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Monsoonal control on glacier discharge and hydrograph characteristics, a case study of Dokriani Glacier, Garhwal Himalaya, India

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Abstract

Stream discharge from Dokriani Glacier, Garhwal Himalaya was monitored during the ablation months (May–October) of 1994, 1998, 1999 and 2000. Contributions from the monsoon rainfall, coincided with the peak ablation period, were quantified by using a water balance. Calculated monsoonal component in 1994 and 1998 was 10–11% of the bulk glacier runoff where as in 1999 and 2000 it was 24–26%. The increase in rainfall component in 1999 and 2000 was due to enhancement of rainfall area rather than an increase in rainfall. The increase in rainfall area was result of a lower temperature lapse rate during these two years. This study suggests that the discharge-rainfall correlation is a questionable method to study the rainfall influence in glacier discharge. Analysis of monthly monsoonal component of bulk glacier discharge and rainfall-discharge correlation are presented and ambiguities discussed. This observation is further supported by the detailed analysis of daily hydrograph which suggests that the rainfall over the glacier produces different responses on discharge hydrograph depending on the season of occurrence, intensity, duration and distribution characteristics. Study suggests that the rainfall with intensity >20 mm d^{-1} influenced the shape of daily discharge hydrograph, which experienced only on 20% of rainfall days of monsoon season. Comparative study of diurnal hydrograph of rainy days and non-rainy days with the mean daily temperature and sunshine hours highlights the flaws in the use of rainfall-discharge correlation as an indicator of rainfall influence on glacial discharge.

Keywords: Dokriani Glacier; Garhwal Himalaya; Ganga basin; Monsoonal component; Glacier discharge; Discharge-rainfall correlation

1. Introduction

Hydrology of eastern and central Himalayan glaciers is greatly influenced by the south- west Indian monsoon, which coincides with the peak summer ablation period of these 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 runoff and other hydrological processes of these glaciers. Vohra (1981) suggested that the Ganga basin experiences

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equal amount of summer precipitation from monsoon and winter precipitation from western disturbances. Higher chemical denudation rates of Dokriani Glacier in Ganga basin (Hasnain and Thayyen, 1999a) and higher sediment erosion rates of Himalayan glacier catchments are also attributed to the monsoonal rainfall (Singh et al.,1995; Hasnain and Thayyen, 1999b). Hasnain et al. (2001) suggested that the water derived from monsoon rainfall is instrumental in changing the subglacial drainage structure of the Dokriani glacier. 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, these suggestions are not supported by quantification and evaluation of role of monsoon precipitation in glacial hydrological processes. Ageta and Satow (1978); Ageta and Higuchi (1984) suggest that glaciers in the monsoon climate are summer accumulation type glaciers. If the temperature regime of this region is warming in consonance with the global trend, it is possible that summer precipitation at higher altitudes will change from snow to rain and lead to a 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. Variations in the spatial distribution of rainfall and snowfall in summer over the glacier is a major variable in determining the discharge volume at the glacier terminus. This may also influence the storage characteristics of the glacier. Accumulation zone of the glacier covering about 60–62% of the glacier area is under the snow cover during the ablations period. Storage characteristics of this area will differ if rain occur in place of snowfall. Hence it is important to assess the role of monsoon precipitation in controlling the hydrological processes of Himalayan glaciers. The goal of this paper is to quantify the monsoon rainfall component in the discharge of Dokriani glacier and evaluate the processes that control the response of rainfall on glacier discharge hydrograph. Validity of rainfall-glacial runoff correlation has also been examined.

2. Study area

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°50′N to 30°52′ N and longitude 78°47′ E to 78°51′ E (Fig. 1). 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 km^2, out of this 7 km^2 is covered with the glacier ice and the non-glacierised area and the seasonal snow cover area is 8.7 km^2. Three fourth of the glacier ablation area is covered by thick supraglacial debris.

2.1. Data collection

Dokriani Glacier is in the headwaters of Din Gad catchment. Three meteorological stations were established in the Din Gad catchment, at Tela (2330 m), Gujjar Hut (3430 m) and at the Base Camp of Dokriani Glacier (3860 m a.s.l.). These stations were monitored through out the ablation period in 1998, 1999 and 2000 (Fig. 1). Rainfall, temperature and sunshine duration data were collected at these stations. Temperature lapse rates calculated between Base camp and Gujjar Hut station pairs were used in this paper, as this station pair is close to the glacier. Meteorological data collected at the Base Camp in 1994, 1998, 1999 and 2000 were used in this paper. The discharge station is 600 m down stream of the glacier and monitored during the summer ablation period (May–October). Discharges were derived from rating curve established by the area–velocity method.

2.2. Separation of monsoonal rainfall component

Quantification of rainwater component in the glacier discharge is achieved by using simple water balance approach, which separated the daily rainfall component from the daily total discharge observed at the gauging site. The loss due to evaporation is considered negligible in such low temperature conditions over the glacier. Total area of the basin is divided into glacierised and non-glacierised zone, as both the zones have different runoff characteristics. In a temperate glacier, rain on the glacier routed to the glacier portal along with the supraglacial meltwater

