Seasonal changes in meltwater storage and drainage characteristics of the Dokriani Glacier, Garhwal Himalayas (India)

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Abstract Storage and drainage characteristics of the Dokriani Glacier (9.66 km^2) located in the Garhwal Himalayas have been studied. In order to understand these characteristics, clear weather (non-rainy) days data for three ablation seasons (1996–1998) are used because discharge is melt-driven on such days. Moreover, diurnal variations in the discharge on clear days represent the true picture of glacier response to streamflow. Results indicate that meltwater storage characteristics of the glacier lead to high discharges in the stream during the night. Consequently, night-time discharges are comparable with those observed during daytime throughout the melt season. Meltwater storage characteristics of the glacier are much stronger in the early part of the melt season and they weaken as the melt season progresses.

Diurnal variations in the discharge are observed to be clearer with advancement of the melt season providing variations in the timing of peak flow. Maximum discharge for different years was observed between 1700 and 1900 hours, showing a lag of 2 hours in the timing of maximum flow over the ablation period. The time to peak flow varied from 8.5 to 11 hours. For all the years, a strong seasonal trend towards increasing diurnal amplitude in discharge until August and thereafter a decreasing trend, was observed. The time lag between Q_{max} and T_{max} varied from 3–6 hours over the ablation season and recession of melt water became faster with time. The time lag is higher at the beginning of the melt season and reduces as the melt season progresses. Recession trends of the hydrographs with time suggested a similar hydrological response of the glacier in June and September. The basin behaved like a single conceptual linear reservoir for these two months, while for July and August it behaved like two conceptual linear reservoirs, namely, accumulation and ablation reservoirs.

Keywords Daytime and night-time discharge; diurnal discharge; drainage characteristics; meltwater storage; streamflow recession; time lag

Introduction and background

Rivers originating from the Himalayas are perennial in nature because they receive water input throughout the year either from rain, snow, glaciers or groundwater. The contribution from each component to the streamflow varies with time. Himalayan rivers get maximum contribution from the snow and glaciers during the summer months when the demand for water is also at its maximum. The water yield from the glaciated regions is considered high and reliable because of significant precipitation in the high altitude regions. Availability of discharge from the glaciers and suitable head in the high altitude region provide excellent conditions for hydropower generation.

More than 5000 glaciers exist in the high altitude region of the Indian Himalayas. All the glaciers in the Himalayan region exist above 4,000 m altitude and are completely covered with snow during winter because the snowline moves down to about 2,000 m during this period. At the beginning of the melt season, around March and onward, the first seasonal snow accumulated in the lower altitudes of the basin diminishes. Generally, all the seasonal

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snow has melted away from the lower part of the basin by the end of May, and the snowline is at an altitude of about 4,000 m by this time. Further upward migration of the snowline starts exposing glacier ice surfaces and melting of glacier ice takes place. With advancement of summer, the exposed glacier ice area increases at the expense of further depletion of snow over the glacier. However, maximum runoff from the Himalayan glaciers is observed in the months of July and August due to intensive melting during these months. However meteorological conditions allow for some melting until October. Thus, for the Himalayan glaciers, the ablation season spreads over a period of about 6 months (May–October) (Singh and Ramasastri 1999), whereas the melt season for the Arctic glaciers covers a period of only 2 to 3 months (Hodgkins 2001). Evidently, the melting season for the Himalayan glaciers is more than two times the duration of ablation for the Arctic glaciers. For the Arctic glaciers, the bulk of the seasonal total meltwater discharge occurs during a relatively short period of high variability, which begins and ends rapidly between mid-July and early August.

In a glaciated catchment, the amount of runoff produced from the basin is governed by the extent of the glaciated area, climatic energy inputs and the amount of liquid precipitation falling in the basin. The changes in physical features of a glacier during the melt period have a significant influence on the hydrological response of the glacier. The trends of the rise and fall of the hydrograph, the time of maximum and minimum discharge, time lag between generation of meltwater and its appearance as runoff at the outlet of the basin, and recession characteristics of discharge are considered as important factors for the hydrological response of the basin. Hodson *et al.* (1998) found that recession of the snowpack across unglaciated and glaciated parts of the Austre Brøggerbreen basin in Svalbard provided an important influence on the lags between energy inputs and meltwater discharge outputs. Such time lags were longer than observed in similar Alpine basins. Recently, Hodgkins (2001) studied the seasonal evolution of meltwater generation, storage and discharge for an Arctic glacier (Scott Turnerbreen, 3.3 km^2) located at 78° in Svalbard. He observed a significant difference in the functioning of the glacier meltwater system in terms of water storage over the melt period of 30 days (20 July to 19 August 1992). A substantial contribution to the proglacial stream was found to originate from the meltwater stored in the snowpack over the glacier in the early weeks of the melt season. It resulted in higher discharge in the stream than expected due to energy input on a single day in the early part of the melt period. Consequently, the proglacial discharge did not respond to the energy fluxes on an hourly or diurnal time-scale, because it was produced in the early weeks of the melt season and was subsequently released discontinuously at varying long-term delays (days rather than hours). This behaviour of discharge in response to meteorological inputs was substantially different from that observed at an Alpine glacier (Gurnell *et al.* 1992, 1994).

