Melt Water Characteristics of Gangotri Glacier, Headwater of Ganga River

Manohar Arora* & Jatin Malhotra
National Institute of Hydrology, Roorkee, Uttarakhand, India

Abstract: Behavior of glacier plays an important role in runoff delaying characteristics of the glacier. Changes in delaying characteristics of the runoff over the melt season can be understood by studying the variation in time to peak (t_p) and time-lag (t_1) between melt generation and its emergence as runoff. In this study, the runoff delaying characteristics of the Gangotri Glacier in the Garhwal Himalayas (glacierized area 286 km^2; drainage area 556 km^2) have been studied. For this purpose, hourly discharge and temperature data were monitored near the snout of the glacier for the entire ablation period (May-October, 2010). In the early stages of the ablation period, poor drainage network and stronger storage characteristics of the glaciers due to the presence of seasonal snow cover resulted in a much delayed response of melt water, providing a higher t_l and t_p. In the beginning of melt season, the night time flow is almost equal to day time flow, but in the later part of the melt season, night time flow is slightly lower than the day time flow. This analysis suggests that storage characteristics are much stronger in the early part of melt season and reduce as the melt season progresses.

Keywords: Gangotri Glacier, Himalayas, Melt Season, Runoff Delay Characteristics, Storage Characteristics

1. Introduction

Glaciers fed rivers provide much of the water supply in some parts of the world. All the major south Asian rivers originate in the Himalayan and their upper catchments are covered with snow and glaciers. The Indus, the Ganga and the Brahmaputra river systems originating from the Himalayan region receive substantial amount of precipitation in the form of snow and glaciers. The perennial nature of Himalayan Rivers and appropriate topographic setting of the region provide a substantial exploitable hydropower in this area. In the Himalayan range there are more than > 10,000 glaciers and feed a number of Himalayan Rivers. This ice exposed surface of the glacier increases with time resulting in higher quantum of runoff. As the melt season advances, the melt water contribution from the glaciers increases. By the end of melt season, the melt runoff is reduced due to increases in air temperature and fresh snowfall on the higher reaches. Evidently, runoff generated from the glaciers in the Himalayan basins has a significant influence on the stream flow of the river. Runoff characteristics (daily and seasonal) differ from other types of stream flow. Runoff is locally used for hydroelectric power generation. The major difference between glaciated and un glaciated basins is in timing of runoff. During ablation season strong daily peaks can be noticed. The melt rate of the glacier is determined by the prevailing climatic conditions and, therefore, varies from year to year. Hydrological investigations of Himalayan glaciers become inevitable because of their importance in water resources, hydroelectric power generation, irrigation and drinking water supply. A number of important Hydel schemes in Uttarakhand, running on Himalayan Rivers and many are under construction/proposed. The power generation from several projects like Bhakra at Satluj, Tehri, and Maneri Bhali, Loharinag pala at Bhagirathi and Tapovan Vishnugad (Runoff River) across the river Dhauliganga depends heavily on the melt runoff generated from melting of snow and glacier.

From a glaciological perspective the glacier itself is considered as storage, as water, in the form of snow and ice, forms the glacier. The associated time-scale is long-term, ranging from years to thousands of years. From a hydrological point of view, storage is generally thought of as water runoff being delayed by the glacier system. Precipitation is stored as snow in winter and released during summer by melting. In addition, water in liquid phase is temporarily stored at various locations in the glacial system and thus delayed depending on the characteristics and evolution of the internal glacier drainage system. These processes mainly operate on a seasonal time-scale. As such storage distinctly modifies catchment hydrology; main implications concern any issues in water resources management. Short-term storage and release of water from glaciers are important for diurnal discharge characteristics as well as glaciohydrological issues related to glacier dynamics. (Jansson et al. 2003)
The storage characteristics of few glaciers have been studied. However, the magnitudes of englacial storage, firn retention, internal refreezing and other hydrologic processes that delay or reduce true water export to the river discharge remain less understood, partly due to a scarcity of in situ measurements. Several studies based on the tracer experiments, isotope studies and analysis of the runoff distribution suggest that major contribution to runoff from stored water results as continuous runoff from the accumulation area (firn area), continuous drainage from the glacier lakes, water filled cavities and ground water flow (Stenborg 1970; Elliston 1973; Tangbom et a1. 1975; Lang H 1973; Collins 1982; Oerter and Moser 1982). Larsen (1978) studied the storage characteristics of the Burroughs glacier. They compared the inflow and outflow records for the four days during the summer of 1973. Weigang et al. (2010) reported strong storage characteristics of the Rongbuk Glacier catchment. There was a time lag ranging from 8 to 14 hours between daily discharge peaks and maximum melting (maximum temperature). The occurrence of maximum stream flow in the glacierized Himalayan Rivers in the late afternoon or evening clearly suggests that a major part of the melt water produced during the day reaches the snout after few hours (Singh *et al*., 2004, 2006, 2011). Mingjie et al (2013) studied characteristics of the daily melt water discharge cycle in the Glacier No 1 basin. The monthly mean daytime discharge was generally greater than the nighttime discharge, primarily because cloudy and rainy weather and lower air temperatures led to less melt water, and precipitation could not make up the loss of discharge from melt water. Daytime melt water contributed only slightly to night time discharge due to the short time lag caused by melt water flow distance. Rennermalm et al. (2013) were first to provide evidence for melt water retention and delayed release within the Greenland ice sheet.

