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Role of storage characteristics of glaciers in the regulation of streamflow

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Abstract
There are more than 5000 glaciers in the high altitude region of the Himalayas and make a significant contribution to the annual flows of the rivers originating from the Himalayas. Melt water storage and drainage characteristics of a glacier regulate the streamflow emerging out from the glacier. The diurnal variation in the melt water runoff is controlled by these characteristics of the glacier. In order to understand these characteristics of the glacier, continuos monitoring of the meteorological and hydrological information is required. In the present paper, storage and drainage characteristics of the Dokriani glacier located in the Garhwal Himalayas have been studied. Total area of this glacier is about 10 km^2. Required data were collected for a period of 4 years for the Dokriani glacier by establishing a meteorological observatory and discharge gauging site with the provision of automatic water level recorder near the snout of the glacier. Observation of discharge round the clock for the summer period shows the availability of considerable amount of runoff during the night period due to these characteristics. Movement of snowline over the glacier due to depletion of snow from the glacier surface results in exposition of glacier ice surface and reduction in storage capacity of glacier. Such variations in physical condition of a glacier attribute to the reduction in the melt water storage of a glacier. The effect of reduction in storage characteristics on the hydrologic response of the basin has also been studied by analysing clear weather hydrographs. The response of the basin becomes faster with advancement of melt season.

INTRODUCTION

To meet the increased demand of water due to increase in population and industraization, continuous development of new sources of water for irrigation, hydropower, domestic and industrial supply is needed. The water yield from the glacierized regions is considered high and reliable because of very good precipitation in the high altitude regions where glaciers exist. Further, glacier melt contribution is maximum during the summer period when the demand for water is at its maximum. Availability of dependable flows from the glaciers and suitable head in the high altitude region provides excellent conditions for hydropower generation. In the basins, which experience only seasonal snow, the total annual runoff cannot exceed the total annual precipitation. But the annual runoff from the glacierized basins may be either less or greater than annual precipitation due to addition of precipitation to the glacier mass or release of additional mass from the glacier depending on the meteorological conditions in the corresponding years.

Keeping in view the glaciers as important source of water, the International Hydrological Decade (1965-74) included major programmes related to glacier hydrology: world wide inventory of perennial and seasonal snow and ice masses, fluctuations of glaciers, and combined heat, ice and water balances at selected glacier basins. Valuable information was gathered under these programmes which has broadened the understanding and knowledge of the subject. Results of such studies can be used for forecasting of glacier generated streamflow for hydro-electric, or irrigation purposes, prediction and avoidance of catastrophic events due to glacier-dammed lake outbursts. A better understanding of these processes for the glacierized regions has resulted in extensive engineering development that use glacier melt runoff in Central Asia, The Alps, Scandinavia and the North American Cordillera. However, to develop water resources from the glacierized areas, information on the melt rate, routing of melt water or storm precipitation through glaciers, is essential.

There is significant contribution from snow and glaciers into annual flows of Himalayan rivers. Usually, seasonal snow contribution ceases by the end of June and after that glacier contribution starts. Hydrological response of a basin is governed by several factors related to the climate and topography. 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. Flow characteristics of a glacierized basin are thus different from those of only rainfed basin. In the present paper storage characteristics and hydrological response of the Dokriani glacier is studied using continuous streamflow records from this glacier.

STUDY AREA AND DATA COLLECTION

Dokriani glacier is located in the Garhwal Himalayas. Total drainage area of this glacier is about 16.13 km^2, out of which about 9.66 km^2 (60%) is covered by snow and ice. The melt stream originating from Dokriani glacier is known as Din Gad and meets Bhagirathi river at Bhukki. The elevation of glacier varies from about 3950- 5800 m. The length of this glacier is about 5.5 km whereas its width varies from 0.1-2.0 km from snout to accumulation zone.

To determine the storage characteristics of the Dokriani glacier, continuous monitoring of the glacier melt runoff was made. For continuous recording of flow an automatic water level recorder was installed very near to the snout of the glacier. The climatological and hydrological data were collected at about 3950 m altitude near the snout for four summer seasons (1995-1998) (June-September).

