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Role of glaciers and snow cover on headwater river hydrology in monsoon regime – Micro-scale study of Din Gad catchment, Garhwal Himalaya, India

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The role of glaciers and snow cover in controlling the headwater river run-off variability of areas under the influence of monsoon is discussed here. This work is based on the studies carried out in a micro-scale catchment in the Garhwal Himalaya, covering an area of 77.8 sq. km. Run-off data of summer ablation period of 1998, 1999 and 2000 were collected from three hydrometric stations established at different altitudes in the Din Gad catchment. These data have been analysed along with the winter/summer precipitation, temperature and mass balance variations of the Dokriani glacier. The study shows that the hydrometric station at 2360 m asl (Tela) experienced 45% reduction in summer discharge from 1998 to 2000, which translated into a two-fold increase in the percentage glacier contribution. This paradox resulted from variations in the winter precipitation characteristics masking the run-off variations of the glacial regime. Glacier degraded run-off volume varied from 3.5% of the bulk glacier discharge in 1994 to 7.5% in 1999. This study suggests that the uncertainties in the precipitation characteristics in a changing climate, especially the winter snowfall have pronounced effect on the headwater river run-off variability rather than the run-off variations from a receding glacier. On the other hand, glaciers play an important role in sustaining the river flows during the years of low summer run-off.

Keywords: Dokriani glacier, Garhwal Himalaya, headwater hydrology, monsoon.

GLACIOLOGICAL studies in the Himalaya are essentially aimed at managing the large frozen water reserves of the glaciers, especially to study the response of glaciers and snow cover to the changing climate of the region, as one of its long-term objectives. Himalayan glaciers are situated above 3500 m asl, and these regions are away from human settlements. Hence water derived from snow and glaciers is being used for drinking, agriculture and power generation only at lower altitudes of the mountain. This peculiar situation, specific to the Himalayan region, de-

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mands development of snow/glacier resources management strategies, far below its origin. Due to lack of information on hydrological processes of snow/glacier regime, water resources management policies at lower reaches of the glacier-fed rivers are often formulated without considering the impact of glaciers and snow cover on river hydrology. A systematic and sustained study of hydro-meteorological processes of snow and glacial regime is necessary for evaluating changes in the hydrology of mountain rivers due to glacier recession and climate change. Discharge of headwater streams in this region comprises monsoon rains, glacier and snowmelt. November to March records the lowest flows in these rivers and peak run-offs occur in the months of July and August. These two months experience highest temperature, highest glacier melt and highest monsoon rains of the year and compound the problem of assessing the variability in water contributions from the glaciers and snow cover to the Himalayan headwater rivers. This is because variations in the monsoon, snow and glacier regimes collectively influence the river run-off variations at lower reaches. Information from these three different hydrological systems is required for effective analysis of its role on the headwater river run-off variability. Generally, snow and glacier melt contribution in the mountain rivers is being studied at the meso-scale catchment outlets covering large areas, considering the glaciers and seasonal snow cover area as a single hydrologic unit, forcing large-scale approximations in the calculations. Such methodologies are capable of providing a broad understanding of snow/glacier melt contribution and run-off variability, but provide little information on the hydro-meteorological processes inducing the variability. A few studies have been carried out to quantify the snow and glacier contribution to the flow of Himalayan rivers. A study of the Chenab basin by water balance method suggested 49% of snow and glacier contribution to the Chenab at Akhnoor¹, and that 80% of annual flow of the Sutlej river occurs between May and September² and the snow/glacier melt contribution³ at Bhakra dam is about 59%. Run-off from upper Indus contributes 35% of the discharge from 17% of the glacierized area⁴. Summer discharge from the Gangotri glacier, the largest glacier in the Garhwal Himalaya was 565×10^6 and 479×10^6 m³ in 1999 and 2000 respectively⁵. Summer-specific run-off from the Dokriani glacier in the Ganga basin⁶ was 3949 mm in 1994. Whereas mean specific run-off from the Siachen glacier in western Himalaya⁷ was 1392 mm between 1986 and 1991. Specific discharge from the Imja river in Nepal⁸ was 1200 mm and discharge variations in the Rikha Samba river are found to be closely linked with variations in the solar radiation fluxes⁹. River run-off in the Langtang valley¹⁰ varied between 0.51 and 13.1 mm d⁻¹ and winter discharge of Langtang valley constitutes 4% of the annual discharge¹¹. Mean daily discharges of central and western Himalayan glaciers were well correlated with the glacierized area¹². During the peak melting period of the Triloknath glacier, one-third