The storage and release of water from glaciers are important for various practical and scientific fields including hydroelectric power, flood forecasting, sediment transport and formation of land forms. The objective of this study is to understand the melt water storage and delaying characteristics of the glacier during ablation period. For this purpose, continuous monitoring of the discharge and hydro meteorological data have been extensively carried out near the snout of the glacier during the year 2007, 2008 and 2010.

2. Study Area

The present study was carried out for the Gangotri Glacier, which is one of the largest glaciers of Himalayas. This glacier is located in the Uttarkashi District of Uttarakhand State (U.A.) falling in the Garhwal Himalayan region. The location of Gangotri Glacier is shown in 'Figure 1'. The study area lies within the latitudes 30°43'N - 30°01'N and longitudes 79°0'E - 79°17'E. The proglacial melt water stream, known as Bhagirathi River, emerges out from the snout of the Gangotri Glacier at an elevation of 4000 m. The approach to the snout of the Glacier includes a trekking of about 18 km distance starting from the Gangotri town. The major part of the trekking is along the Bhagirathi River. A meteorological observatory and discharge site were established and data was collected for the entire ablation period.

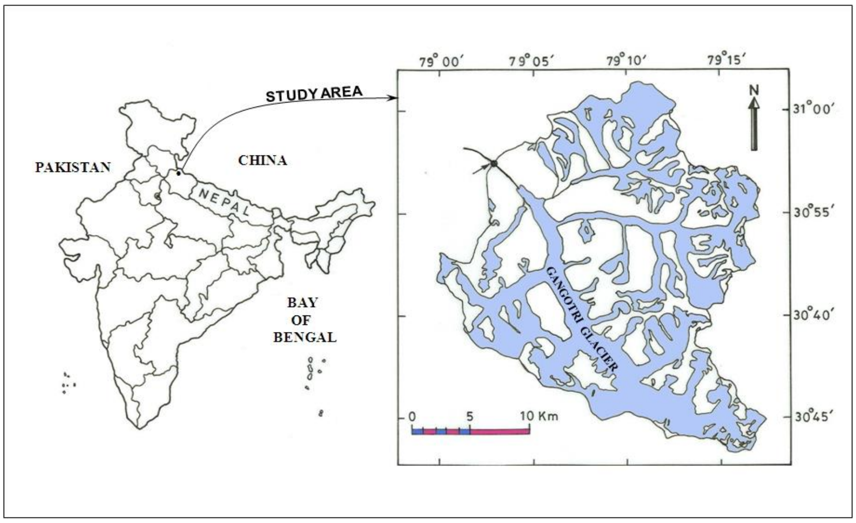


Fig. 1 | Location and basin map of the Gangotri Glacier in the Garhwal Himalayas.

3. Data Collection

In order to determine storage characteristics of Gangotri Glacier a Gauge and Discharge site has been established at River Bhagirathi near Bhojwasa and data was collected for the entire melt period (May – September, 2007, 2008 & 2010) during the year. Continuous monitoring of the glacier melt runoff was made, because to define hydro-meteorological condition of any glacier the first and foremost requirement is availability of continuous reliable flow data.

4. Discussion

Characteristics of Day time and Night time Discharge

Since, Gangotri glacier is the second largest glacier (286 km^2) in the Indian Himalyas and is the origin of the River Ganges, it is important to understand the melt water storage behavior of this glacier. For this purpose the stream flow data collected at the site were divided into daytime flow (0900-2000 hours) and nighttime flow (2100-0800 hours), respectively. Daily mean daytime and nighttime flow for different months are shown in 'Figure 2', whereas daily discharges for the respective periods are presented in 'Figure 3'. The ratio of monthly mean daytime discharge to that of nighttime discharge was computed and is given in Table 1. It is observed that the ration of day time discharge to night time discharge (Q_d/Q_n) is about 1.0 in the month of May from all the three years but as the season progresses the day time discharge becomes slightly greater. For the study period the ratio Q_d/Q_n varied between 1.0 to 1.16. The maximum variability in the ratio (1.16) was observed during September 2007 though there was rain for 3 days. This may be because of higher day time mean monthly temperature and rainfall only in the lower altitude during day time. Whereas in September 2010 though there was rainfall in 12 days but the prevailing overcast conditions and rainfall in the late evenings was the reason for the ration being 1.02.