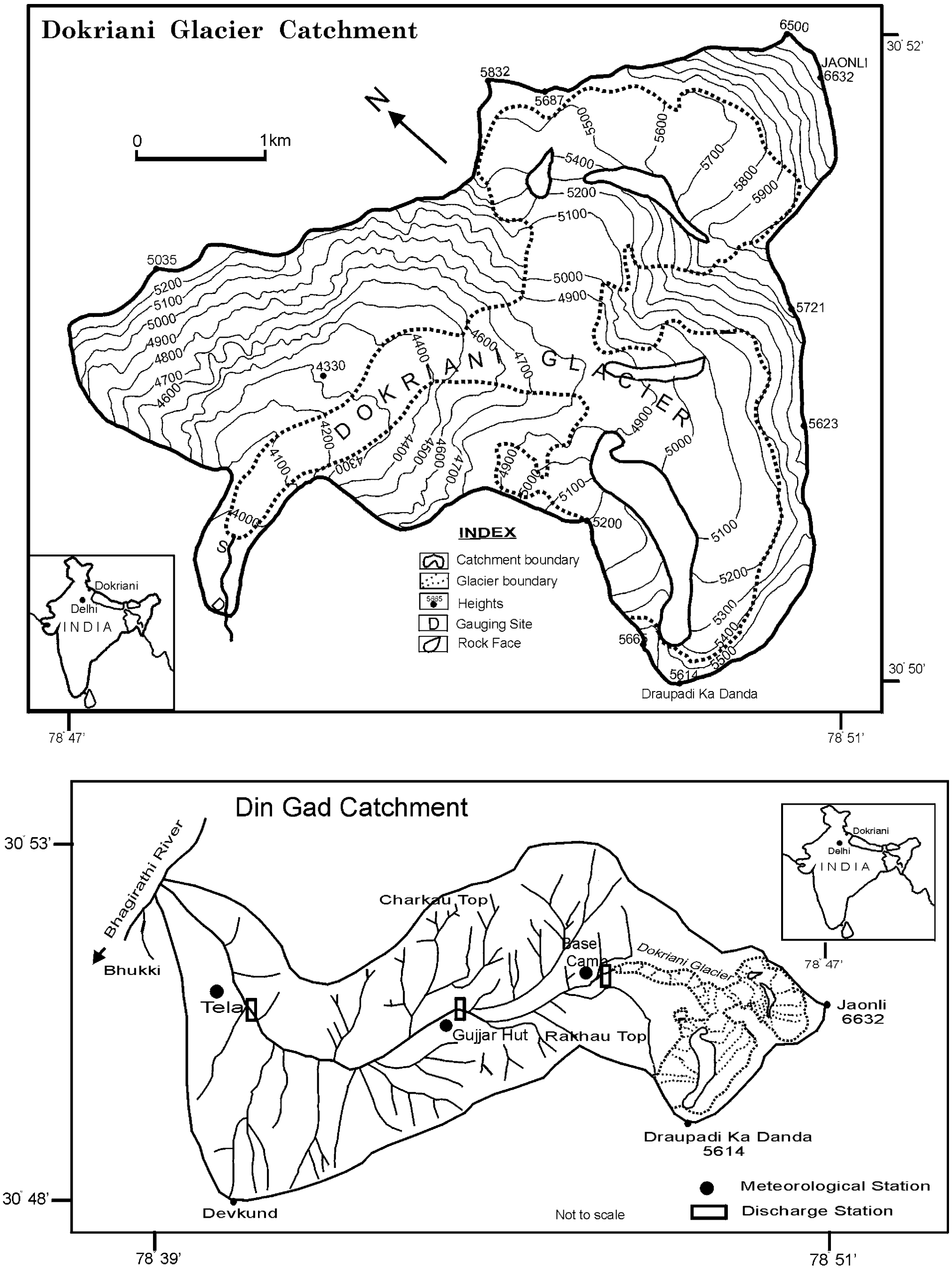

Fig. 1. Location map of the area showing Dokriani Glacier catchment and hydrological and meteorological monitoring stations in the Din Gad catchment (after Survey of India,1995).

through the glacial drainage system without major losses. But the rain falling on the non-glacierised part of the catchment experiences minor losses due to infiltration. Area around Dokriani Glacier has steep bare slopes and a runoff coefficient of 0.7 (Mutreja, 1986) is considered appropriate. The occurrence of snow at higher elevations depends on the temperature prevailing during the storm. Studies in the Nepal

Table 1
Mean monthly lapse rate (°C/100 m) used in this study

Year	May	June	July	August	September	October	November
1994	0.65	0.57	0.75	0.64	0.8	0.8	–
1998	0.36	0.71	0.71	0.67	0.70	0.56	−0.13
1999	0.58	0.37	0.35	0.40	0.36	0.21	0.28
2000	0.44	0.42	0.44	0.34	0.30	0.38	–

Calculated from Gujjar Hut–Base camp station pairs. This meteorological station pairs is in the Alpine catchment and closest to the glacier.

Himalaya suggest 50% probability of snowfall occurrence when air temperature is at 2 °C (Higuchi et al.1982; Ageta and Higuchi, 1984). In this study, temperature of 2 °C is taken as rain-snow threshold (Upadhyay, 1995). The area of rainfall versus snow delineated on daily basis using monthly mean lapse rate values calculated using the temperature data from two meteorological observatories close to the glacier. In Table 1 calculated monthly lapse rate values during the four observation years have been tabulated. Basin precipitation was calculated from daily precipitation values at the Base camp observatory. The following relationship has been used to separate the rainfall component from the bulk daily glacial discharge (Thayyen, 1997).

For glacierised region $R_g = P \times A_g$

And for non-glacierised region $R_{ng} = 0.7\ P \times A_{ng}$

$R_c = R_g + R_{ng}$

where R_g, rainfall component from glacierised zone, R_{ng}, rainfall component from non-glacierised zone, R_c, total daily rainfall component (m^3), P, precipitation in meter, A_g, area of glacierised zone of the catchment warmer than 2 °C in m^2, A_{ng}, area of non-glacierised zone of the catchment warmer than 2 °C in m^2

Total catchment area of Dokriani Glacier is 15.7 km^2, out of which 7 km^2 covered with glacier ice and non-glacierised and seasonal snow cover area is 8.7 km^2. Rain in the Dokriani basin starts in early June characterized by low intensity and short duration. Where as the monsoon rains are

