HIGH ALTITUDE HYDROLOGY

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INTRODUCTION

The high altitude hydrology encompasses the studies related to snow and glaciers which are well known prime source of water to the river systems originating from the Himalaya. The spring and summer runoff comprising mostly snowmelt and glacier melt, is source of water for irrigation, hydroelectric power generation and drinking water supply.

The majority of precipitation at high altitudes (above 2500 m) occurs as snow and falls during the mid to late winter period caused by western disturbances. In those parts of earth where rate of precipitation is greater than rate of melting of snow, glaciers are formed. At high altitudes water is stored either in the form of snow or glaciers in the winter when it is least required and released in the summer when it has maximum demand. Moreover glaciers have self regulating mechanism releasing more water in drought years as compared to the wet years. The contribution from the seasonal snowmelt generally starts by March and extends till June/July depending upon the amount of snowfall in the preceding winter season and prevailed climatic conditions. The melt from glaciers starts from late July and contributes till Sept./October.

The snow and glacier hydrology is influenced by the interaction of climate and topography. Precipitation and energy components are two most important climatic parameters affecting the melting of snow and ice. The structure of the basin hydrological system through which precipitation is transfered to runoff is complex not only because of existence of water in the form of solid state but also as a result of changes which occur in storage as snow undergoes metamorphism to firn and subsequently to glacier ice. Investigations to understand the melt processes , the drainage system of snow and glaciers and estimation of the resulting melt runoff are of vital importance for our contry to make proper utilization of the abundant water resosurces available in the Himalayan region.

As such before independence only few visits were made to some selected glaciers and very limited snow surveys were conducted in the Himalayas. The details of these activities are furnished in the following sections. Still the high altitude hydrology is considered one of the challenging subject and requires specific attention for the growth of this subject.

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SNOW HYDROLOGY

The importance of snowmelt studies was felt first time in our country at the Annual Research Meeting of the Central Board of Irrigation (CBI) in August,1945, where late Shri Kanwar Sain presented a paper entitled ' The role of glaciers and snow in hydrology of Punjab rivers'. In this paper ,the necessity for undertaking snow and glacier studies for forecasting run-off in the Himalayan rivers in the critical summer months of April, May, June was stressed. As a result of discussions on this paper, it was decided to invite Dr. J E Church, then President of International Commission on Snow and Glaciers and an authority on snow surveying, to initiate snow surveys in the Himalayas for assessing the need of snowmelt forecasting in the summer months. From the experience gained from the snow surveys conducted in the eastern Himalaya during the spring seasons of the years 1947, 1948, and 1949, it was seen that snow surveying has little utility in this region for snowmelt forecasting. It was reported that up to altitudes as high as 5000 m. (asl) whatever snowfall takes place in the winter months does not accumulate but melts away rapidly due to prevailing high temperatures in this part of Himalayas. The snowmelt studies carried out in the Himalayan region are broadly categorized as studies related with regression analysis , empirical relationships and application of snowmelt simulation models.

Development of Regression Relationships

In most of the studies in this category, regression analysis has been made to correlate snowcover area and runoff. Efforts have also been made to correlate winter snowfall and snowmelt runoff. Generally snow cover area has been assessed from satellite imageries. The low resolution meteorological satellite data and photo interpretation techniques were used by Rango et al (1977) to map snow covered areas during early April over the Indus river using data of 1969-1973. The early spring snowcovered area was significantly related to April through July 31 stream flow in regression analysis for each watershed. Predictions of 1974 seasonal streamflow using the regression equations were found within 7% of the actual flow.

The relationship between snowcover area and run-off of the Beas basin has been studied by Gupta et al (1982). Snowcover area was mapped from Landsat images for a number of years in various subcatchments. The snowcover area and subsequent run-off in different sub-basins was found to be well correlated. It has been interpreted that there have been years of uniformly heavier and lighter snowfall all over the basin and snowmelt discharges have consequently systematically varied. For a particular sub-catchment, the relationship between snowcover area and snowmelt run-off seems to be independent of geographic factors like solar radiation, catchment orientation and relative location. On the other hand, it appears to depend on geomorphological factors such as size of sub-catchment, permanent snowcover area, average altitude, lithology and stream order.

Jeyram and Bagchi (1982) estimated snowline altitude and snow cover using Landsat imagery for Tons basin in Himalayan region. A relationship amongst snowline of Beas ,Ravi, and Tons has been observed. Also, using Landsat imagery a relationship between the snowcovered area and time from beginning of snowmelt season (1st April) has also been established for Tons basin.

Lean season discharge of Sainj river, a tributary of river Beas has been studied by Krishnan (1983) in reference to winter snowfall and discharge to establish the relationship between two variables. The studies have revealed that both these parameters have a fairly high correlation coefficient of 0.91. Based on this study, a simple linear regression model was evolved to forecast three to four months in advance, the lean season discharge of Sainj river solely on the basis of winter snowfall. To verify the validity of model, developed on the basis of data for the years 1967-68 to 1978-79, expected lean season discharge for the years 1979-80 to 1981-82 were computed against the observed discharge and were found to exceed 5%, 9% and 23% respectively. The studies have also brought to light that on an average 31% of annual flow of river Sainj is derived from seasonal snowcover. It was also concluded that in the absence of snow course data, total winter snowfall at a place is good indicator of lean season discharge of the nearby rivers.

