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Correlations between discharge and meteorological parameters and runoff forecasting from a highly glacierized Himalayan basin

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Abstract To assess the predictive significance of meteorological parameters for forecasting discharge from the Dokriani Glacier basin in the Himalayan region, discharge autocorrelation and correlations between discharge and meteorological factors were investigated on a monthly and a seasonal basis. Changes in correlations between discharge and meteorological variables, lagged by 0–3 days, were determined. Discharge autocorrelation was found to be very high for each individual summer month and for the melt season as a whole. This suggests that a substantial meltwater storage in the glacier, which results in a delayed response of runoff, and therefore discharge, from the highly glacierized basins is very much dependent on the previous day's discharge. A comparison of correlations between discharge and temperature, and discharge and precipitation shows that temperature has a better correlation with discharge during June and September, while precipitation has good correlation with discharge in July and August. Variations in the physical features of the glacier, weather conditions, and precipitation and its distribution with time over the basin account for changes in correlations. To forecast the runoff from the Dokriani Glacier basin, multiple linear regression equations were developed separately for each month and for the whole melt season. A better forecast was obtained using the seasonal regression equation. A comparison of correlations for the Dokriani Glacier with those for the Z'mutt Glacier basin, Switzerland, illustrates that, for both basins, the previous day's discharge (Q_{i-1}) shows maximum autocorrelation throughout the melt period. Whereas a good correlation between discharge and temperature was observed for the Z'mutt Glacier basin for the whole melt period, for the Dokriani Glacier basin it was strong at the beginning and end of the ablation season. Runoff delaying behaviour in the Dokriani Glacier basin is found more prominent than in the Z'mutt Glacier basin early in the melt season. Water storage appears to be less significant in the Dokriani Glacier than in the Z'mutt Glacier towards the end of the ablation season. The strength of correlation between discharge and precipitation is higher for the Dokriani Glacier basin than for the Z'mutt Glacier basin. This is due to higher rainfall in the Dokriani Glacier basin. In general, for both glacier basins, maximum correlation is found between discharge and precipitation on the same day.

Corrélations entre débit et variables météorologiques et prévision des débits sur un bassin glaciaire himalayen

Résumé Afin d'évaluer la capacité des variables météorologiques à prévoir le débit du bassin du glacier Dokriani (Région de l'Himalaya), on a étudié l'autocorrélation des débits et la corrélation entre débit et variables météorologiques aux échelles mensuelle et saisonnière. Les modifications des corrélations entre débit et variables météorologiques ont été déterminées pour des décalages de 0 à 3 jours. L'autocorrélation des débits s'est révélée très importante pour tous les mois d'été et pour la saison de fonte dans son ensemble. Cela suggère qu'il existe dans le glacier un substantiel stock d'eau de fonte, nourrissant un débit retardé de ce bassin glaciaire qui dépend fortement du débit des jours précédents. Une comparaison des corrélations entre débit et température et entre débit et précipitations montre que la meilleure corrélation entre débit et température est obtenue en juin et en septembre, alors qu'il s'agit des mois de juillet et d'août pour les précipitations. Les variations des caractéristiques physiques du glacier, le temps, les précipitations et leur distribution sur le bassin au cours du

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temps sont responsables de la modification des corrélations. Afin de prévoir l'écoulement du bassin du glacier Dokriani, nous avons établi des équations de régression multiple pour chaque mois et pour l'ensemble de la saison de fonte. La meilleure prévision est obtenue grâce à l'équation de régression saisonnière. Une comparaison des corrélations obtenues pour le glacier Dokriani avec celles obtenues pour le bassin du glacier Z'mutt en Suisse montre que, pour les deux bassins, le débit du jour précédent (Q_{i-1}) présente une autocorrélation maximale pendant la saison de fonte. Alors qu'une bonne corrélation entre débit et température a été observée pour le bassin du Z'mutt à l'échelle de la saison de fonte dans son ensemble, c'est au début et à la fin de cette période qu'elle est bonne pour le bassin du Dokriani. Le retard à l'écoulement dans le bassin du glacier Dokriani est plus important que dans le bassin du Z'mutt au début de la saison de fonte. Le stockage d'eau semble moins important dans le Dokriani que dans le Z'mutt à la fin de la saison d'ablation. La corrélation entre débit et précipitations est plus forte pour le bassin du glacier Dokriani que pour le bassin du Z'mutt, ce qui est du à des pluies plus importantes sur le bassin du glacier Dokriani. En général, pour les deux glaciers, la corrélation maximale est obtenue entre débit et précipitation de la même journée.

INTRODUCTION

The outflow from glacierized basins consists of contributions from snowmelt, ice melt, baseflow, and precipitation. Because of the complex storage and drainage characteristics of the glacier, water generated due to melt on a particular day contributes to runoff at the snout partially on the same day and partially on subsequent days. Accurate forecasting of total streamflow and its distribution in time is essential for the management of water resources, which includes flood control, reservoir operation, agriculture planning, hydroelectric production, etc. A better understanding of snowmelt, glacier melt and drainage processes is needed for forecasting runoff in high altitude basins. Estimation of meltwater runoff in high altitude glacierized basins is more complex than that of runoff from precipitation in plain areas. Prediction of streamflow becomes very difficult in high mountain basins, where there is high precipitation in addition to snow and glaciers. The basic reason for this is that the input to the glacier system is controlled by various factors such as the extent of snow cover, snow depth, albedo and physical qualities of snow and ice, and the variable glacier drainage system. Net radiation at the glacier surface increases throughout the ablation season because of the exposure of the glacier ice surface owing to depletion of snow cover. This influences the meltwater yield from a glacierized basin. These variables show distinct variations in the course of the melting season. Spatial and temporal observations of such variables are difficult. In high altitude basins, installation and maintenance of a dense monitoring network to record all the variables necessary for determination of snowmelt runoff, are difficult and expensive. Therefore, some correlations are developed between discharge and meteorological parameters.

