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UNDERSTANDING HYDROLOGICAL PROCESSES OF HIMALAYAN GLACIER REGIME: CHALLENGES AHEAD

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Abstract *This paper focuses on problems associated with the present approach of extrapolating hydrologic and climatic variables using generalised relationship to the glacier regime to estimate the runoff without standardizing the altitudinal response of these parameters within the glacial regime of Himalaya. Distribution characteristics of major glacier runoff variables such as melt rate, temperature, monsoon rainfall and winter SWE are discussed with examples from Dokriani glacier. The need of hydrological and weather data above 2500-3000 m asl, across the Himalayan arc for characterising the hydrological and climatic processes operating in the Himalayan snow and glacier regime and study of its variability in a longer time scale to assess the future changes to the glaciers and to the headwater river runoff, is emphasized. An approach towards undertaking conjunctive studies of glacier, snow and monsoon regimes in the headwater catchments is proposed to model the headwater river runoff variability in Himalayan snow/glacier resource management perspective.*

INTRODUCTION

Runoff modeling of glaciated region of Himalaya is one of the prime objectives of the glaciological research in the country. A good glacier/snow melt runoff model evolves with comprehensive understanding of hydrological processes of snow/glacier regime and related regional climatic processes. Precipitation characteristics of Himalayan arc vary east to west. In eastern Himalaya major amount of perception is due to monsoon as compared to western Himalaya where western disturbances have substantial influence during the winter months. Within a meso-scale climatic zone in the Himalaya, there are areas of varying climatic responses, controlled by the topography of the region, such as rain shadow zones within the monsoon dominated areas. Alford (1985) suggested that the hydrologic regime of a mountain range or an individual basin within that mountain range are determined by the altitudinal interval above sea level occupied by the mountain range, in its interaction with the properties of the synoptic-scale air mass crossing the mountain. Understanding major air mass properties could even help us in explaining fluctuations in glacier growth and shrinkage (Hoinkes, 1968).

Runoff from glaciers of central and eastern Himalayas comprise three major components (1) Snow melt runoff, (2) Glacier degraded runoff, and (3) Monsoon runoff. In the western Himalaya, runoff from glaciated region is largely due to first two processes. Therefore, there is the need of region specific data collection, with an objective to understand regional hydrological and climatic processes across the

Himalaya. The melt water from glacier surface is routed through the glacier storage and drainage system before it emerges at the glacier snout. Hence, understanding of the hydrological processes related to each of these three runoff components and the understanding of glacier storage and drainage characteristics are essential for glacier runoff modeling. This paper focuses on some of major problems related to the runoff and snow/glacier melt estimation, role of monsoon in determining the runoff characteristics of Garhwal Himalayan glaciers and problems associated with the lack data on winter snow water equivalent for runoff models. Further, a monitoring strategy for developing a model for headwater river runoff and its variations induced by the glacier/ snow regime is proposed. The processes related examples presented here are based on the work carried out as part of glaciological studies of Dokriani Bamak glacier. Studies of Dokriani Bamak were initiated in 1991 by the Wadia Institute under the Himalayan Glaciology programme of Department of Science and Technology.

Dokriani glacier is a small central Himalayan glacier in the Ganga basin. It is located in Uttarkashi district of Uttaranchal state. It extends from latitude $30^0$50'N to $30^0$52' N and longitude $78^0$47' E to $78^0$51' E. Total length of the glacier is 5 km. The stream emerging from the Dokriani Bamak is known as Din Gad and it joins with the Bhagirathi River near Bhukki village. Total area of the glacier catchment is 15.7 sq.km., out of which 7 sq.km. is covered with the glacier ice and the non-glacierised area and the seasonal snow cover area above the upper limit of the glacier is 8.7 sq.km.

ACCURACY OF DISCHARGE DATA OF HEADWATER RIVERS

Measurement of glacier melt water discharge at stations close to the glacier have been carried out by various research organizations. Discharge is the most important hydrological data generated from the glaciers and continuous runoff data for number years are important for understanding any hydrological system. Runoff variations in the headwater rivers are assimilation of various hydrological processes and their variability operating in the catchment. Hence, the processes related studies are greatly dependent on the discharge data. In runoff modeling observed discharge data is used for calibration and validation. Hence, the accuracy of discharge measured at headwater hydrometric stations are imperative for a reliable runoff model. At present most of the agencies involved in the glaciological studies in the country use Area-Velocity Method to compute stream discharge by measuring the stream flow velocity by float method. This is an unsuitable method for discharge measurements of turbulent streams of Himalaya. Under the turbulent conditions, float method produces 15-20% error in the discharge data and more for streams with higher discharge. Hence, continuation of discharge measurement by float method needs to be replaced by alternative method with higher level of accuracy for glaciological studies in the country. Current meter has its limitations to measure flow rate of turbulent streams. Construction of flow measuring structures in the high altitude is not an easy task. Under the given conditions, dilution technique using fluorescent dyes offers a viable solution; this technique has been successfully used in Nepal. Advantage of this method is that it dose not require either area or flow velocity information. The only requirement in this method is that the stream should be turbulent enough for effective mixing of dyes within the selected mixing reach of the stream. High turbulence of the mountain streams is advantageous for effective mixing at a shorter mixing length. Improvement in the quality of discharge data collection system of glacial streams in the country holds the key for the development of viable working glacier runoff models.

VARIABLE MELT OF GLACIER SURFACE - SOME OBSERVATIONS

Quantification of glacier degraded runoff component is achieved by mass balance studies. Proper networking of ablation stakes over the glacier surface also provides valuable information on surface melt distribution. Varying melt rate of glacier surface is clearly demonstrated in the results obtained from Dokriani glacier. Melting of Dokriani glacier was monitored regularly by 42 ablation stakes spread across the ablation zone during the ablation period (May-October). Figure 1 shows surface melt distribution of Dokriani Glacier during the past four years.

