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Melt-Runoff Delaying Characteristics of Gangotri Glacier

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ABSTRACT: Most of the Himalayan basins have considerable snow and glacier covered areas. The melt contribution in such rivers augments their flows in the lean season, thereby reducing the variation in water availability. Depending upon the prevailing climatic conditions, the runoff contribution from the glaciers in the Himalayan rivers starts in May after depletion of accumulated seasonal snow. Usually melt contribution from these glaciers continues till October. The melt water generated in the glacierized basin appears as runoff at the snout of glacier with a time-lag. 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 the recent 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 collected near the snout of the glacier (approx 4000 m) for the entire ablation period (May–October, 2004). The diurnal variations in the hydrograph and temperature observed under clear weather provided useful information for this study. 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. A comparison of runoff delaying parameters with discharge ratio clearly indicated that changes in time-lag and time to peak are inversely correlated with variations in discharge.

Keywords: Garhwal Himalayas, Diurnal variation, Gangotri Glacier.

INTRODUCTION

World's Mountain systems cover about one-fifth of the earth's continental areas and are all inhabited to a greater or lesser extent except for Antarctica. Mountains provide direct life support for close to 10% of the world's population, and indirectly to over half. Because of their great altitudinal range, mountains such as the Himalayas, the Rockies, the Andes, and the Alps, exhibit, within short horizontal distances, climatic regimes. Mountains are also a key element of the hydrological cycle, being the source of many of the world's major river systems. Shifts in climatic regimes, particularly precipitation, in space or seasonally in a changing global climate, would impact heavily on the river systems originating in mountain areas, leading to disruptions of the existing socio-economic structures of populations living within the mountains and those living downstream.

The mountain ranges of south-central Asia, including the Karakoram, Kun Lun Shah Hindukush and Pamir have about 109,000 km^2 ice covered area (Sharp, 1988). The total water resources of our planet are 1359×10^6 km^3, out of which only 38×10^6 km^3 (2.8%) is available in the form of fresh water. About 75% of the world's total freshwater are stored in the form of glacier ice and out of this about 90% is stored in Antarctica alone. However, only about 3.5% of the permanent snow and ice are accumulated over mountains outside the Polar Regions. They are very good source of water, storing water in winters in the form of snow and releasing in dry summers. Most of large river systems of the world originate from mountains where a significant quantity of fresh water is stored in the form of snow and glaciers. In the context of India, all three major river systems (Ganga, Brahmaputra and Indus) originate from the Himalayas, and have substantial contribution from melting of snow and glaciers. The Indian Himalayan region contains total of about > 5000 glaciers covering an area of about 38,000 km^2. Now Himalayas are under increasing pressure due to growing demand for fresh

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water in the country due to population growth, urbanization and industrial development.

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. The streamflow characteristics of the glacierized basin are different from those of only rainfed basins .Usually, seasonal snow contribution increases by the end of June and after that glacier contribution starts. Broadly the amount of runoff produced from a glacierized basin is governed by the amount of liquid precipitation falling in the basin, the amount of ice melt from the ablation area and the amount of snowmelt occurring in the accumulation area of glacier.

STUDY AREA

Gangotri Glacier (30°43' N – 31°01' N and 79°00' E – 79°17' E) is the largest glacier of the Garhwal Himalayas. This glacier is located in Uttarkashi district of Uttaranchal state and classified as valley type glacier. It covers the upper most part of the Bhagirathi River basin. Although commonly it is known as Gangotri Glacier, but infact it is Gangotri Glacier system consisting of a cluster of many large and small glaciers (Figure 1).