In the Himalayan context, the majority of the rivers have their upper catchment in snow and ice covered areas and flow through steep mountains. In spite of the vital importance of snow and glacier contribution to the total streamflow, very limited attempts have been made to assess their contribution to annual flows of these rivers (Singh *et al.*, 1997). A few hydrological studies have been carried out for limited glacierized basins in the Himalayan region (Singh, 1993; Singh *et al.*, 1995, 1999; Singh & Kumar, 1996, 1997a,b; Hasnain, 1999; Thayyen *et al.*, 1999; Swaroop *et al.*, 1999). One of the main reasons for the lack of hydrological studies in these high altitude basins is unavailability of data. In the present study, data have been collected by the authors for a high altitude basin, which is highly glacierized. This is the first high altitude glacierized basin in the Himalayas for which continuous data for the ablation season have been collected over several years. Since such data are not available for any other glacierized basin in the Himalayan region, such correlation studies could not be carried out before. Discharge autocorrelations, and correlation between discharge and both temperature and precipitation have been established for this basin and these are compared with those of an Alpine glacierized basin. Attempts are made to forecast the runoff from the Dokriani Glacier basin using regression equations developed on a monthly and a seasonal basis.

PHYSICAL CHARACTERISTICS OF THE DOKRIANI GLACIER BASIN

The Dokriani Glacier basin is a high altitude basin located in the Garhwal region of the Himalayas. It has a total drainage area of about 16.13 km^2, of which about 9.66 km^2 (60%) is covered by snow and ice. The altitudinal distributions of basin area and glacier area in the basin are shown in Fig. 1. The maximum glacier area (12.86%) lies in an altitude range of 5000–5100 m, followed by 12.44% glacier area between 5100 and 5200 m. In the lower part of the basin, the glacier free area is higher than the glaciated area, but the upper part of the basin is almost fully occupied by the glacier.

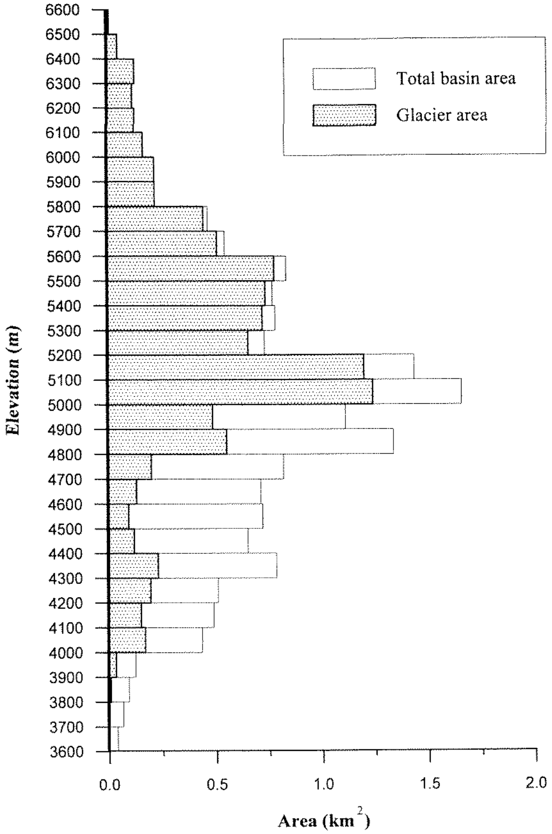

Fig. 1 Distribution of glacier area and total basin area of the Dokriani Glacier in different elevation bands.

The elevation of the glacier varies from about 3950 m to 5800 m a.m.s.l., the length is about 5.5 km and its width varies between 0.1 and 2.0 km from the snout to the accumulation zone. The snout of the glacier is covered by huge boulders and debris. The approach to the Dokriani Glacier basin is extremely challenging. One has to trek about 25 km on foot to reach the Dokriani Glacier base camp. This trek starts from a Bhukki village and most of the trek passes through a dense forest. In general, one night halt is made in between to reach the glacier base camp. The base camp was established about 1 km from the snout of the glacier.

DATA COLLECTION

Collection of relevant data for any hydrological study of a high altitude basin in the Himalayan region is a difficult and challenging task. Such basins are located in very remote areas with no habitation. Poor accessibility through rugged terrain makes logistics and transportation of instruments and other necessary material to the site very difficult. Harsh weather conditions restrict the stay of personnel for long periods and there are no means of communication. Availability of trained personnel to observe the data is limited. Repairing of instruments is not possible nearby, so manual or semi-automatic instruments are used. These are the reasons that data are not available for longer duration for high altitude basins in the Himalayan region. This is the first time that data for such a long period have been collected for a high altitude glacierized basin in the Himalayas.