STORAGE CHARACTERISTICS OF THE DOKRIANI GLACIER

In the glacier fed streams only a portion of the melt water produced each day emerges as runoff from the snout on the same day. The remaining melt water is stored within the glacier which gets delayed and adds to later melt contribution. During the summer period a considerable contribution to streamflow is received from the water stored at the several locations of the glacier. In fact, the diurnal cycle of runoff also consists of a part of this stored melt water. This shows that the streamflow of a glacier fed stream is controlled by storage characteristics of the glacier and determined by delayed response of the basin.

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; Tangborn 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.

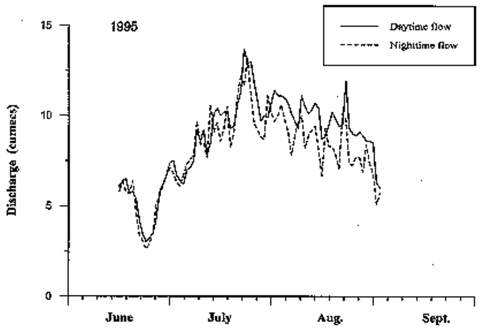

Figure 1(a). Daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) mean discharge observed at the Dokriani glacier gauging site during summer 1995.

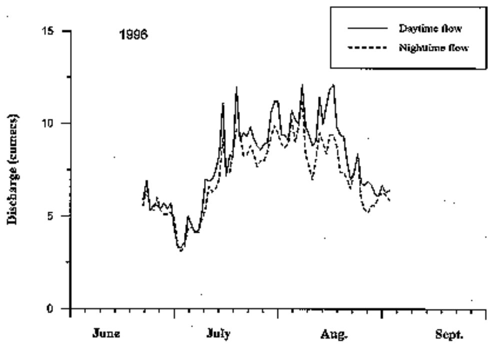

Figure 1(b). Daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) mean discharge observed at the Dokriani glacier gauging site during summer 1996.

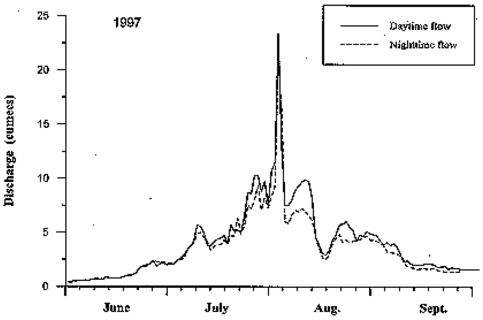

Figure 1(c). Daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) mean discharge observed at the Dokriani glacier gauging site during summer 1997.

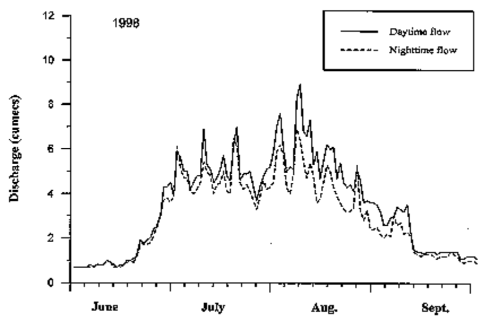

Figure 1(d). Daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) mean discharge observed at the Dokriani glacier gauging site during summer 1998.

In order to study the storage and drainage behaviour of a glacier, hydrological and meteorological data for clear weather conditions is needed. If continuous hydrographs for clear weather conditions for few days are available, a better picture of the storage behaviour can be obtained. Consideration of clear weather days becomes very important for such analysis to arrive at accurate estimation of the glacier melt runoff. On the rainy days contribution from the rain is added to the streamflow and separation of this contribution is difficult. Moreover, on the rainy days when rain is observed near the base camp, depending upon the prevailing temperature conditions it is likely that snow may occur in the upper part of the glacier. Under such conditions whole glacier surface does not necessarily contribute to runoff due to rain.

