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HYDROLOGICAL IMPORTANCE OF HIMALAYAN SNOW, ICE AND GLACIERS

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Abstract *The paper introduces Himalayan snow, ice and glacier fields as the tallest water tower of the world having great spatial and temporal variability in microclimatic conditions and specific water yields from the mountainous catchments. The status of glacier inventory as given by various workers has been included pointing out that about 50,000 km^2 of glacier area lying in India, Nepal, Bhutan, China and Pakistan, drain into the Indian land mass. Atmospheric circulation and general climatological aspects are outlined including the powerful heating effect of Tibetan Plateau, westerly disturbances, monsoon depression, vertical meridian circulation and local warm islands on each mountain. Hydrological characteristics of the high mountain watersheds are treated in some details with regard to drainage variations from melt-water contributions in space and time domain. Indian contributions to snow and glacier hydrology have been reviewed since 1945 giving the salient findings by various investigators. The research needs have been highlighted for maintaining multidisciplinary thrust in the important fields of snow and glacier hydrology to the nation.*

INTRODUCTION

Himalayan snow, ice and glaciers form the tallest water tower of the world and are the source of abundant fresh water resource. Ancient human civilization flourished around them. These high mountain areas are susceptible to water related disasters due to increased orographic precipitation and steep and unstable slopes. Increasing human and animal population and economic transformation have exerted considerable pressure on the natural resources of the region. Changes in the land use and land cover have brought out modifications in water flows, nutrients, sediments and pollutants resulting in loss of biodiversity almost everywhere in the mountains.

However, the ecohydrological processes in the high mountain area, especially the role of natural processes, impact of human interference and climate change on the availability of water, highland-lowland linkages and sustainable use of water are poorly understood. Thus, there is an urgent need for a better understanding of the vulnerability of the land-water system to human activities and climate change impacts in the high mountain areas, because of their fragile ecology and susceptibility to irreversible change. The investigations need interactive studies, both with the geosphere on one side and the atmosphere on the other, affecting bio-prodictivity.

Freshwater resource availability in the Indian Himalayan region is estimated to be 1757 m^3/year per capita in Indus basin, 1473 m^3/year per capita in Ganga basin and 18,417 m^3/year per capita in Brahmaputra. These estimates are already on the lower side with global averages ranging from 1000 m^3/year per capita to over 50,000 m^3/year per capita. Hence, an all-out effort is needed for improved management of water resources of the Himalayan region.

In this paper, information on snow, ice and glacier fells, atmospheric circulation and general climatology, hydrological characteristics of mountain watersheds, a brief review of Indian contribution to snow glacier hydrological are discussed along with the challenges to be met in the new millennium.

HIMALAYAN SNOW, ICE AND GLACIER FIELDS

The Himalaya is known as the abode of eternal snow and ice. The extensive mountain systems have 14 peaks above 8000 m, hundreds over 7000 m and 530 peaks above 6000 m level. It is the world's youngest, highest, most sensitive and strongly coupled ocean-land atmospheric system. Huge snow and ice cover conditions result in potentially destructive conditions due to intense freeze-thaw cycle, modifying the environment.

The mountain ranges were created by a geological event that triggered an ice age. It is now believed that during the period 10 to 50 million years ago, the subcontinent of India riding over its own tectonic plate collided with the rest of the Eurasian landmass. The pressure squeezed the earth crust, forcing it to prop up further inland. The uplift of Himalayas took place in three stages i.e. (i) Early Miocene (21-17 MY) (ii) Late Miocene (17-7 MY) and (iii) Quaternary (1.6 MY) to the present. The Himalayan uplift estimates vary from 2 to 12 mm/year while the Tibetan plateau has shown an average rate of about 5 mm/year over the last 10,000 years. The uplift is still continuing and is manifested in the form of regular earthquakes.

Unlike Europe and North America, Asia was not covered by continental ice sheet during Quaternary (2 million years ago). The Quaternary period consists of Pleistocene glacial period (2 million years ago to 10,000 years before present), followed by postglacial (Holocene i.e. 10,000 years before present to the present). During Pleistocene, glaciers occupied 30% of the earth's surface as against 10% at the present.