Dey and Goswami (1983) have presented results of studies involving utilization of satellite snowcover observations for seasonal streamflow estimates in Western Himalayas. A regression model relating seasonal flow from April through July, 1974 to early April snowcover explained 73% of variance, of measured flows in Indus river. It has been shown that remotely sensed snowcover area data provides the best available input in empirical snowmelt prediction techniques for the remote Himalayan basins. The study has also indicated high correlation of concurrent flows in adjoining Himalayan basins like Indus and Kabul.

A regression model using percentage of snowcovered area of Satluj basin above Bhakra and seasonal snowmelt run-off (April-June) for years of 1975-1978 was developed by Ramamoorthi (1983,1984,1986) at National Remote Sensing Agency. The delineation of snowcovered area for basin under consideration was made from NOAA imageries of the month of April. This model was used in 1980 to predict the seasonal snowmelt run-off of Satluj. For the forecast the percentage snowcovered area on the days of very heavy snowfall during January to March 1980 were extracted from judiciously selected cloud free NOAA imageries. At the end of June 1980 it was found that the difference between the forecast quantity and observed flows was 9%. This model was subsequently modified while giving seasonal snowmelt run-off for the years of 1981 and 1982.The forecasts as per the revised model were found to be within 10% than the actual observed flows. The seasonal flow forecasts were made for other years also. BBMB (1988) reported that forecasts made by NRSA and the actual flows during period April-June for 5 years period from 1980 to 1984 varied from 18% to 49%. in different years. In the year 1988 NRSA forecast of snowmelt run-off was 8.6% less than the observed flows. Similar snowmelt run-off forecasting models have been developed using NOAA satellite data and used in predicting the snowmelt run-off of Ganga at Devaprayag in the years of 1981 and 1982 which were within 10% difference from actual.

A model of snowcover area versus run-off against a concurrent flow correlation model in the Western Himalayas has been evaluated by Dey and Goswami(1984), using data of Satluj,Indus, Kabul and Chenab rivers. It was found that the concurrent flow correlation model explains more than 90% of the variability of flows of these rivers, while the snowcover model explains somewhat less of the variability in flows. It is mentioned in the study that these rivers carry significant amount of snowmelt run-off, which on an average,account for more than 55% of the mean annual flows. The mean seasonal snowmelt run-off (April to June) in Indus, Kabul,Satluj and Chenab rivers are given as 4027, 851735 , and 1508 cumecs respectively for catchment areas of 162100,88600,38000 and 26155 sq.km. The following relationship between snow cover area and seasonal run-off have been established.

(i) $Y = 0.06493\ X - 0.363325$ for Satluj river (1)

(ii) $Y = 0.472\ X + 4.73895$ for Indus river (2)

Where,

Y = Seasonal run-off (April-July) in $10^9 m^3$
X = Average percent of snowcover of the basin

The importance of permanent snowcovered area in any study of snowmelt in Himalayan basins was brought out by Furguson (1985). A study was carried out for glacierized mountains (upper Indus in Pakistan) and a model was developed for annual variation of run-off and its forecasting . The approach is based on identification of a number of glaciological and climatological factors other than snowcovered area. Neglecting the rainfall run-off and ground water discharge, and also losses, the total melt water run-off has been assumed to be sum of three components : (i) complete melting of a glacier snowpack, (ii) complete melting of glacier ablation snow cover, and (iii) glacier ice melt from a contributing fraction of area. The useful information is provided about characteristics of high mountain basins in Himalayan region based upon 1975-1978 data. The details of the results are given in Table 1.

Table 1: The Snowcover and Run-off Characteristics

S No.	River basin	Area sq. km	Run-off mm(mean) Apr-Aug.	Snowcover (%)	Icecover mean estimates (%)
1.	Hunza	13000	763	88	38
2.	Gilgit	26000	578	86	27
3.	Indus	160000	303	83	11
4.	Shyok	33000	292	93	9
5.	Jhelum	25000	644	74	2