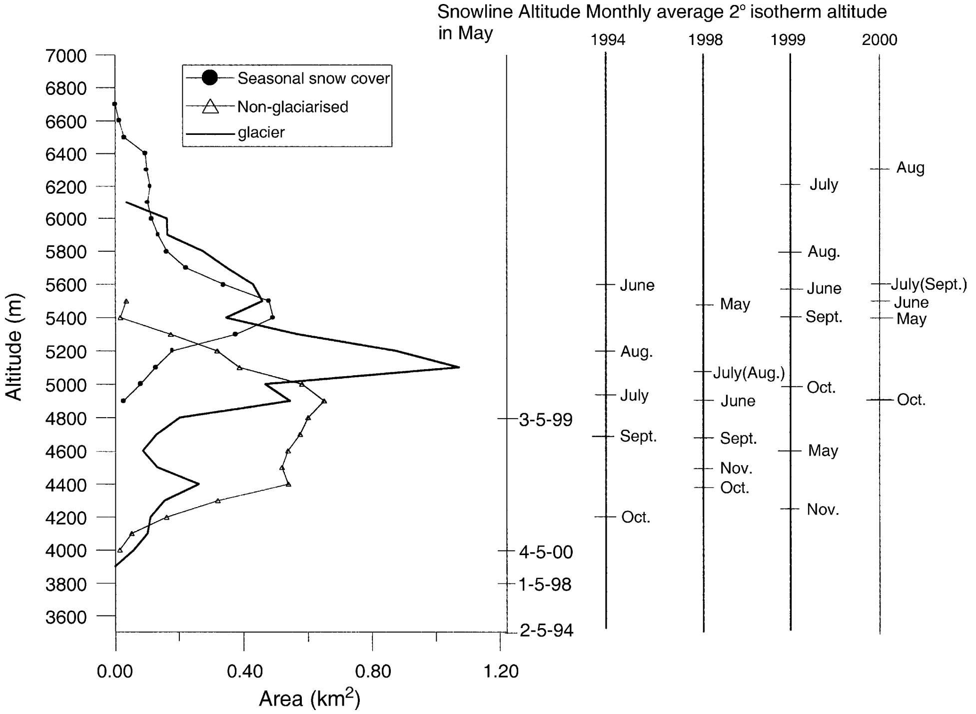

Fig. 2. 2 °C isotherm altitude variations in different years of observation along with altitude-area distribution of glacier catchment and variations in the snowline altitude in May during the observation years.

characterized by prolonged and moderate rainfall with occasional high intensity storms.

Use of monthly average lapse rates for the separation of daily rainfall component is a source of error in this study. Diurnal variability of 2 °C isotherm and variations in the rainfall distribution in the catchment, depends on the characteristics of topoclimatic zones within the basin, also produces error. Experience from Nepal Himalaya suggests precipitation along the valley's of small glaciers do not vary significantly (Ageta, 1976; Higuchi et al., 1982) and it could be 4–5 times higher around peaks and ridges as compared to the valley bottom(Yasunari and Inoue, 1978). Seasonal differences in altitudinal dependence of precipitation is also reported from this region (Seko, 1987; Yasunari, 1976).

3. Results and discussion

3.1. Monsoonal component in glacier discharge

In the Garhwal Himalayas, monsoon sets in around June 25th and continue till end of September (Das, 1988). Meteorological station at Base Camp of Dokriani Glacier (3860 m a.s.l) recorded rainfall ranging from 1098 to 1314 mm during the summer months of four observation years. It is found that more areas of the Dokriani glacier catchment experienced rain during 1999 and 2000 observation period as compared to 1994 and 1998 as indicated by the major shift in two-degree isotherm to the higher altitudes in these years (Fig. 2). This scenario resulted from reduced lapse rates observed within the Alpine catchment (Gujjar Hut, 3430 m and Base camp, 3860 m a.s.l) during these two years (Table 1). Lower lapse rates in 1999 and 2000 may be the result of reduced distribution of snow cover in the glacier catchment as indicated by the snowline altitude in the beginning of the summer observations in May (Fig. 2). Large areas of the glacier catchment became snow free in early ablation period due to reduced snowfall in these two years. This ensures more homogenous temperature distribution in the catchment resulting in lower temperature variation between lower and higher altitudes.

Table 2
Calculated monthly rainfall component, monthly discharge flux, monthly rainfall and mean monthly temperature at Base camp meteorological station during 1994, 1998, 1999 and 2000 ablation months

1994	Discharge (Q) $10^4 m^3$	Rainfall component (R_c) $10^4 m^3$	Percentage rainfall component (R_c%)	Rainfall (mm)	Mean monthly temperature (°C)
May (15–31)	165			0	–
June	868	110	13	115	12.2
July	2188	230	11	500	11.4
August	1834	263	14	457	10.7
September	910	74	8	190	9.7
October	292	2	1	26	5.5
Total	6257	679	11	1289	
1998					
May (15–31)	207	10	5	9	9.4
June	720	60	8	193	10.0
July	1614	140	9	212	11.4
August	1593	218	14	356	10.9
September	764	59	8	240	8.7
October	332	35	10	232	5.3
Total	5231	522	10	1243	
1999					
May (15–31)	205	30	14	97	6.8
June	592	154	26	171	8.7
July	1293	385	30	304	10.8
August	1159	324	28	225	10.1
September	728	197	27	225	8.7
October	288	22	8	33	4.3
Total	4265	1112	26	1098	
2000					
May (15–31)	305	48	16	68	9.1
June	736	202	27	265	9.3
July	1652	612	37	555	10.2
August	1728	340	20	269	10.5
September	829	154	19	146	7.5
October	362	2	1	10	6.1
Total	5612	1357	24	1314	

Table 2 summarizes the results of the separation of rainfall component in the discharge from Dokriani Glacier. Rainfall contribution to the bulk glacier discharge rose from 11 to 10% in 1994 and 1998 to 26 and 24% in 1999 and 2000. Rainfall contribution in glacier discharge peaked in July 1999 and 2000, amounting 30 and 37%, respectively. Where as in 1994 and 1998 peak rainfall component in glacial discharge was in August (14%). Two-fold increase in the rainfall component was observed in 1999 and 2000 as compared to 1994 and 1998. Such an increase in the rainfall component of bulk glacier discharge even in a year of lower rainfall, as observed in 1999 is significant to model glacier runoff in monsoon regime. An increase in the rainfall contribution to the bulk glacier runoff is evident during the summer months of 1999 and 2000 (Table 2). This variation primarily resulted with the increase in the catchment area receiving rainfall during 1999 and 2000 ablation period. 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 results in higher rainfall component in the glacier discharge (Singh et al., 2000) is questionable. This study suggests that the glacier runoff models for Himalayan catchments in monsoon regime need to incorporate the models that can account for rainfall component in glacier discharge. Lower lapse rates during 1999 and 2000 resulted in increased temperature regime in higher altitudinal zones of Dokriani glacier even in the absence of considerable variations in temperature at the Base camp (Table 2). Precipitation over the glacier generally has negative effect on glacier runoff as the incoming solar radiation is reduced during the precipitation event (Rothlisberger and Lang, 1987). Studies have also indicated that the runoff variability is less in glacierised basins than in glacier free catchments where runoff is dominated by rainfall (Collins, 1982; Fountain and Tangborn, 1985). Two-fold increase in rainfall component in glacial runoff from 1994 to 2000 with very little variation in rainfall as well as temperature is capable of affecting the efficiency of glacier runoff models that do not address the possible changes in distribution characteristics of precipitation over the glaciers in the monsoon climate.