As pointed out earlier, the snow, ice and glacier fields over Himalayas form the apex natural reservoirs of freshwater resources. A sufficient area of the high mountain system lie higher than the snow line (Isotherm 0°C) and in this area, snow falls round the year. In these mountains, it is estimated that 10 to 20% of the total surface area is covered by glaciers while an additional area ranging from 30 to 40% is overlain by seasonal snow cover. The extent of Himalayan snow cover could be more than 1.5×10^6 km^2 while the glacier cover is around 10,000 km^2.

Figure 1 shows the nine years averages of 6 days snow area from SMMR (Scanning Multichannel Microwave Radiometer) charts and fifteen years average of digitised weekly snow cover from NOAA (National Ocean and Aeronautic Administration) satellite snow charts (Peiji, 1994).

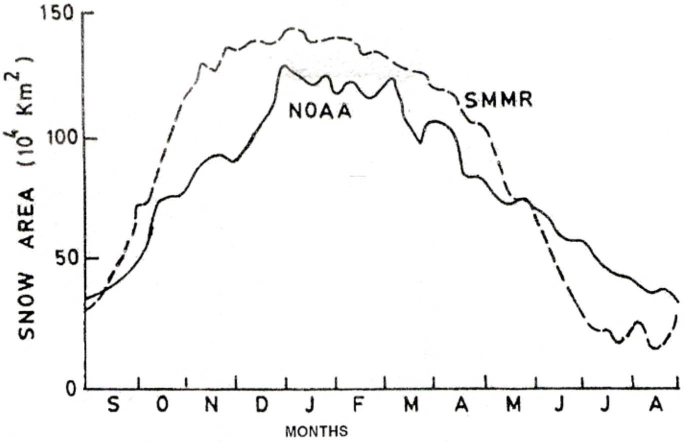

Fig. 1 Normal annual cycles of snow cover in entire western China and Tibetan Plateau (Peiji, 1994).

The snow season begins in mid September over the Tibetan Plateau. From mid October to early November snow cover spread is rapid. It increases to late November – early February peak with maximum occurring in January. This is followed by a slow decline until June. During growth progression of snow cover, the increase in areal extent leads to snow volume increase, whereas the decay phase, decrease in snow volume is followed by decrease in snow cover area. The seasonal progress of snow cover in the lowlands of western china, derived from station data, is different from that in Tibet in two ways. In lowlands, the snow season begins one month later and ends two months earlier. The winter, spring and autumn are represented by 45.2%, 28.0% and 21.2% of the annual snow volume, respectively, over the Tibetan Plateau. The seasonal variability of the snow cover suggest the following:

(i) Snow cover effects on climate vary with seasonal cycle. The snow-albedo effect is dominant during the growth progression. In contrast, the snow-hydrological effect is more significant during the decay progression.

(ii) In late spring, snow cover is the major variable in the radiative and hydrological environment over the Tibetan Plateau.

The large year to year variability of snow cover over the Tibetan Plateau is the most striking feature. The variance in snow volume is more noticeable than those in snow cover area. The ration between the highest annual volume and the lowest is 1.91 for Tibetan Plateau, and 1.39 for western China while the area ration is 1.59 and 1.27 respectively.

Figure 2 gives the distribution of glaciers in the Himalayan region with major mountain ranges and rivers. Total glacier area is 94,55.4 km^2. The percentage glacier area is shown in brackets for various mountain systems (Lin Jijun and Xu Shuying, 1984). It is claimed that 49.8% of the glacier cover is in Chinese territory.