of bulk run-off comes from the ablation over the glacier¹³. The present study was conducted under the ongoing research programme on Himalayan glaciology, sponsored by the Department of Science and Technology, New Delhi. The Din Gad catchment encompassing the Dokriani glacier at its higher altitude was selected as an experimental catchment under this programme, and glacio-hydrological studies are being conducted since 1992. Run-off data from three stations, representing three different mountain hydrological units, generated during the ablation months (May–October) of 1994, 1998, 1999 and 2000 were analysed to evaluate the role of snow cover and glaciers in controlling the headwater flow regimes.

The Din Gad valley is located in the headwater region of Ganga basin in Garhwal Himalaya. The general aspect of this valley is NW and it lies between lat. 30°48'–30°53'N and long. 78°39'–78°51'E. The first hydrometric station at Tela covers the entire catchment area of 77.8 sq. km in which 54% of the catchment is under forest cover and 31% is covered by Alpine meadows (Figure 1). Dokriani and Hura glaciers are part of this catchment and occupy the rest of the area. The second station at Gujjar Hut covers an area of 36 sq. km and the third station, 600 m downstream the glacier snout, covers an area of 15.7 sq. km. The Din Gad stream emerges from the Dokriani glacier at an altitude of 3900 m asl and joins the Bhagirathi river near Bhukki village. Monsoon reaches Din Gad catchment after 15 June and prevails till mid-September. The amount of rainfall ranges from 1000 to 1600 mm during May–October. July and August account for nearly 40–50% of this rainfall. Seasonal snow cover in this catchment usually extends up to 2300 m during the winter months. During the years of normal winter snowfall transient snowline recedes to 3700–3900 m asl by the beginning of May.

The data collection strategy was devised to understand the hydrological and climatological variability of monsoon, snow and glacier regimes of the catchment. Three hydrometric and meteorological stations covering different altitudinal zones of the catchment were established (Figure 1), which enabled the monitoring of run-off variability along the stream continuum from the glacier to the valley. The discharge stations were established at 3800, 3400 and 2360 m asl, which were monitored throughout the ablation season from May to October in 1998, 1999 and 2000. Base flow separation of discharge from Tela catchment is performed by the straight-line method. Winter snowfall was measured at the Base camp since the 1998–99 season and snow-pack thickness and durations were monitored along the snow course, established between 3400 and 4800 m asl. Position of the snowline, which is indicative of snow-cover duration, is also monitored at the beginning of the ablation season in May. Glacier mass balances were calculated by glaciological method and cumulative positive degree-days were calculated from temperature measurements at the Base camp. Run-off data generated from three alti-