Establishment of the meteorological observatory

A standard hydrometeorological observatory was set up at about 3950 m altitude. In 1995, the observatory was equipped with an ordinary raingauge and maximum and minimum thermometers, but in 1996 the observatory was improved by installing a self recording raingauge, evaporimeter, thermograph, hygrograph, dry and wet bulb thermometers, anemometer, wind vane and sunshine recorder. For precipitation observations, both an ordinary raingauge and self recording raingauge (SRRG) were used. Continuous recording of rainfall by SRRG provided rainfall intensity. Meteorological observations were made daily at 08:30 and 17:30 h.

Establishment of the discharge gauging site

A discharge gauging site was established about 800 m downstream of the snout of the Dokriani Glacier. Most of the boulders were removed from the channel. A temporary wooden bridge over the glacier meltstream was used for determination of the cross-section area of the channel. A stilling well was constructed at the gauging site and an automatic water level recorder was installed for continuous monitoring of the flow. A graduated staff gauge was installed at the left bank of the stream for manual observations of water level fluctuations in the meltstream. In order to establish a stage–discharge relationship, observations of water level and discharge were also made. The velocity–area method was used to estimate flow in the meltstream for developing the stage–

discharge relationship. In addition to the use of floats for velocity determination, a propeller-type pigmy current meter was used for the measurement of velocity. The stage–discharge relationship was established for each year and used to determine flow from stage records for the corresponding year. There was a marginal change in the stage–discharge relationship from year to year. Continuous recording of water stage provided very accurate information on the total streamflow and its distribution with time. Mean daily discharge was computed by averaging hourly discharge values over 24 h.

HYDROLOGICAL CHARACTERISTICS AND ABLATION SEASON OF A HIMALAYAN GLACIER

In the Himalayan region, snow accumulation usually takes place from October to March. The seasonal snow melts from April to May/June. For a glacier, the ablation season extends from June to September. The beginning of this period (June) represents the initiation of melt runoff from the glacierized part of the basin. At this time, a large part of the glacier surface is covered by snow and, therefore, net absorption of solar energy is reduced due to the high albedo of snow. As the summer season advances, the seasonal snow deposited on the glacier surface starts melting and the contribution from glacier icemelt becomes substantial. Thus, the middle part of the ablation season (July–August) corresponds to a high melt rate of glacier ice providing maximum discharge and an improved drainage network. In September, melting is significantly reduced in high altitude basins because of a drop in air temperatures and there is very little runoff in the stream due to baseflow. Sometimes glaciers are partly covered with fresh snow at this end of the ablation season. When the glacier surface is at 0°C or more, rain falling on it does not freeze, but contributes to meltwater draining from the glacier.

Changes in storage and drainage characteristics of the glacier with time influence the response of streamflow from glacierized basins. Although very accurate assessment of variation of these parameters with time is not possible, they can be taken into account by dividing the melt season into different time intervals and by assuming that the processes in each interval are stationary. A similar concept of subdivision of melt season into intervals was adopted by Lang (1973), Jensen & Lang (1973), and Lang & Dayer (1985) for highly glacierized basins in the Alpine region. In the present study, the ablation season is divided into four months namely, June, July, August and September. Data for each month cover the corresponding parts of the three years' ablation seasons (1995–1997) (for example, the data series for June includes data for all three years). The time series of daily means are then considered as stationary within each interval. Correlations and regression equations were developed for each month separately and for the whole melt season.

RESULTS AND DISCUSSIONS

Discharge autocorrelation

Discharge autocorrelations established for different summer months and for the melt season as a whole using daily data are shown in Fig. 2(a). A time lag of 1 to 3 days