The status of hydrological studies for the Himalayan glaciers is not as good as that for the Alpine and Arctic glaciers. Keeping in view the glaciers as an important source of water, the International Hydrological Decade (1965–74) included major programmes related to glacier hydrology and valuable information was gathered for Himalayan glaciers under these programmes which has broadened the understanding and knowledge of the subject. Since 1986, a new glaciology programme has been initiated in India and studies are being carried out on various glaciers. Still relatively limited studies have been carried out to investigate the hydrological aspects of the glaciers in the Himalayan region (Singh 1993; Singh *et al.* 1995, 1999, 2000b; Singh and Kumar 1996, 1997a, b; Hasnain 1999; Thayyen *et al.* 1999; Swaroop *et al.* 1999; Singh and Jain 2002). One of the main reasons for lack of hydrological studies in these high altitude basins is unavailability of the required data. No study has examined the changes in hydrological response of a glaciated basin in the Himalayan region, while an understanding of the melting and drainage processes of glaciers is needed for the modelling of streamflow from such basins. In the present study, attempts have been made to understand the variation in the hydrological response over the ablation season for the Dokriani Glacier located in the Garhwal Himalayas.

Study Area and Data Collection

The Dokriani Glacier is a valley type of glacier situated in the Garhwal Himalayas. A detailed description of the study area including its location, approach and accessibility to this glacier is given by Singh *et al.* (2000b). In brief, this glacier covers about 9.66 km^2 encompassed between 3,950–5,800 m altitude. The length of this glacier is about 5.5 km whereas its width varies from 0.1–2.0 km from the snout to the accumulation zone. The maximum glacier area (~25%) lies between 5,000–5,200 m altitude. The melt stream emerging out from the Dokriani Glacier is known as Din Gad, which joins the main Bhagirathi River near Bhukki village in the Uttarkashi District of Uttaranchal State.

Discharge and meteorological data were collected near the snout of the glacier for three ablation seasons (1996–1998). For the collection of discharge data from the study glacier, a discharge gauging site was established about 800 m downstream of the snout of the glacier. The altitude of the gauging site was about the same as that of the snout (3,950 m). An automatic water level recorder was installed at the gauging site for continuous recording of flow in the stream. These water levels were converted into discharges using a stage-discharge relationship developed for the site. A standard meteorological observatory was also established near the snout of the glacier for collecting the weather data.

The most typical feature of the study area is the occurrence of rain throughout the melt season. The average rainfall for the summer months (June–September) in this area amounts to more than 1,000 mm, being greatest in August (375 mm) followed by July (245 mm). Usually, the intensity of rainfall is < 2 mm/hour. Mean daily temperatures vary between 8 and 11 °C during the summer period (June–September). The average monthly discharge from the Dokriani Glacier basin for June, July, August and September has been observed to be 7.34, 18.05, 19.0 and $5.09 \times 10^6 m^3$, respectively (Singh and Ramasastri 1999).

Daytime and night-time discharges and their variation during the melt season

In the glacier-fed streams only a portion of the meltwater produced each day emerges as runoff from the snout on the same day. The remaining meltwater is stored within the glacier. During the summer period a considerable contribution to streamflow is received from the meltwater stored in the glacier. Even on a diurnal cycle, the runoff also contains a part of this stored meltwater. This shows that the streamflow of a glacier-fed stream is controlled by storage characteristics of the glacier and determined by the delayed response of the basin. The size of the glacier, extent of snow cover, depth of snow over the glacier and drainage network of the glacier are the important factors which control the magnitude of the volume of the water occurring as runoff. Several studies based on tracer experiments, isotope studies and analysis of the runoff distribution suggest that a major part of the runoff from the stored water results as continuous runoff from the accumulation area (firn area), continuous drainage from the glacier lakes, water-filled cavities and groundwater flow (Stenborg 1970; Elliston 1973; Tangborn *et al.* 1975; Collins 1982; Oerter and Moser 1982). The magnitude of delay in response is also a function of the ablation and accumulation area ratio. The runoff dominated by the meltwater from the accumulation area has a longer time of concentration as compared to the meltwater generated in the ablation area. Hodgkins (2001) reported that in the early part of the melt season the major contribution to the Arctic proglacial streams is provided from the stored meltwater in the glacier.

In order to examine the storage characteristics of the study glacier, daily (24 hours) streamflow records were subdivided into daytime flow (0900–2000 hours) and night-time flow (2100–0800 hours), respectively. Daily mean daytime and night-time flow for three