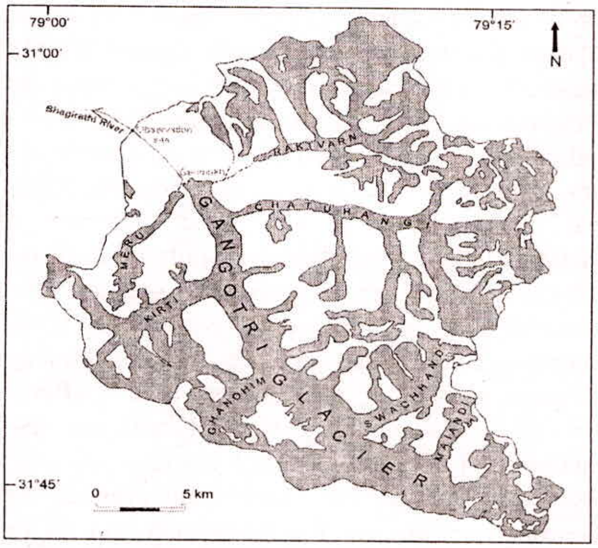

Fig. 1: Map showing location of Gangotri Glacier

This system comprises of three major glacier tributaries, namely, Chaturangi Glacier (Length 22.45 km; Area 67.70 km^2), Raktvarn Glacier (Length 15.90 km; Area 55.30 km^2) and Kirti Glacier (Length 11.05 km; Area 33.14 km^2) with main Gangotri Glacier (Length 30.20 km; Area 86.32 km^2) as trunk part of the system. Besides these three major glaciers 4 other tributary glaciers draining directly into Gangotri Glacier system are Swachand, Maindi and Ghanohim.

The approach to the snout of the glacier includes a trekking of about 18 km distance starting from the Gangotri town. Total catchment area of the Gangotri Glacier study basin upto discharge gauging site is about 556 km^2, out of which glacierized area is 286 km^2. The elevation range of the study basin varies between 3800 to 7000 m.

DATA COLLECTION

To determine the storage characteristics of the Gangotri Glacier, continuous monitoring of the glacier melt run-off was made, because to define hydro-meteorological condition of any glacier the first and foremost requirement is availability of continuous reliable flow data. Discharge and meteorological data were collected near the snout of Gangotri Glacier which can provide records from melt seasons (May–October, 2004) during the year. A standard meteorological observatory was established about 3 km downstream to the Gomukh. An automatic water level recorder was installed on the stilling well to record round the clock variations in the water levels. Stage discharge relationship established for the gauging site was used to convert the water levels into corresponding discharge. Over the study period meteorological data were digitized on hourly basis. The digitized variables were: dry and wet bulb temperatures, relative humidity and rainfall, etc. The dry bulb temperature gives the air temperature. Values were digitized as hourly and daily means.

STORAGE CHARACTERISTICS

Experiments on diurnal cycles of hydrograph in snow-fed streams in Himalayas provide a useful technique for measuring the time it takes water to travel from the cover of the snowpack, where snowmelt typically peaks in the afternoon, to the river gauge, where the daily maximum flows may arrive few hours later. Hourly stage measurements in Gangotri Glacier subbasins (km^2) of the Bhagirathi River in Garhwal Himalayas illustrate travel time delays during the melt seasons (May–October, 2004). Travel times increase with longer percolation (Jessica D, 2005) times through deeper snowpacks. These storage characteristics of the glaciers or snowpacks are responsible for delayed response of melt water generated over the glacier surface into runoff. The size of the glacier, depth of snow over the glacier and drainage network of the glacier are the important factors which control the magnitude of the volume of water as runoff from the stored water including its delaying response. 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 al.*, 1975; Lang *et al.*, 1979; Collins, 1982; Oerter and Moser, 1982). The magnitude of delay in response is a compound effect of ablation and accumulation area of the basin. The runoff dominated with melt water from the accumulation area has higher time of concentration as compared with melt water generated in the ablation area. That storage occurs as ice, snow and water associated with three time scale (Jansson, 2003).

Melt water storage in a glacier can be classified as (i) long-term storage—includes storage of water as ice and snow and storage or release of water depending on climate, (ii) intermediate-term storage—includes seasonal runoff variations and seasonal water balance, (iii) short-term storage—includes diurnal storage of meltwater in snow, firn and englacial and subglacial channel. Short-term storage or diurnal storage, which controls the magnitude of the water runoff, depends on the dynamics, size, drainage network, seasonal snow cover and firn cover, depth of snow, and ablation and accumulation area of the particular glacier. Water can be stored in the glacier in a number of ways: in surface snow and firn, crevasses, surface pools, englacial pockets, subglacial cavities, englacial and subglacial drainage network and in basal sediments (Jansson, 2003). Short-term melt water storage characteristics result in the diurnal variation of discharge from the glacier. Due to this storage, the total melt water produced in a day does not drain out as runoff from the snout on the same day. The remaining melt water emerges gradually on subsequent days. Thus runoff observed at particular time is generated by a combination of melting occurred on the same day and on previous days. Run-off delay varies with the intensity and maturity of the snow and firn on the glacier. The occurrence of maximum streamflow in the glacierized rivers in the late afternoon or evening clearly suggests that a major part of the melt water produced during the day period reaches the snout after few hours (Singh, 2003). To understand the melt water storage behaviour of the Gangotri Glacier, round the clock streamflow records were divided into daytime flow (0900–2000 hours) and night-time flow (2100–0800 hours), respectively. Daily mean daytime and night-time 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 night-time discharge was computed and is given in Table 1.