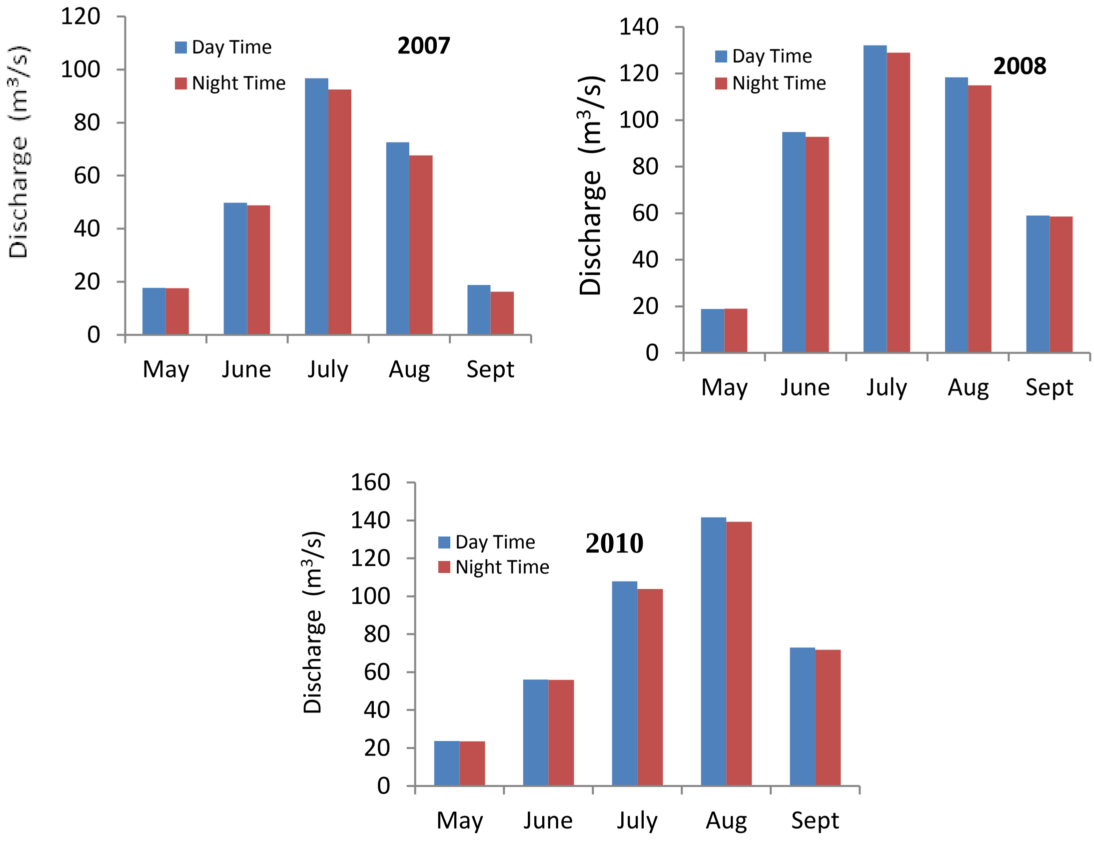


Figure 2 | Monthly distribution of daytime (0900-2000 hours) and nighttime (2100-0800 hours) discharges observed during melt seasons 2007, 2008 & 2010 near the snout of Gangotri glacier.

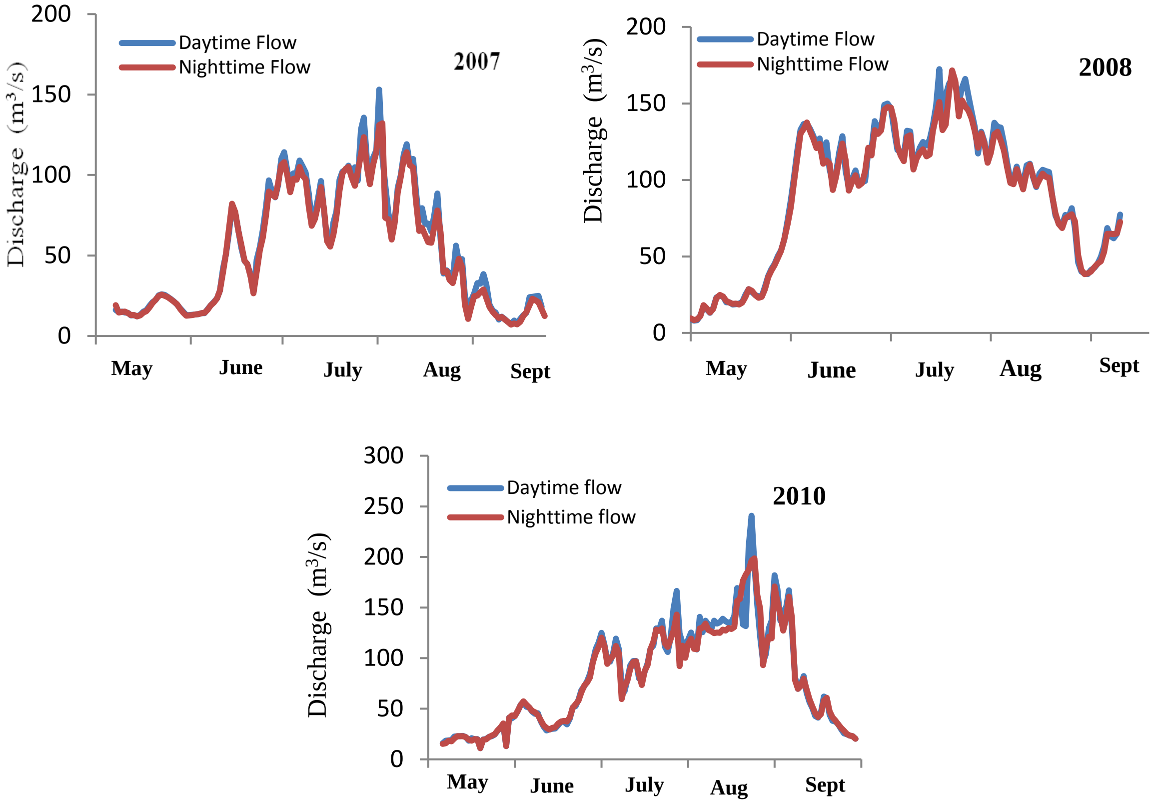


Figure 3 | Daytime (0900-2000 hours) and nighttime (2100-0800 hours) mean discharges observed during melt seasons 2007, 2008 & 2010 near the snout of Gangotri glacier.