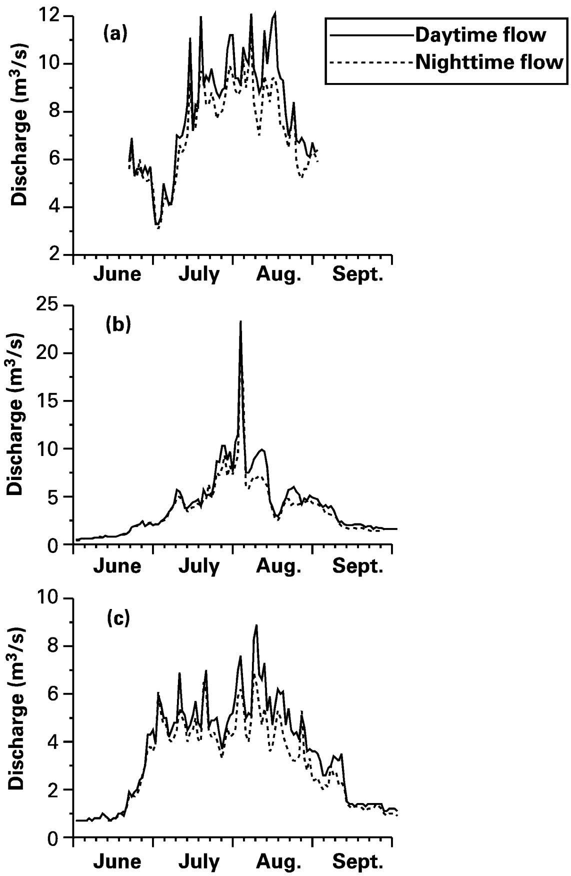

Figure 1 Daytime (0900–2100 hours) and night-time (2100–0800 hours) mean discharge observed near the snout of Dokriani Glacier during three ablation seasons (a) 1996, (b) 1997 and (c) 1998

different years are shown in Figure 1, whereas monthly discharges for the respective periods are presented in Figure 2.

The ratio of monthly daytime discharge to that of night-time discharge was computed and is given in Table 1.

It was found that this ratio varies from 0.83 to 1.02 during the ablation season, being at a maximum in the early melt period. The magnitude of the streamflow during daytime and

Table 1 Variation in ratio of daytime monthly discharge to that of night-time for different months during three ablation seasons (1996–1998)

Year	Month	Ratio of daytime discharge to night-time discharge
1996	June	0.97
1996	July	0.91
1996	August	0.88
1997	June	1.02
1997	July	0.90
1997	August	0.85
1997	September	0.86
1998	June	0.93
1998	July	0.90
1998	August	0.79
1998	September	0.83

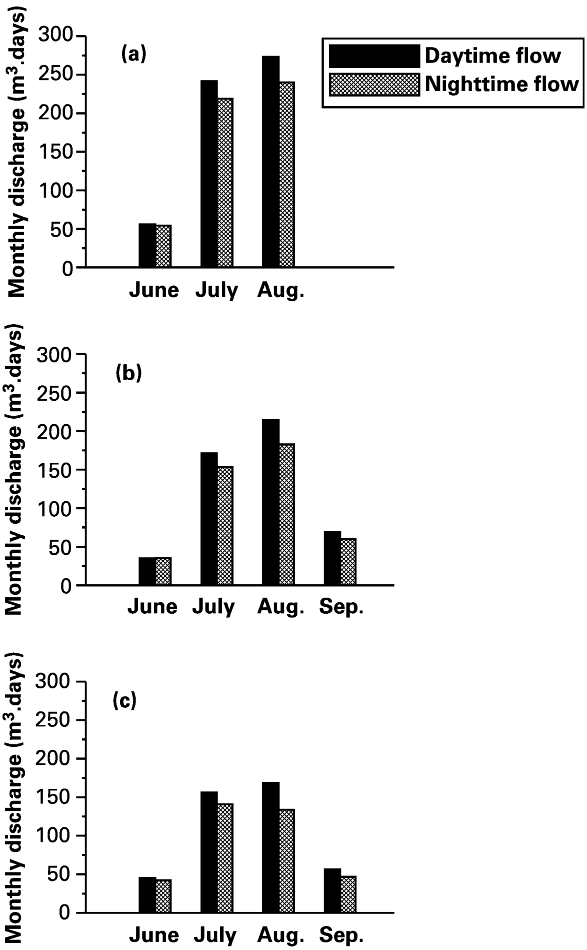

Figure 2 Monthly distribution of daytime (0900–2100 hours) and night-time (2100–0800 hours) mean discharge observed near the snout of Dokriani Glacier during three ablation seasons (a) 1996, (b) 1997 and (c) 1998

night-time indicates that at the beginning of the melt season, the volume of the night-time flow is very close to the daytime flow, but in the later part of the melt season, night-time flow reduces in comparison with the daytime flow (Figure 2). Such trends of the daytime and night-time flows are observed for all the years. Very little or no melting takes place on the glacier surface during the night, but still a high amount of discharge is observed in the stream during the night. It shows that meltwater produced during the day is partly stored in the glacier and released later, while such trends in the rain-fed rivers do not exist. This analysis suggests that meltwater storage characteristics of the glacier are much stronger in the early part of the melt season and reduce as the melt season develops. Trends of variations in the ratio of daytime flow to night-time flow with melt season can be explained on the basis of availability of snow cover on the glacier body and development of the drainage network in the glacier. The greater extent of snow cover in the early part of the melt season, along with a poorly developed drainage network, results in a much delayed response of the meltwater from the basin to the outlet, producing a reduced difference between daytime and night-time streamflows. The reduction in the extent of snow cover and progressive development of the drainage network with the melt season contribute to a faster response of meltwater in the mid or late melt season, which increases the difference between the daytime and night-time flows.

As shown in Figure 2, the seasonal distribution of streamflow for both day and night shows that discharge from the Dokriani Glacier starts increasing in the early part of the melt season, reaches its maximum during July and August, and thereafter starts decreasing. The meltwater storage characteristics existing in the early part of the season change the hydrological response of the basin, but these are not strong enough to provide the maximum flow in the early part of the melt season, as was observed in the Arctic glacier stream. For the Arctic glaciers, in the early part of the melt season, the meltwater storage characteristics are so strong that the discharge at the outlet of the glacier on a particular day is observed to be much higher than the volume produced on that day. Hodgkins (2001) reported that the surface drainage was effectively absent at Scott Turnerbreen until late June and meltwater generated at the surface of the glacier was stored in the snowpack till about the middle or end of July. Physical features of the glaciers (flat and uncrevassed) allow for water to accumulate at the surface in greater volumes than on the temperate glaciers of comparable size. Release of this stored water in the early part of the melt season changes the seasonal distribution of streamflow in the Arctic glaciers.