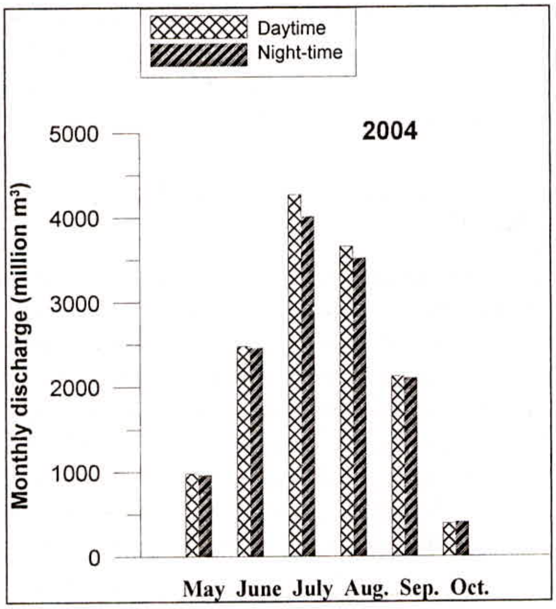

Fig. 2: Monthly distribution of daytime (0900–2000 hours) and night-time (2100–0800 hours) discharges observed during melt seasons, 2004 near the snout of Gangotri glacier

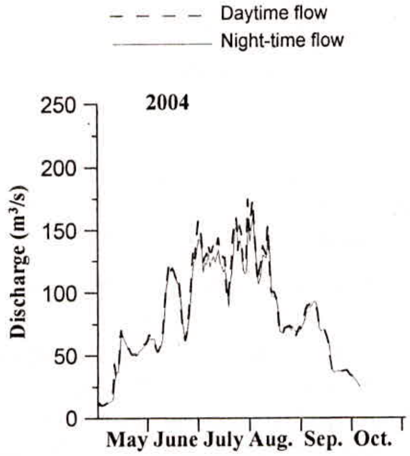

Fig. 3: Daytime (0900–2000 hours) and night-time (2100–0800 hours) mean discharges observed during melt seasons, 2004 near the snout of Gangotri glacier

Table 1: Variation in ratio of monthly daytime discharge to that of night-time discharge for different months during four-ablation period (2004)

Months	*2004*
May	2.58
June	1.36
July	1.11
August	0.75
September	1.15
October	2.81

It was found that this ratio varies from .75–2.81, during the year 2004. Streamflow at Gangotri Glacier during daytime and night-time indicates that in the beginning and at the end of the melt season, volume of the night-time flow is very close to the daytime flow (Figure 2), but during the peak melting season, night-time flow reduces in comparison to the daytime flow.

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.

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.

It is observed that discharge starts increasing from May onwards, reaches its maximum in July and August then starts reducing. Both limbs of hydrograph are almost flat during early and later part of melt season. 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. 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. Under such conditions, runoff, can have much delayed response because melt water passes through the snowpack and flows as interflow after reaching the ground surface. Consequently, in the early and later part of the season, both limbs of hydrograph are almost flat. The flatness of the hydrograph representing no significant changes in the later part of seasons is because of little or no melting due to cold temperatures during this period. 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. As shown in Figure 4, the distribution of hourly discharge indicates that maximum runoff (Q_{max}) is observed in the evening (1700 to 1900 hours) and minimum flow (Q_{min}) in the morning (0800 to 1000 hours).