Table 1 | Variation in ratio of monthly daytime discharge to that of nighttime discharge for different months during ablation period

Year	Month	T_d	T_n	T_{avg}	T_{max}	T_{min}	Q_d avg	Q_n avg	Ratio Q_d/Q_n	P (mm)	D
	May	8.1	2.6	5.4	19.5	-5.5	17.7	17.6	1.01	37.1	3
2007	June	14	8.3	11.2	21.2	0.0	49.8	48.8	1.02	16.8	2
	July	14.2	10.4	12.3	19.1	0.4	96.7	92.6	1.04	48.7	7
	Aug	13.2	9.3	11.3	18.6	4.0	72.6	67.6	1.07	49.2	6
	Sept	11.9	5.4	8.7	19.0	-2.5	18.8	16.2	1.16	83.6	3
	May	9.6	5.5	7.5	16.0	-2.5	18.9	19.0	1.00	13.3	1
2008	**June**	12.4	8.6	10.5	19.5	2.6	94.9	92.7	1.02	28.6	4
	July	12.5	9.7	11.1	19.2	2.6	132.1	128.9	1.03	79.0	8
	Aug	12.1	9.3	10.7	17.5	3.0	118.4	114.9	1.03	62.4	9
	Sept	9.6	5.3	7.5	18.0	-2.8	59.0	58.5	1.01	108.9	5
	May	10.1	4.4	7.3	19.4	-1.7	23.7	23.5	1.01	39.3	5
2010	June	11.8	6.7	9.3	19.2	-0.4	56.1	55.9	1.02	43.4	4

	July	12.0	9.4	10.7	19.7	-0.1	107.9	103.8	1.04	116.5	8
	Aug	15.5	12.9	14.2	17.5	0.5	141.6	139.2	1.02	93.7	10
	Sept	14.1	10.7	12.4	17.6	-0.2	72.9	71.8	1.02	196.4	12

T_d, mean day time air temperature; T_n, mean night time air temperature; T_{avg}, mean daily air temperature; T_{max}, mean maximum daily air temperature; T_{min}, mean minimum daily air temperature; Q_d, mean day time discharge; Q_n, mean night time discharge; P, rain; D, number of days with rainfall.

Seasonal Variations in Diurnal Discharge

Diurnal variation, generally observed in hourly streamflow measurements from snowfed rivers, provide a new way of understanding basin hydrology. The daily cycle of solar forcing yields major changes in snowmelt and streamflow over the course of each day, and the difference between the time of highest melt rate and the time of peak discharge provides a measure of average runoff travel times through the river basin These travel times provide information about snowpack properties, in-channel flow velocities, and distances to the primary snowmelt-source areas. The ability to predict travel times may prove useful for flood forecasting, reservoir and hydropower operations, and characterizing and predicting chemical transports in Mountain Rivers.

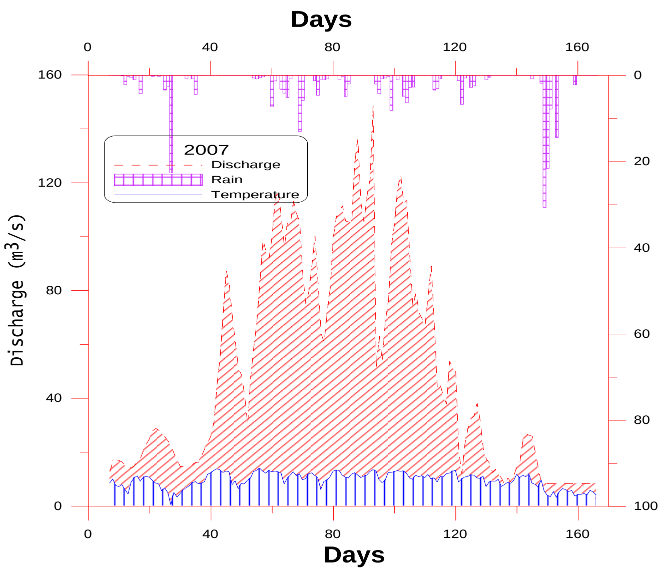


Figure 4(a) | The variation of discharge, temperature with rainfall during the melt season of 2007.