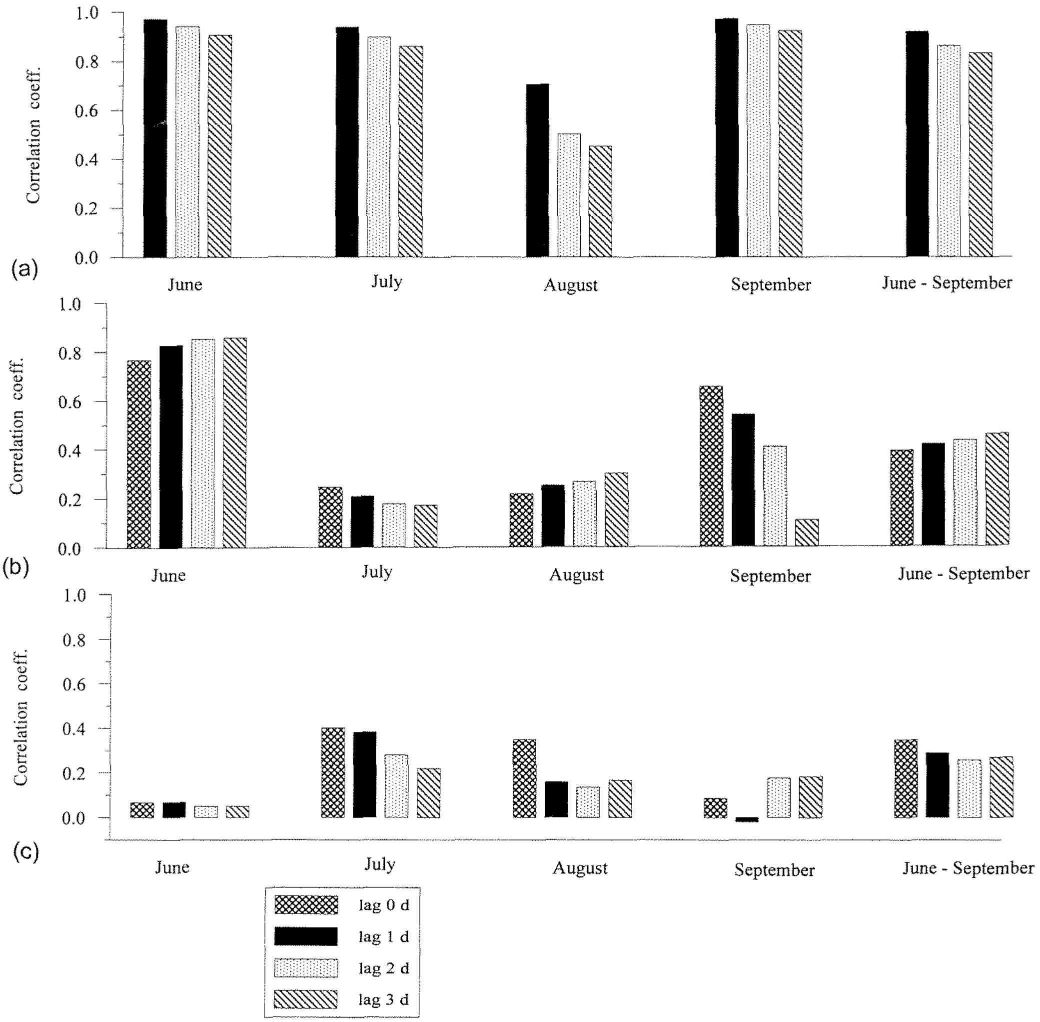

Fig. 2 (a) Discharge autocorrelation, (b) correlation between daily mean discharge and air temperature, and (c) correlation between daily mean discharge and precipitation, as a function of 0–3 days lag for the Dokriani Glacier basin for summer months and for the whole melt season.

($Q_{i\text{-}1}$, $Q_{i\text{-}2}$, $Q_{i\text{-}3}$) was considered for this analysis. The range of correlation for a time lag of 1–3 days for each month and for the whole melt season is given in Table 1. The distribution of discharge autocorrelation shows that it varies with time. Variations in the value of autocorrelation observed in monthly series may be attributed to changes in the melting condition of the glacier, and in the precipitation pattern and water storage and drainage characteristics within the basin. The highest correlations are observed for September, followed by June. September, being at the end of the ablation season, represents the recession of meltwater from the basin. The dominance of delaying characteristics of the glacier and little contribution from rainfall to the streamflow in June and September provide higher discharge

Table 1 Range of correlation coefficients between discharge, temperature and precipitation for different months and for the whole melt season.

Variables used for correlations	June	July	August	September	June–September
Discharge (Lag: 1–3 days)	0.972–0.908	0.939–0.861	0.706–0.435	0.972–0.924	0.920–0.834
Discharge and temperature (Lag: 0–3 days)	0.768–0.858	0.171–0.245	0.216–0.300	0.108–0.654	0.390–0.458
Discharge and precipitation (Lag: 0–3 days)	0.041–0.068	0.220–0.402	0.136–0.350	(-)0.020–0.184	0.260–0.350

autocorrelations. A comparison of discharge autocorrelations for different months indicates that, for this glacierized basin, discharge autocorrelation is very high for all the summer months, except August. In August, melt from the glacier is at its maximum and rainfall contribution is also significant. A high variability in discharge occurs during July and August due to high rainfall, which significantly contributes to total streamflow. Thus, the discharge autocorrelations for July and August are lower than those for June and September.

The discharge autocorrelation decreases with an increase in the lag period of discharge, both on a monthly and on a seasonal basis. The decrease in discharge autocorrelation with an increase in time lag is stronger on a monthly basis than on a seasonal basis. However, this reduction is not significant except for the month of August, when autocorrelation is drastically reduced from 0.706 to 0.435 with an increase in time lag from 1 day to 3 days. In general, changes of autocorrelation with time lag are pronounced in this month. Such variation in discharge autocorrelation is possibly due to the physical properties of the glacier, which include fast response of the basin to streamflow due to higher exposure of glacier ice surface and improved drainage network.

A high discharge autocorrelation is also obtained for the seasonal series. The seasonal distribution of discharge autocorrelation suggests that, although a good autocorrelation exists for all considered time lags, the maximum autocorrelation coefficient is found with the previous day's discharge (Q_{i-1}) for all months and seasons. The value of maximum discharge autocorrelation with Q_{i-1} varies between 0.706 and 0.972 for different months and for the season as a whole. High discharge autocorrelation throughout the melt season indicates the dominance of storage characteristics in the response of runoff from the glacierized basin. The results show that discharge for a particular day is very much dependent on the previous day's discharge. Thus, for the forecasting of discharge from the glacierized basin for a particular day, the previous day's discharge becomes a significant predictor.