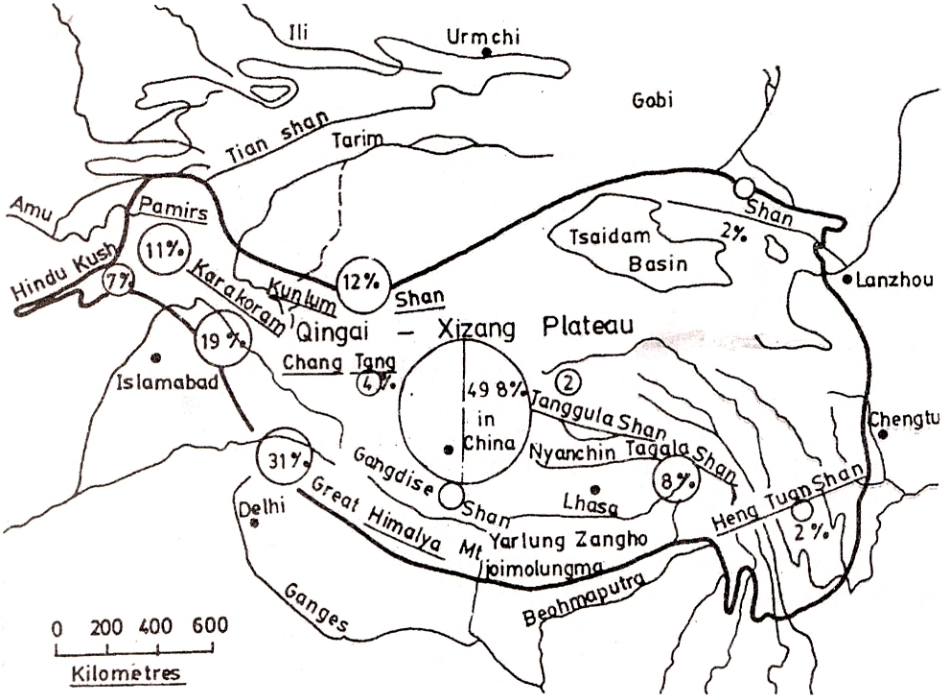

Fig. 2 Distribution of glaciers on the Qinghai-Xizang Plateau.

The available status of glacier inventory in the Himalayan region as given by various investigators is given in Table 1.

Table 1 Himalayan glacier cover

Sl. No.	Area of glacier cover	Source of information
1.	33,200 km^2 of Himalaya (17%) 16,000 km^2 of Karakoram (37%)	Wissman (1959)
2.	94,554 km^2 including Tibet (49.8%) in Chinese Territory	Lin Jijun and Xu Shuying (1984)
3.	38,479 km^2 covering 4795 glacier	GSI (1995)
4.	25,725 km^2 glacier cover of the principal glacier fed covers of Indian Himalayas	Bahadur (1985) based on the data provided by Survey of India
5.	Permanent snow & ice covering 97,020 km^2 Including Tibet Hindukush - 6200 Karakoram –15670 Himalaya – 43000 Tibet - 32150	Upadhyay (1985)
6.	37,959 km^2 covering 5243 glaciers	GSI (1999)
7.	50,000 km^2 glaciers drain into Indian landmass	Bahadur, (2000)

ATMOSPHERIC CIRCULATIONS OVER HIMALAYAS AND GENERAL CLIMATOLOGY

The uplift of the Himalayan Mountains has not only resulted in cooling and glacier growth but also in changing the atmospheric circulation and climate of the region. Some major elements could be grouped (Lin Jijun and Xu Shuying, 1984) as follows:

(a) Powerful Heating Effect of Tibetan Plateau

The major effect on atmospheric circulation is due to powerful heating effect of Tibetan Plateau. In summers, a special atmospheric condition, being characteristic of a low near the surface of the plateau and warm high above it, which punctuates the subtropical planetary high-pressure zone. This induces, or at least enhances, the Indian Ocean monsoon circulation of Asia, which is completely opposite to famous Hadley's circulation in the direction.

(b) Westerly Disturbances

The westerly circulation move southwards being induced and enhanced by the plateaus blocking action and the natural thermodynamic effect and release abundant precipitation over the western mountains. The heavy snow precipitation at high altitude supports one of the highest intensity glacierized region on the earth. The effectiveness of precipitation from these disturbances reduces as one moves eastwards.

