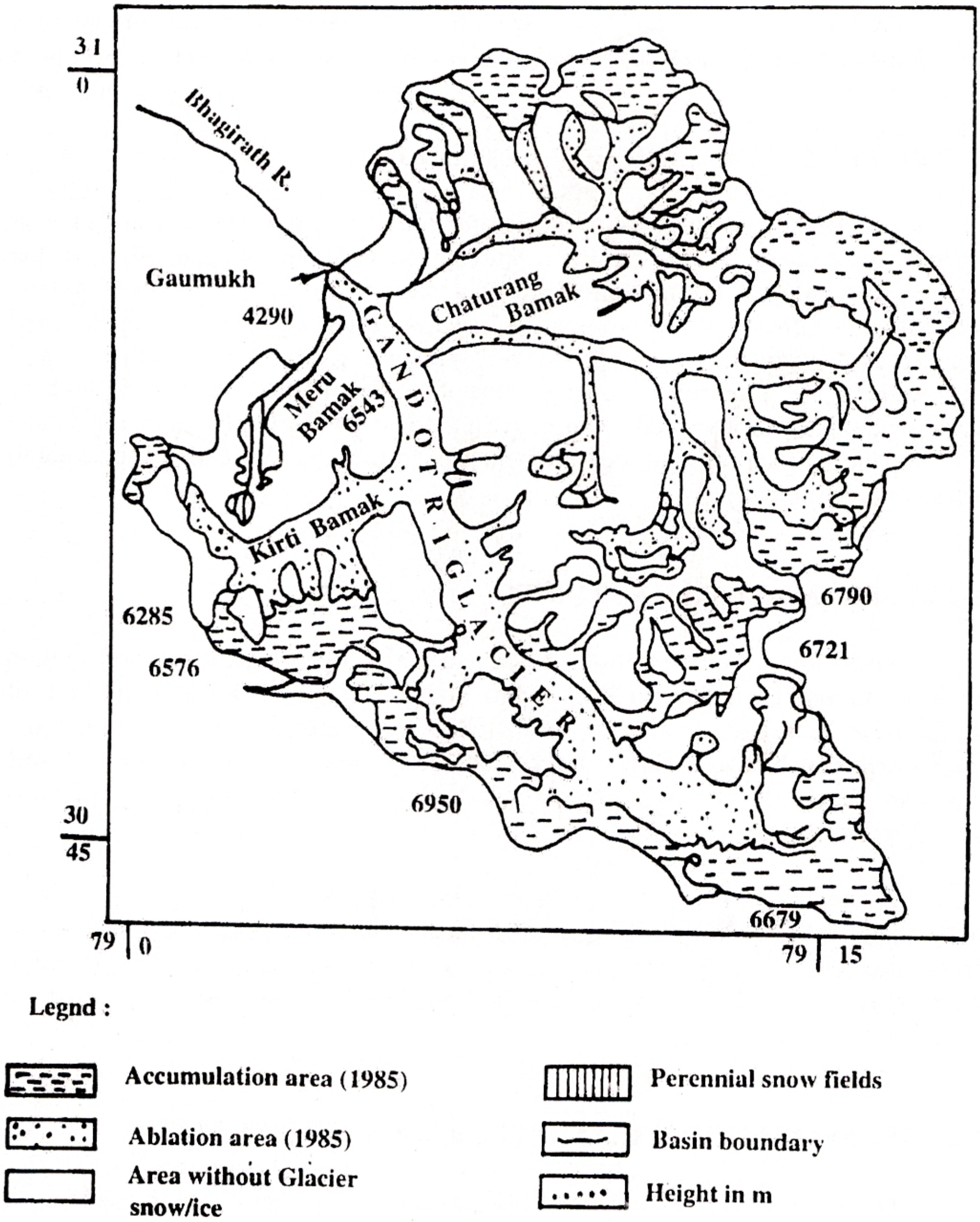

Fig. 2 Remote sensing inventory of Gangotri Glacier.

NUCLEAR TECHNIQUES FOR SNOW AND ICE

For the last three or four decades, a number of isotope techniques are in use for the study of snow and ice. The areas of interest are determination of water equivalent of snowcover, location of ice lenses in snow packs, regional snow surveys, determination of snow accumulation over glacier, differentiation between contribution from snow and glacier melt, contribution to river flow, delineation of flow patterns of glacier ice, resurrection of paleo-environmental conditions and climatic oscillations. These have been successfully covered by using one or combination of isotopic techniques.

In India, nuclear isotopes have been used for determining water equivalent of snow through nucleonic snow gauges at SASE [Virendra Kumar, 1988] and measurement of river discharges in mountain streams [Bhishm Kumar et al, 1992]. Nizampurkar and Rao [1988] used the isotopes for dating Glacier ice in Chhota Glacier.

CLIMATE CHANGE

Variability of the climate in both time and space is of consequent importance not only to human being but animals and plants as well. All living organisms, generally, have the capability to adapt themselves to variations in climate in due course of time. The concentration of trace gases in the atmosphere have continued to increase for the last few decades. At the current rate of emissions, the global warming is expected to increase the Eearth's temperature by 2.0 to 2.5°C by the end of the present decade. The current level of knowledge does not permit any forecasts as to how and in what magnitude the climate warming would affect the snow and glacier system the world over in general and the Himalaya in particular. More simulation studies need to be done before jumping at conclusions.

EDUCATION AND TRAINING IN SNOW HYDROLOGY

Sometime back the Department of Hydrology at the University of Roorkee proposed a specialised postgraduate course in Snow Hydrology. The course, however, could not start due to lack of financial support.

The National Institute of Hydrology and Central water Commission had organised short duration workshops on Snow Hydrology at Roorkee, Manali and Shimla. The Geological Survey of India has been organising Foundation courses in Glaciology since 1993. These efforts are far below the requirement and need to be given the necessary thrust and encouragement. The Government of India should provide the necessary funds and the international organisations should extend the cooperation in these efforts.

RESEARCH AND DEVELOPMENT IN SNOW HYDROLOGY

The present status of snow and glacial research in India provides the necessary base for further efforts in this direction in the coming years. These studies would be of immense value for water resources and hydropower development in the country.

A long-term perspective programme for Glaciological studies in the countries of the region has to be evolved and intensive studies are to be carried on a few selected glaciers with greater water resources potential.

Studies relating to effect of variations in seasonal snowcover on the monsoon weather in region and the changes in climate on the Himalayan glaciers need to be done on a systematic and scientific way.

FUTURE NEEDS

From a practical point of view, the most urgent needs are:

- To improve our ability to predict spatial and temporal variations in the quality and quantity of surface runoff from mountain catchments.
- To relate these variations to possible impacts of various land and resource use practices at the level of these practices as well at the level of the larger river systems of which they are a part.
- To communicate the results to planners, managers and decisions makers as well as the community of water resource professionals.
- To educate and train water resource professionals and technicians in the principles governing mountain hydrologic systems and water resources management in these systems.
- The proposed course on Snow Hydrology at the Department of Hydrology should start soon.

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