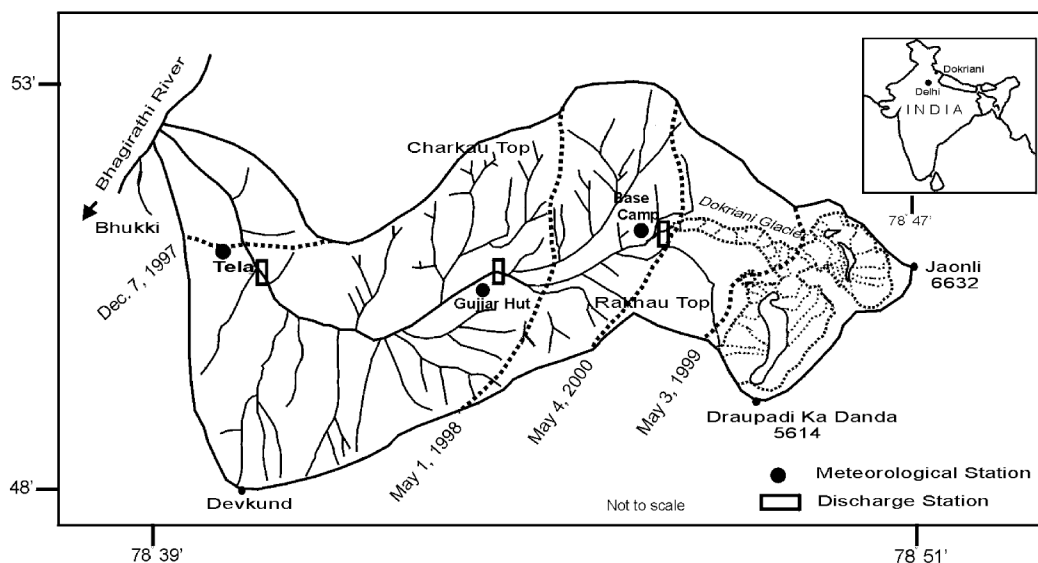


Figure 1. Location map of Din Gad catchment, Dokriani glacier and data collection stations. Transient snow line positions in May during the study period are also shown.

Table 1. Summer discharge flux at Dokriani glacier snout, Gujar Hut and Tela stations in the Din Gad catchment during 1998, 1999 and 2000

Year	Run-off (10^6 m^3)			Rain (mm)		
	Snout (15.7 sq. km)	Gujjar Hut (36 sq. km)	Tela (77.8 sq. km)	Snout	Gujjar Hut	Tela
1998	52.3	111.5	289.9	1365	1624	1609
1999	42.7	93	214.2	1147	1237	1014
2000	56.1	100.7	158.3	1313	1328	1107

tudinal zones of the catchment are analysed in terms of variability observed by monsoon, snow and glacier regimes.

Summer discharge flux and rainfall observed at the three hydrometric stations are shown in Table 1. Figure 2 shows mean daily discharge variations at three stations during the observation period. About 60% of the discharge at the snout was recorded in July and August alone. Discharge at the snout varied from 0.4 to $13.5 \text{ m}^3/\text{s}$ and average specific run-off from the glacier during the ablation period (Q_{5-10}) was 3133 mm, with July and August alone accounting for 2000 mm of run-off. At 3400 m asl (Gujjar Hut station), July and August months together contributed 52–62% of discharge of the ablation season. Maximum discharge observed at this station was $33 \text{ m}^3/\text{s}$ in July 1999, and the minimum was $1.9 \text{ m}^3/\text{s}$. Average specific run-off of Gujar Hut catchment during the ablation period (Q_{5-10}) was 2825 mm, in which July and August accounted for 1500 mm. Tela catchment experiences snowfall as well as rainfall in winter months at its lower elevations. Summer discharge (May to October) at 2360 m asl (Tela) reduced progressively from $290 \times 10^6 \text{ m}^3$ in 1998 to $158 \times 10^6 \text{ m}^3$ in 2000, amounting to 45% reduction. Major variations in the river flow at Tela

have been observed in May and June, a period dominated by the snowmelt. July and August account for 48% of discharge in 1998 and 55–58% of discharge in 1999 and 2000. Highest discharge observed at Tela station in 1998, 1999 and 2000 was 41, 77.5 and $35 \text{ m}^3/\text{s}$ respectively, and the lowest was $2.3 \text{ m}^3/\text{s}$. Average specific run-off of the Tela catchment during the ablation period (Q_{5-10}) was 2838 mm with specific run-off of July and August ranging between 1790 mm in 1998 and 1180 mm in 2000.