Roohani (1986) related the information about extent of snowcover obtained from the Landsat MSS images for months of March to June with the snowmelt run-off assumed as total flow minus base flow for different sub-basins of Chenab basin. A general linear relationship has been obtained . It has been found that as the catchment size increases the regression lines , fitted for snowcovered area and subsequent premonsoon cumulative run-off are successively right shifted along the X-axis. There is also a systematic variation in slope of the regression line for different sub-basins. This is related to interplay of several factors like catchment area, permanent snowcover area , average altitude of the sub-basin , relief and channel slope,all of which can be generally considered together in terms of a single parameter i.e. stream order . The relationship obtained after the analysis of available information about snowcover from satellite images is useful in predicting subsequent snowmelt run-off in sub-basins of Chenab basin cumulated up to June 30, if the snowcover area is known at any stage after the end of snow accumulation . In this study, the analytic approach of SSARR model was found appropriate for expressing the relationship between snowcover depletion of any sub-basin and corresponding snowmelt run-off. The simple model structure based upon split watershed approach, subdividing it into permanent snowcovered, temporary snowcovered and snow free areas, and also dividing into melt and nonmelt areas using daily data of temperature and lapsed at a rate of 6.5 °C /km, change in elevation, has given a good performance in simulating daily flows. Base temperature of 0°C and rain freeze temperature of 0.56 °C have been found appropriate. The melt of snow has been computed using simple degree-day method, assuming initial melt rate on 1st March as 0.38 mm/°C/day and varying (increasing) it linearly using appropriate rate for sub-basin.

Mohile et al (1988) carried out a study to develop a regression relationship between temperature of Kaza and snowmelt runoff collected at a proposed dam across Spiti river 4 km upstream of Kaza at an elevation of about 3639 m in the Satluj basin. The extension of discharge data at the proposed dam site was made based on this relationship. Efforts were also made to develop a relationship between discharges of Kaza and Namgia in the same basin.

The correlation between snow temperatures and air temperatures has been established by Upadhyay et al (1981). However, these relations are valid for the months of January and February when air is found normally to be colder than snow surface. The study on heat transfer in seasonal snowpack has indicated that heat transfer from one part to the other part by conductions is restricted only to a few centimeters because of poor thermal conductivity of snow crystals. The bottom layer remains always near 0°C owing to ground heat whereas the upper layers of snow cover are influenced by temperature of atmosphere and exhibit diurnal variation.

Application of Empirical Relationships

Several snowmelt studies using empirical relationships between temperature and snowmelt runoff have been made. Such empirical relationships are generally a function of degree . day factor and snow cover area. Thapa (1980) estimated snowmelt by considering melt due to the influence of temperature and rainfall in the snowcovered area for Beas catchment up to Larji. A technique for estimation of snowmelt run-off during premonsoon period was studied. An attempt has been made to study the relationship between snowcover, acquired with the help of satellite imageries. and the cumulative discharge of the months of March, April and May of the year 1973.

1975,1976 and 1977. An exponential trend has been observed. Efforts have also been made to identify and delineate the vegetal cover and land use features using visual interpretation technique. Due to availability of the limited meteorological and hydrological data , the study for estimation of snowmelt run-off has been confined to the sub-basin upstream of Manali. The sub-basin has been divided into permanent and temporary snow covered zones. The degree-day method and the melt due to rainfall on snow have been used to estimate to snowmelt run-off. With several trials the degree day factor of 0.0018 cm/°C/day for March and April and 0.00315 cm/°C/day for May have been assigned for the years 1977, 1978 and 1979. The snowmelt is then routed from various zones to the outlet of Manali catchment taking into account the recession coefficient as 0.90. The excess rainfall run-off from temporary and permanent snow covered zones and excess rainfall from the non snow covered zones also included. The run-off coefficients of o.595 and 0.275 have been calculated for the rainfall on the snowcovered and non snowcovered areas respectively. Since the time of concentration in the catchment is less than one day the run-off due to rainfall on the non snowcovered area is superimposed on the same day on the calculated hydrograph obtained from the snowmelt and the run-off from the rain falling on the snow covered area.

Bagchi (1981) carried out a study of snowmelt run-off in Beas basin using satellite imageries. For determination of snowmelt temperature index method was used assuming a lapse rate of 6.5°c/km. The value of degree day factor was considered as 2.1mm /°C/day . For finding effective precipitation at different altitudes in the Beas catchment, a coefficient as an orographic increase factor was used. It was shown that this coefficient increased from unity to 3.25 with a change of altitude from 1900m to 4000 m and then decrease to 0.9 at 5900 m. The percentage of snow in total precipitation has been assumed as a function of minimum daily temperature of the station.

An empirical model for prediction of snowmelt run-off in Satluj basin has been used by Upadhyay et al (1983). The empirical model for the computation of snowmelt run-off has been presented as a function of degree day factor. A techniques for computing total discharge with the input of rainfall, area of homogeneous state with a given rainfall, soil moisture deficiency, ambient air temperature ,wet bulb temperature, wind, altitude of freezing level, glaciated area and albedo has been evolved. Analyzing past 50 years data of rainfall and discharge of the basin, snowmelt and rainfall components have been presented as two distinct series. Upadhyay et al(1983) also analyzed the various components of energy input to a snowcover and monthly budget for net energy available for snowmelt have been worked out for a number of stations in Himalaya. Estimations of short-wave radiation, long-wave radiation, convective transfer and latent heat of condensation have been made by indirect approach using meteorological data on temperature, vapour pressure, wind and cloudiness. Chatterji and Chopra (1976) have studied snowmelt contribution in Satluj catchment for the purpose of flood and low flow forecasting of Bhakra reservoir. The average value of degree day factor was assumed as 0.05 inch per °C per day. 60% of rainfall was considered as contributory to run-off while 90% of snowmelt was considered as contributing to run-off.