(c) Monsoon Depression

The monsoon nurtures the glaciers on southern slopes of Himalayas and particularly of south –eastern region having the warmest glaciers on the earth. The effectiveness of precipitation from these disturbances reduces as one moves westwards.

(d) Vertical Meridonal Circulation

The overflow that converges from the north occurs on the thinner and shallower 500-mb surface, develops a branching flow, southern subsiding over current is checked by south-west monsoon while the northern branch is enhanced by the low altitude downward sliding wind below the 500mb surface, creating a drier zone of continental glaciers.

(e) Local Circulation

During summer, each and every mountain is a "warm island" and centre for condensation of water vapour. Each worm island releases large quantifies of latent heat into atmosphere with a rising air column maintaining the high pressure in summer in the upper stratum of the troposphere. The large-scale transportation of energy provides the glaciers with plentiful snow precipitation.

The above atmospheric circulation situations result in Mediterranean maritime (Alps) type of climate in the western Himalayas, monsoonal (both maritime and continental) in eastern and central Himalayas and inland continental glacier systems in Tibetan Himalayas.

The Tibetan Plateau, towering to mid-troposphere height, plays an important role in the general atmosphere circulation (Gao You-Xi et al., 1981) as a cold and heat source. In summer (and during the day time), the heating effect resulting from intensive solar radiation over the plateau causes the atmosphere of the mid-troposphere to assure a state of high temperatures, low pressure, high humidity, week breezes, instability, and of being in convective clouds, thunderstorms, and hailstorms as low pressure vortices, shear lines, and strong thermodynamic boundary layer prevail. The summer monsoon thermal low over the plateau is big and strong, the plateau monsoon and its vertical circulation during the summer season prevail, and the plateau experiences its rainy season.

During winter (especially at night), the plateau functions as a cold source or weak heat source, and the atmosphere over the plateau is in a state of low temperatures, high pressure, low humidity and strong wind. Although the air is unstable and corrective clouds are still the principal cloud system, there are no thunderstorms or hailstorms, the thermodynamic boundary layer is week and thin, the cold high of the plateau monsoon prevails, the winter monsoon and Hadley all are well developed, and the plateau is than in its dry and windy season. During the transition seasons, the cold-and-heat source configuration changes rapidly. The plateau is very probably the motivating region that leads to seasonal long-wave adjustments of the atmospheric circulation.

The complexity of the relief features as well as differential effect of the weather systems in different regions are responsible for a variety of climatic patterns absorbed in the Indian Himalayan region (Ramanathan, 1982).

Summer temperature of the stations in the western Himalayas are higher than the stations in eastern region located at the same altitude. This reflects the greater effects of monsoon currents and associated cloudiness in eastern Himalayas. Even during post monsoon season (Oct-Nov) the stations in the western Himalayas continue to record higher maximum temperature than in the east at similar altitude. This is due to the fact dry clear weather generally prevails (except Kashmir valley) stably in western Himalayas during this season while in eastern Himalayas, the air is damp during the season giving rise to frequent occurrence of fog and mist. During pre monsoon season also temperature is lower in eastern Himalayas because of greater frequency of thunderstorms and associated humidity and cloudiness.

The mountain creates extreme complications in wind structure at lower levels. At higher level the winds are strong and westerly accompanied by gusts sometimes exceeding 160 km/hr. The wind strength varies with altitudes and is about 50 to 60 km/hr at 6000 m and 120 km/hr at the top of higher mountains.

During summer, winds weaken and are on an average 40 km/hr and increase to 70 km/hr at the highest level.

The mountain system is giant screen in the way of moisture carrying airflow coming in from Atlantic and the Indian oceans. It plays an important role in forming the Tibetan anticyclone and the Indian summer monsoon. The mountain ridges, rising parallel to one another over hundreds of kilometres, rise from the outer to the inner edge of the mountain land. Therefore, precipitation falling from the incoming airflow declines progressively at the foot of every subsequent ridge, but increases up the slope of all ridges. The creeping nature of the precipitation-forming cloudiness is essential for this process. It is inherent in the frontal cloudiness of the winter Mediterranean cyclones and cold recursions, which produce maximum precipitation in winter and spring. Some of the precipitation characteristics over high Himalayas have been discussed by Bahadur (1996).