During three years of run-off observations, the lowermost station in the Din Gad catchment at 2360 m asl experienced the largest yearly summer run-off variation and the station near the glacier recorded the minimum (Figure 3). Glacier mass balance studies show that the melting of glacier ice contributed $4.83 \times 10^6 \text{ m}^3$ to $5.17 \times 10^6 \text{ m}^3$ during 1994–2000, which constituted 7.7 to 12.7% of bulk glacier run-off. After accounting for the net accumulation ranging from $2.2 \times 10^6 \text{ m}^3$ to $2.7 \times 10^6 \text{ m}^3$, glacial degraded run-off component in the bulk glacier discharge constitutes 3.5–7.5% (Figure 4). Monsoon rainfall component¹⁴ ranged between 10% in 1998 and 26% in 1999. The remaining is snowmelt over the glacier and groundwater/subglacial contribution (54–79%), in which contribution

from the snowmelt is overwhelmingly high. The year 1998 was the warmest of the past 119 years globally, since reliable instrumented records began¹⁵. Meteorological stations in the Din Gad catchment also show higher temperatures in the 1998 ablation period compared to the subsequent years. However, the highest negative mass balance for Dokriani glacier was experienced in 1999 in association with lowest bulk glacier discharges and lower temperatures at the Base camp (Figure 4). This shows that the lower temperatures during the summer season need not necessarily

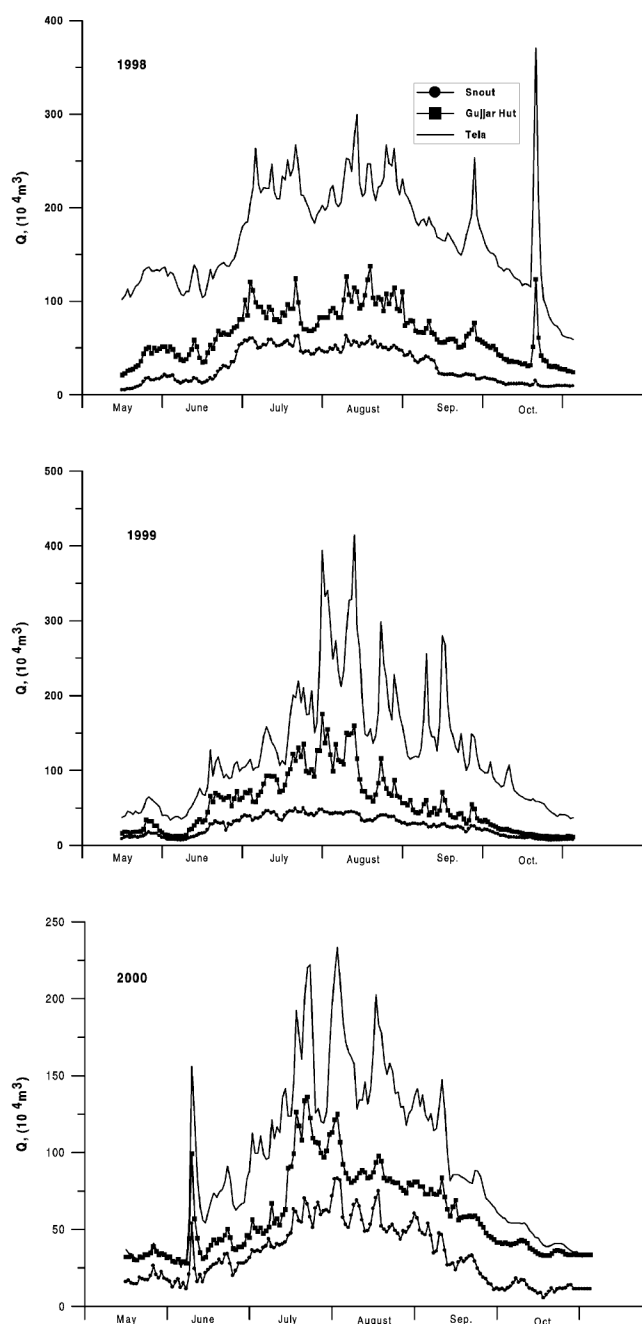


Figure 2. Mean daily discharge variations at the snout, Gujjar Hut and Tela stations during the 1998, 1999 and 2000 ablation period.

ensure lower glacial degraded run-off. Some peculiar characteristics of temperature distribution of glacial regime during 1998–2000 are discussed elsewhere¹⁶. This result shows that temperature and precipitation play equally important roles in determining the glacier mass balance and run-off, and the amount of winter snow has a predominant role in determining the discharge volume from the glacier.