The snowmelt run-off generation for a sub-catchment of Beas basin was made by Agarwal et al (1983), using point energy and mass balance approach. The contribution of various energy sources in different conditions was also worked out. Melt run-off has also been estimated using degree-day method. Melts thus arrived at have been compared with the observed run-off. Study was based on the ground data for the year 1981-92 collected from a snow courses located in the sub catchment. Results indicate that although net radiation balance remains the dominated source of melt energy, yet sensible and latent heat contribute in the range of 40% to 60% in total energy for the altitudes below 3000 m in the open areas during clear and partly cloudy days in the active snowmelt period. The effect,however, becomes insignificant during cloudy days and longwave radiations. The positive longwave radiations take over the process of melt. The influence of radiations on cloudy days ranges from 20% to 34%. It has been demonstrated that flow generated through energy balance method generally agrees with the observed flow. However, the melt run-off determined through degree-day method shows variation up to + 226%. The results clearly demonstrate the relative merits of energy and mass balance method over the conventional degree-day method. It is also reported that low status of the generated flow using energy balance method and its variation with respect to the observed one has many contributory factors such as inaccurate delineation of physical parameters due to non availability of large scale maps, inaccurate knowledge of the extent of forest canopy density, lack of knowledge of the behaviour of reflected longwave radiations during partly cloudy days, non use of the principles of liquid water transmission through the snowpack, omission of routing techniques and the inaccuracies in the observed flow.

Jeyram et al (1983) have made study on snowmelt run-off computation for Beas river catchment up to Manali. Using the areal snowcover information obtained from Landsat imageries for the period April to July ,1971-1976. The basin area was divided into twenty altitude zones having each 200 m elevation difference. The daily snowline altitudes were obtained by linear interpolation of depletion curves . Every tenth day snowline elevation values are plotted against time from April-July from 1971-1976. The close examination of these curves indicated that snowcover depletes slowly in the month of April to mid of May and as soon as a small portion of the cover melted ,snowcover depletes very fast in the month of May and June. The comparison of depletion curves over a period of six years showed the similarity in the shape but shifted in time. This time shift is function of the volume of snow stored in the watershed. The study of relative displacement is useful in providing a rough estimate of volume of water produced when it melts. For computing daily melt, maximum daily temperature has been used alongwith a value of degree-day factor of 2.1 mm/°C/day. The lapse rate of temperature has been assumed to be 6.5°C/km for obtaining temperature at mid altitudes of different elevation zones from temperature at the gauging station. The recession coefficient has been taken as an nonlinear function of discharge. The value of R^2 for performance of model varied from 0.5 to 0.80.

Using nomograms based on energy balance approach a computation for snowmelt run-off was made by Daoo and Shirvaiker (1983). Input data required for using the nomograms were insolation , cloud cover, air temperature, relative humidity ,and wind speed which are routinely measured at most of the weather stations. Estimates obtained from nomograms compare well with observed data from Beas catchment for clear or partly covered sky conditions. The computation was made for the months of April, May and June of 1969. However, for overcast or near overcast conditions, (> 0.70

), the nomograms underestimated the melt rates by a factor of about three. This is because of bulk parameterization formula for net long-wave radiation flux always overestimates the actual flux for overcast conditions (Kondratyev, 1969), underestimating the net radiation flux and resulting in underestimation of snowmelt rates. Delay period for snowmelt water to reach the gauging point has also been approximately established.

An approach for estimation of maximum water equivalent of snowcover and time distribution of snowmelt from April to June using features like area - elevation relationship, freezing level, surface temperature, was presented by Abbi et al (1983). Monthly snowmelt has been computed using degree-day concept and compared with actual observed discharge at Kullu ,at the confluence of Beas and Parvati river with a view to evolve a relationship for forecasting discharge on the basis of snowmelt. Considering the variation in elevation, the watershed has been divided into two district zones namely where the precipitation occurs as snow during winter and where the precipitation occurs in the form of rainfall.

Upadhyay et al (1985) have shown for Beas and Satluj basin that snowmelt caused by incoming solar radiation is predominant over other physical processes such as longwave energy transfer at the snow air interface,the convective heat exchange and latent heat released by condensation. It has also been shown that the degree-day approach for snowmelt computation does not exhibit significant difference from the results obtained by thermal quality approach. The degree-day approach was recommended for operational use because of the relative ease in computation.

Application of Snowmelt Simulation Models

Only limited studies have been made either to develop or testing of existing snowmelt simulation models in the Himalayas.