Discharge–temperature correlation

Correlations established between discharge and air temperature with a time lag of temperature from 0 to 3 days (T_0, T_{i-1}, T_{i-2}, T_{i-3}) are shown in Fig. 2(b). It was found that the discharge–temperature correlation changes significantly with time. The range of discharge–temperature correlation for June, July, August, September and for the whole melt season are given in Table 1. The analysis shows that discharge is highly correlated with temperature only for the month of June, when the major contribution to the streamflow is derived from snowmelt because a large extent of glacier surface is covered with snow at this time. The presence of snow delays the response of streamflow from the basin and has a stronger delaying effect on runoff generation at the beginning of the melt season. Further, there is little contribution from rainfall to total streamflow in this month. It is understood that a combination of systematic melting conditions and the existence of snow over the glacier ice body increases meltwater storage in the basin. These factors contribute to a high correlation between discharge and temperature for June. Correlation increases with time lag in June, reaching a maximum value for T_{i-3}. However, the increase in discharge–temperature correlation with time lag is not very significant for a time lag from 0 to 3 days.

For both July and August, a poor correlation is found between discharge and temperature for all the lag periods considered. In the middle of the glacier melt season (July and August), contributions from both the snow-covered area and ice-covered area reach the outlet of the basin. The melt rates of snow and ice are different for a particular temperature. In July and August, insolation is slightly reduced and the average albedo of the glacier surface also falls rapidly as old, dirty ice is exposed, resulting in a higher melt rate than in June. Further, the lower and middle parts of the glacier are partly covered with debris, which results in a totally different melt rate. Consequently, under particular temperature conditions, uneven melting takes place over the glacier surface, which partly contributes to a reduction in correlation of discharge with temperature. The observed mean monthly rainfall for June, July, August and September was 186, 245, 376 and 234 mm, respectively. This shows that a significant amount of rain also occurs in the basin in July and August, producing the fluctuations in the streamflow. Using a temperature lapse rate of 0.60°C/100 m and mean monthly temperatures, observed at about 3950 m altitude, of 10.45° and 9.67°C for July and August, respectively, the zero temperature line for these months was computed to be 5690 and 5560 m, respectively. This suggests that most of the glacier experiences liquid precipitation. Thus, it is understood that uneven melting conditions over the glacier surface and substantial rainfall in the basin generate fluctuations in the streamflow resulting in poor correlations between discharge and temperature for this basin. A better correlation would be expected for the glacierized basins which have little or no rainfall during the melt period.

An analysis of the discharge–temperature correlation for September shows that it is higher than those for July and August, but is about half of the correlation for June. Systematic recession of flow due to weaker melting conditions and little contribution to streamflow from rainfall may be the factors responsible for a good correlation for this month. The correlation coefficient decreases significantly with an increase in the time lag; for example, it reduces from 0.654 to 0.108, when time lag is increased from 0 to 3 days. For September, the maximum correlation between discharge and temperature is obtained when temperature is considered without any lag, i.e. T_i, which shows that delaying response is reduced. It is understood that by September—which is almost the end of the ablation season—a large extent of glacier ice surface is exposed because of depletion of snow cover which allows for a faster effect of the meltwater generated over the glacier surface. It can be noted that the trend of variation in correlation of discharge with an increased time lag for September is the opposite of that observed in June.

The seasonal series of discharge and temperature show a good correlation with a time lag of temperature from 0 to 3 days. The correlation indicates an increasing trend with time lag, but the magnitude of increase is not very significant. Changes in correlation with time lag are found not to be very significant for the whole season. The trend of the discharge–temperature correlation on a seasonal basis matches that of June, but the correlation for the whole melt season is found to be less than that for June. As such, the maximum discharge–temperature correlation ($r = 0.458$) is obtained for T_{i-3} on the seasonal basis.

Discharge–precipitation correlation

The correlations between discharge and precipitation with lags between 0 and 3 days (R_0, R_{i-1}, R_{i-2}, R_{i-3}) for different months and for the whole season are presented in Fig. 2(c). Table 1 shows the range of variation in the correlations for June, July, August, September, and for the whole melt season. Correlations between discharge and precipitation are found to be very poor for June and September in comparison to July and August. In July and August, the response of streamflow to rainfall becomes faster compared with other months because of changes in the physical conditions of the glacier. During this time, the glacier ice surface is exposed to a large extent. The response to rainfall is always faster from an ice covered surface compared with a snow covered one: rain falling on a snow-covered surface is first absorbed by the snowpack and later released to the streamflow, whereas the ice surface is impervious. Hence, rain contributes to the runoff at the outlet in a relatively shorter time period. The drainage network within the glacier is well established by July and August, which results in meltwater, as well as rain water, arriving faster at the basin outlet. Thus, the lag time of the runoff generated from the rainfall over the ice surface is shorter than that for rain over the snow surface. Further, in July and August, the effect of rainfall from the non-glacierized part of the basin on runoff is also stronger, because the soil is saturated during this period. Singh & Ramasastri (1999) reported a soil moisture content above 70% in this basin during July and August. Under such conditions, losses from the rain input are much less and a large portion of rain appears as runoff, and that too at a shorter time interval. Thus, in July and August, a high variability in discharge results from higher rainfall and its fast effect on streamflow. Consequently, the correlation between discharge and rainfall improves for these months, compared with June and September.