Monthly contribution from the glacier catchment to the discharge at 2360 and 3400 m asl during the study period is shown in the Figure 5 a and b. Average contribution from the glacier catchment to the Gujjar Hut and Tela stations in 1998 and 1999 was 47 and 18% respectively. Whereas in 2000 contribution from glacier basin to the Gujjar Hut and Tela station rose to 56 and 35%. During the peak flow period of July and August, contribution from the glacier catchment to the Gujjar Hut station ranged from 40 to 66%. At Tela station, contribution from the glacier catchment during the same period ranged between 17 and 24% in 1998 and 1999, which rose to 37% in 2000. Glacier contributions to the stream flow showed least variations (47–56%) at 3400 m asl, compared to the nearly two-fold increase in glacier contribution at the lower station at 2360 m asl. This increase in glacier component in the stream flow was a result of lower contributions from non-glacierized areas of the catchment as reflected in 45% reduction in the summer run-off at this station.

This demonstrates a characteristic change in the role of glacier on stream discharge characteristics, as the stream flows farther away from the glacier. Gujjar Hut station, where the glacier contribution ranged between 47 and 56%, is under the controlling regime of the glacier, whereas at Tela, contribution from the glacier catchment (18–35%) plays only a regulatory role in determining the river hydrology. Influence of glacier on run-off at lower altitudes has varying dominance, regulated by the run-off generated from the non-glacierized zone of the catchment including snowmelt. Studies on meso-scale evaluation of hydrology of Nepal Himalayan rivers in the context of its contribution to the Ganges demonstrated that the maximum percentage contributions from the Himalaya occurs during

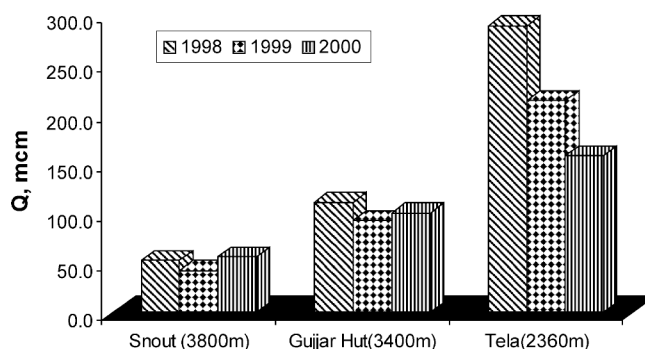


Figure 3. Summer discharge flux variations at three stations. Lower-most station at Tela experienced larger run-off variability.