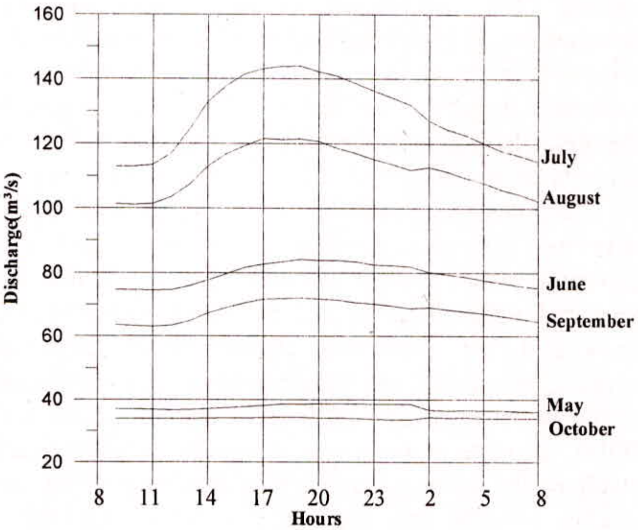

Fig. 4: Diurnal variations in discharge computed for different summer months using year 2004 data

MELT-RUNOFF DELAYING CHARACTERISTICS: TIME-LAG AND TIME TO PEAK

There is a time-lag between the melt water, generated over the glacier and its appearance as runoff at the