Seasonal variations in diurnal discharge

The diurnal variations in the discharge from a glaciated basin primarily depend on the weather conditions, the surface condition of the glacier (whether snow covered or snow and firn free) and physiographical features of the basin. Prevailing weather conditions govern the melting rate, while the drainage pattern of the runoff is controlled by the physiographical features of the glacier. Changes in diurnal variation in the streamflow in the ablation season provide important information on the hydrologic response of the basin. Analysis of clear weather (non-rainy days) hydrographs provides useful information on the storage and drainage characteristics of the glacier. On rainy days, rainfall events generate peaks in discharge and diurnal variations in discharge, which do not represent the melt-driven trend on such days. Further, contribution from the rain is also added to the streamflow and separation of the rain component from the streamflow is difficult to obtain the runoff from the melt only. Therefore, it becomes important to select non-rainy days over the melt season to study the diurnal variations and other hydrological characteristics of the glacier. Wolfe and English (1995) examined meteorology and runoff from a small, glaciated catchment on Ellesmere Island, Canada and reported that the air temperature on non-rainy days gave the best correlation with runoff. Thus, selection of non-rainy days discharge over the melt period becomes a prerequisite to study the characteristics of the melt-driven discharge. In the present study, days having rainfall < 2 mm and experiencing temperatures high enough for

Table 2 Details of meteorological data for clear weather days selected for hydrograph analysis

Date	Mean temp. (°C)	Rainfall (mm)	Mean discharge (m^3s^{-1})	Relative humidity (%)
27.06.96	10.05	0.1	6.10	81
11.07.96	10.15	0.8	6.85	88
25.08.96	8.50	1.5	6.25	94
25.06.97	9.95	1.8	2.73	91
09.07.97	12.10	0.2	5.50	84
21.08.97	10.25	0.0	5.45	93
13.09.97	8.10	1.2	1.90	92
24.06.98	10.90	0.0	2.30	92
23.07.98	9.70	0.0	4.96	90
09.08.98	12.10	0.0	5.58	89
04.09.98	8.40	0.2	2.83	90

the melting of the glacier, were selected as clear weather days. Meteorological data for the selected clear weather days are given in Table 2. The present study area experiences adequate rainfall throughout the melt season, therefore, only a few days were found without rainfall or with very little rainfall, but they were sufficient to reveal the trends of the hydrologic response of the glacier over the melt season.

The diurnal variations in discharge for selected clear weather days over the ablation season for different years are shown in Figure 3.

The shape of the hydrographs changes with advancement of the melt season and trends of variation over the melt season are also similar for all the years. In the early part of the melt season, for example in June, snowmelt gives a damped effect in streamflow due to dominance of flow by relatively slow percolation and its delayed release. Diurnal variations

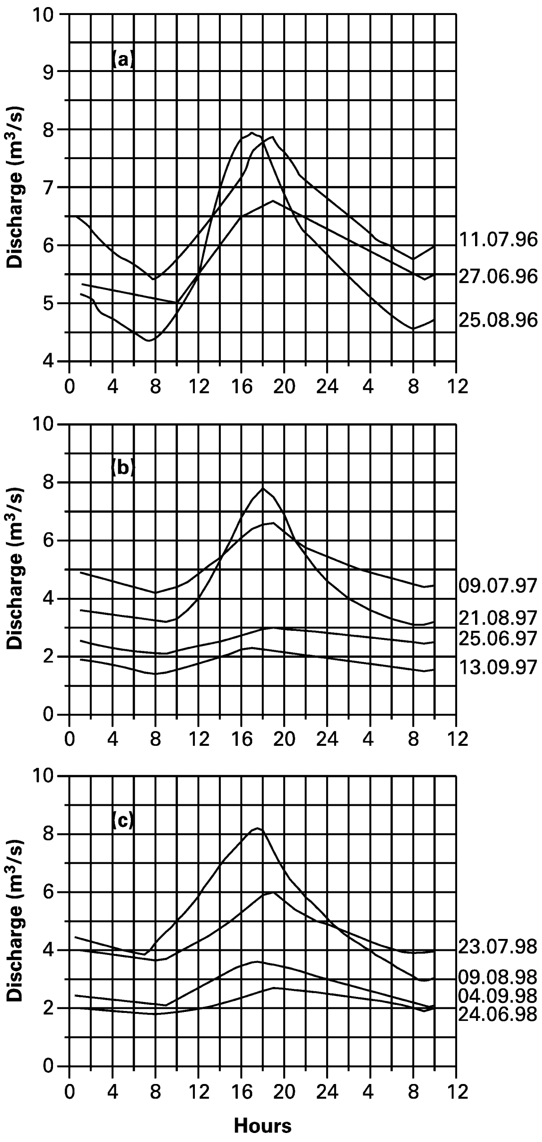

Figure 3 Diurnal variations in discharge on clear weather days observed near the snout of Dokriani Glacier during three ablation seasons (a) 1996, (b) 1997 and (c) 1998

in the months of June and September were not very clear, but were much more pronounced in July and August. Intense melting of ice and a larger extent of exposed glacier ice in the months of July and August, contribute to a relatively steep rise and fall of the discharge and to the higher peak of runoff. Icemelt produces a peaked discharge owing to the low albedo of ice and dominance of flow by relatively rapid surface runoff. Therefore, the hydrological system tends to respond more rapidly to the meltwater inputs and the diurnal hydrographs due to an increase in the ice-exposed area of the glacier.