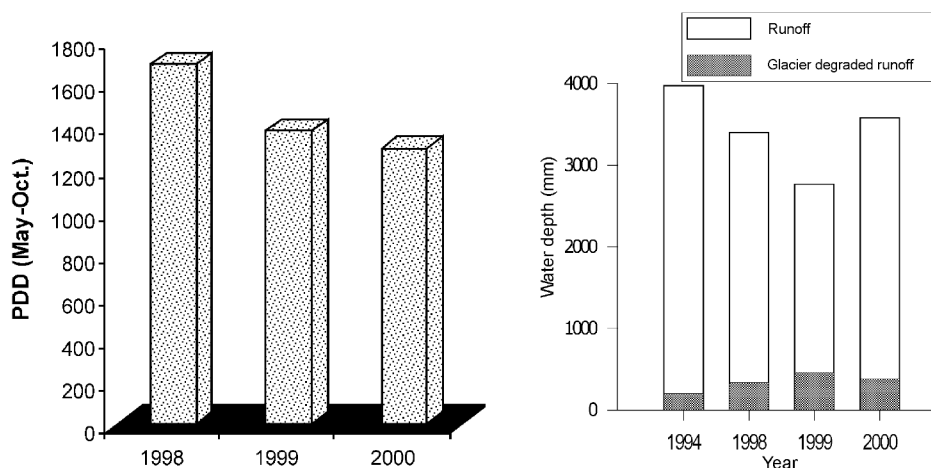


Figure 4. Run-off from Dokriani glacier and contribution from glacier degradation during the study period. Increase in negative mass balance in consecutive years with respect to lower temperature has demonstrated equally important role of winter precipitation and temperature in glacier mass balance fluctuations. Temperature is shown as sum of positive degree-days at the Base camp during the ablation months. Glacier response in 1999 summarizes the complexities involved in the climate-glacier-run-off relationship, with lower temperature producing higher specific negative mass balance and lowest bulk glacier run-off.

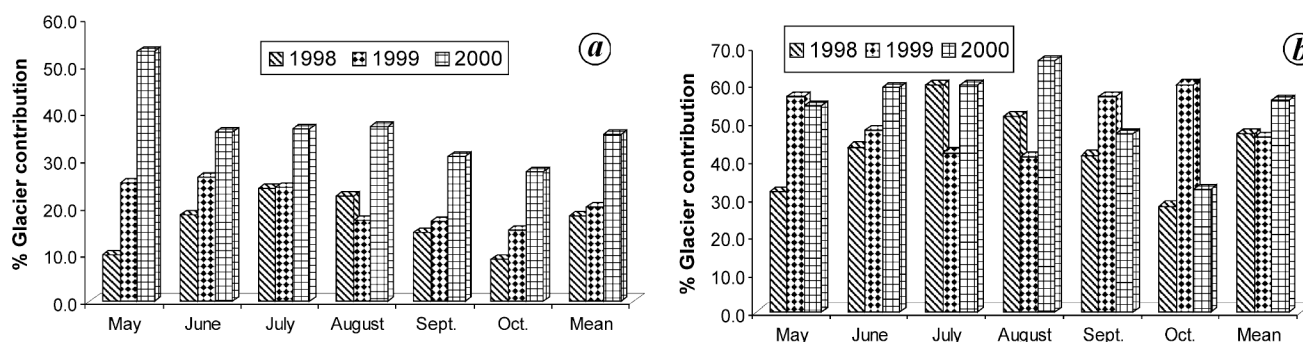


Figure 5. Monthly and summer mean (M_{5-10}) percentage run-off contribution from the glacier at (a) Tela station and (b) Gujar Hut station.

the years of minimum discharge in the Ganges river¹⁷. The present study on a micro-scale Himalayan catchment also demonstrate the same characteristics as seen at Tela station, where a two-fold increase in the percentage glacier contribution associated with minimum flow regimes of the river.

The sources of run-off from non-glacierized areas of the catchment are winter snowfall and monsoonal precipitation. The transient snowline in the Din Gad catchment has been around 3400 m asl in the beginning of May every year during the observation period. Once the snowline recedes, the snowmelt contributed to the stream only as interflow and base flow. In summer months, the base flow of Tela sub-catchment is primarily constituted by snowmelt from the regions below the Gujar Hut station. Hence the base-flow volume is determined essentially by the amount of snow precipitation in the previous winters. Figure 6 shows the base-flow separation for the discharge below the Gujar Hut station as measured at Tela ($Q_{\text{Tela}} - Q_{\text{Gujjar Hut}}$). Remarkable reduction in the base flow from

1998 to 2000 was observed. The base flow volume was 2258 and 939 mm respectively, in 1998 and 1999. In 2000, calculations showed no base flow from the region below the Gujar Hut station. A realistic assessment of this result would be that many parts of the stream, between Gujar Hut and Tela station, demonstrated influent stream characteristics in 2000, indicating changes in the hydrological characteristics of the catchment below 3400 m asl. Table 2 shows the summer-specific run-off from Tela catchment below Gujar Hut hydrometric station and direct run-off. Higher direct run-off (DRO) than rainfall from the Tela subcatchment implies that the three meteorological observatories in the catchment are not enough to capture the distribution characteristics of monsoon rainfall in this catchment. Around the peaks and ridges of the catchment, monsoon rainfall could be 4–5 times higher compared to the valley bottom¹⁸ and seasonal differences in altitudinal dependence also occur in this region^{19,20}. This is a major impediment in employing water balance method in such mountain catchment.