A snowmelt run-off model was developed and verified using 1977, 1978 and 1979 years data of Beas river catchments up to Manali by Seth (1983). The model uses the information regarding the areal extent of permanent and temporary snowcover obtained by comparison of satellite imageries, observed data of precipitation for November to May and daily temperature for premonsoon season. The model considers altitudinal effect on temperatures, orographic effect on precipitation, melt water effect of rain falling on snowcovered area. Simple routing relationship has been used for obtaining daily streamflow at catchments outlet. This study also deals with three different values of number of elevation zones viz. four, eight, and sixteen. The eight parameters representing degree-day factor for two parts of the season, losses from the snowmelt, rain on snow covered areas and rain on nonsnow covered area; lapse rate, melt due to rain and routing (recession) factor have been estimated for different alternative number of elevation zones, by pattern search optimization techniques using least squares objective criteria. The cross correlation analysis and sensitivity analysis have also been used for examining reasons for good or bad reproduction of observed flow It was concluded that inspite of limitation of data and simple approach, for all the three years there is reasonably good reproduction of observed direct run-off.

It was found that the results generally improved with increase the number of elevation zones in comparison to those for case of 4 elevation zones as reported by Seth (1981).It has been suggested that as the area for elevation zones have been obtained by interpolation, the results are expected to improve if better information on area-elevation becomes available. The availability of satellite imageries for different times during melt period will also improve the performance of the model.

Singh (1989) has tested the snowmelt run-off model (SRM) developed by Martinec and Rango for Beas basin up to Manali in the Himalayan region for a limited period. The parameters used in this modelling study have been established for the basin. The result of model computation are verified by comparing observed and computed daily discharge for the years of 1978 and 1979. A good consistency has been found between the simulated and measured discharge. The goodness of fit measure has been computed to be 0.83 and 0.61 for the years of 1978 and 1979 , respectively. The higher value of goodness-of-fit measure for the year of 1978 attribute to the good information available regarding snowcover area of the basin.

Quick and Singh (1992) made snowmelt simulation studies in Spiti basin in the Satluj catchment using UBC Watershed Model. The snowmelt estimates and measured streamflows are used in combination to determine precipiataion gradients in the basin. These analysis indicate very large increase of precipitation at higher elevations and give emphasis to the hydrological importance to the high mountain regions which feed both snowmelt and glacier melt. The snowmelt and glacier melt was computed using a simplified energy budget methos which is dependent on daily maximum and minimum temperature data and daily precipitation data. The accuracy for the all three years considered for simulation was found reasonably high.

PROPOSED SNOWMELT MODELLING STUDIES FOR SATLUJ CATCHMENT

A project of snowmelt modelling study has been conceived by the Snow and Ice Panel of Indian National Committee on Hydrology (INCOH) in Satluj catchment up to Rampur. In this river significant amounts of snowmelt runoff are known to contribute to the river flows during snowmelt season. Forecasts of the spring seasonal flows are required for regulation of release in the lean season from Bhakra reservoir by Bhakra Beas Management Board (BBMB). The total catchment area of Satluj is about 56874 sq. km of which 37047 sq. km lies in Tibet and remaining 19826 sq. km in India. There is an adequate network of snow gauges stations of BBMB in the basin. 21 number of snow gauges is maintained by BBMB above Rampur. Snow stakes were also installed near the snow gauges to measure snow depth. Temperature data is available for 5 observatories namely Kaza, Rakchham, Namgia, Kalpa and Rampur for last 6-7 years. The snow cover area would be delineated from the satellite imageries at different periods in the snowmelt season. The Landsat and IRS imageries will be used for this purpose.

It is proposed to carry out snowmelt study using temperature index method because of limited availability of precipitation and temperature data in the basin. The snowmelt models such as UBC, SRM, SSARR and HEC-1 are proposed to be tested for the basin for snowmelt simulation over a period of three years data.

To carry out the study, the catchment would be divided into various elevation zones and temperature would be interpolated / extrapolated using the derived computed lapse rate for the basin. The snow cover depletion curves would be established with time and degree-days as well. The other hydrological parameters of the basin to be used in snowmelt modelling would be established from available data of streamflow and characteristics of the basin. If required , The catchment will be divided into sub-catchments and study would be carried out for each sub-catchment separately and the flows would be routed to the outlet. The model's capability for operational use for forecasting snowmelt contribution would be tested.

GLACIER HYDROLOGY

Interest in snow and glaciers of Himalayas began with observations regarding snowline or the line of perpetual snow early in 1840s (Vohra,1981). The Pindari glacier was first to be investigated upon (Madden,1947) and Himalayan glaciology was accepted as a scientific pursuit by nineteenth century. Few visits to Gangotri glacier were made by Hogson and Herbert (1842) in 1817,Greisbach (1891) of Geological Survey of India in 1891 and Auden (1935) in the year of 1935. During these visits sketch of snout of Gangotri glacier was prepared. Auden prepared the map with reference to the cairns erected by him. He stated that the glacier must have receded by 2400 ft during the last century alone. Write and Ross (Auden,1935) of Survey of India also visited Gangotri glacier in the same year and resurveyed the glacier.