Table 3
Rainfall-discharge correlation coefficients (*r*) during 1994, 1998, 1999 and 2000 ablation period (May–October, M_{5-10}). Rainfall with different daily intensities was grouped together with corresponding daily discharge for correlation analysis. Correlation coefficients for monthly and entire ablation period were also given. Table is presented in the form of *r*(*n*), where *r* is the correlation coefficient and *n* is number of samples. Correlations which are statistically significant at $P <= 0.05$ were shown in bold

Rainfall range (mm)	May	June	July	August	September	October	Total
1994							
R_{0-10}		−0.45 (16)	−0.41 (10)	−0.46 (10)	−0.49 (14)	−0.01 (12)	0.35 (62)
R_{10-20}		0.05 (4)	−0.61 (8)	−0.17 (11)	0.94 (4)		0.16 (27)
R_{20-30}			−0.15 (4)	0.33 (5)			0.23 (9)
$R_{>30}$			0.75 (5)	0.90 (4)			**0.77** (9)
Total		0.33 (20)	0.24 (27)	0.26 (30)	**0.66** (18)	−0.01 (12)	**0.50** (107)
1998							
R_{0-10}	−0.91 (4)	−0.17 (14)	0.32 (11)	0.34 (12)	0.06 (12)	**0.70** (8)	0.25 (61)
R_{10-20}		−0.34 (3)	0.47 (6)	−0.48 (11)	−0.38 (9)		−0.06 (29)
R_{20-30}		−0.61 (4)	0.74 (5)				0.05 (9)
$R_{>30}$							—-
Total	−0.91 (4)	0.03 (21)	0.20 (22)	0.09 (23)	0.07 (21)	−0.27 (8)	−0.03 (99)
1999							
R_{0-10}	−0.59 (8)	0.37 (13)	0.10 (15)	0.39 (15)	0.01 (17)	0.16 (7)	0.05 (75)
R_{10-20}	−0.48(3)	−0.26 (6)	−0.62 (3)	0.24 (6)			−0.09 (18)
R_{20-30}			0.23 (3)	−0.85 (4)	0.09 (5)		0.14 (12)
$R_{>30}$			**0.99** (4)				**0.99** (4)
Total	−0.40 (11)	−0.41 (19)	**0.44** (25)	0.38 (25)	0.13 (2)	0.16 (7)	**0.30** (109)
2000							
R_{0-10}	−0.01 (6)	0.1 (15)	−0.1 (10)	0.18 (17)	0.24 (20)	—	**0.37** (68)
R_{10-20}	0.37 (3)	−0.40 (6)	0.40 (11)	−0.65 (6)	**1.0** (3)	—	0.12 (29)
R_{20-30}			0.08 (5)				−0.08 (5)
$R_{>30}$			−0.04 (5)				−0.04 (5)
Total	−0.28 (9)	**0.67** (21)	**0.54** (31)	0.38 (23)	0.35 (23)	—	**0.45** (107)

3.2. Glacier discharge–rainfall relationship

Correlation coefficients between discharge and rainfall have been used to illustrate the influence of rainfall on glacier discharge (Singh et al., 2000). Table 3 shows the correlation between daily rainfall and corresponding daily discharge for different rainfall intensities. Monthly and yearly *R*–*Q* correlation for four observation years are also presented. Seasonal low flow regime of May and October often showed negative correlation between these two variables. Even in the month of June, July and August low and moderate intensity rainfall sometimes produced negative correlation. Low *R*–*Q* correlation was observed in July 1994 and August 1998 (0.09–0.26) when catchment experienced 957 and 568 mm rainfall and better *R*–*Q* correlations were observed (0.54–0.38) in the same months in 1999 and 2000 for less rainfall of 572 and 824 mm. Table 3 also shows that the *R*–*Q* correlation do not improve with the increase in rainfall. It is also observed that the monthly *R*–*Q* correlation do not substantiate the correlations coefficients between discharge and different daily intensities of rainfall. Is this correlation coefficients represent rainfall control on glacial discharge in monsoon months? Analyses of correlation coefficients (Table 3) together with the percentage monthly rainfall contribution during the four years (Table 2) suggests that the variations observed in the discharge-rainfall (*Q*–*R*) correlation coefficients are irrespective of rainfall contributions to the bulk flow. For example in August 1994 and 1998 when rainfall contribution was 14%, the *Q*–*R* correlation coefficient (*r*) was 0.26 and 0.09, respectively. In August 1999 and 2000 correlation coefficient was 0.38 when rainfall contribution was 28 and 20%, respectively. In September 1994 when rainfall contribution was just 8%, corresponding correlation coefficient was 0.66. Fig. 3 shows cumulative curves of discharge and rainfall, plotted for the each of the observation years. The discharge cumulative curve is a smooth curve compared to the cumulative curve of the rainfall.