Precipitation with zero time lag shows a better correlation with discharge than with other time lags for July and August, which represents a faster response of streamflow to rain at the basin outlet. For these two months, the correlation between discharge and rainfall decreases with an increase in time lag of rainfall, giving the highest correlation with R_i. There is a gradual reduction in correlation for July compared to August when correlation reduces drastically as time lag is increased from 0 to 1 day. It can be seen that for July, both R_i and R_{i-1} have similar values of correlation coefficient. This indicates a faster response to rain in August, and a major contribution to streamflow is obtained for the same lag.

A poor correlation is found between discharge and precipitation for September and, as such, no trend of variation is observed with time lag. The values of R_{i-2} and R_{i-3} show slightly better correlation compared with those of R_i and R_{i-1}. During this period, the melting–freezing process also adds to delaying the effect of the rain as the weather begins to be colder. The value of the correlation coefficient is reduced significantly for this month. This may be due to the occurrence of precipitation as rainfall in the lower part of glacier basin and as snowfall in the upper reaches of the basin. The form of precipitation and its distribution over the basin influence the effect of precipitation on the runoff. The form of precipitation generally determines whether the correlation is positive or negative. When precipitation falls as snow, melting of the glacier ceases and discharge is reduced. Under such conditions, discharge and precipitation are negatively correlated. On the other hand, rainfall events in the basin are responsible for a positive correlation because liquid precipitation contributes to runoff faster.

On a seasonal basis, the discharge–precipitation correlation shows the highest correlation ($r = 0.350$) with R_i. A decreasing trend is observed with an increase in time lag, but the reduction is not found significant for time lags from 0 to 3 days. In other words, it shows the maximum contribution of rainfall to runoff on the same day.

A COMPARISON OF CORRELATIONS WITH AN ALPINE GLACIERIZED BASIN

A comparison is made between discharge autocorrelation, and the correlations between discharge and temperature, and discharge and precipitation, for a Himalayan glacierized basin (Dokriani) and an Alpine glacierized basin (Z'mutt Glacier basin in Switzerland). The elevation range of the Z'mutt Glacier basin ranges from 2213 to 4476 m a.m.s.l. The total drainage area is 34.5 km^2, of which 54% is occupied by the glacier. The drainage area of the Dokriani Glacier basin (16.13 km^2) is less than that of the Z'mutt Glacier basin, but the area covered by glacier as a percentage of the total drainage area is slightly higher (60%). The gauging site on the Z'mutt Glacier meltstream was located near to the terminus of the glacier and the meteorological site was very close to the gauging site.

Jensen & Lang (1973) established correlations between discharge and various meteorological parameters for the Z'mutt Glacier basin over a period of four years (1967–1970). The correlations determined for a time lag from 0 to 3 days for the beginning, middle and end parts of the ablation season are given in Fig. 3(a)–(c). A general trend of correlations and their variations with time lag may be understood by consideration of these data. In order to compare these results with the Himalayan glacier, it was assumed that June corresponds to the beginning of the ablation season, July and August to the middle and September to the end. A comparison could be made only for monthly correlations as seasonal correlations were not established for the Z'mutt Glacier basin.

Discharge autocorrelations

A comparison of Figs 2(a) and 3(a) shows that a high autocorrelation exists throughout the melt period for the Z'mutt Glacier basin, whereas for the Dokriani Glacier basin, it