The survey of Gangotri glacier was continued even after Independence. Jangpangi (1958) of GSI visited this glacier in 1956 and surveyed the snout with reference to the cairns erected by Auden. The retreat of glacier was determined to be of the order of about 90 m in 21 years since 1935. Further Tiwari (1967) of GSI prepared a sketch map showing the position of snout of the glacier in 1956 and 1967. He estimated the recession of the snout to be about 600m from its 1935 position.

Historical records of fluctuations of glaciers in Himalayas and trans-Himalayas date back to early nineteenth century but records are widely distributed. However, a good account covering regional synthesis of 112 glaciers since 1812 has been reported by Mayewski and Jeschke (1979). In a gross sense Himalayan and trans-Himalayan glaciers have been in a general state of retreat since 1850.

The Indian National Committee for International Hydrological Decade (HYDCOM) in its early deliberations identified a major gap in the information regarding our water resources viz. snow and glaciers in the Himalayas and their water resources potential. The HYDCOM set up a High Level Committee on Ice, Snow and Glaciers areas and assigned to the committee the task of making scientific glacier surveys of glacier areas to assess their water resources potential. The first inter-disciplinary team of scientists for training cum study expedition to Gangotri glacier was sent under the leadership of Dr. C.P. Vohra, then Senior Geologist of the GSI. The other members of expedition were from Departments like the Survey of India (SOI), India Meteorological Department (IMD), Central Water and Power Commission (CWPC) and Defence Science Organisation. The expedition was organised in September-October , 1971 and the water discharge from the glacier determined by the salt dilution technique in early October was reported to been 29.5 cumecs. The relevant geological and geomorphological studies were also carried out by the team of scientists. It included glacier movement along two lines in the ablation zone of the glacier.

Systematic and planned studies could be carried out in India only after 1974. These studies have been grouped in the following broad areas from hydrological studies point of view.

Glacier Inventory

The glacier inventory in the Himalayan region was initiated in 1974 by the GSI after the inception of Glaciology Divisions. The Glaciology Divisions in the Northern Region at Lucknow and in the Eastern Region at Calcutta came into existence in 1974 and 1979 respectively. The first generation of inventory of glaciers in J&K, H.P.,U.P. and Sikkim has been completed by GSI. This inventory covers the number of glaciers, glaciation level and area of glaciers etc with few generalised ideas about the glaciers. The second generation of inventory is in progress. The data on second inventory is under compilation for publication (Sahai,1992). Kulkarni (1991) used satellite images for the purpose of glacier inventory. The literature reveals that various authors have shown different number of glaciers in the Indian Himalayas. A brief summary has been given by Rao (1992).

Mass Balance Studies

Glacier mass balance is the most meaningful description of its hydrological cycle and a way to evaluate the water storage aspects and associated processes of snow movement, variation in glacier thickness, erosive and deposition capacity resulting in creating the glacial landscape. Mass balance in considered as the life history of a glacier at any particular time stage. It is either positive or negative displaying a surplus or deficit of ice on the glacier body. Surplus mass balance results in glacier advance while deficit results in glacier retreat. The main part of the change in mass is usually assumed to take place in a relatively thin surface layer of the glacier (Bahadur,1992). It is mainly related to temperature and precipitation but other micrometeorological elements e.g. radiation, humidity, evaporation and wind velocity and direction also play their role in altering the balance. Such studies require a long term (5 to 10 years) monitoring of the glaciers considered for the mass balance assessment. Mass balance studies on Himalayan glaciers are limited (Raina et al.,1977; Kaul,1990)

Mass balance studies were first initiated in India at Gara glacier is Satluj basin in 1974 by GSI and studies were continued till 1983 i.e. over a period of ten years. The reconnaissance work to this glacier was done in 1973. The mass balance was measured to be positive during 1974-75 and 1975-76 balance years and since then it has shown a negative mass balance. The similar studies also have been conducted by GSI at Neh-nar glacier (J&K) (1975-1984). The glaciological studies on this glacier were taken under IHD Programme. This glacier was selected as a representative in the Sindh Valley, a tributary of Jhelum. The glacier has shown a negative specific budget between 1977 and 1982.

The Gor-garong glacier (H.P.) was selected by GSI for detailed glaciological studies in 1976 for studies on south facing glacier for comparing itsresults vis-a-vis a north facing glacier. Studies since 1976 have indicated that this glacier has shown negative mass balance till 1980-81 . It was found positive for next two years and was again negative for 1983-84 . Mass balance studies at Shaune Garang glacier, since 1981, have indicated negative mass balance of the glacier except in 1982-83 and 1989-90 balance years when positive mass balance was recorded.

Tipra Bank glacier (U.P.) was selected in 1981 for glaciological studies by GSI. The specific net balance during the budget years from 1981-82 to 1985-86 was found negative for this glacier. GSI initiated glaciological studies on Dunagiri glacier (U.P.) in the year of 1984. For six consecutive years the net balance has been found to be negative. Similar studies have also been carried out by GSI at Zemu and Changme Khangpu glacier (Sikkim), Harmukh (J&K) and Rulung (J&K).