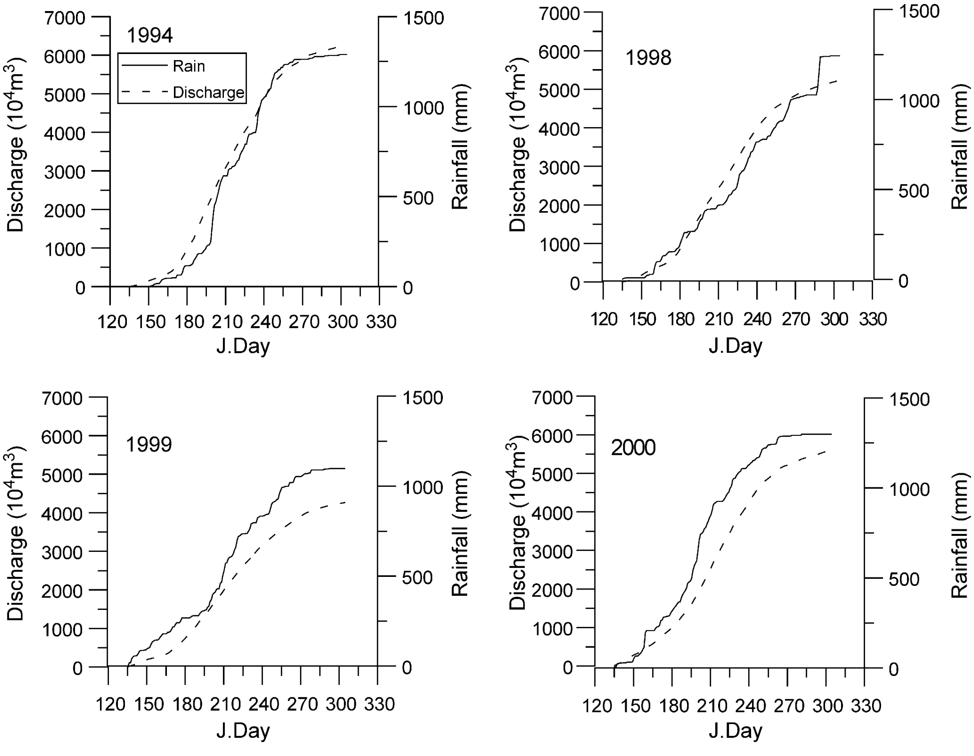

Fig. 3. Cumulative discharge and rainfall for four years of observation showing same trend for both the variables through the ablation period.

Both the variables have the same trend but the increase in the glacier discharge in the monsoon months is mainly related to increased glacier melt due to higher summer temperatures rather than the rainfall contribution. However, same trend of both the variables in these months resulted in producing spurious correlation coefficients between these two variables. Hence better correlation between discharge and rainfall need not necessarily mean greater influence of rainfall on discharge. As we have seen in the earlier section, the amount of water contributed by the rainfall to the glacier is controlled by the variations in the aerial distribution of rainfall in the glacier catchment rather than the depth of precipitation itself. The complex response mechanism of rainfall on glacier discharge, which makes *Q–R* correlation irrelevant is discussed in the following sections.

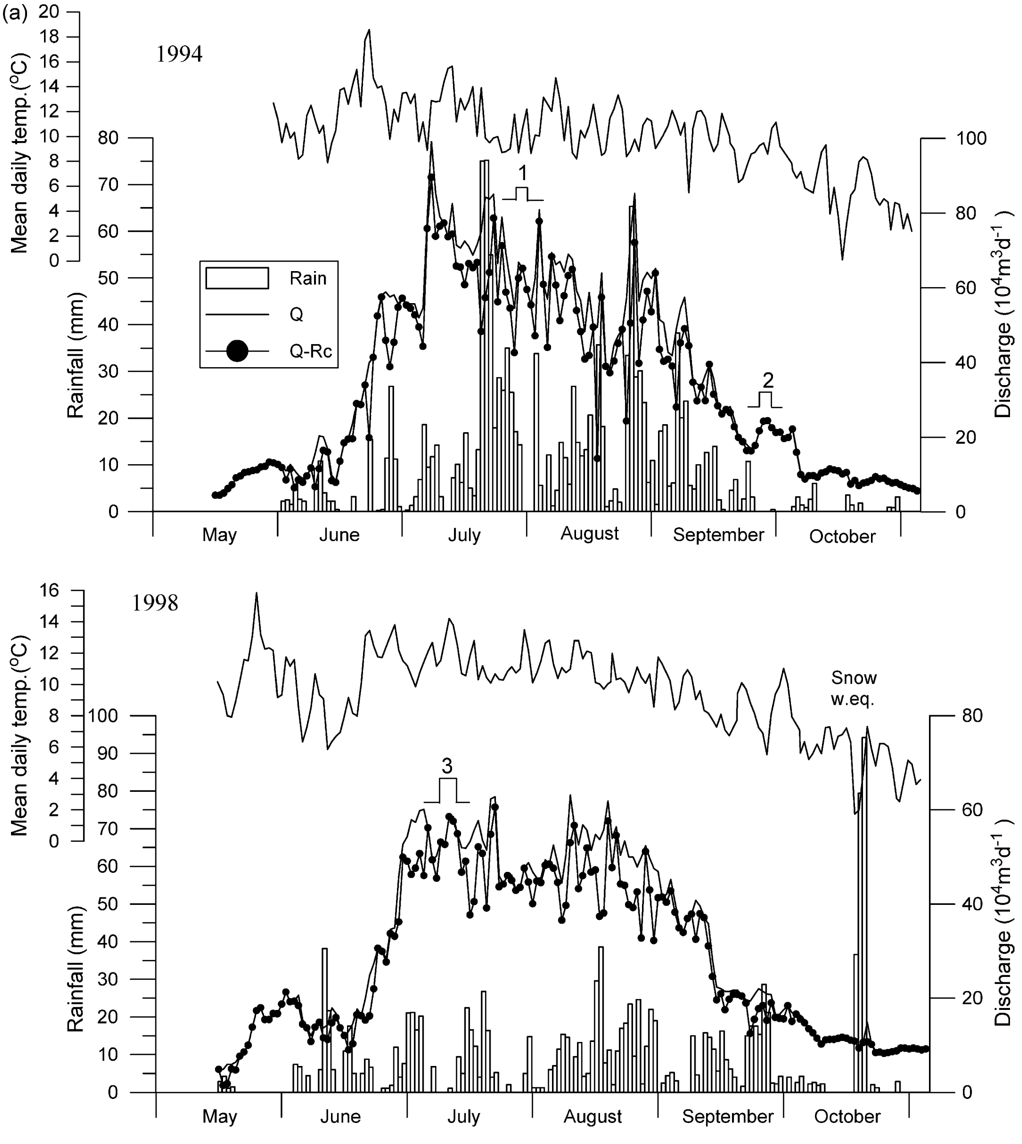

Fig. 4. (a,b) Figure showing daily total discharge, rainfall and daily discharge after deducting rainfall component during 1994, 1998, 1999 and 2000 observation period. Numbers show combination of rainy days and non-rainy days having different response on the hydrograph.