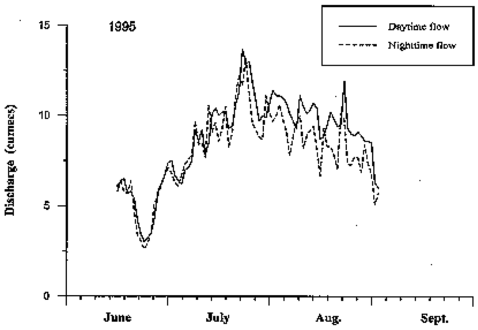

Figure 2(a). Monthly distribution of daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) discharge observed near the snout of Dokriani glacier in summer 1995.

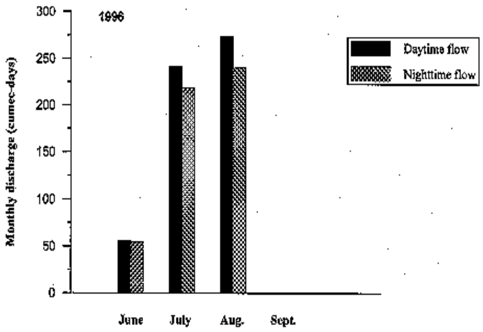

Figure 2(b). Monthly distribution of daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) discharge observed near the snout of Dokriani glacier in summer 1996.

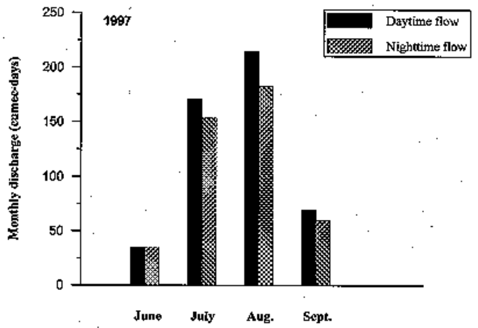

Figure 2(c). Monthly distribution of daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) discharge observed near the snout of Dokriani glacier in summer 1997.

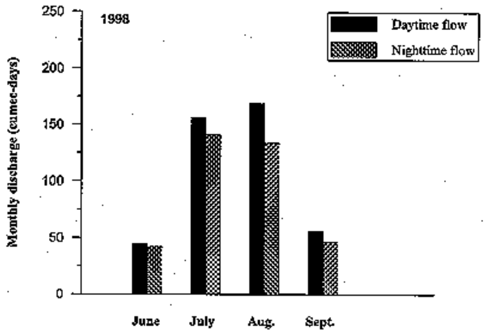

Figure 2(d). Monthly distribution of daytime (0900-2000 hrs) and nighttime (2100-0800 hrs) discharge observed near the snout of Dokriani glacier in summer 1998.

DAY AND NIGHT DISCHARGE

Melt water storage characteristics of the glacier leads to high discharge in the glacier fed melt stream even during the night time, while rain fed rivers do not show such behaviour. In the present study streamflow records were split into daytime flow (0900-2000 hours) and nighttime flow (2100-0800 hours) using hourly data. Mean daily daytime and nighttime flow for 4 different years is shown in Figure 1, whereas monthly discharge for respective period is shown in Figure 2. The ratio of monthly nighttime discharge to daytime discharge is plotted in Figure 3. It is noticed that all through the melt season, night time flow is also as high as day time flow. As such very little or no melting takes place on the glacier during the night period, but a high amount of discharge in the glacier fed streams is observed even during the night time due to melt water storage characteristics of the glaciers. In the beginning of melt season, night time flow is almost equal to day time flow, while 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 very much stronger in the early part of melt season and reduce substantially by the end of melt season. Such influence of storage characteristic may be explained on the basis of availability of snow cover on the glacier body in the beginning and end of the melt season. Higher snow cover and poor drainage network would amount to longer delayed response from the basin, as shown in the early part of melt season.