The diurnal variations in discharge for the study glacier indicate clearly only one maximum and one minimum level of discharge. At the beginning of the melt season the discharge has a broader maximum but it becomes sharper and sharper as the melt season progresses. The maximum streamflow, Q_{max}, in the Dokriani Glacier melt stream was observed in the late afternoon or evening (between 1700–1900 hours), suggesting that a major part of the meltwater produced during the day reaches the snout within a period of few hours. Diurnal changes in the streamflow clearly indicate the variations in the timing of peak runoff with melt season. Timings of Q_{max} for different years are given in Table 3.

For different years a difference of about 1.5 to 2 hours was observed in the timings of maximum flow from June to September (Figure 3). Time taken by the hydrograph to reach its maximum from the start of rising is known as time to peak, t_p. The value of t_p for the Dokriani Glacier for the different months is given in Table 3. It is found that for this glacier t_p varies from 8.5 to 11 hours over the ablation season. Similar to the reduction in timing of Q_{max} with advancement of the melt season, t_p also reduces, *i.e.* an early peak is observed with advancement of the melt season. Changes in the physical features of the glacier with time are responsible for such variations in t_p. An early peak in the runoff with advancement of the melt season suggests a relatively faster response of the drainage basin due to a larger extent of exposed ice surface, reduction in snow cover area and depth of snow, and improvement in the drainage network. Thus, reduction in the meltwater storage capacity of the glacier also influences the pattern of diurnal variation with time.

Figure 3 also shows a strong seasonal trend towards increasing diurnal amplitude in discharge until August and thereafter a decreasing trend, for all the years. Variations in diurnal amplitude of discharge with season are given in Table 4. The diurnal amplitude varies from 1.4–3.4, 0.45–4.7 and 0.8–5.25 $m^3 s^{-1}$ for the 1996, 1997 and 1998 ablation seasons, respectively, representing mean diurnal discharges from 23–54.4%, 16.5–86.2%, and 34.8–94% for the corresponding ablation seasons.

Table 3 Timings of Q_{max}, Q_{min} and time lag for different months during three ablation seasons (1996–1998)

Date	Time of T_{max} (hours)	Time of Q_{max} (hours)	Time lag between T_{max} and Q_{max} (hours)	Time of T_{min} (hours)	Time of Q_{min} (hours)	Time lag between T_{min} and Q_{min} (hours)	Time to peak, t_p (hours)
27.06.96	1300	1900	6.0	0400	0900	5.0	11.0
11.07.96	1400	1900	5.0	0400	0800	4.0	11.0
25.08.96	1300	1700	4.0	0500	0800	3.0	10.0
25.06.97	1300	1900	6.0	0500	0900	4.0	10.0
09.07.97	1400	1900	5.0	0400	0900	5.0	11.0
21.08.97	1400	1800	4.0	0600	0800	2.0	9.0
13.09.97	1400	1700	3.0	0600	0900	3.0	9.0
24.06.98	1300	1900	6.0	0500	0900	4.0	11.0
23.07.98	1400	1900	5.0	0400	0900	5.0	11.0
09.08.98	1400	1730	3.5	0500	0900	4.0	10.0
04.09.98	1400	1730	3.5	0600	0930	3.5	8.5

Table 4 Variation in amplitude of diurnal discharge ($Q_{max} - Q_{min}$) and recession coefficients with season

Date	Q_{max} (m^3s^{-1})	Q_{min} (m^3s^{-1})	Q_{mean} (m^3s^{-1})	$Q_{max} - Q_{min}$ (m^3s^{-1})	$(Q_{max} - Q_{min})/Q_{mean}$ (%)	k_b	k_c
27.06.96	6.80	5.40	6.10	1.40	22.95	0.007	0.007
11.07.96	7.90	5.80	6.85	2.10	30.65	0.016	0.009
25.08.96	7.95	4.55	6.25	3.40	54.40	0.022	0.015
25.06.97	3.00	2.45	2.73	0.55	20.14	0.006	0.006
09.07.97	6.60	4.40	5.50	2.20	40.00	0.020	0.011
21.08.97	7.80	3.10	5.45	4.70	86.23	0.046	0.023
13.09.97	2.40	1.50	1.90	0.90	47.36	0.012	0.012
24.06.98	2.70	1.90	2.30	0.80	34.78	0.009	0.009
23.07.98	6.00	3.90	4.96	2.10	42.33	0.021	0.013
09.08.98	8.20	2.95	5.58	5.25	94.00	0.035	0.027
04.09.98	3.60	2.05	2.83	1.55	54.77	0.016	0.016

Trends of variation in diurnal amplitude with season are opposite to the trends reported for an Arctic glacier (Hodgkins 2001). It is important to note that, as opposed to Arctic glaciers, the maximum discharge for the Dokriani Glacier was observed when the diurnal cycles were very clear in the discharge (August). While for the Arctic glacier, the maximum discharge was observed during the early part of the melt season when diurnal cycles were not very evident in the discharge. Figure 4 shows the relationship between daily total and daily maximum discharge for different months during the ablation season. A linear relationship ($R^2 = 0.90$) has been found between maximum discharge and total discharge for the set of data used in the study. It shows that maximum discharge increases as total discharge increases for a particular day.