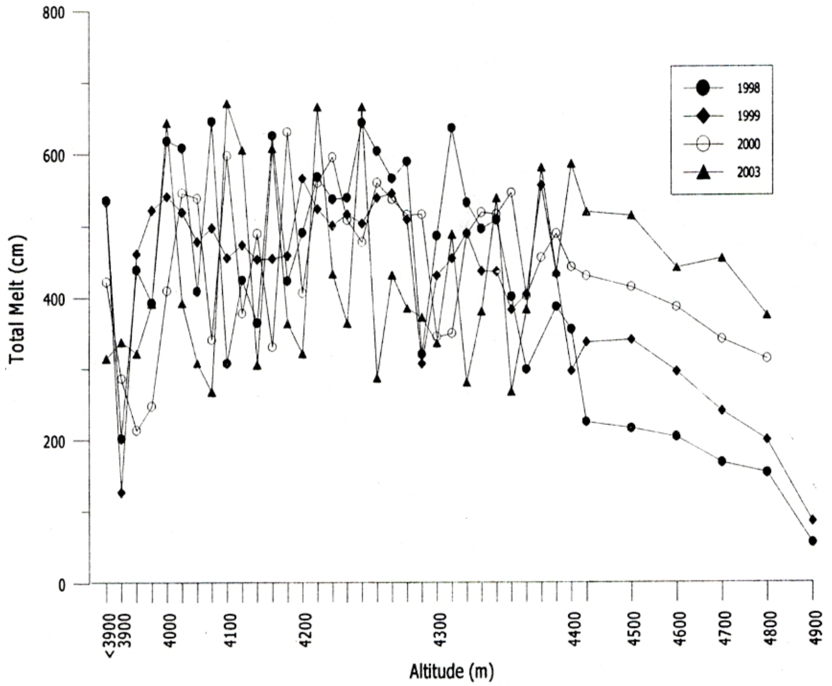

Fig. 1 Glacier surface melt distribution in 1998, 1999, 2000 and 2003 ablation season of Dokriani glacier, Garhwal Himalaya. Varying melt rate at lower part of the ablation zone below 4400 m asl is well demonstrated. Increased melting at higher elevations in subsequent years since 1998 is intriguing.

Variability in surface melt rate of the glaciers is governed by the extent of supra-glacial debris cover, position of snow line (glacier surface characteristics determining the Albedo), topographically controlled climatic sub-zones within the glacier catchment, formed by aspect factor and shading by surrounding topography on solar radiation receipts and effect of glacier surface slope (which influence the temperature and precipitation characteristics of the sub-zones). Thick cover of supraglacial debris covers ablation zone of the glaciers of eastern and central Himalaya. Supraglacial debris predominantly cover the lower part of the ablation zone, areas which are most susceptible to higher melting.

Experiments conducted to establish the melt pattern under debris cover, in Nepal Himalaya by Fujii (1977) suggest that the ablation rates are accelerated under a thin debris layer and are retarded under a thick one as compared with that of a natural snow surface. The critical thickness for snow (the debris thickness at which the ablation rate is same as for clean snow/ice) was found to be 1.6 cm and acceleration of ablation was greatest under 0.5 cm thick debris cover. In Sweden (Ostrem, 1959) and in the Japanease Central Alps (Moribayashi, 1972) similar results were reported. Table 1 summarises the information of melt under debris cover from various glacial regimes.

Table 1 Information related to the melting under debris cover from different mountain regions

Glacier	Critical thickness (cm)	Effective Thickness (cm)	Degree Day factor	Source
Rikha Samba Glacier, Nepal (of snow)	1.6	0.5	-	Y. Fujii (1977)
Khumbu Glacier, Nepal (of ice)	5.0	-	Bare Ice 16.9 mm °C^{-1} d^{-1} 10 cm debris layer 11.1 mm °C^{-1} d^{-1} 40 cm debris layer 5.3 mm °C^{-1} d^{-1}	Kayastha et. al (2000)
Isfallsglaciaren, Sweden (of snow)	1.5	0.5	-	Ostrem (1959)
Japanease Central Alps (of snow)	1.5	0.5	-	Moribatashi (1972)
Kaskawulsh glacier, Alaska (of ice)	5.0	1.0	-	Loomis (1971)
Lirung glacier, Nepal (of ice)	-	2.6	Albedo Debris - 0.11 Clean ice - 0.4	Rana et. al (1998)
Dokriani glacier, Garhwal Himalaya	-		Clean snow 5.8mm °C^{-1} d^{-1} Dusted snow 6.4mm °C^{-1} d^{-1} Clean ice 7.3mm °C^{-1} d^{-1} Dusted ice 8.0mm °C^{-1} d^{-1}	Pratap Singh et. al (2000)

More detailed studies are required to understand the melt processes under debris cover better. Some of the factors which need to be investigated are role of debris size, albedo of debris cover, heat fluxes within the debris layer and heat transfer characteristics of different rock types. However, in most glaciers in Himalayan region, debris cover area is, occupied by thick supraglacial debris layer above the critical thickness, ranges up to 5-7 m and retard the melting. Ablation data of Dokriani glacier in 2003 demonstrated that the annual average ablation of clean ice area was 4.4 m w.eq., and under the debris cover area it was 3.04 m w.eq. In a study of Lyman and Columbia glaciers in North Cascade, Washington, annual ice ablation was 3.3 and 3.4 m w.eq. for clean glacier ice area and 2.3 and 2.6m w.eq. under the debris cover area (Pelto, 2000). Another comparative study of debris cover and debris free glaciers from Canadian Rocky mountains demonstrated that the thick debris cover could act as a regulator of stream flow producing less annual variation in discharge, compared to the debris free glacier (Mattson, 2000).

The linear models used in glaciology such as degree-day models fail to incorporate these wide variability in the surface melt processes. The solution to this problem is to work towards developing a distributed physically based model, which takes care of the effect of glacier surface slope, aspect and shadow by the surrounding topography on solar radiation receipts, glacier melting under debris cover and snowline recession and related surface albedo changes. The pre requisite for developing a distributed glacier runoff model is a Digital Elevation Model (DEM) of the glacier catchment. The topographic information of glacierised regions of the country is available from the Survey of India toposheets published in 1962. As glacier is one of the most dynamic system on earth, any DEM developed using these toposheets will have major difference with the present day surface topography of the glacier, including overall shrinkage of glaciers during the last 40 years. Further more, the scale of available maps (1:50,000) dose not account for the details of glacier surface topography and the details provided by these maps are far less than required. As a prelude to good glacier runoff models, either for distributed or for linear temperature index modeling, a large scale map is required. The changes in glacier surface topography is a continuing process. During the shrinking phase, ablation zone of the glacier develops more ice cliffs and crevasses that increases the effective ice surface area available for melting and new areas of ablation zone enter into the debris covered zone. To account these changes, we should have a glacier surface topography monitoring programme for selected typical glaciers with a defined interval to produce quality data base for glacier runoff models. Table 2 shows morphogeometrical changes of Dokriani glacier between 1962 and 1995 based on SOI maps.