HYDROLOGICAL CHARACTERISTICS OF MOUNTAIN WATERSHEDS

In high mountain watersheds, the runoff contributions do not depend on direct precipitation inputs but on the interaction of precipitation with environmental thermodynamic characteristics variations in energy availability lead to fluctuations in melting of snow and ice and the production of melt-water. Because of the thermal threshold, the snow and ice masses are prevented from entering the liquid phase until the crucial melting temperature has been attained. Seasonal variation in the form of precipitation (from winter snowfall to summer rain) and of energy supply usually peaking to a summer maximum, produce strong seasonal periodicity of hydrological activity in mountains, influencing quantity, quality and timing of drainage. Temporal variation throughout an annual cycle is accompanied by spatial variability of energy availability and precipitation quantity and form, and hence water storage (as snow and ice) within a catchment area.

Precipitation input enters temporary storage if solid, or the drainage if liquid. Subsequently, when produced at the surface, melt-water is released from snow and ice and enters the drainage system. In the first stage of the drainage process, the rainfall or melt-water passes through or across the medium forming the terrain surface. In the network of surface or subsurface flow, rain and melt-waters are routed to the catchment outlet to form runoff. The 0°C threshold is important in determining behavior in the storage component links of the chain. The structure of the basin hydrological system through which the precipitation is transformed to runoff is complex, not only because of the existence in storage of water in the solid state but also as a result of changes which occur in storage as snow undergoes metamorphism to firn and subsequently glacier ice. A further complication is that the initial drainage process for leading liquid water form the site of production precipitation is often related to movement of water through the mass of the stored solid water, either in snow-pack or on the surface of the glacier ice. The movement of liquid water through various forms of its own solid phase, in diffuse and concentrated flow is of critical importance for the response characteristics of high mountain catchment areas. A glacier is a present, stable and fixed-location feature of a basin throughout an annual hydrological cycle, but the snow-cover, which covers both the ice and ice-free areas in winter months is transitory, and variable in areal extent and spatial distribution. Snow-pack acts as a source of melt-water production and as a substrate through which melt-water and rainfall have to drain. In this role, variable spatial distribution of snow-cover during the year determines the changing proportion of the basin area under glacier ice which is available for melt-water production and which acts also as a drainage substrate. Therefore, through time, the quantity of the liquid water drainage reflects only energy supply variations but also changing locations and proportions of catchment area contributing liquid water to runoff.

The high mountain hydrological system may be subdivided into glacier-covered and ice-free zones. In some catchment of high relief, permanent ice may be absent, as every year all the accumulated snow melts during summer. In other mountain basins, some snow will persist from one year to the next, at higher elevations nourishing glaciers-cover over a portion of basin area, whereas in the remainder, almost all the ice will melt leaving a few residual snow patches, which may persist through nival (ice-free) and partially glacierized basins are that glacier ice melt provides a source of runoff throughout summer, from the time at which snow first clears from the glacier tongue, and that the lower albedo of ice, by comparison with snow leads to higher meltrates.

Just as quantities of precipitation vary, between mountain ranges, within mountain ranges, seasonally and from one year to another, types of precipitation also vary; the freezing elevation is not constant and thus the proportions of rain and snow from place to place and through time vary considerably.

In high mountain areas, over an annual discharge cycle, specific runoff is generally higher than in surrounding plains because of greater precipitation inputs and reduced evaporation. With increasing elevation of basin, specific runoff is usually enlarged. This statement must be modified for some of the higher mountain ranges where there is a reduction in specific runoff at greater elevation. It also needs to be modified for most glaciers on which specific runoff is greater on the low-lying ablation areas than on other higher-level accumulation areas. However, the distinctive characteristics of high mountain runoff relate to the timing of flows. Because some of the precipitation accumulates in snow-pack during winter, at temperatures below the melting point of 0°C, much runoff is delayed from the time of precipitation until later in the year. Not only is the solid form of precipitation retained, but also rain falling over a snow cover is absorbed and retarded. Flows of streams and rivers in mountains are therefore concentrated in spring and summer months where water is released by melting from snow and ice.