Time lag between T_{max} and Q_{max}

The hydrological system of a glaciated basin through which meltwater reaches the snout of the basin is complex. The average time lag of a glacier basin is a combined characteristic of its ablation and accumulation areas. The time lag between maximum melt runoff,

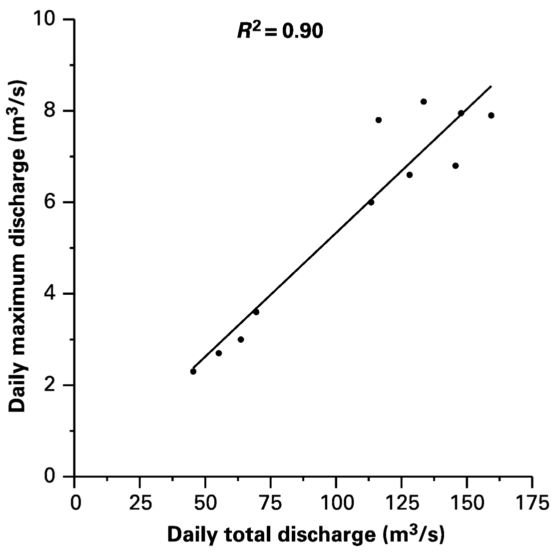

Figure 4 Relationship between daily total and maximum discharge observed near the snout of Dokriani Glacier on clear weather days during three ablation seasons (1996–1998)

Q_{max} and maximum temperature, T_{max} indicates the travel time of water from its point of generation in the glacier to the discharge measuring site. A comparison of the daily hydrograph with temperature for clear weather days for different years is shown in Figure 5(a)-(c).

Assuming that maximum melting takes place when the energy availability for the melt is at its maximum, *i.e.* most likely at the maximum of solar radiation which is fairly close to the timing of maximum air temperature, one can determine the time lag between the generation of maximum melt over the glacier, and its appearance at the snout. These figures show the time lag between T_{max} and Q_{max} to be 3.0–6.0 hours for different years, whereas the time lag

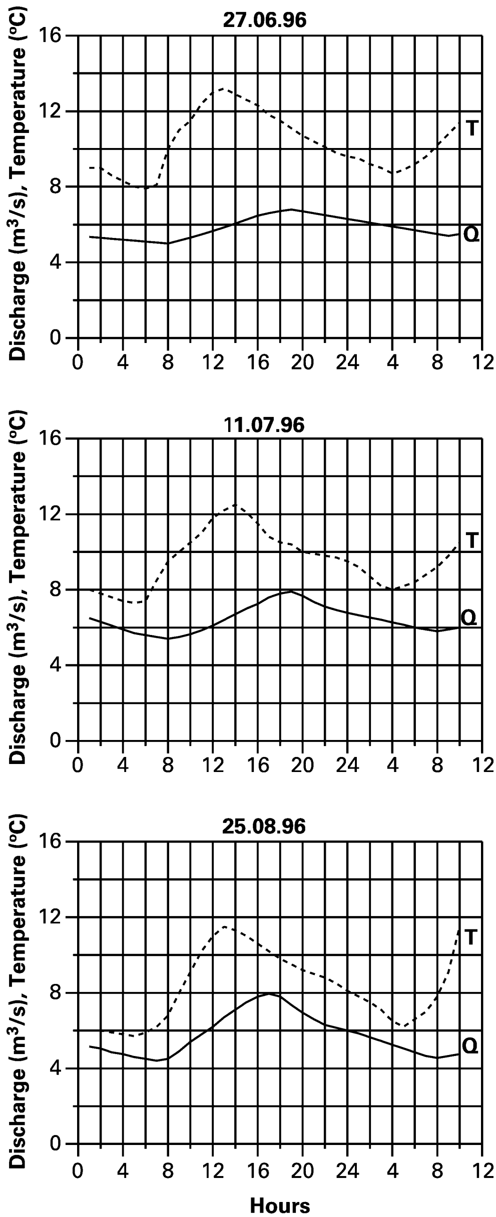

Figure 5(a) Diurnal variations in air temperature and discharge observed near the snout of Dokriani Glacier during the 1996 ablation season