TEMPERATURE INDEX MODELING AND VARYING LAPSE RATE OF ALPINE ZONE

Research during the last few years on Dokriani glacier threw up some interesting glacier melt processes related problems. Figure 2 shows mean monthly temperature at base camp during the observation years of 1994, 1998, 1999 and 2000.

Table 2 Surface topography changes deduced from 1962 and 1995 SOI maps of Dokriani Glacier.

Parameters	1962	1995
Glacierised area	11.17 km^2	10.20 km^2
Glacier area	7.78 km^2	7.00 km^2
Accumulation area	-	04.84 km^2
Ablation area	-	02.16 km^2
Glacier length	6.0 km	5.5 km
Snout position	3810 m	3882 m
ELA	-	4995 m
Elevation range	3800-6000 m	3900-6000 m
Average thickness	55 m	50 m
Surface slope	11°	12°
Ice volume (w.eq.)	385.11.8x10^6 m^3	315.0x10^6 m^3

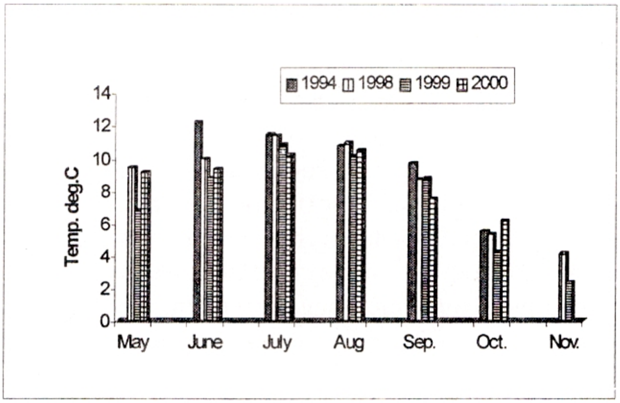

Fig. 2 Mean Monthly temperature at Base camp during the ablation seasons of 1994, 1998, 1999 and 2000.

It was observed that the base camp experienced reduced mean monthly temperature in many months in consecutive years. If we extrapolate this temperature to the glacier surface by using the standard temperature lapse rate values (0.60°C/100m) and standard degree day factor we will be getting less melting in corresponding years. However the mass balance measurements during these years showed increased glacier degraded runoff. (Fig. 3). So we have a situation in which reduced temperature at base camp producing higher melt over the glacier, clearly suggesting higher temperature regime over the glacier in spite of lower temperatures measured at base camp. The enhanced thinning of glacier surface over 4400 m is also evident in the ablation stakes measurement (Fig. 1) and the accelerated thinning was persistent through out the observation years

To understand this phenomenon we investigated the variations in the slope lapse rate values during the observation years within the Alpine zone as well as on valley scale by making use of temperature data collected from three meteorological observatories at Tela (2540 m asl), Gujjar Hut (3483 m asl) and Base Camp (3763 m asl). The results revealed some interesting patterns as discussed in subsequent sections.

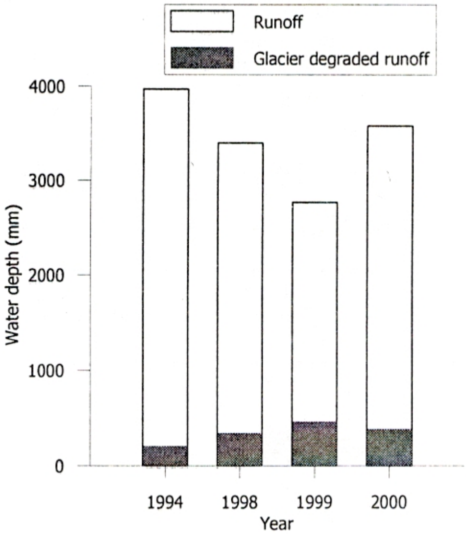

Fig. 3 Mass balance and runoff of Dokriani glacier during the past few years. Increasing negative mass balance in consecutive years.

Monthly and Yearly Variations in Slope Lapse Rate

Summary of monthly lapse rates of slope air temperature between the station pairs during the three observation years are given in Table 3. During this period monthly variations of lapse rate in summer months have been minimum between the Tela-Base Camp station pairs, ranging between 0.71-0.50^0 C per 100m, with an average lapse rate of 0.59^{0}C /100m. Lapse rate between these two stations represents the valley scale lapse rate of Din Gad basin was 0.81^{0}C/100m in May 1998. Between Tela and Gujjar hut stations, the highest monthly mean lapse rate value recorded among the station pairs and the lowest value between this pair was 0.52^{0}C/100m in August 1998. Monthly variations in lapse rate between Gujjar Hut and Base camp station was the highest, within the range of 0.71^{0}C in June and July of 1998 to 0.28^{0}C/100m in November 1999 with certain periods in October and November experiencing temperature inversion characteristics. These station pairs in the alpine zone show distinctly lower lapse rate in 1999 and 2000 as compared to the 1998 values. Lapse rate during the peak ablation months of 1999 and 2000 June, July and August, was 40-50% less when compared to the values calculated for the same months in 1998. Lapse rate values of June, July and August months in 1999 and 2000 were close to the lapse rate values reported by Legates and Willmott (1990), 0.30/100m for July at an altitude of 3010m in Himalaya. It can be suggested that the sparse snow cover during 1999 and 2000 resulted in more homogenous warming in the higher altitude, causing lower temperature variations between the meteorological stations. Temperature at meteorological stations located at the lower altitude seems to be unaffected by the variations in the snow cover at higher altitude. This is evident from the lower monthly variations in lapse rate during these three years between Tela-Base camp and Tela-Gujjar hut pairs. These results suggests that the use of constant value for lapse rate for snow/glacier runoff model will lead to large errors in the model out put.

Table 3 Slope lapse rate values between station pairs in Din Gad Catchment during 1998, 1999, 2000 ablation period.