By contrast, winter discharges are lower of negligible, according to the duration below freezing, controlled by the frequency of fluctuation of the freezing level. Mountain runoff largely reflects change in heat available for melting. Whether the melt is derived from seasonal snow-cover alone or from a basin also containing perennial snow and glacier ice, runoff is a hydrological response to variation in thermal conditions.

In addition to storage as snow and ice, liquid water may be stored in glaciers and in marginal lakes against glaciers. An outstanding characteristic of glacial runoff is the occasional outburst flood created by sudden drainage of large quantities of water stored in glacial, sub-glacial and ice-marginal sites. Even small water bodies or lakes can produce very large floods because of the abrupt release of water. Some lakes may be dump several times each year, others annually, and larger lakes every two or five years.

High mountain hydrology is concerned with problems rather different from those of low elevation areas, many conventional hydrological prediction techniques cannot be used; usual precipitation-runoff models are inappropriate. A unique set of physical hydrological processes is associated with snow and ice in mountains. Investigation of these processes requires information about the properties of snow and ice and the behavior of glaciers in addition to an understanding of the components of the usual liquid water equation.

A rough estimate shows that about 50,000 km^2 glaciers cover the Himalayan mountain drain into the world's largest water drainage system of Indus, Ganga and Brahmaputra rivers. Average annual discharges of these rivers and specific water yields for the river basin as a whole and the mountain watersheds (Gao You-Xi et al., 1981) are given in Table 2.

The higher specific water yield for the mountain watersheds is due to orographic lifting at the moisture. The orographic contribution is higher for Indus due to major precipitation in winter months caused by westerly disturbances and is minimum for Brahmaputra due to excessive summer monsoon precipitation. It is estimated that the glaciermelt contributions are more than 50% (vary from 60 to 80%) in the western Indus basin; above 30% for Ganga (vary between 30 and 40%) which is reduced to about 10% for eastern Brahmaputra. It is also estimated that the specific runoff in the Himalayas is at a maximum in the altitude range (1500 to 3500 m) of considerable human activity and the volume is about 515 km^3/year from the upper mountains.

Table 2 Average water discharges of Himalayan rivers

River with measurement station	Average annual discharge km^3/yr	Mountainous watershed	River basin as a whole
Indus near Arabian Sea	207.8	460	163
Ganga at Hardinge Bridge	494.3	975	473
Brahmaputra at Bahadurabad	510.4	1039	922

INDIAN CONTRINUTION TO SNOW AND GLACIER HYDROLOGY

In 1945, a paper on the role of glaciers and snow hydrology of Punjab rivers was presented by Kanwar Sain (1946) at the Annual Research Committee of Central Board of Irrigation. At that time, it was felt that the snow and glaciers form very important natural storage reservoirs of water for the Punjab Canals and it was highly desirable that a proper account of these reservoirs is kept to forecast discharge of these rivers. Snow surveys are required for forecasting river discharges from March to June.