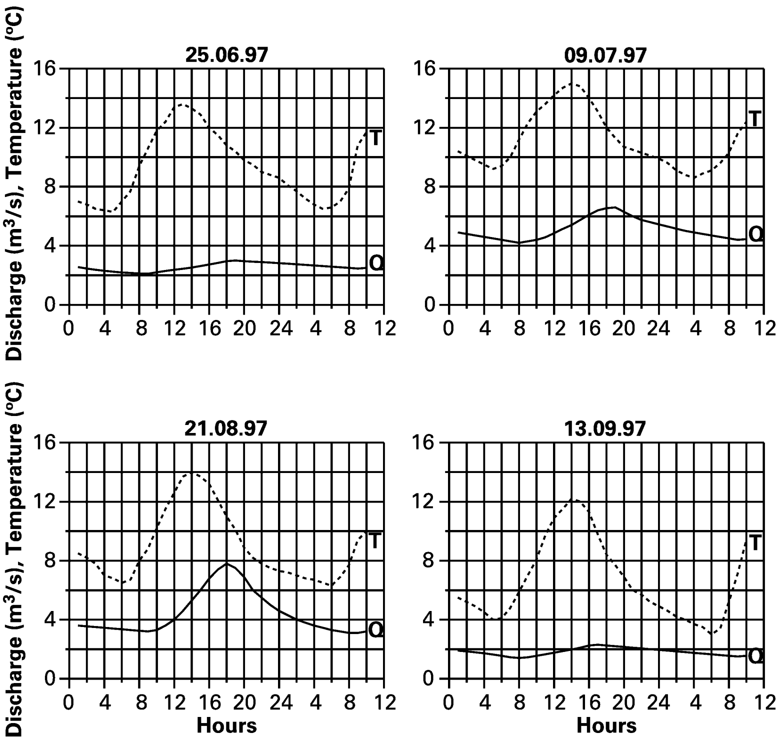

Figure 5(b) Diurnal variations in air temperature and discharge observed near the snout of Dokriani Glacier during the 1997 ablation season

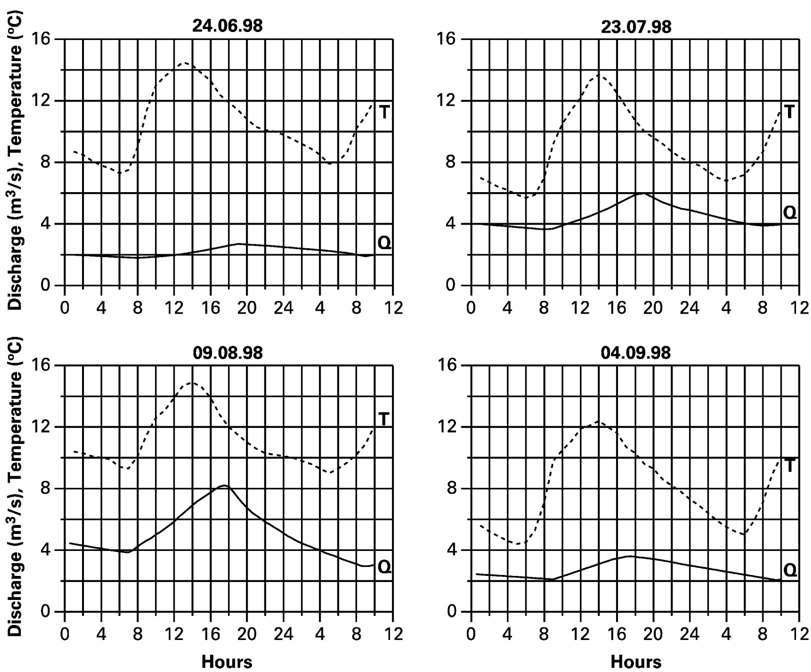

Figure 5(c) Diurnal variations in air temperature and discharge observed near the snout of Dokriani Glacier during the 1998 ablation season between T_{min} and Q_{min} is 2.0–5.0 hours (Table 3). The time lag in both cases is higher at the beginning of the melt season, but reduces as the melt season progresses. As discussed above, a reduction in meltwater storage characteristics reduces the time lag between meltwater generation and its appearance as discharge at the snout of the glacier.

Recession characteristics

Streamflow recession represents the reduction of the water from the storage, *i.e.* less inflow than outflow. As discussed above, a part of the meltwater is stored in the glacier and gradually released from the glacier. The magnitude of the delay in the response is a compound effect of the ablation and accumulation area of the basin. The recession characteristics of the glacier, which also vary with time, control the discharge in the stream. The falling limb of the hydrograph represents a decrease of discharge with time. Analysis of hydrograph recession curves can help in identifying linear storage elements for the routing of the runoff from the basin (Barnes 1939; Bako and Owoade 1988; Nathan and McMohan 1990; Gurnell 1993), whereas Singh *et al.* (2000a) used the recession characteristics of snowmelt hydrographs for assessing the snow water storage located in the Austrian Alps basin.

For the glacier-fed streams, rising and falling trends in the streamflow are observed on the diurnal scale, therefore, variation in the recession trends of the glacier can be studied over the melt season. The lower part of the falling limb represents the trend of baseflow recession and can be expressed as an exponential decay function as given below:

$$Q_t = Q_0 e^{-t/k} \quad (1)$$

where Q_0 is the flow at an initially selected time, or at $t = 0$, Q_t is the flow at t unit times, t is the time and k is a constant, known as the recession coefficient. In order to determine k, the above Eq. (1) can be written in the log-transformed form as:

$$\log\ Q_t = \log\ Q_0 - t/k \quad (2)$$

The slope of the recession limb can be used to determine the value of k. Plots of the log-transformed values of the discharge with time for clear weather days for three ablation seasons are shown in Figure 6.

Further, examination of the falling limb of the hydrograph for different months indicates that for July and August, the falling limb can be divided into upper and lower parts having different values of k, *i.e.* k_b and k_c, respectively. Values of k_b and k_c for different months in the different years are given in Table 4. In a broad sense, k_b and k_c represent the runoff delaying response of the ablation zone and accumulation zone of the glacier, respectively. Results indicate that both k_b and k_c increase as the melt season progresses and k_b is always higher than k_c for July and August for all the years. It indicates that the response of the meltwater becomes faster with time for both ablation and accumulation zones, and the response from the ablation area is always quicker than the accumulation area.