Months	Base camp - Gujjar hut		Tela-Base camp		Tela-Gujjar hut
	1998	Average of 1999-2000	Average of 3 years	From (max, min) average of 3 years	Average of 3 years
May	0.36	0.51	0.66	0.52	0.73
June	0.71	0.39	0.62	0.46	0.66
July	0.71	0.39	0.54	0.33	0.55
August	0.67	0.37	0.53	0.34	0.55
September	0.70	0.33	0.58	0.37	0.61
October	0.56	0.30	0.61	0.35	0.70
November	-0.13	0.28	0.60	0.31	0.76

Selection of Slope Lapse Rate for Modeling Glacier Hydrological Processes

Table 4 summarises the lapse rate values reported from different mountain regions of the world, demonstrating wide spatial and seasonal variations. These results raise a pertinent question about the selection of suitable altitudinal range for monitoring slope lapse rate for snow/glacier melt runoff models, which would be most representative of the glacier catchment. Comparison of monthly lapse rates derived from three station pairs show considerable variation in the lapse rate values between different station pairs. Three year average of summer lapse rate between Tela-Base camp and Tela-Gujjar hut station pairs are 0.59°C and 0.65°C/100 m respectively, whereas average summer lapse rate of Gujjar Hut-Base camp pair in 1998 was 0.62°C/100 m and average of 1999 and 2000 was 0.36°C/100 m. Hence, it can be suggested that the use of valley scale lapse rate to determine the point temperatures at higher altitude may be feasible but calculation of temperature distribution over the glacier by extrapolation, as required for temperature index glacier runoff models using valley scale lapse rate, may introduce large errors. This study suggests a change in slope of the lapse rate gradient above 3000-3500 m of the Din Gad catchment along the main axis of the valley. Lapse rate below this elevation shows less monthly and yearly variation and the station pair above this zone shows substantial monthly and yearly variations, mainly attributed to the snow cover variations and related manifestations. Considering these altitudinal variations in lapse rate, it is suggested that the lapse rate observed in the alpine zone of the catchment is the representative lapse rate of the glacier catchment.

Table 4 Summary of slope lapse rate values reported from different mountain regions (cited in de Scally, 1997)

Location	Elevation Range (m)	Time of the Year	Average lapse Rate	Author
Mt. Fuji, Japan	3500	February	0.61	Yoshino (1966)
		November	0.54	
Great Britain	300-1300	Annual	0.84	Harding (1978, 1979)
		Winter	0.6-0.7	
		Spring	0.9-1.0	
St. Elias Mountains, Canada	2600	July	0.56/0.52	Marcus (1969)
	1850	July	0.65/0.82	
			Night/Day	
Appalachians, U.S.A	1500	Annual	0.59	Pielke and Mehring (1977)
		May-Oct.	0.63	
		July	0.66	
		October	0.52	
Hawaii U.S.A	?	Annual	0.55	Blumenstock & Price (1967)
Andes, Columbia	5000	?	0.45-0.70	Snow (1975)
Alps, Austria	1500	Winter	0.49/0.66	Von Hann (1906)
		Summer	0.60/0.89	
			Night/Day	
Alps, Germany	685	May	0.43	Baumgartner (1955)
Alps, Austria	2800	July	0.63-0.68	Lauscher (cited in Geiger, 1965)
Himalaya, India				
Humid-Kashmir	1490	July (one week)	0.8	Brazel & Marcus (1991)
Arid-Ladakh	1930	July	1.0	
Himalaya, India/Pakistan	3010	July	0.30	Legates & Willmott (1990)
Punjab Himalaya, NWFP, Pakistan	2410-4200	May-August 1986 and 1987	0.48-0.78	F.A. De Scally (1997)
Himalaya, Nepal	3350	Annual	0.51	Doremez (1976)
Karakoram, Pakistan	1200	Sept-Oct	0.78	Kuhleand Ludecke (1989)

However it is prudent to assume that the lapse rate between the station pair over the glacier will be less than the lapse rate of closest pairs in ice free area, especially when the glacier catchment experience heavy monsoonal rains in the summer ablation months. Hence, most accurate lapse rate values for snow/ice melt model can be derived only rom station pair established over the glacier itself, but has operational difficulties in the field conditions of Himalayan glaciers. However, given the important of more accurate lapse rate values on model out put, future lapse rate studies for glaciological studies in the Himalaya needs to be concentrated in the alpine zone of the catchment. More comprehensive studies are required to establish the control of snow cover, slope, aspects etc on lapse rate to develop predictive model for temperature lapse rate variations in glaciated Himalayan catchments. While considering the range of yearly variation observed in the lapse rate within the alpine zone, modeling slope lapse rate is an important objective to be achieved for the successful modeling of hydrological processes of Himalayan glaciers.

Figure 4 shows extrapolated degree-days of summer months (May-November) by using standard lapse rate value of 0.6°C/100 m for 1998 and 1999 and by using derived monthly lapse rate values of alpine zone of the Din Gad catchment. The huge difference between both the methods and, higher thermal regime as demonstrated by the calculated lapse rate values support the higher melt observed in 1999 and 2000 in that region, especially at upper altitudinal zones of accumulation area covering large areas. This clearly demonstrates the shortcomings of using standard lapse rate values for glacier runoff model.

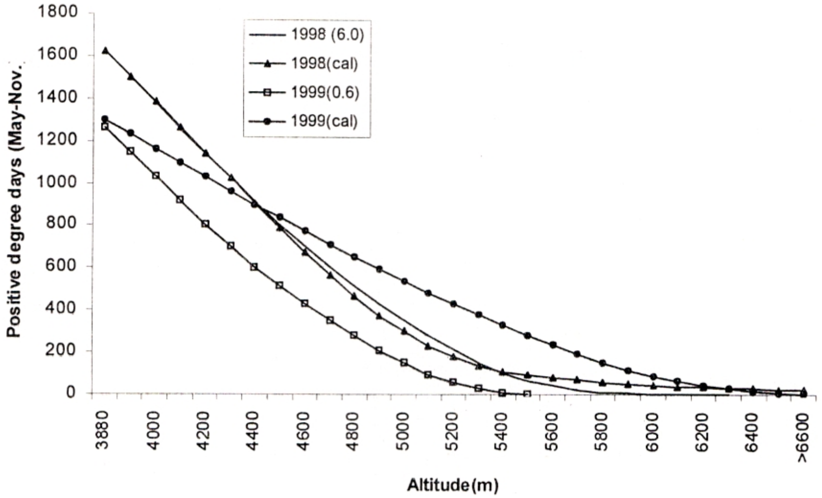

Fig. 4 Comparison of positive degree days distribution at different elevation bands of the Dokriani glacier calculated using standard lapse rate value used in snow/glacier runoff models of 0.6°C/100 m and with calculated lapse rate of the Alpine basin of Dokriani glacier (Table 4). As per the standard value, there is no melting conditions prevails above 5600 m in 1999, but field observations suggests extensive melting above 5600 m in 1999.