Sahai (1992) reported that Gangotri glacier vacated an area of 0.243 sq.km during the last 55 years (1935-90). Moreover in the last 13 years (1977-90), the glacier melt water channel (the Bhagirathi) has shifted 30 m with respect to the position of 1977 cairns and has now carved nearly 4m of valley fill.

The mass balance study conducted at Chhota Shigri Glacier (H.P.) has shown negative signature (Kumar, 92).

Glacier Melt Measurements

In order to deciper the quantam of melt water discharge from a glacier during summer months and its fluctuation vis-a-vis its mass balance and weather parameters, melt water runoff is observed by GSI for all the glaciers monitored by GSI for mass balance studies. The water discharge measurements are made at the gauging sites located down stream of the snout of the glaciers, generally, from last week of June to end of September.

More extensive study for glacial melt measurements and its diurnal variation have been carried out for Chhota Shigri glacier under multidisciplinary expedition for the years from 1986-1989. Participants from NIH, CWC and JNU made consolidated efforts to understand the behaviour of flow variation in the melt stream. It was found that generally maximum discharge occurs during day between 1530 hrs and 1900 hrs, while minimum occurs between 0300 to 0800 hrs. The ratio of maximum and minimum discharge was found in the range of 1.35 to 1.59 which indicates that during the nights also a signficant contribution from the glacier was received in the channel due to characteristics of melt water storage in the accumulation zone of the glacier. The time lag between melting at the glacier surface and reaching at gauging site was determined to be between 2-3 hrs.

The maximum flow was observed in the middle of August and minimum in July. The average velocity flow was determined to be 2.238 m/s . During the 1988 expedition, an automatic water level recorder was installed by NIH at the gauging site and stage discharge relationship was established. The density of firn in the accumulation area has been measured to be 0.55 gm/cc. The crystals of the round shape and apoproximately 1 mm in size were found in the snowpack.

During preliminary visit to Kolhai glacier by NIH and Irrigation & Flood Control Dept. of J&K state and SOI was made in the year of 1989 , flow measurements for short duration were made (Singh 1990).

Suspended Sediment Transport

Regular and repeated sampling for the assessment of the suspended sediment in the melt stream is carried out by GSI for the glacier undertaken for study. NIH also estimated suspended sediment transport for the Chhota Shigri glacier by collecting the samples from the channel. The silt load passed on a day varied between 83T/day to 2011 T/day (Kumar, 1992). It indicates that sediment transport characteristics of the melt stream fluctuates widely. No direct relationship could be established between discharge and sediment though broadly it could be concluded that an increase in discharge corresponds to increase in suspended sediment concentration. A drastically high concentration observed on the day of first high peak of discharge is supposed to be due to side wash load stored in moraines, debris and other alluvial fills.

GSI has reported that Lime stone country produces half the quantity of suspended sediment per sq.km. of ice cover, as compared to gneissic or granitic terrain (DST, 1984).

Radio Isotope Study

Since 1977, the Glaciology Groups of Physical Research Laboratory has been engaged in applications of isotopic techniques to study diverse glaciological problems on few selected Himalayan glaciers. During last decade, problems related to ice dynamics (movement of glacier ice, accumulation ratio of ice) based on natural and artificial radio isotopes like ^{32}Si, ^{210}Pb, ^{137}Cs etc. and climatic variations in the Himalayan environment based on stable isotopes have been studied. Basically, these isotopes provide ages (residence time of snow/ice in the glacier) of the glacier ice all along the glacier and provide time index to study various processes and glaciological parameters of different time scales. In the recent years, studies on chemical pollution using chemical tracers on Chhota Shigri glacier have also been undertaken, (Nizampurkar, 1992). These studies were conducted earlier in collaboration with GSI. The physical characteristics of the glaciers with snow ages and average flow rates have been given in Table 2.

A review of isotopic techniques for snow and glacier hydrology has benn made by Bahadur (1983), and Jain and Navada (1983)

CONCLUDING REMARKS

Inspite of the fact that first snow surveys to assess the utility of snowmelt forecast in the Eastern Himalayan region were conducted way back in 1947 under the guidance of U.S. Expert Dr J E Church., the studies on daily or seasonal snowmelt runoff forecasting have not been carried out to the desired level, while these are of prime importance for the management of the water resources of our country. The present status of snowmelt studies shows that only regression relationship between snow cover area and runoff has been established for Satluj catchment.Very limited studies on snowmelt pocesses and simulation of snowmelt runoff are carried out. Further, these studies are confined to one or two watersheds and are inconsistent. This may be because of poor network in the Himalayan catchments to observe required data for snowmelt forecasts. In the recent years, the condition of the network in several Indian snowbound catchments has been improved.