The transformation of the snow-covered area into the glacier ice-exposed area (accumulation area into ablation area) increases with time and influences the recession characteristics of the glacier. In the early melt season, in June, recession is dominated by the snow-covered area, giving little variation in k_b and k_c for this month, *i.e.* the ablation area is not well established at this time. By the months of July and August, a substantial snow-covered area changes into a glacier ice-exposed area, and its influences on the recession characteristics are evident by the difference in values of k_b and k_c. A little melting takes place in the basin in the month of September and water is continuously released from the stored water. The hydrological response of the glacier in September is found to be similar to June,

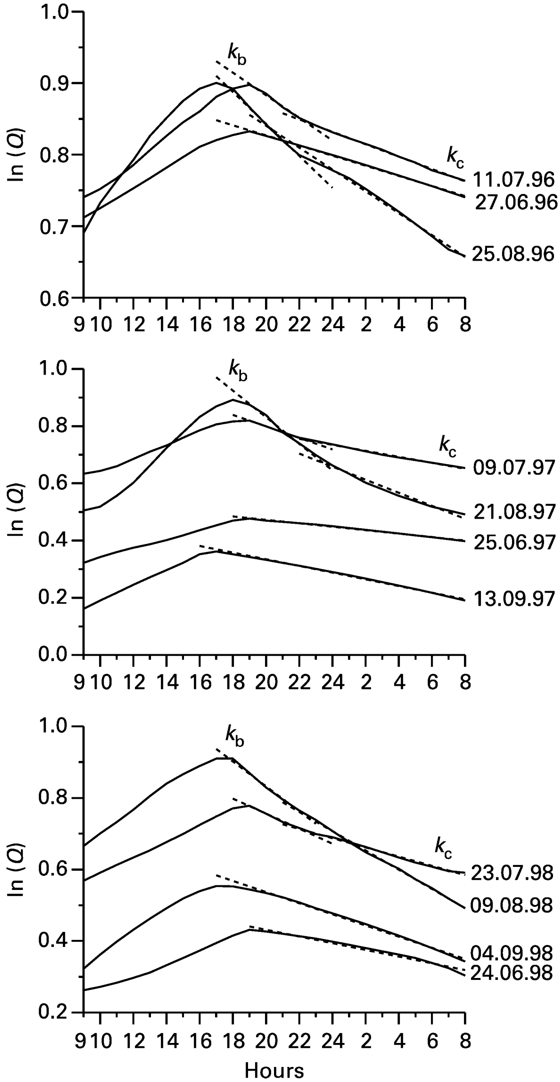

Figure 6 Variation in recession trends of discharge on clear weather days during three ablation seasons (1996–1998). k_b and k_c represent the runoff delaying response of the ablation and accumulation zones, respectively

i.e. k_b and k_c are the same. The present study shows that a small difference in k_b and k_c in June and September indicates that the basin behaves like a single conceptual reservoir for these two months. But due to larger and well distinguished differences in k_b and k_c in July and August, the basin can best be considered as two distinct conceptual reservoirs (accumulation and ablation reservoirs) for these months.

Conclusions

The changes in the physical features of the glacier during the melt period have a significant influence on the storage and drainage characteristics of the glaciated basin, which in turn influence the hydrological response of the basin. In the present paper variations in hydrological response over the ablation period for the Dokriani Glacier located in the Garhwal Himalayas, have been studied. The distribution of daytime and night-time discharge over the ablation period shows that, in spite of little melting or no melting during the night-time over the glacier, the night-time flows are as high as those of the daytime throughout the melt season. This indicates that the glacier stores a part of the meltwater produced during the day and gradually releases it during the night. The storage capacity was found to be much stronger in the early part of the melt season, due to a greater extent of snow cover over the glacier surface and a poorly developed drainage network. As the melt season advances, both extent and depth of snow decreases, glacier ice-exposed area increases, and development of drainage network progresses. Such physical changes in the glacier reduce the meltwater storage capacity of the glacier, which in turn improves the hydrological response of the glacier.

Diurnal variations in the discharge show that the hydrologic response of the basin becomes faster with time, which is reflected by the steeper rise and fall of the hydrograph. The maximum discharge in the Dokriani Glacier melt stream was observed in the late afternoon or evening (between 1700–1900 hours), suggesting that a major part of the meltwater produced during the day reached the snout within a few hours. As the melt season progressed, the time of peak flow occurred earlier in the day. A difference of about 2 hours was noticed in the timings of maximum flow over the ablation season. The time to peak flow, t_p, ranged between 8.5 and 11 hours, indicating a maximum reduction of 2.5 hours during the melt season. The time lag between Q_{max} and T_{max} ranged from 3 to 6 hours during the melt period. The recession of the flow became faster with time due to changes in physical conditions of the basin. It resulted in a quicker response of the meltwater to the streamflow in mid or late melt season. Based on the recession trends, it was observed that the hydrological response of the study glacier was similar in June and September, *i.e.* k_b and k_c were equal, while in July and August there was a large and well distinguished difference between k_b and k_c. These results suggest that the basin behaved like a single conceptual linear reservoir for June and September, but for July and August, its response was like two conceptual linear reservoirs, namely accumulation and ablation reservoirs.

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