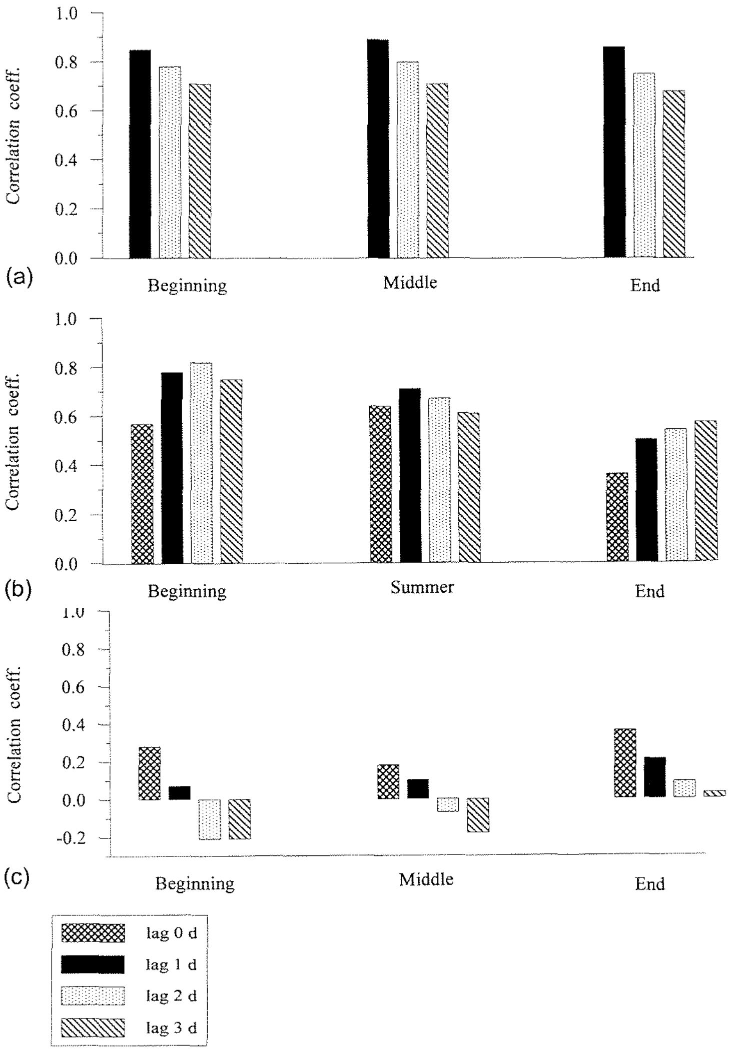

Fig. 3 (a) Discharge autocorrelation, (b) correlation between daily mean discharge and air temperature and (c) correlation between daily mean discharge and precipitation, as a function of 0–3 days lag for the Z'mutt Glacier basin, Switzerland, for the beginning, middle and end of the ablation season.

is high at the beginning and end of the ablation period and low in the middle part, particularly in August. Occurrence of sufficient rainfall during the middle part of ablation season in the Dokriani Glacier basin is considered to be responsible for the reduction in discharge autocorrelation in August. For both the Himalayan and Alpine glacierized basins, Q_{i-1} values have shown maximum discharge autocorrelation throughout the melt period, which suggests that discharge from the highly glacierized basins is very much dependent on the previous day's discharge. A similar decreasing trend of discharge autocorrelation with an increase in time lag is observed for both glacier basins.

Discharge–temperature correlations

At the beginning of the melt season, correlations between discharge and temperature are comparable for both basins (Figs 2(b) and 3(b)). In this period, the highest correlation ($r = 0.82$) is observed for T_{i-2} for the Z'mutt Glacier basin, whereas for the Dokriani Glacier it is highest ($r = 0.85$) for T_{i-3}. This suggests that, during this period, the delaying behaviour of the Dokriani Glacier basin is more marked than that of the Z'mutt Glacier basin. For both basins, the correlation between discharge and temperature at the beginning of the melt season increases with an increase in time lag. For the Dokriani Glacier basin, the discharge–temperature correlation increases gradually with an increase in time lag from 0 to 3 days, while for the Z'mutt Glacier basin, it increases when the time lag is increased from 0 to 2 days and decreases thereafter.

In the middle part of ablation season, there is a considerable difference in correlations between discharge and temperature for both glacier basins. Correlation is about two times higher for the Z'mutt Glacier basin than for the Dokriani Glacier basin. For the Z'mutt Glacier basin, correlation is highest for T_{i-1} and there is no significant change with increase in time lag. For the Dokriani Glacier basin, correlation is very poor for all time lags during this period. As discussed above, the occurrence of rainfall during this period is the main reason for the reduction in discharge–temperature correlations in the Dokriani Glacier basin.

At the end of the ablation season, the correlation coefficient for the Dokriani Glacier basin is drastically reduced with an increase in time lag, i.e. $r = 0.654$, 0.539, 0.407, 0.108 for T_i, T_{i-1}, T_{i-2}, T_{i-3}, respectively. For the Z'mutt Glacier basin, the corresponding values of correlations are 0.36, 0.50, 0.54, 0.57. This shows that both glacier basins exhibit different trends of variation with time lag, i.e. an increase with time lag for the Z'mutt Glacier basin and a decrease for the Dokriani Glacier basin. Consequently, for the Z'mutt Glacier basin, the highest value of discharge–temperature correlation is obtained for T_{i-3}, whereas for the Dokriani Glacier it is for T_i. This shows that the storage characteristics of the Dokriani Glacier are reduced at the end of the ablation season, while the Z'mutt Glacier has stronger delaying characteristics. These results are commensurate with those of Kulkarni (1992), who reported that the accumulation area ratio (AAR), which represents the ratio of snow-covered area to the total glacier area, is substantially lower in the Himalayan region than that for North American and European glaciers. A larger accumulation area of a glacier produces stronger delaying characteristics because of the presence of snow in the accumulation area, as observed in the case of the Z'mutt Glacier.

For the Z'mutt Glacier basin, the maximum discharge temperature correlations obtained for the beginning, middle and end of the ablation season are 0.82, 0.71 and 0.57, respectively. These values indicate that the discharge–temperature correlation decreases as the melt season advances. In the case of the Dokriani Glacier basin, the maximum correlations, $r = 0.858$, 0.245, 0.300 and 0.654, are obtained for June, July, August and September, respectively. It can be noted that, at the beginning and end of melt season, the correlations between discharge and temperature for the Dokriani Glacier are higher than those for the Z'mutt Glacier basin; however, for the middle part of ablation season, they are higher for the Z'mutt Glacier basin.

Discharge–precipitation correlation

A comparison of Figs 2(c) and 3(c) indicates that, for the Dokriani Glacier basin, the correlation between discharge and precipitation is higher than for the Z'mutt Glacier basin, owing to higher rainfall occurring in the Dokriani Glacier basin. In general, for both glacier basins, the maximum correlation is found with the same day precipitation (R_i). At the beginning and end of the ablation season, correlation is higher for the Z'mutt Glacier basin, but for the middle of the season, it is higher for the Dokriani Glacier basin. Like the discharge–temperature correlation, no systematic trend of variation can be observed for the Z'mutt Glacier. The negative correlation with precipitation for the Z'mutt Glacier basin may arise from the snowfall on the glacier.