MONSOON OVER HIMALAYAN GLACIERS – AN ENIGMA

Role of monsoon in defining the hydrological characteristics of Himalayan glaciers still remains an enigma. Logically every one accepts that the monsoon play an important role in determining the hydrological processes of the Himalayan glaciers, especially of eastern and central Himalayan glaciers. Processes involved in determining forms and distribution of precipitation and the response of glacier discharge to the rainfall is an important aspect to be studied prior to the initiation of modeling of runoff and other hydrological processes of these glaciers. If the temperature regime of these regions is warming up in consonance with the global trend, it is possible that the summer precipitation at higher altitudes will change from snow to rain and lead to change in summer accumulation pattern (Higuchi and Ohata, 1996). Such a shift in accumulation pattern will have pronounced effect on the mass balance of these glaciers and accelerate the shrinkage of Himalayan glaciers under the monsoon climate. Hydrological regime of these glaciers is also expected to undergo considerable change. Hence it is important to assess the role of monsoon precipitation in controlling the hydrological processes of Himalayan glaciers.

To characterize the role of monsoon in Himalayan catchments we require understanding of (1) Rainfall component in glacier discharge and rainfall – runoff (Q-R) relationships, (2) Role of rainfall in enhanced melting of glaciers (by melting of ice surface by higher temperature of rain drops and by the latent heat release by refreezing of rainwater, (3) rainfall gradient in a glacier basin, (4) Effect of monsoon cloud cover on radiation balance and thermal regime of the glacier catchment, (5) Role of rainfall in subglcial drainage development, (6) role of rainfall on suspended sediment delivery to the glacier fed streams, (7) Role of rainfall in chemical weathering and water quality of glacier fed streams, and finally (8) most crucial aspects of summer accumulation over Himalayan glaciers.

In the past, researchers tried to address many of these aspects. In a classification based on the dominance of winter and summer monsoon precipitation over the Himalaya, Vohra (1981) suggested that the Ganga basin experiences equal amount of summer and winter precipitation. Higher chemical denudation rates of Dokriani glacier in Ganga basin (Hasnain and Thayyen,1999) and higher sediment erosion rates of Himalayan glacier catchments are also attributed to the monsoonal rainfall (Singh et.al.,1995, Hasnain and Thayyen,1999).Good correlation between glacier discharge and rainfall in the months of July and August were suggested to be indicative of prominent role of monsoonal rainfall in determining the runoff characteristics of the glacier (Singh et. al, 2000). However many of these suggestions are based on assumptions rather than quantification and evaluation of role of monsoonal precipitation in glacial hydrological processes.

In Dokriani glacier we tried to quantify the monsoonal component in bulk outflow from the glacier by using mass balance method. Following relationship has been used (Thayyen, 1997):

For glacierised region $Rg = P \times Ag$
For non-glacierised region $Rng = 0.7\,P \times Ang$
For whole (non-glacierised + non-glacierised) region
$Rc = Rg + Rng$

where Rg is rainfall component from glacierised zone; Rng is rainfall component from non-glacierised zone; Rc is total daily rainfall component (m^3); P is precipitation (m); Ag is area of glacierised zone of the catchment warmer than 2°C (m^2); Ang is area of non-glacierised zone of the catchment warmer than 2 °C (m^2).

The results of this study show that the rainfall contribution to the bulk glacier discharge has risen from 11% and 10% in 1994 and 1998 to 26% and 24% in 1999 and 2000. Rainfall contribution in glacier discharge was maximum in the month of July in 1999 and 2000 amounting to 30% and 37%, whereas, in 1994 and 1998 maximum rainfall contribution (14%) was in the month of August (Fig. 5). Two-fold increase in the rainfall component was observed in 1999 and 2000 as compared to 1994 and 1998. Such a significant increase in the rainfall component of bulk glacier discharge, even in a year of lower rainfall, as observed in 1999, is an important aspect to be considered while modeling glacier runoff.

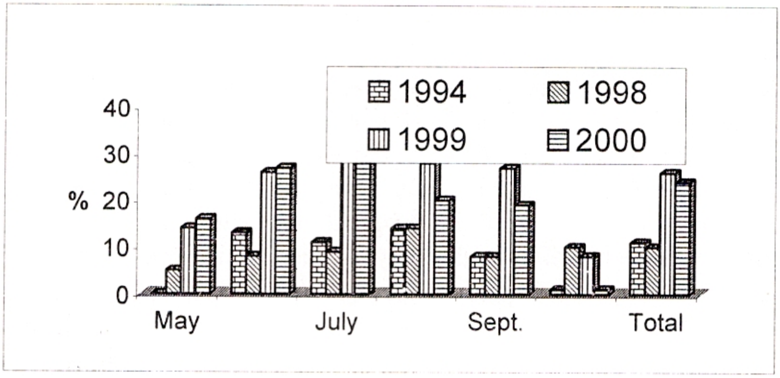

Fig. 5 Calculated rainfall component of glacier discharge as percentage of bulk glacier runoff. Rainfall component in 1998 and 2000 has increased mainly due to rise in 2°C isotherm altitude resulting rainfall in large areas of accumulation zone.

These results suggest that the rainfall component of glacier discharge cannot be determined from the rainfall data alone, hence the assumption that the higher rainfall will result in higher rainfall component in the glacier discharge is questionable. Our study suggests that any attempts to develop glacier runoff models for Himalayan catchments must incorporate the sub-models that can determine rainfall component. Monthly mean temperature at base camp show slight reduction in the months of July and August from 1994 to 2000. However, this reduction in the monthly mean temperature has not translated into reduction of areal distribution of rainfall as evident from the upward movement of 2^0 isotherms due to lower slope lapse rates during 1999 and 2000. These results emphasis the fact that the possible warming of this region in concurrence with the global warming will enhance the possibility of rainfall occurrence at higher altitude and contribute more water to the glacier system as seen in 1999 and 2000. Two fold increase in rain derived runoff from 1994 to 2000, with very little variation in rainfall as observed in this study, is capable of affecting the efficiency of glacier runoff models, which do not address the possible changes in rainfall distribution pattern on the glaciers in the monsoon climate.

In our study correlation between discharge and rainfall during monsoon months is found to be a bad tool in analyzing the influence of rainfall on glacier discharge. Both the variables have shown increasing trend in the peak ablation months but the increase in the glacier discharge in the monsoon months resulted due to increased glacier melt as a result of higher temperatures in summer rather than the rainfall contribution as evident from the calculated rainfall components in the monsoon months. Daily and diurnal glacier hydrograph response to the rainfall is inconsistent and weak especially in monsoon months, which coincided with the crest of ablation hydrograph. This is due to the complex interrelationship with the temperature, rainfall intensity, duration and distribution of rainfall, distribution of sunshine hours in a day and efficiency variation of glacier drainage network during the ablation season. This study has very clearly highlighted the fact that there is a need for in depth evaluation before attributing various hydrological characteristics of Himalayan glaciers to monsoon.