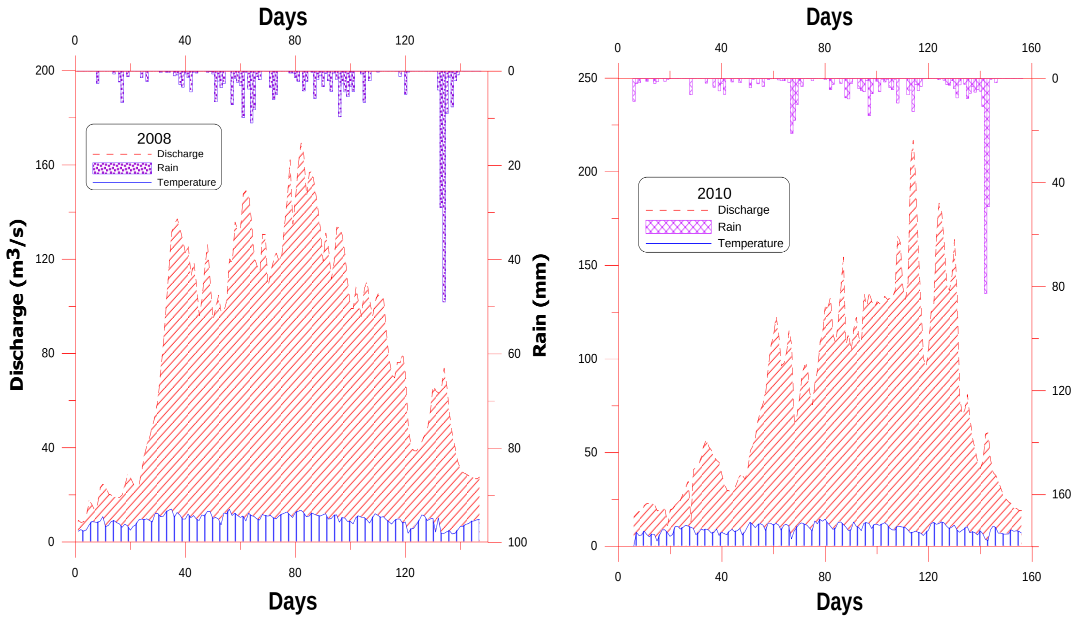
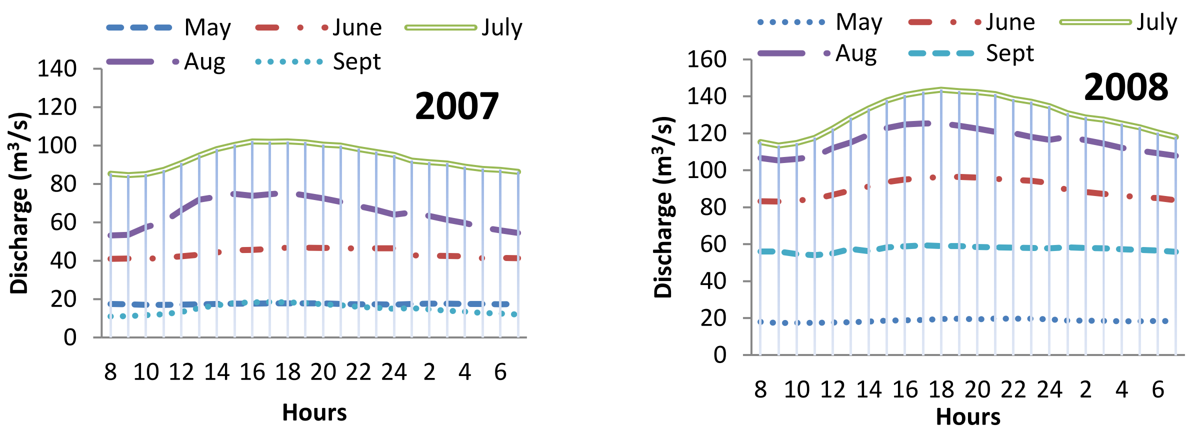


Figure 4(b & c) | The variation of discharge, temperature with rainfall during the melt season of 2008 and 2010

'Figure 4(a) – (c)' represents the variation of discharge, temperature with rainfall for melt seasons 2007, 2008 and 2010. It is observed that the variation of discharge generally had trends similar to air temperature. The prolonged increase in discharge follows the trend of temperature increase. However, instantaneous increase is observed because of rainfall. Though, sometimes the mean daily discharge declined due to reduced temperature on the overcast days.

A variation in discharge occurs on hourly, daily and annual cycles, on an irregular basis because of the passage of weather systems. Discharge variation consists of a cycle of rising and falling flow superimposed on baseflow, minimum daily discharge. Changes in discharge on diurnal scale for different months are depicted in 'Figure 4'.



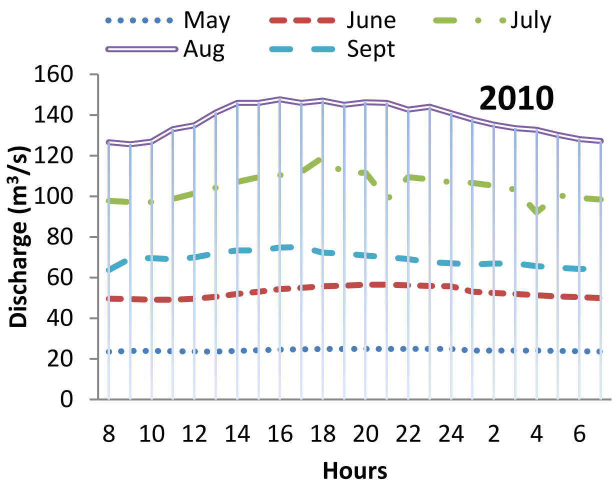


Figure 5 | Diurnal variations in discharge computed for different summer months using year 2007, 2008 & 2010 data.

There are several important factors which affect a streamflow hydrograph during a runoff event. These factors are (a) drainage characteristics, (b) snow cover characteristics, (c) rainfall or snowmelt characteristics and (d) soil and land use. 'Figure 5' shows that discharge starts increasing from May onwards, reaches its maximum in July and August then starts declining. The rising and recession limbs of hydrograph are almost flat during early and later part of melt season. Seasonal snowmelt is the dominant hydrological forcing in this area and subsequent precipitation events during monsoon season are far less significant, have random timing and distribution and are superposed upon the seasonal snowmelt hydrograph. The melt rate of snow is lower in the beginning of melt season, but enhances with advancement of summer. The availability of snow causes a much delayed response to rainfall or snowmelt because water availability at the surface takes time to pass through the snowpack and flow as sub glacial and englacial streams in the glacier. Rising and falling limbs of the hydrograph become steeper with advancement of the melt season but the rising limb of the hydrograph is always steeper than the recession limb. As the melt produces is governed by prevailing temperature conditions. During mid part of melt season July and August intense melting takes place due to availability of higher radiation and larger extent of exposed glacier ice. It results in faster response of melt runoff producing well distinguished diurnal change in discharge. At this stage, without being significant storage of melt water at the glacier surface, melting contributes rapidly to the diurnal hydrograph, and system becomes more responsive to diurnal forcing. Recession in flow during a time of no input contains information about the reservoirs that supply streamflow. Such diurnal variations in hydrograph with season can be explained by the changes in physical features of the basin with time. In the beginning of the melt season, less pronounced diurnal fluctuation in discharge from the glacierized basin may be because of the depth and large extent of seasonal snow over the glacier, which can have dampening effect on the melt runoff. At the start of the season the channel network is also not established and runoff, can have much delayed response. Consequently, in the early and later part of the season, both limbs of hydrograph are almost flat. As shown in ‘Figure 5’ the distribution of hourly discharge indicates that maximum runoff (Qmax) is observed in the evening (1700 to 1900 hours) and minimum flow (Qmin) in the morning (0800 to 1000 hours).