Following the above, Dr. J.E. Church, formerly President of the International Commission on Snow and Glaciers was invited by the Govt. of India to initiate snow surveys and stream flow forecasting in the Himalayas and to train the necessary personnel in the specialized field of high altitude science. A good description of the collaborative effort of various departments of the Govt. of India has been compiled by Dhir and Singh (1956). Unfortunately the work was not persued with vigour due to hardships involved in the field yet and lack of adequate financial support. At that time, Dr. Church recommended that the students trained in geophysics and various sciences connected with the hydrology be selected from various universities to provide a keen observation of all the phenomena connected with water in the Himalayas. Even a Mountain Snow Laboratory can be visualized to lead and inspire in the forecasting of stream flows. It was observed that the April-June flow of the mountain catchment of the Beas and the Jumna in low, that of Indus, Chenab, Ravi and Satluj is medium, while that of Jhelum is high. The April-July flow is low only for the Beas and Jumna, while five rivers viz, Indus, Jhelum, Chenab, Ravi and Sutlej are high. But, if the entire snowmelt season of April-August is considered, all the streams except the Jumna alone are high and provide to 66.5 to 73.7% of their annual flow. Even the Jumna provides 58.2% contribution. In absence of systematic data on snow and glaciers in Sutlej basin, an attempt was made to study the snowmelt and glacier drainage (Bahadur, 1975). It was observed that the available qualitative snow-fall data best related with longitude, probably due to drifting of snow by strong westerly winds of winter circulation. The character of hydrographs during the glaciological year (March-Feb) at Namgia (2400 m), Rampur (1200 m) and Bhakra (600 m) show the predominance of snow and glaciers melt contributions.

Bahadur et al. (1978) analysed the precipitation data of 25 hydro-meteorological stations and stream flow at 11 gauge and discharge locations in Chenab catchment. Water yield varied from 1.95 m to 2.18 m for various sub-catchment, increasing with the percentage of glaciation. The correlation coefficient between sediment yield and runoff is very strong i.e. 0.87 for rainfall dominated sub-catchments. In a paper contributed (but not presented) to International Symposium on the Role of Snow and Ice Hydrology, Banff, Sept. 1972 Gulati (1973) dealt the subject in a simplest manner and the contributions from glacier melt were not taken into account and monsoon and pre-monsoon months for various Himalayan river streams. Floods of glacial origin were introduced (Bahadur, 1981) highlighting the importance and urgency of initiating multi-pronged scientific studies of Himalayan snow, ice and glaciers with a view to draw larger benefits from this great gift of nature and reduce the damages from flood disasters. Upadhyay and Bahadur (1982) presented hydro-meteorological aspects of precipitation in western Himalayas, analysing 50 years data to bring out altitude effects, windward and leeward precipitation patterns, storm characteristics and specific yields from various Himalayan mountains catchment. Topics like water equivalent of snow-pack location of ice, lenses in snow-packs, regional snow surveys for assessment of water supply, determination of rate snow accumulation, differentiation between snow and glacier melt to river flows, dating of glacier ice, delineation of flow patterns of glacier ice and resurrection of paleo-environments are reviewed (Bahadur, 1986) for application of isotopic techniques for the snow and glacier hydrology.

The extent of snow and glacier melt contributions high altitude for Himalayan rivers is estimated 70 to 80% (Bahadur, 1983) of all the snow and glacier melt runoff occurs during the months of June to Sept, for mountains. It is, therefore, suggested that this huge melt-water contribution could be stored within High Mountain region (3000-4000 m) and could be used for cheap hydropower generation and flood control for regeneration and economic development of the region. Peculiar problems of Himalayan region i.e. high intensity of glaciation, severe freeze-thaw cycle, sedimentation and seismicity are outlined for integrated development of Himalayan water resources (Bahadur, 1983) involving investigators in various disciplines in physical, chemical, biological and social sciences. Principal Himalayan river systems which receive glacier melt contributions are listed in Table 3 with their approximate mountain areas, glacier area and percentage glaciation (Bahadur, 1985) based on the information supplied by the Survey of India, Dehradun and Chandigarh. For the first time, a regression model was developed by Ramamoorthi (1983) to forecast to seasonal runoff of Sutlej from judiciously selected cloud free pictures from NOAA satellite. The forecasts have been within 10% of the actual flow observed.