By and large our study concludes that the storms ≥ 20mm d^{-1} in a glacier catchment generate recognisable response on glacier hydrograph, and contribution from < 20mm d^{-1} rainfall is not distinguishable from the snow/ice melt contribution. 50% to 60% of monsoonal rainfall is the contribution from rainfall intensity ranging between 0-20 mm d^{-1} and its responses need not necessarily be evident on the glacier discharge hydrograph. A comparison of daily hydrograph of 1994 and 1998 with 1999 and 2000 did not show any major variation in shape even though there was two-fold increase in rainfall contribution in the year 1999 and 2000. This increase is mainly attributed to the rainfall occurrence in the higher altitude, the farthest areas of the catchment. This water reaches the glacier snout only after traversing through the glacier drainage and storage. During this period storm characteristics were completely assimilated by the drainage and storage characteristics of the glacier (Thayyen, 1997). Hence it is suggested that the hydrograph analysis is a poor tool for studying the rainfall influence on glacier discharge.

In our studies we also tried to establish a rainfall gradient for Din Gad catchment from the data from three altitudinal zones of the catchment. Figure 6 shows the monthly rainfall in these three stations. Figure 6 demonstrates the wide variability between the months and between the years in rainfall pattern in the Din Gad catchment. One general trend emerging is the reduced rainfall above the Gujjar Hut station (3400m). To establish a rainfall gradient for glacier regime we need measurement stations above 5000m. Considering the role of monsoon rains in defining the hydrological characteristics of Himalayan glaciers, it is an important aspect that still needs in-depth study. As of today, what we can conclude is that there is a non- linearity of the rainfall gradient in a Himalayan catchment. The question of summer accumulation, proposed by Ageta and Higuchi, 1984, also needs to be investigated thoroughly as this single process has tremendous implication on melt processes in accumulation zone and thereby on the runoff models and glacier mass balance, especially the mass reduction processes of glaciers in the global warming scenario. The relationship between monsoonal cloud cover-solar radiation-melt processes is also an important area of investigation, about which we have little information today.

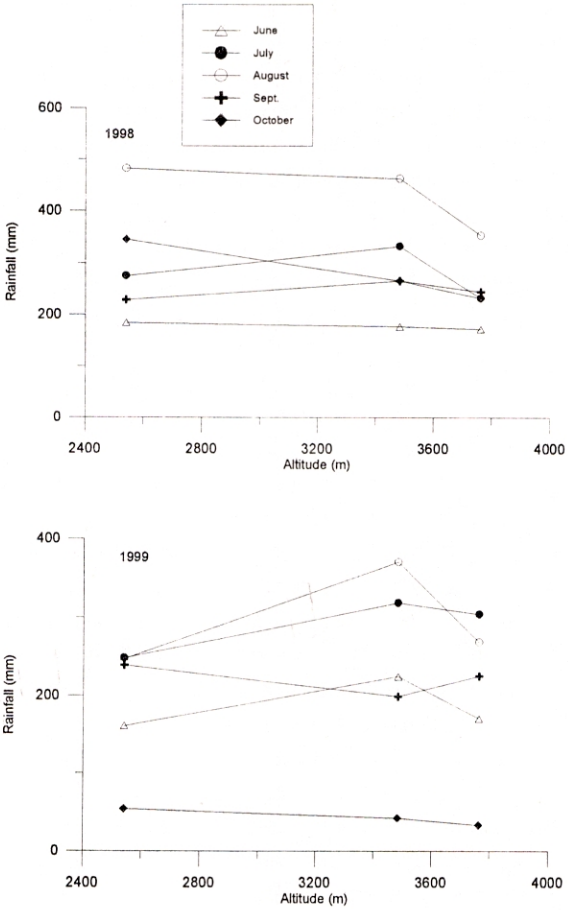

Fig. 6 Monthly rainfall during the summer season (June-October) in 1998 and 1999 at three meteorological stations in the Din Gad catchment demonstrating lower rainfall at the highest station of Base camp.

ASSESSMENT OF WINTER SNOW WATER EQUIVALENT (SWE): AN UPHILL TASK

One important aspect of glaciology that did not get desired attention in India is the quantification of Snow Water Equivalent (SWE) in winter. About 80-90% of glacier discharge is derived from snowmelt. At present there is a complete lack of information on SWE to characterise the snow precipitation and weather from glaciated catchments of Indian Himalaya. However, data of winter weather and amount and distribution characteristics of snowfall in the higher altitude hold the key to the runoff variations in the headwater streams and recession and shrinkage of glaciers.

The effect of changing climate of the region is better understood from the variations of winter weather, especially the winter temperature and snowfall characteristics. The glacier mass balance studies are incomplete without winter balance information. The glacier response (shrinkage and advancement) is resulting not only from the variations in the temperature but also due to the variations in the precipitation characteristics over the glaciers, in which precipitation is the dominant factor (Reichert et. al, 2001). The most important input parameter in any snow/ glacier forecasting runoff model is the SWE in the catchment. Long term rise in the snowline and reducing snow pack duration have serious adverse effect on summer yield from mountain catchment (Barry, 1990). The problem acquires larger dimensions when coupled with the lack of information on winter weather and climate of the accumulation zone. The Accumulation Area Ratio (AAR) of Himalayan glaciers is on an average between 0.60 and 0.70 and our experience suggests that 50% to 60% discharge at glacier snout is being derived from the accumulation zone alone. Inaccessibility of most of the areas of accumulation zone of the glaciers, lack of infrastructure support, lack of deployment of automated equipment, lack of trained and dedicated man power together with short term research strategies in project mode compounded the problem of generating quality data from the accumulation zone of the glaciers. Hence it is important to develop strategies to overcome these problems.

Realising the importance of winter SWE in glacier melt runoff models and for winter balance estimation, we initiated winter snow depth survey and collection of weather data in winter months at Dokriani glacier base camp for 1998 onwards. As a beginning, snow depth was monitored on a snow course established along the centerline of the catchment from 3400 m (at Gujjar Hut) to 4600 m.

Ideally, the snow course should be established across the valley at defined elevation intervals. Due to lack of logistic support, such a huge task could not be initiated. Our limited objective, within the available resources was to try and establish an altitudinal gradient for winter SWE for Dokriani glacier catchment, which will enable us to calculate the winter balance and generate SWE information for runoff model. Snow course along the central line, which is free from snow avalanche deposits from the valley wall is supposed to provide good estimate of altitudinal gradient for winter SWE.