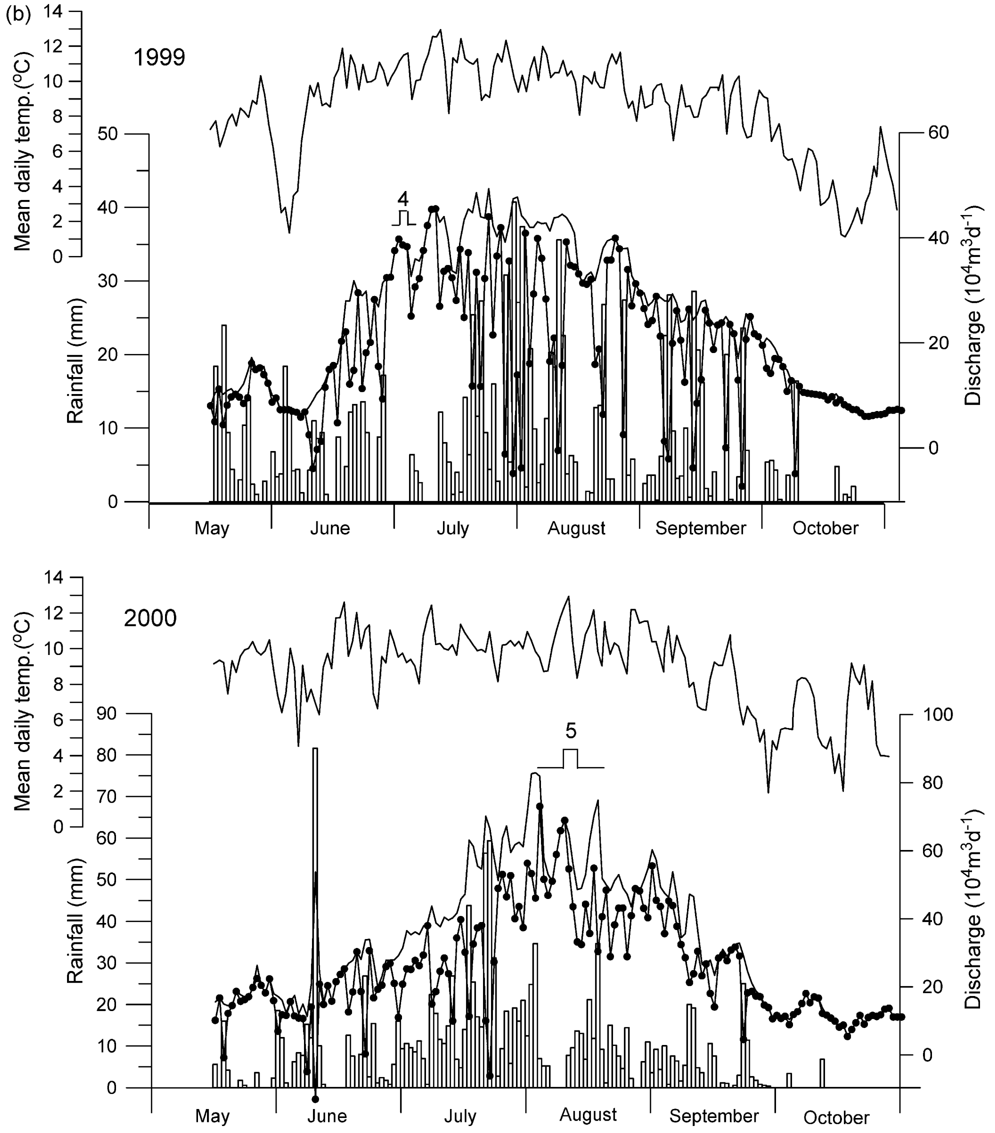

Fig. 4 (*continued*)

3.3. Response of rainfall on daily glacier hydrograph

The effects of monsoon rains on the characteristics of glacier discharge hydrograph are also analyzed. Fig. 4a and b show four years of daily discharge, daily rainfall and daily glacier discharge after deducting the rainfall component, assuming that the entire rainfall contribution appeared at discharge station on the same day. An analysis of glacier discharge hydrographs in these four years suggests that the rainfall contribution is not evident on the hydrograph even during the months when the rainfall component was 30 and 37% (Fig. 4b). Rainfall over the glacier produces various responses on discharge hydrograph depending on the season of its occurrence, surface conditions and storage characteristics of glacier, intensity, duration and distribution of rainfall. Analysis of daily rainfall intensity with daily

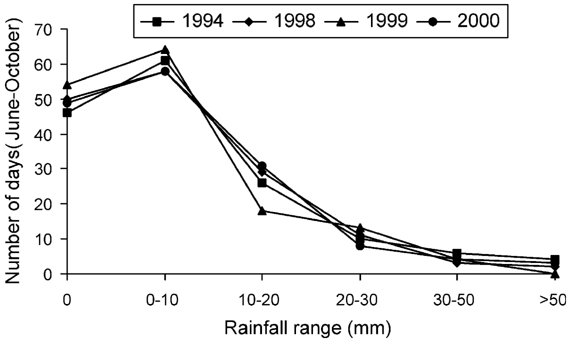

Fig. 5. Number of rainfall days with different rainfall intensities during ablation period.