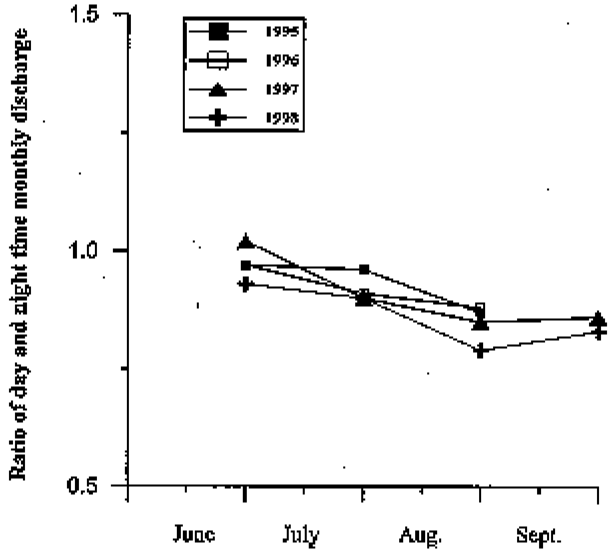

Figure 3. Ratio of nighttime and daytime monthly discharges observed near the snout of Dokriani glacier during different ablation seasons.

VARIATION IN HYDROLOGIC RESPONSE WITH TIME

The shape of the hydrograph exhibits the integrated effect of diurnal changes in ablation rate and hydrological response of various parts of the basin. The discharge from the glacierized basin consists of a diurnal rhythm superimposed upon a baseflow generated from the melt water stored in the basin. The diurnal rhythm is considered a distinguished feature of the glacier fed streams and primarily controlled by diurnal fluctuations in the energy available for melting of snow and ice and fast response of the ablation area of the glacier.

For a basin, the trends of rising and falling limbs of hydrohraph, and the time of peak runoff are considered important factors to represent the hydrological response of the basin. In order to study the variations in the trend of hydrograph of the study basin during the melt season, few hydrographs of clear weather conditions were selected and analysed. The diurnal variation in the hydrograph for selected dates in June, July, August and September are shown in Figure 4. Details of weather conditions on these days are given Table 1. These graphs clearly show the change in the shape of hydrograph with advancement of melt season. The hydrograph recorded in the month of June represents the beginning of melt season and does not show significant diurnal variation in the hydrograph. In other words, for this month a slow variation in the rising and falling limbs of hydrograph is observed. This may be possible due to percolation of melt water through snowpack, its storage in the snow and then very slow recession of this stored water. Thus, hydrograph of June represents very strong delaying characteristics due to high storage characteristics of the basin in this period. In the month of July, melt water storage capacity of the glacier is reduced because of reduction in snow depth due to melting of snow. The influence of reduced storage capacity can be clearly noticed from the shape of hydrograph of July month. The variation in hydrograph for July is much sharper than the month of June showing faster hydrologic response of the basin. The hydrologic response of the basin becomes further faster in the month of August, which can be noticed from steeper rise and fall in the hydrograph of this month. In the month of September, the melting from the glacier is very little and the streamflow has almost all contribution from the stored water in the glacier body. It results in very slow recession in the month of September. These results indicate that the delaying influence of the glacierised basin reduces with time due do changes in physical condition of the basin and hydrologic response of the basin becomes faster accordingly.

Table 1: Details of meteorological data for the days selected for hydrograph analysis.

Date	Mean Temperature (°C)	Rainfall (mm)	Relative Humidity (%)	Sun shine (hours)	Evaporation (mm)
23.6.98	9.9	0.0	90	7.7	3.0
23.8.98	9.4	0.0	90	4.7	2.1
9.8.98	12.2	0.0	89	4.0	2.6
4.9.98	7.9	0.2	90	4.0	2.0