Figure 7 shows measured snow pack thickness at different period of winter months during 2000 and 2001. Snow density measurements were taken only during the last measurement in end April or early May to calculate SWE along the central profile. However no SWE gradient could be established during the measurement years between the elevation zone measured. It is certain from the glacier discharge that much more snow is deposited in the accumulation zone than in the lower elevations. Establishment of rainfall gradient and winter SWE gradient in the Dokriani glacier catchment remains to be the biggest challenge.

To have a better understanding of hydrological processes of Himalayan glaciers and to develop good runoff models we need to put more effort to understand the hydrological processes of the accumulation zone. Measuring SWE at accumulation zone and monitoring of weather at ELA using Automatic Weather stations, which provide weather data of the accumulation zone, is the major future initiative of the Dokriani glacier project.

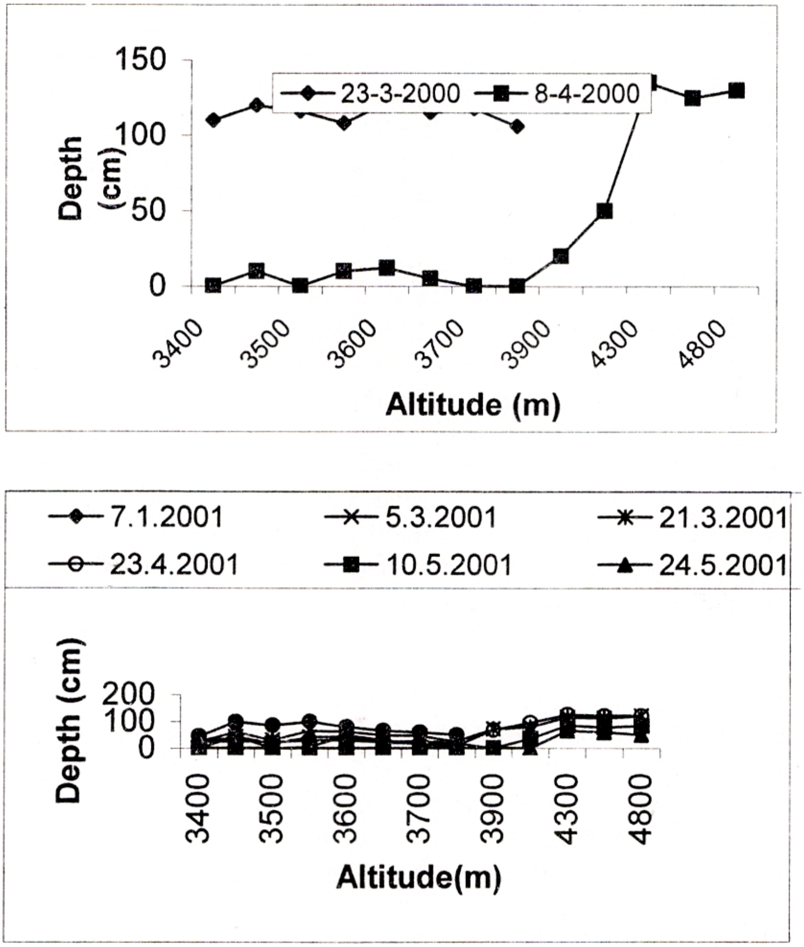

Fig. 7 Snow pack thickness of Alpine zone of the Din Gad catchment during different periods in winter of 2000 and 2001. With these data establishment of winter SWE gradient for glacier catchment is found to be difficult. Information from accumulation zone of the glacier is found to be necessary.

HIMALAYAN GLACIER RUNOFF MODELS – RESOURCE MANAGEMENT PERSPECTIVE

Development of glacier/snow melt runoff models essentially aimed to manage large frozen water reserves of glaciers, especially the study of response of glaciers to the changing climate of the region, as one of the long-term objectives. The Himalayan glaciers are situated above 3500 m, far away from human settlement. Hence, unlike in the Alps, the Himalayan headwater glacier fed rivers require water resources management strategies far below its origin at the glacier snout, where this water is utilised for drinking, agriculture and power generation. This makes it important to understand the role of glaciers and snowmelt in controlling the river hydrologic regime. Modeling of these processes will help in evaluating the ensuing changes in the hydrology of mountain rivers due to glacier recession and climate change. Monsoon rains in July and August coincide with the peak ablation period of the glaciers in the Garhwal Himalaya and compound the problem of assessing the water contribution from the glaciers in the Himalayan headwater rivers. The influence of glaciers on hydrology of headwater rivers are progressively reduced in accordance with reducing glacier cover area of the river catchment. Hence, the glaciers have only modulating role on the river flow in the headwater rivers rather than controlling it (Alford, 1992). Sparse database on hydrology and hydrometeorology of mountain catchments of the Himalayan region is one of the major problems in studying the hydrological characteristics of Himalayan catchment. This situation has lead to the formulation of hypotheses on changes of river hydrological characteristics due to glacial recession and global warming based on the studies reported from other mountain regions of the world. With continuing absence of systematic glacio-hydrological studies of the region, these hypotheses have gained credibility and are threatening to influence the water resources management strategies of the region. Generally, the snow and ice melt contributions in mountain rivers are being studied at meso-scale catchment outlets, covering large areas considering the glaciers and seasonal snow cover area as a single hydrologic unit, and thus forcing large scale approximations in the calculations. Such methodologies are capable of providing broad understanding on runoff variability but provide little information on hydrological processes inducing their variability. The solution to this problem is probably the micro-scale data collection strategies, following the stream hydrology progression from its origin at the glacier snout, through the seasonal snow cover and forested area. Further, this progression encompasses meso-scale catchments and provides useful information on runoff variations in major headwater rivers, which will help developing effective water resources management strategies for the mountain region. Monitoring meteorological parameters of the region is also an essential part of these data collection strategy.