discharge suggests that the storms with intensity >30 mm d^{-1} influence the glacier discharge of that day (Fig. 4a and b). Rainfall with intensity ranging from 20–30 mm d^{-1} also influence the daily discharge flux occasionally, depending on the period of its occurrence. The influence of such storms on daily discharge is more during June, July and August months and less if it occurs in May or October. This is evidently due to the presence of snow cover or reduced area experiencing liquid precipitation in these months. Storms with intensity >30 mm d^{-1} was experienced only on few days during the six-month long ablation season. More than 80% of rainfall days in Dokriani Glacier catchment experienced <20 mm d^{-1} of rain (Fig. 5) and those rains has not shown positive signature on the daily glacier discharge hydrograph. In fact rainfall with intensity <20 mm d^{-1} in May and October effectively reduces the glacier discharge. From June to September, including the monsoon months, rainfall with intensity <10 mm d^{-1} reduce the daily glacier discharge (Fig. 4a and b). Rainfall of 10– 20 mm d^{-1} seems to be compensating the reduced snow/ice melt and rainfall >20 mm d^{-1} produces distinct peaks on daily hydrograph. By and large it can be concluded from this study, that the storms ≥ 20 mm d^{-1} in a glacier catchment generate recognisable response on glacier hydrograph and contributions from <20 mm d^{-1} rainfall is not distinguishable from the snow/ice melt contribution. Characteristics of hydrograph of such rainy days are more representative of glacier drainage characteristics than the rainfall. The complex response of rainfall on glacier discharge can be better understood by evaluating the daily hydrograph of rainy days together with subsequent non-rainy days at various stages of ablation season in different years. Three such combinations were marked as 1–4 in the Fig. 4a and b.

1. Lower discharge on non-rainy days as compared to the rainy days having rainfall >30 mm d^{-1} (1 and 5, Fig. 4a and b).
2. Higher discharge on non-rainy days as compared to the following rainy days having rainfall of ≤ 10 mm d^{-1} (2 and 4, Fig. 4a and b).
3. Almost same discharge on non-rainy days and rainy days having $\approx$ 20 mm d^{-1} rainfall (3, Fig. 4a).

50–60% of monsoonal rainfall is the contribution from rainfall ranging between 0–20 mm d^{-1} and its responses need not necessarily 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 at the glacier snout only after traversing through the glacier drainage and storage. During these period storm characteristics were completely assimilated by the drainage and storage characteristics of the glacier (Thayyen, 1997). This study suggests that the hydrograph analysis is a poor tool for studying the rainfall influence on glacier discharge. This study also shows why rainfall did not evoke representative and consistent response on glacier discharge and further explains the irrelevance of discharge-rainfall correlation in studying the glacial hydrological processes.

3.4. Response of rainfall on diurnal glacier hydrograph

For a detailed analysis of rainfall influence on diurnal hydrograph characteristics, hourly hydrographs of non-rainy days were analysed in comparison with the rainy days. Two such combinations were identified; one on the rising limb of the ablation hydrograph from 5–17 June and another on the crest of the hydrograph from 28 July to 10 August in year 2000 (Fig. 6a and b). Discharge and meteorological

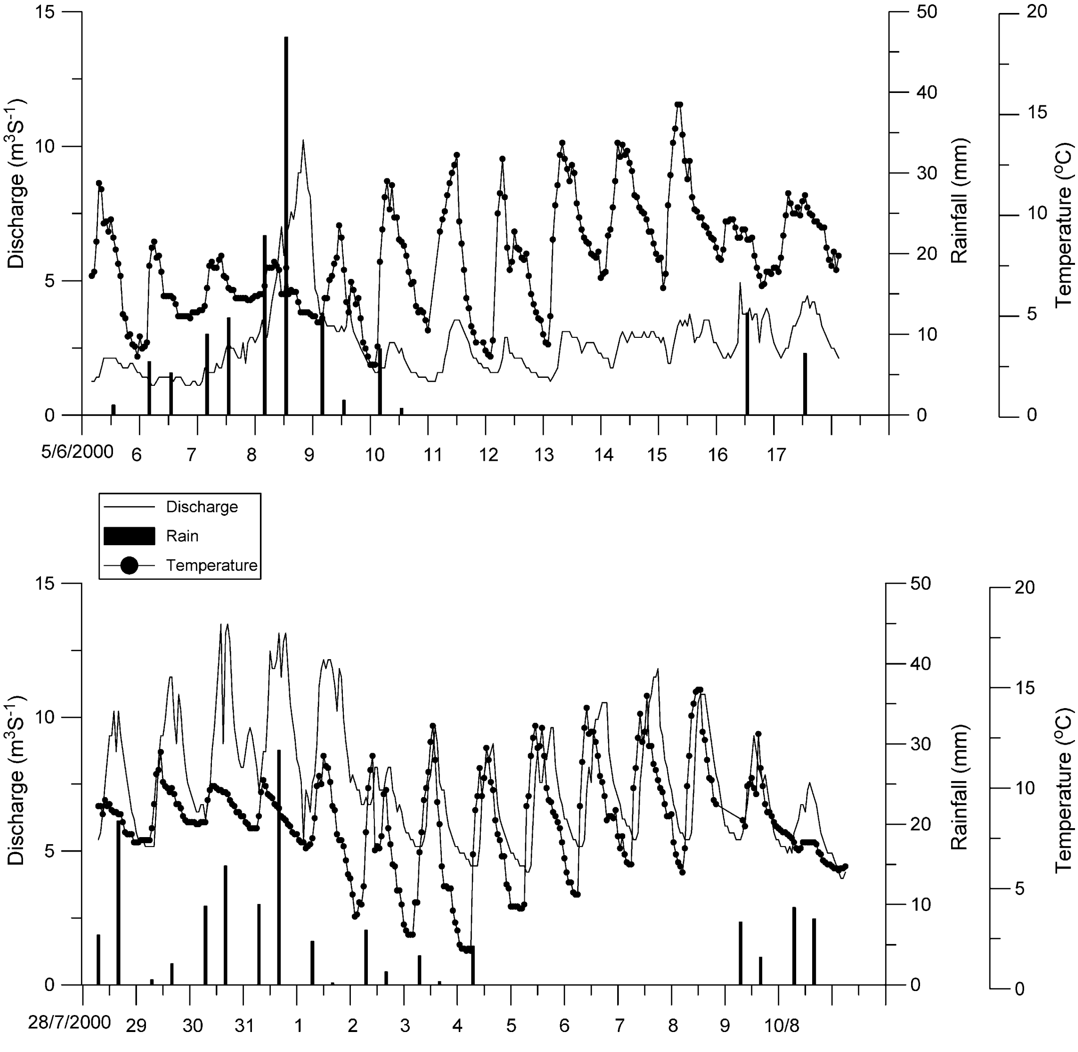

Fig. 6. Diurnal variations in discharge on rainy days and non-rainy days in selected period in the year 2000 along with rainfall and hourly temperature variations.