Melt-Runoff Delaying Characteristics: Time-Lag and Time to Peak

To study the melt runoff delaying characteristics of a glacierised basin one has to understand the variations in time to peak (tp) and time-lag (tl) between generation of melt water and its emergence as runoff from, the data collected during the field observations for 2007, 2008 and 2010 is used. Radiation fluxes generally account for most of the energy used in snowmelt therefore the necessary criteria for such study is that hydrograph should be of clear weather day which means: either there is no rain and if it is there than it should be less than 2 mm and clear sky, which brings maximum insolation and high air temperatures. Other important factor in such analysis is the measurement of discharge at the basin outlet. Therefore, a detailed study considering clear weather hydrographs of different months respective of the ablation season is done because year-to-year variation in discharge is not significant. For this purpose hydrographs observed in the field has been digitised on hourly basis, which provides close information on important parameters like time lag and time to peak. For identifying the delaying characteristics, an analysis of hydrographs of three or four consecutive clear weather days provides a clear picture. ‘Figure 6’ shows comparison between temperature and discharge at an interval of four hour for consecutive days in different months of melting seasons 2010. In the early part of the melt season both tl and tp are larger because of the distributed drainage systems such as linked-cavity networks and strong storage characteristics of the glaciers due to the presence of seasonal snow cover. The tl as well as tp is reduced with the advancement in melt season because of the efficient and well developed drainage network (Willis et al. 1990; Hock and Hooke 1993). The channelized network system results due to the exposed ice surface, reduction of snowpack area and snow depth. Towards the end of the melt season, diurnal variations are more pronounced and follow fluctuations in available energy for melting. It is observed that the during this period both tl and tp are higher, similar to the start of the melt season. The inter relationship between the variation in runoff and delaying characteristics of the glacierized basin, changes in the discharge ratio, i.e., Qmax /Qmin were computed over the melt period. As illustrated in ‘Figure 7 (C)’, this discharge ratio for the Gangotri Glacier varied between 1.03 and 1.37, indicating a large variation in the runoff over the melt period. A comparison of runoff delaying parameters with discharge ratio clearly indicates that changes in tl and tp during the melt season are inversely correlated with variations in discharge.