The maximum streamflow in the Dokriani glacier melt stream is observed in the late afternoon or evening, suggesting that a major part of the melt water produced during the day period reaches the snout within a period of few hours (Figure 4). Diurnal variations recorded in the streamflow during the melt season clearly indicates the changes in the timing of peak runoff. Figure 4 shows a difference of about one hour is observed in the timings of maximum flow from the June to September. An early peak in runoff with advancement of melt season suggests a relatively faster response of the drainage basin due to faster runoff from the exposed ice surface, reduction in snowpack area and depth as well. Progressive development of drainage network with melt season also attribute to a faster response of melt water in mid or late melt season. In the later part of ablation season diurnal fluctuations are more pronounced and follow fluctuations in available energy for melting. Thus, the changes in the storage capacity of the glacier attribute to a faster response of the basin with time as confirmed by the shape of the hydrographs observed during the melt season. These results also support a reduction in the ratio of nighttime to daytime flows in the later part of melt season.

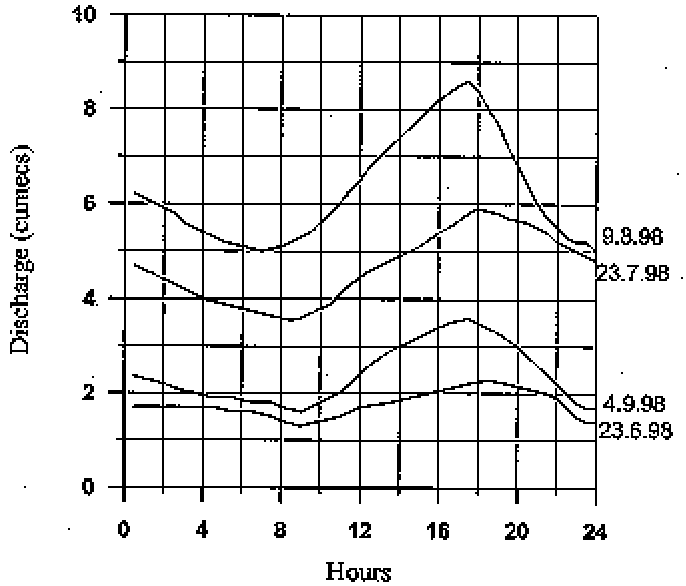

Figure 4. Dinural variation in discharge observed near the snout of Dokriani glacier in summer 1998.

Figure 4 also illustrates that as melt season advances, in addition to variation in diurnal cycle of melt runoff, an increase in the baseflow also can be seen when continuous higher melting takes place over the glacier. Under higher and continuous melting environment, higher rate of recharge occurs to firn aquifer and an increase in streamflow is observed. The volume of the baseflow changes very slowly as compared with superimposed portion of the melt runoff. The diurnal flow which is superimposed over the baseflow has a major contribution from the ablation part of the glacier. Melt water from the accumulation area dominated by delayed response also contributes partly to the this flow. The contribution from the ablation area reaches faster to the glacier outlet through super-glacial and sub-glacial streams. Glacier melt runoff recorded for the whole melt season shows that changes in the baseflow are very slow in comparison to the diurnal cycled flow. It can be understood from the behaviour of melt water response from the various parts of the glacier. Broadly contribution in the streamflow arises from two areas namely ablation area and accumulation area. Depending on the response of melt water from these areas they can be designated as fast and slow reservoirs, respectively. Sudden diurnal variations in the melt rate over the glacier influence the runoff from the ablation area immediately while runoff coming from the water stored in the accumulation area has little immediate impact of such events unless those are continues for several days.

CONCLUSIONS

The storage characteristics of the Dokriani glacier and the influence of changes in storage capacity on the hydrologic response of the basin have been studied. The distribution of day and night streamflow shows that nighttime 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. It is observed that the hydrologic response of the basin becomes faster with time during the melt season, which is reflected by steeper rise and fall of the hydrograph. The time of peak flow occurs earlier in the day as summer progresses. A difference of about one hour is observed in the timings of maximum flow from the June to September. An early peak in runoff and steep rise and fall in the hydrograph limbs with advancement of melt season suggests a relatively faster response of the drainage basin. 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.

Acknowledgement

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