parameters including rainfall, daily mean temperature, sunshine hours during these periods are tabulated in Table 4. The storm on the rising limb persisted from 5th to 9th June and peaked on 8th June experiencing 81.6 mm of rainfall. This storm was effective in disturbing the diurnal rhythm of glacier hydrograph and produced a characteristic storm hydrograph. The diurnal hydrograph of non-rainy days also have multiple peaks as that of rainy days. On non-rainy days these multiple peaks were generated by the temperature fluctuations. However, it is evident that the multiple peaks of rainy days are prominent than the non-rainy days. Diurnal hydrograph during this period show low amplitude variations as compared to the diurnal temperature variation. This shows that the diurnal glacier discharge hydrograph on rising limb of the ablation hydrograph is regulated by the glacier drainage characteristics except during high intensity rainfall (Thayyen et al.,1999, 2003).

At the crest of the hydrograph between 28th July and 4th August, rainfall intensity of ~30 mm d^{-1} was not capable of disturbing the diurnal rhythm of glacier hydrograph, mainly due to higher base flow from glacier during this period. Analysis of mean

Table 4
Comparison of meteorological and hydrological parameters of rainy days and non-rainy days

I	Rain fall (mm)	Mean daily temperature	Sunshine hours	Q (10^4 m^3)
5/6/00	7.8	6.6	6.6	15
6/6/00	15.2	6.0	2.2	11
7/6/00	12.0	6.6	0.0	21
8/6/00	81.6	6.1	0.0	54
9/6/00	10.1	5.7	0.4	24
10/6/00	0.8	8.0	7.6	16
11/6/00	0.0	7.5	9.4	20
12/6/00	0.0	7.4	4.5	16
13/6/00	0.0	9.9	8.1	22
14/6/00	0.0	10.4	5.2	24
15/6/00	0.0	10.9	7.4	25
16/6/00	12.6	8.3	0.0	27
17/6/00	7.6	9.6	0.3	28
II				
28/7/00	16.0	8.2	0.0	61
29/7/00	21.0	9.2	0.5	7.1
30/7/00	12.4	9.1	0.0	83
31/7/00	24.8	8.5	0.0	83
1/8/00	34.6	7.6	5.3	82
2/8/00	7.0	6.4	3.6	58
3/8/00	5.2	6.2	7.3	53
4/8/00	5.2	7.5	9.1	51
5/8/00	0.0	8.8	7.0	59
6/8/00	0.0	9.7	6.3	66
7/8/00	0.0	9.9	8.0	69
8/8/00	0.0	12.3	8.2	65
9/8/00	7.8	8.9	2.0	56
10/8/00	9.6	6.7	0.0	49

daily temperature on non-rainy and rainy days in association with sunshine hours brings out some interesting results. In July and August, rainy days with zero sunshine hours produced similar range of mean daily temperature as that of days with no rainfall and >6 h sunshine (Table 4). This is associated with low amplitude diurnal variations of temperature during the rainy days having >10 mm of rainfall. As a result, highest daily discharge observed during the study period is associated with the days having high rainfall and high mean daily temperature combination. So the discharge peak on rainy days cannot be attributed to rainfall alone. For the days having rainfall <10 mm, diurnal amplitude of temperature remains a same as that of non-rainy days (Fig. 6a and b). In another scenario, mean daily temperature on rainy days with low rainfall is lower than the mean daily temperatures of non-rainy days. This combination translates into reduced discharge on rainy days with rainfall intensity ≤ 10 mm.

The study of hydrograph of rainfall days and non-rainfall days at rising limb and crest segment of ablation hydrograph suggests that response of diurnal hydrograph to the rainfall also have seasonal variations. In the rising limb rainfall ≥ 10 mm d^{-1} have prominent influence on diurnal discharge hydrograph where as on the crest segment rainfall of ≥ 35 mm d^{-1} have little influence on the diurnal hydrograph. However, combination of rainfall with intensity of >30 mm d^{-1} and <1 h of sunshine results in higher daily average temperature and produces the highest discharge peak of the ablation season. The response of diurnal hydrograph to the rainfall is related to the percentage contribution of rainfall and the drainage characteristics of glacier at a particular period of ablation season. It is quiet evident from the study of hydrographs of rainy days and non-rainy days that the response of glacier hydrograph to the rainfall is weak especially in monsoon months which coincided with the crest of ablation hydrograph due to complex interrelationship with the temperature, rainfall intensity, duration and distribution of rain, distribution of sunshine hours in a day and efficiency variations of glacier drainage network.

4. Conclusions

In this study an attempt has been made to quantify and evaluate the role of monsoons in glacial runoff processes. Monsoonal component in glacial discharge during 1999 and 2000 ablation period increased to 26 from 10% in 1994 and 1998. This increase resulted mainly due to the variations in rainfall distribution pattern over the glacier rather than the variations in rainfall depth. Results suggest that the glacier runoff models for monsoon regime should incorporate quantification of rainfall component. 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 increasing trend in the peak ablation months. However, increase in glacier discharge during monsoon months resulted from increased glacier melt due to higher temperatures in summer rather than the rainfall contribution. Daily and diurnal glacier hydrograph response to the rainfall is inconsistent and weak especially in monsoon months, which coincided with the crest of the 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 need for in depth evaluation before attributing various hydrological characteristics of Himalayan glaciers to monsoon.

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