Table 2 : PHYSICAL CHARACTERISTICS OF THE GLACIERS WITH SNOUT AGES AND AVERAGE FLOW RATES

Glacier	Location	Altitude (m.a.s.l.)	Length of glacier(km)	Si Modelage (yr.)	Post flowrate (m/yr)	Modern flowrate (m/yr)
Nehnar (Kashmir)	34 09'N 75 31'E	3920-4925	3.4	500	6	>12
*Chhota Shigri (H.P.)	32 15'N 77 31'N	4050-5000	9.0	250	28	23
Gara (H.P.)	31 30'N 78 26'E	4710-5600	6.0	200	20	60
*Gorgarang (H.P.)	31 26'N 78 24'E	4765-5360	3.5	160	18	NA
*Zemu (Sikkim)	27 43'N 88 17'E	4260-6000	26.0	120	200	NA
Chang me Khangpu (Sikkim)	27 58'N 88 42'E	4850-5800	5.8	100	40	13

Unpublished data as on 1.3.1988

The monitoring of snowfall in Western Himalayas at present is being done by India Meteorological Department (IMD) . Central Water Commission (CWC). Bhakra Beas Management Board (BBMB).and Snow and Avalanche Study Establishment (SASE). Snowfall is measured by IMD using snow gauge and snow depth is measured by snow stakes. The CWC has a dense network of 33 stations in Chenab basin using snowgauges and 9 stations in Yamuna basin with a snowpillow installed at Jubbal. The BBMB has a network of 21 snow gauge stations in Satluj basin above Rampur where snow gauges and snow stakes are used for monitoring of snow. The SASE has good network of snow gauges stations at very high elevations in the Himalayas extending from Kashmir to hills of Uttar Pradesh. At some of the locations weighing type precipitation gauges or snow stakes are used and at few locations snowpillows are being used. This enables to carry out the investigations in the field of snowmelt forecasting.

Mostly only precipitation and temperature data is being collected in the Himalayan snowbound catchment. Keeping in view the rugged topography, type of data collecton by the existing network, high altitude based large basins of Himalayas which are mostly inaccessible and hazardous, it is evident that only simple model structures with reasonable physical base, limited data requirements and capablity of using remotely sensed data for snowcover area seem to be appropriate. Attempts are required for regression analysis between available hydrological and meteorological variables for various basins. The snowmelt simulation models based on temperature, precipitation and snow cover data obtained through the remote . sensing technique and having option for dividing the basin into elevation zones may suit to Himalayan catchments. Subdivision of river catchment into elevation zones is considered desirable because of the strong elevation dependent gradients of temperature and precipitation in the mountainous areas. Extrapolation of temperature and precipitation data to various zones would also compensate the limited data availability at different altitudes in the basin. Co-ordinated efforts by different organisations are needed to develop and test the regression or snowmelt models for short term and long term forecasting in an operational mode. In order to get reliable results, the refinements in the models may be done from time to time. Such investigations would offer a great potential as a forecasting tool and means to improve understanding of snowmelt processes.

A number of advances in snowmelt runoff forecasting have been made in the past few decades. These advances resulted from an improved understanding of the physical processes of snowmelt and basin runoff and the development of new technologies in the area of data collecton and computer technology. This has contributed to the development of simple as well as complex snowmelt models which are used for operatonal purpose in developed countries. The snowmelt models such as SSARR, SRM, UBC, NWSRFS required data which is generally available in Himalayan watersheds. UBC has given good results for snowmelt simulation in the Satluj basin (Singh,1992), exercises are to be carried out for snowmelt forecasting. Other models also are to be tested.

As in the case of snowmelt, melting of glaciers is also controlled by energy exchange and topography of the region. Investigations for the better understanding of complex interaction of climate, topography and glacial geometry in influencing the processes of accumulation and ablation are to be made. However, such studies require extensive data round the year for the regions where glaciers exist. The observational network should be designed with a comprehensive view and systematic approach should be adopted to achieve long term goals in expanding the networks of the Himalayas for monitoring of glaciers during the period when these are inaccessible. The automated instruments for the collection of meteorological, hydrological and geological data are needed. Presently no such instruments have been installed at any glacier. The feasibility functioning automated instruments is yet to be tested. Effect of glaciers on streamflow variation is also to be studied

Glacier fluctuations are also to be treated as important observations in context of prediction of runoff into the streams. It can provide a meaningful indication of changes in storage both related to variation in climatic conditions and in connection with meltwater runoff.Remote sensing techniques are quite promising in the assessment of glacier size, location including other relevant characteristic of glaciers. The data base is to be established for longterm and correlation between changes in climatic conditions and glacier fluctuations may also be developed. Since altutide approach to have a long influence on mass balance of the glaciers, the gradient of mass balance with altitude may be a useful information if the glaciers are identified at different levels in the same region. To study the effect of global warming on the glaciers also further need a longterm temperature data and continuous monitoring of the system.

The relationship between glaciermelt runoff and sediment load transport has not been developed for any glacier and need attention because sedimentation is becoming day by day a serious problem is mountainous hydro-electric projects

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