As part of this research strategy, runoff of Din Gad stream is being monitored at three discharge stations at different altitude; first station near the glacier snout (3793 m asl) covering 15.7 km^2, second station Gujjar Hut (3400 m asl) covering seasonal snowfields (36 km^2) and the last station at Tela (2470 m asl) includes the forested area of the catchment (77.8 km^2). During the three years of runoff observation at these, the stations lower most station at Tela experienced maximum yearly summer runoff variation and the snout station recorded the minimum. In 1998, contribution from the glacier catchment to the Gujjar hut and Tela stations was 47% and 18%, whereas in 1999, it was 46% and 20% and in 2000, 56% and 35% respectively. Maximum flow observed during July and August months ranged between 48% and 62% of total discharge during the ablation months at all the three stations. During these months contribution from glacier catchment at the Gujjar hut station ranged from 40% to 66%. At Tela station contribution from the glacier catchment in July and August months ranged between 17% to 24% in 1998 and 1999. However in 2000, glacier contribution at Tela station during the month of July and August was 37%. At Gujjar hut station, glacier contributions showed least variations (47-56%) during the observation years and Tela station showed two-fold increase in glacier contribution during the same period, essentially as a reflection of 50% reduction in the total summer runoff at this station.

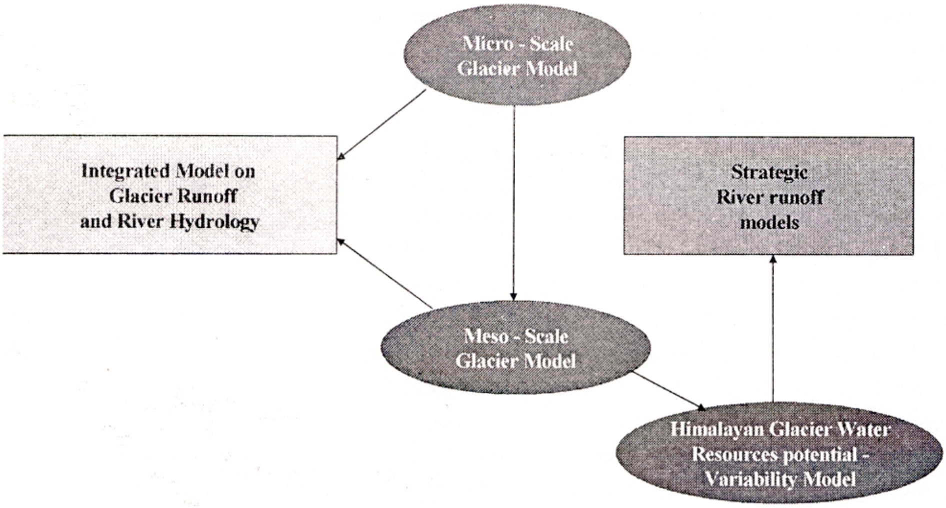

Fig. 8 Schematic diagram illustrating a possible research strategy, which leads to the development of Himalayan Glacier Runoff Model (HGRM) for effective management of glacier/snow resources in the headwater streams.

This demonstrates a characteristic change in the role of the glacier in influencing the stream discharge response, as the stream flows further away from the glacier. At Gujjar hut station, where the glacier contribution ranges from 47% to 56%, is under controlling regime of glaciers, whereas at Tela station, contribution from the glacier catchment (18-35%) plays only regulatory role in determining the river hydrology. Influence of glacier on runoff at Tela has varying dominance, regulated by the runoff generated from the non-glacierised zone of the catchment including snowmelt. Studies on meso-scale evaluation of hydrology of Nepal Himalayan rivers in the context of their contribution to the Ganga river demonstrate that the maximum percentage contributions from the Himalaya occurred during the years of minimum discharge in the Ganga river (Alford, 1992). Our study on micro scale hydrological characteristics of Himalayan catchment also demonstrate same trend as seen at Tela station, where two-fold increase in percentage glacier contribution was associated with minimum flow regimes of the river. To demonstrate the relationship in runoff variability between these stations, a plot of difference in summer runoff during the three years of observation period at three discharge stations on the ordinate and the percentage glacier cover of the respective catchment on the abscissa is shown in Fig. 9. The limited data points show an exponential relationship between these two variables suggesting that the headwater rivers, having progressively reducing glacier cover as the river flow down through the mountains, experience large yearly variability in river discharge at lower reaches.

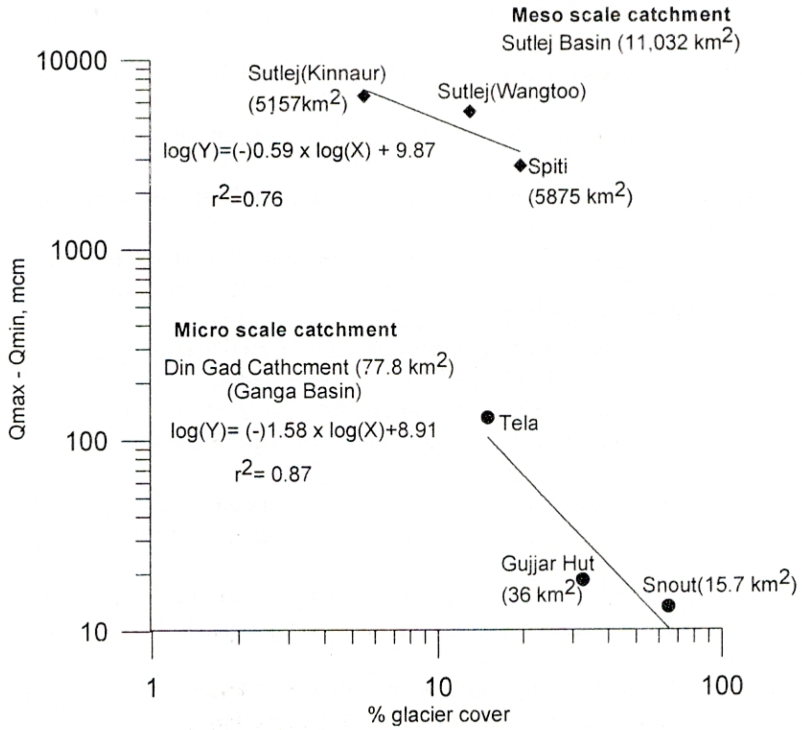

Fig. 9 Relationship between runoff variations in headwater stream to the glacier cover area of catchment. In the figure, 3 year data from Din Gad catchment (micro scale) and 9 year data from Indian part of Sutlej basin (meso scale) is plotted together to demonstrate the extension of same relationship from micro-scale catchment to meso-scale catchment. This relationship suggests that the headwater rivers require efficient management strategies as these flow further away from glacier regime (data source of Sutlej basin, Sharma et. al, 1991).

Runoff data from three hydrometric stations in the Sutlej basin is being used to experiment this relationship on a meso-scale catchment. The exponential trend observed in runoff variations with glacier catchment area is observed in this meso-scale catchment also. It demonstrates that the information on hydrological processes of glacier/snow regime is more crucial for management of headwater rivers at locations away from the glacier catchment.

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