Analysis of snowfall characteristics in these three years demonstrates the reason for such a large reduction in base flow of Din Gad stream below Gujar Hut station. Figure 1 shows the position of transient snowline in the beginning of May and snowline observed in December 1997. Figure 7 shows snow-pack thickness and winter precipitation during 1998–99 and 1999–2000. Winter of 1997–1998 experienced heavy early snowfall, which started during the third week of November and covered the entire catchment up to Tela. In the last week of November 1997, snow pack at the glacier snout was 80 cm thick. Snow-pack thickness at Tela during the first week of December 1997 was 60 cm. Average snowline altitude in the first week of May 1998 was 3500 m, covering the entire Gujar Hut catchment. Winter of 1998–99 experienced lowest snowfall in recent history of Garhwal Himalaya, measuring 144 mm at the Base camp (3762 m asl) and the snowline on 3 May 1999 was at 4800 m asl, close to the ELA of the glacier (4950 m asl). Summer of 1999 also witnessed drying up of springs in the region, even at the Base camp, for the first time since the studies on Dokriani Glacier were initiated in 1991. Snowfall at the Base camp during 1999–2000 winter was 330 mm, with most of the snowfall recorded during February and March (Figure 7). Snowline in early May 2000 was at 4000 m asl. During

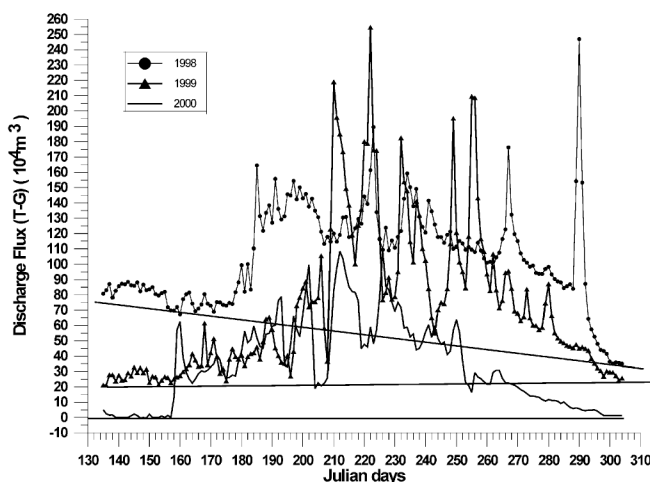


Figure 6. Reduced base flow from Tela catchment ($Q_{\text{Tela}} - Q_{\text{Gujjar Hut}}$) during the study period.

Table 2. Summer specific run-off from Tela catchment below Gujar Hut station (T-G), direct run-off (DRO) and summer rainfall recorded at Tela meteorological station

Hydrograph analysis of Tela catchment below Gujar Hut station (T-G) (41.8 sq. km)			
Year	Specific run-off (T-G) mm	DRO (mm)	Rain (mm)
1998	4267	2009	1609
1999	2900	1961	1014
2000	1381	1381	1107

both these years, most of the precipitation at the upper reaches of the Tela catchment experienced rain in place of snow. These changes in winter snowfall characteristics resulted in a sharp decrease in run-off at Tela station from 1998 to 2000 ablation period. It is observed that the low winter precipitation during a particular year reduces the stream run-off in the subsequent years also². Reduction of base flow from 1999 to 2000 ablation period continued even when the catchment experienced the same range of monsoon rainfall (Table 1). This suggests that the reduced snowfall and snow-cover duration have affected the base-flow volume in a much greater way than variations in the monsoonal rainfall. Reduction of base flow in the Tela catchment was also reflected in the hydrograph characteristics as higher diurnal variability in stream flow²¹ during peak discharge periods and progressive reduction of lowest summer discharge, 6.5, 3.7 and 2.3 m³/s in 1998, 1999 and 2000 respectively.