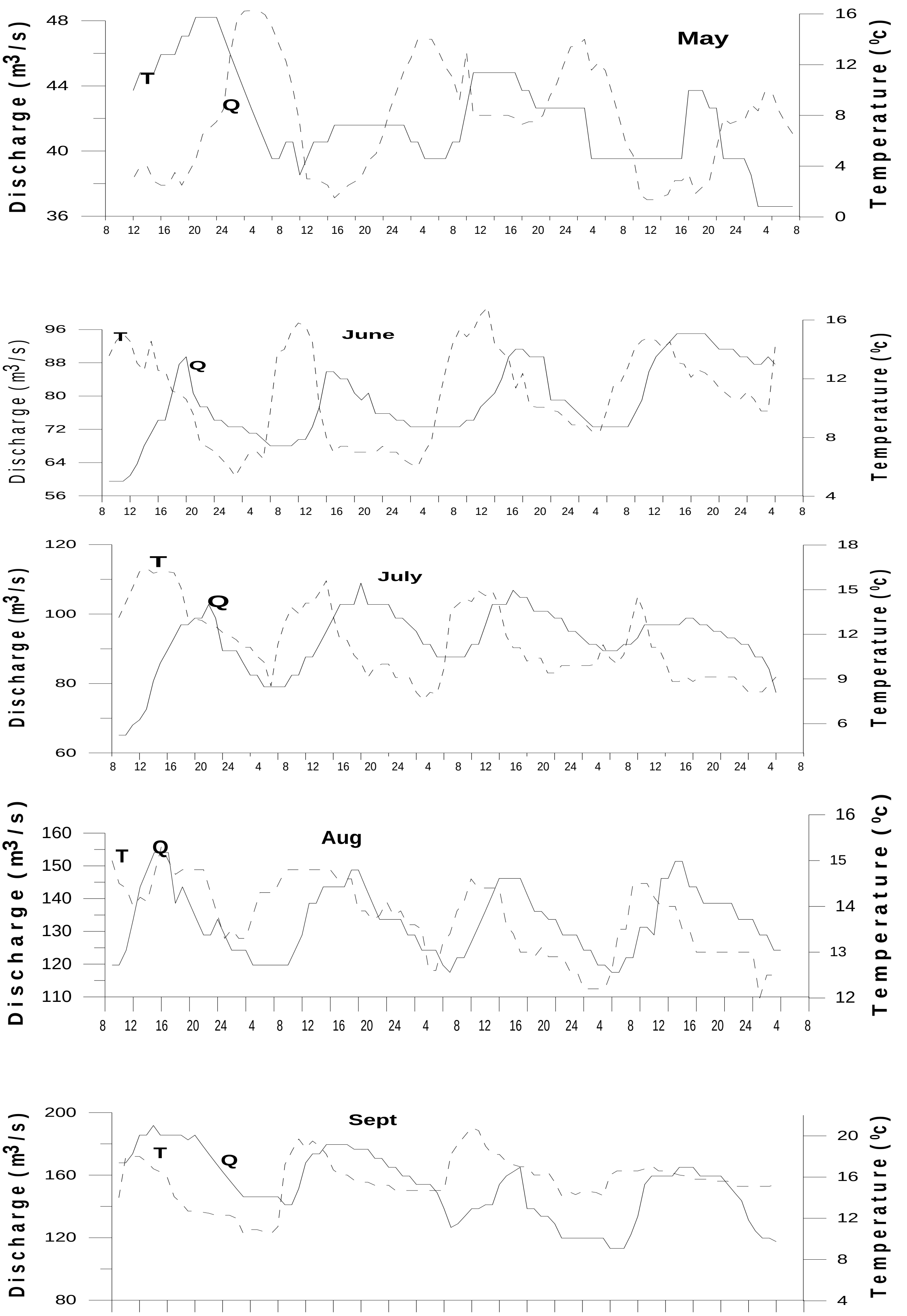

May
T
Q
Discharge (m3/s)
Temperature (0c)
June
July
Aug
Sept

Figure 6 | Diurnal variation in discharge (Q) and Temperature (T) for selected clear weather days for melting year 2010.

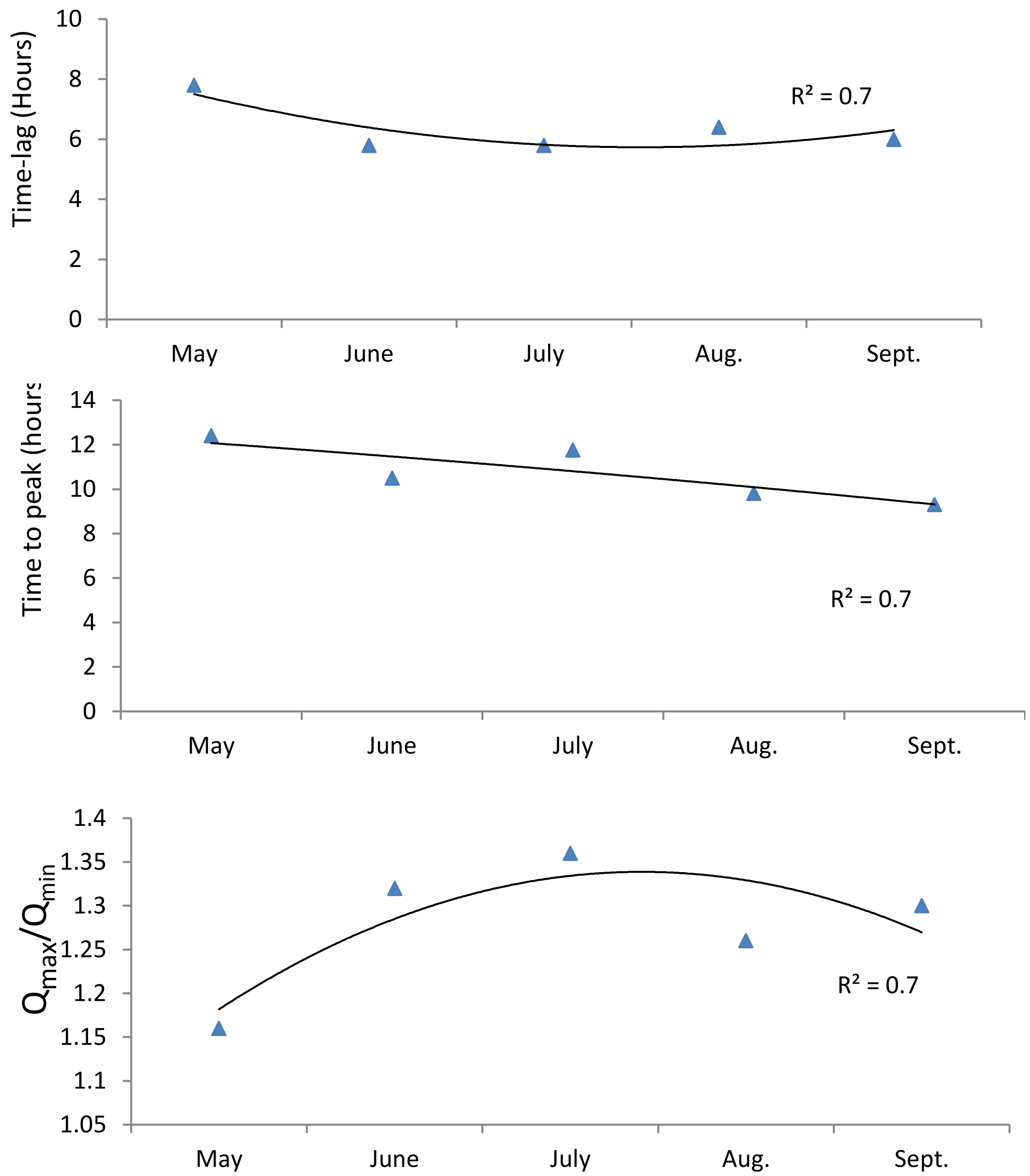


Figure 7 | Average value of (A) melt- runoff time – lag, (B) time to peak, and (C) discharge ratio for the melting seasons observed near the snout of Gangotri Glacier.