Table 3 Principal glacier-fed Indian river systems of Himalayan region

No.	Name of river	Major river system	Mountain area (km)	Glacier area (km)	Percentage glaciation
1.	Indus	Indus	2,68,842	8,790	3.3
2.	Jhelum		33,670	170	5.0
3.	Chenab		27,195	2944	10.8
4.	Ravi		8,029	206	2.5
5.	Satluj		4,79,515	1,295	2.7
6.	Beas		14,504	638	4.4
7.	Jamuna	Ganga	11,655	125	1.1
8.	Ganga		23,051	2,312	10.0
9.	Ramganga		6,734	03	0.4
10.	Kali		16,317	997	6.1
11.	Karnali		53,354	1,543	2.9
12.	Gandak		37,814	1,845	4.9
13.	Koshi		61,901	1,318	2.1
14.	Tista	Brahamaputra	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.	Brahmaputra		2,56,928	1,080	0.4
19.	Devang		12,950	90	0.7
20.	Luhit		20,720	425	2.1
	Total		10,01,294	25,724	2.6

Snowmelt Runoff Models (SRM) are used for over three decades worldwide. Problems common to all snowmelt runoff models include (i) definition of spatial and temporal distribution of model input (ii) measurement or estimation of snow accumulation, snowmelt and runoff-process parameters for a large range of basin areas and (iii) development of accurate short-term and long-term snowmelt forecasts.

A SRM was developed and verified for data of Beas river upto Manali by Seth (1983) using the areal extent of permanent and temporary snow cover obtained from satellite imageries, observed data of precipitation for November to May and daily temperatures, the orographic effect on precipitation, melt-water effect on rain falling on snow covered area, simple rating relation was used for obtaining the daily stream flow at the catchment outlet. Kumar et al. (1991) has demonstrated that even with incomplete and fragmented ground data, SRM can be carried out with adequate accuracy for snowmelt runoff forecasts every 15 days interval from to June, 21. The adjustment of model parameters represents a crucial task. In 1992, the authors improved the model forecasts giving 7 days predictions for Beas and Parvati rivers Kumar et al. (1992). Ramasastri (1999) reviewed snowmelt forecasting and modelling studies in India pointing out the gaps in knowledge stating that there is a lot to accomplish towards the state-of-the-art in current modelling approaches. In a recent paper, Singh (2000) reviewed available snow and glacier melt runoff models and the development of a simple conceptual model (SNOWMOD) keeping in view the sparse network of observatories and complexity of the Himalayan basin. In this model, computation of snowmelt and glacier melt is made using temperature index approach. The model is based on area-elevation characteristics of the basin and utilises the relationship describing temperature lapse rate and orographic precipitation distribution. Contributions from various sources are made separately including losses. The ranking of surface and subsurface flow is done sing the concept of linear cascade reservoirs. Results of Beas river basin are presented.

Attention of potential investigators is drawn to recent attempts made for precipitation-runoff simulations for small Himalayan basins (135-340 km^2) in Nepal (Buchtele, 1998) using the conceptual SACRAMENTO model in connection with Anderson's snow model using six years data-set from 1988 to 1992. A set of data collection and modelling efforts are needed for realistic evaluations.

i. Improvement of data-measurement and extrapolation techniques use of new techniques and the continued application of point and areal-measurement technologies need to be investigated. Procedures to expedite the processing and distribution of remote sensing data for near real-time applications needs to be developed.
ii. Development of a river physically based understanding of the hydrologic processes and process interactions involved in snow accumulation and melt and in basin-runoff response. To deal with the complexity of hydrological systems, all the model components rely on empirical relationship. However, when these relations were based on the physics of the process, the parameters

are more likely to be measurable or readily estimated form climatic and basin characteristics.

iii. Development of parameter measurement and estimation techniques that are application over a range of space and time scales. In conjunction with the development of the variability and applicability of these parameters physically based parameters, at different spatial and temporal scales needs to be determined.

iv. Improvement in forecasting techniques to include objective procedure for updating component of the modified system and the forecast itself. Improvement in data quality and availability and in hydrologic process simulation will prove forecast capabilities.

v. Development of modular modelling system and data-management shells for developing, analysing, testing and applying of model components and for facilitating the incorporation of advances made in (i) to (iv). Such shells provide a common framework in which to focus multidisciplinary research efforts on the selection of a variety of problems. Maximum use of current and future advance in the field of expert systems, geographic information systems, remote sensing, information management and computer science needs to be made in the development of these shells.

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