Yearly variability in summer discharge from different zones of the catchment is further demonstrated by the variations of specific mean daily discharge of the sub-catchments (Table 3). Large specific run-off variations at Tela catchment (22–12 mm d⁻¹) between 1998 and 2000

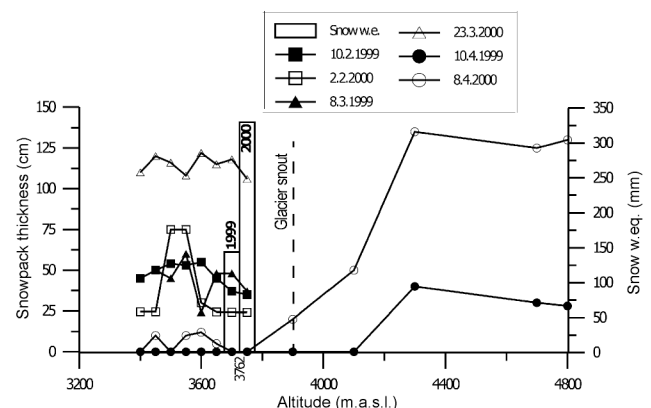


Figure 7. Winter precipitation and snow-pack thickness variations during 1998–99 and 1999–2000 winter months.

Table 3. Summer mean daily discharge and summer specific mean daily discharge during 1998, 1999 and 2000

Station	Year	Summer mean daily discharge (10 ⁶ m ³)	Specific mean daily discharge (Q_{5-10}) (mm)
Snout	1998	0.31	20
	1999	0.25	16
	2000	0.33	21
Gujjar Hut	1998	0.66	18
	1999	0.55	15
	2000	0.60	17
Tela	1998	1.73	22
	1999	1.27	16
	2000	0.94	12

and lower variations at snout and Gujjar Hut stations ($21\text{--}16\text{ mm d}^{-1}$) demonstrate the role of glaciers in buffering the stream discharges. Productivity of non-glacierized area of the catchment during the years of good snowfall equals that of the glacierized area, whereas during the years of reduced snowfall, productivity of non-glacierized area had lowered to half. The linear negative trends of snow cover extent over Eurasia during the last three decades^{22,23} and rise in winter temperature over western Himalaya²⁴ demonstrate the changing climate of the region. This study suggests that the change in precipitation characteristics in a changing climate has a pronounced effect on the river hydrology rather than variations in the glacial degraded runoff volume itself. An important aspect demonstrated by this study is that the lower reaches of the headwater rivers, away from the glaciers, where many hydroelectric power stations are planned or are already operational, would be most affected by the changes occurring in the snow and glacier regimes of the Himalaya.

This study demonstrates that the enhanced melting of the glacier does not increase the river run-off, where winter snow and monsoon precipitation determine the regional hydrology. On the contrary, changing precipitation characteristics, mainly lowering of winter snow-cover extent and duration could reduce the headwater river flow drastically, while the glacier component sustains the low flow as explained in this study. The observed sharp run-off decline of 45% during the short duration of three years demonstrates the stress which the Himalayan cryosphere experiences in a climate change regime. The results suggest that the lower reaches of the Himalayan headwater rivers could expect larger annual run-off variations in future, as buffering efficiency of shrinking glaciers reduces further. Understanding the extent of such variability will be of immense help in operating hydroelectric power stations and developing water resources management strategies for the Himalayan headwater regions. A long-term sustained and integrated research strategy incorporating Himalayan and sub-Himalayan catchment hydrological processes is imperative for generating useful information on the effect of climate change on the Himalayan cryosphere and headwater river run-off.

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