5. Conclusions

The melt water storage characteristics of snow and glacier fed rivers can be demonstrated by analyzing hourly data of streamflow. The magnitude of daytime and nighttime streamflow indicates that the volume of the nighttime flow is comparable with the daytime flow. In the beginning of melt season, the night time flow is almost equal to day time flow, but in the later part of the melt season, night time flow is slightly lower than the day time flow. These results suggest that melt water storage characteristics of the glacier are much stronger in the early part of the melt season and reduce as the melt season develops. The reduction in snowpack area and depths resulting in exposition of larger extent of glacier ice surface, and development of drainage network with melt season are understood to be the main factors attributing to reduction in storage capacity with advancement of melt season. The delaying influence of the Gangotri glacier basin reduces with time due to changes in physical condition of the basin.

Hourly discharge pattern shows that maximum discharge was observed in evening (1700 – 1900 hours) and minimum discharge in the morning (0700 – 1000 hours). Diurnal variations in discharge followed diurnal variations in temperature with a certain lag of time. The value of time-lag varies over the melt season showed that temperature was the most important factor and a change from clear skies to overcast resulted in a reduction of the ablation rate in early afternoon with an immediate reduction in the height of the daily peak on the discharge. The time-lag between temperature and discharge (3.00 – 5.00 hours) and time to peak (9.00 – 12.00 hours) were higher in the beginning and towards the end of the season as compared to the peak melt season. The discharge ratio Qmax /Qmin for the Gangotri Glacier varied between 1.16 and 1.38, indicating a large variation in the runoff over the melt period. A comparison of runoff delaying parameters with discharge ratio clearly indicates that changes in tl and tp during the melt season are inversely correlated with variations in discharge.

References

Collins, D. N. (1982). Water storage in an alpine glacier. *IAHS Pub,* No. 138, pp. 113-122.

Elliston, G. R. (1973). Water movement through the Gornergletscher. *Symposium on the Hydrology of Glaciers (proc. Cambridge Symp., September 1969), IAHS Pub*, No. 95, pp. 79-84.

Hock, R. & Hooke, R. l. B. (1993). Evolution of the internal drainage system in the lower part of the ablation area of storglaciaren, Sweden. *Geol. Soc. Am. Bull,* 105, 537–546.

Jansson, P., Hock, R. & Schneider, T. (2003). The concept of glacier storage: a review. *J.Hydrol,* 282 (1-4), 116–129.

Larsen, G. J. (1978). Meltwater storage in a temperate glacier Burroughs glacier, South Alaska.. *Institute of Polar Studies. The Ohio State University Institute of Polar Studies.* Report No. 66.

Lang, H. (1973). Variations in the relation between glacier discharge and meteorological elements. *Symposium on the Hydrology of Glaciers* (Proc. Cambridge Symp., September 1969, IAHS Pub\. No. 95, pp. 85-94.

Mingjie, G., Tianding, H., Baisheng, Y. & Keqin, J. (2013). Characteristics of melt water discharge in the Glacier No. 1 basin, headwater of Urumqi River. *Journal of Hydrology,* 489, 180-188.

Oerter, H. & Moser, H. (1982). Water storage and drainage within the firn of a temperate glacier. *IAHS Pub*, No. 138, pp. 71-91.

Rennermalm, A. K., Smith, L. C., Chu, V. W., Box, J. E., Forster, R. R., VandenBroeke, M. R., VanAs, D. & Moustafa, S. E. (2013). Evidence of meltwater retention within the Greenland ice sheet. The Cryosphere, 7, 1433-1445, doi:10.5194/tc-7-1433-2013.

Stenborg, T. (1970). Delay of runoff from a glacier basin. *Geogr. Ann,* 52A (1), pp. 1-30.

Singh, P., Haritashya, U. K. & Kumar, N.(2004). Seasonal changes in melt water storage and drainage characteristics of the Dokriani Glacier, Garhwal Himalayas (India). *Nord. Hydrol,* 35 (1), 15–29.

Singh, P., Haritashya, U. K., Kumar, N. & Singh, Y. (2006). Hydrological characteristics of the Gangotri Glacier, Central Himalayas, India. *Journal of Hydrology,* 327(1–2): 55–67.

Singh, P., Kumar, A. & Kishore, N. (2011). Meltwater storage and delaying characteristics of Gangotri Glacier (Indian Himalayas) during ablation season. *Hydrol. Process,* 25, 159-166.

Tangborn, W. V., Krimmel, R. M. & Meier, M. F. (1975). A comparison of glacier mass balance by glaciological, hydrological and maping methods, South Cascade Glacier*”.*

Weigang, L., Jiawen, R., Xiang, Q., Jingshi, L., Qiang, L.,_Xiaoqing, C. & Yetang, W. (2010). Hydrological Characteristics Of The Rongbuk Glacier Catchment In Mt. Qomolangma Region In The Central Himalayas, China[J].*Journal Of Mountain Science*, 7(2):146–156.

Willis, I. C., Sharp, M. J. & Richards, K. S. (1990). Configuration of the drainage system of Mitdalsbreen, Norway, as indicated by dye-tracing experiments. *J. Glaciol*. 36, 89–101.