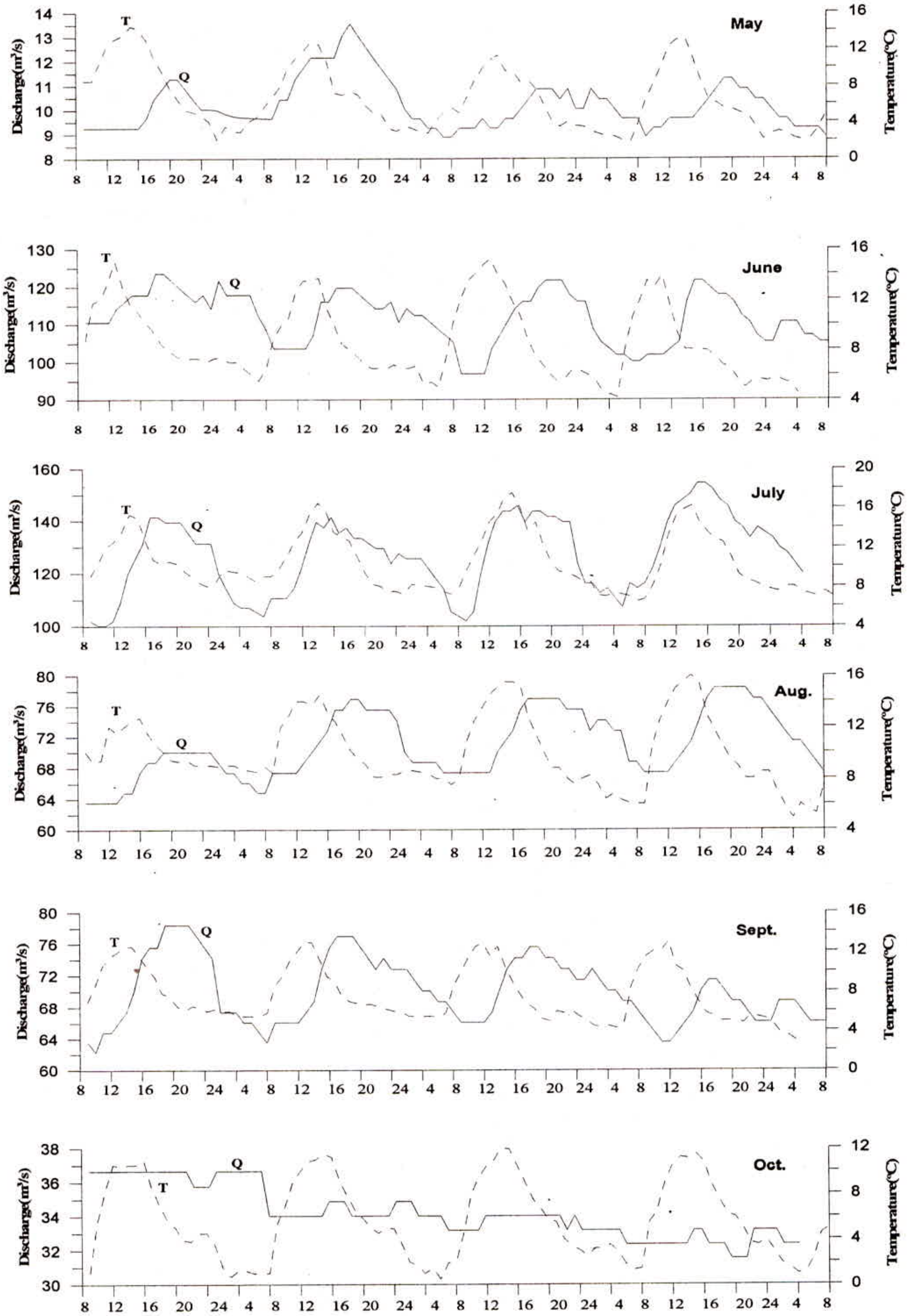

Fig. 5: Diurnal variation in discharge (Q) and Temperature (T) for selected clear weather days for melting year 2004

snout of the glacier. 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 observation period 2004 was used. As solar radiation directly influences the melting, 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 streamflow at or nearest to the snout to minimize the impact of time taken by the water to travel from snout to gauging site and to eliminate the possible contribution from any other sources within the reach from the snout to gauging site. 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 5 shows comparison between temperature and discharge at an interval of four hour for consecutive days in different months of melting seasons 2004. 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., Q_{max}/Q_{min} were computed over the melt period. As illustrated in Figure 6(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.

CONCLUSIONS

The storage characteristics of the Gangotri glacier and the influence of changes in storage during one complete melt season (2004) have been studied. The distribution of day and night streamflow shows that night-time flow is also as high as daytime flow throughout the melt season. 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. 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. These results also indicate that the delaying influence of the glacierised basin reduces with time due do changes in physical condition of the basin and it results in a quicker response of melt water to streamflow in mid or late melt season.

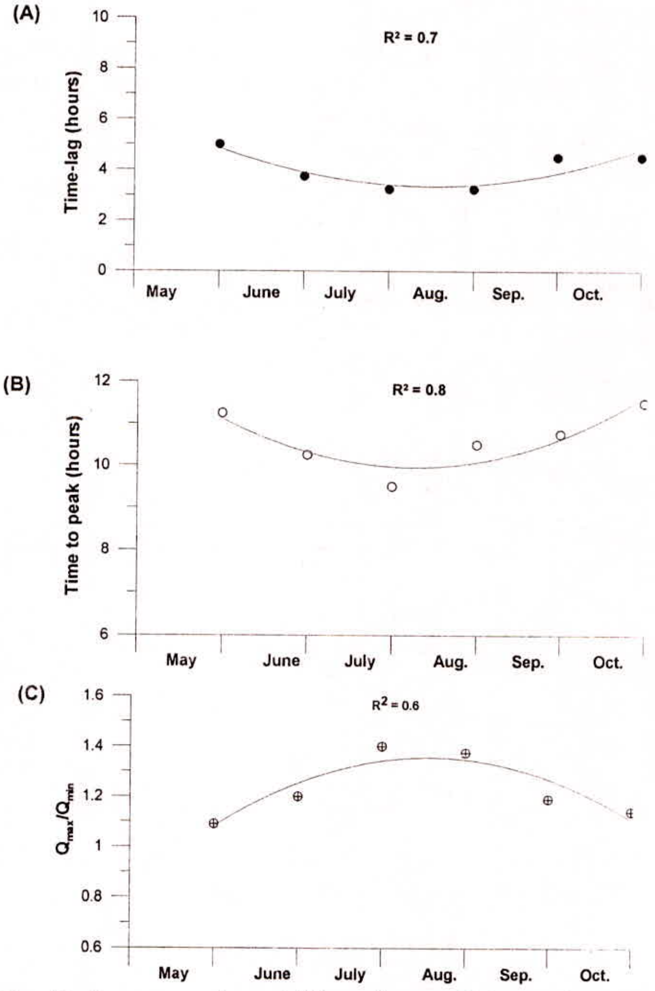

Fig. 6: Average value of (A) melt- runoff time – lag, (B) time to peak, and (C) discharge ratio for the melting seasons observed near the snout of Gangotri Glacier

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 (300–500 hours) and time to peak (900–1200 hours) were higher in the beginning and towards the end of the season as compared to the peak melt season.

In order to investigate the inter-relationship between the variation in runoff and delaying characteristics of the glacierized basin, changes in the discharge ratio, i.e., Q_{max}/Q_{min} were computed over the melt period. As illustrated in Figure 6(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.

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