DEVELOPMENT OF MULTIPLE LINEAR REGRESSION EQUATIONS FOR STREAMFLOW COMPUTATION

To forecast daily streamflow from the Dokriani Glacier basin, multiple regression equations were developed separately for each summer month and for the whole melt season. Data of two years (1995 and 1996) were used. The regression equations were developed considering the possible climatic factors, which may significantly influence the runoff. Discharge from the basin was used as the dependent variable and five variables namely, Q_{i-1}, T_i, T_{i-1}, and R_i, R_{i-1}, respectively, were used as independent variables. Since discharge itself provides comprehensive information about the conditions in the drainage basin, antecedent discharge was used as one of the variables to forecast the runoff. In order to create the data series for a particular month, data of that month for different years were arranged in sequence and stepwise regression was used to arrive at statistically significant regression equations. The resulting multiple regression equations obtained through stepwise regression and corresponding values of correlation coefficient for different months and for the whole season are given in Table 2. It can be noted that some of the variables were dropped in the monthly and seasonal regression equations due to their statistical insignificance determined by stepwise regression approach. The highest correlation coefficient is found for June followed by July, and it is lowest for August. For the whole season (June–August) a high correlation coefficient is also obtained. A comparison of regression coefficients for different independent variables suggests a highest value of regression coefficient for Q_{i-1}. Regression coefficients for T_i and R_i are low as compared with Q_{i-1}. This further confirms that the previous day's discharge plays a very important role in the prediction of streamflow for the next day.

Table 2 Monthly and seasonal regression equations developed for the Dokriani Glacier basin using stepwise regression approach.

Period	Regression equations	Correlation coeff. (r)	Standard error of estimate
June	$Q_i = -0.560 + 0.819\,Q_{i-1} + 0.135\,T_i$	0.963	0.520
July	$Q_i = -0.473 + 0.762\,Q_{i-1} + 0.234\,T_i + 0.026\,R_i$	0.923	0.889
August	$Q_i = -0.413 + 0.722\,Q_{i-1} + 0.237\,T_i + 0.035\,R_i$	0.871	0.772
June–August	$Q_i = -0.671 + 0.901\,Q_{i-1} + 0.125\,T_i + 0.016\,R_i$	0.958	0.791

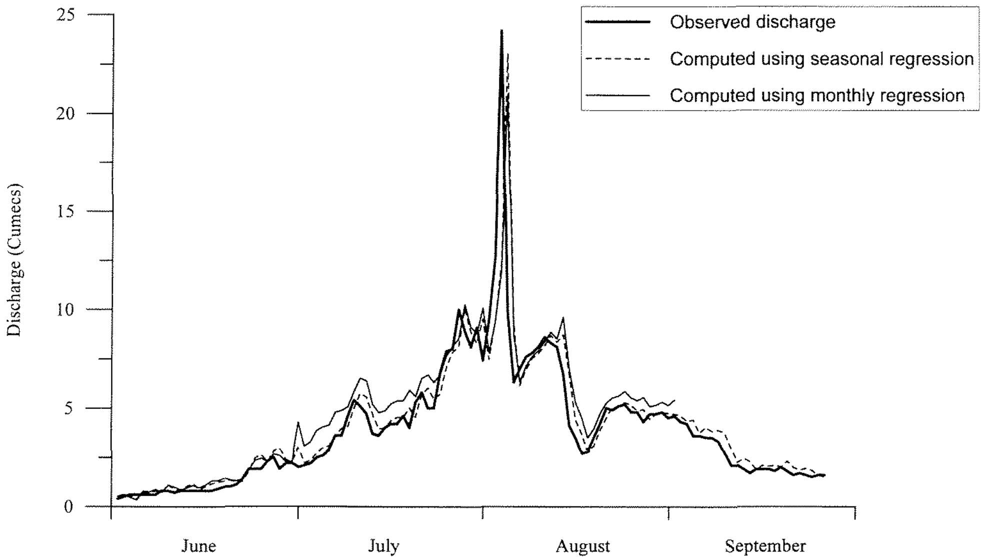

Fig. 4 Observed and forecast discharge for the Dokriani Glacier basin for the ablation period of 1997.

The regression equations developed were used to forecast daily streamflow for the summer months of an independent year (1997). The forecast was made using both monthly and seasonal regression equations. In the former case, streamflow was forecast using a different regression equation for each month. In the latter case, only one regression equation (seasonal) was used for streamflow forecasting for all months. However, it should be pointed out that the seasonal regression equation was developed using the data for June–August, but the same equation was also used to forecast the flow for September and it gave a very good forecast for this month also. A comparison of the observed daily streamflow using monthly and seasonal regression equations is given in Fig. 4. The coefficient of determination, R^2 (Nash & Sutcliffe, 1970) was determined for each case. It was found that, using monthly regression equations and a seasonal regression equation, the value of R^2 obtained is the same, i.e. 0.66 for the period June–August. When the period is extended to include September, using seasonal regression, the value of R^2 is increased to 0.68. Climatic conditions for a single month have large variations over the years and, hence, the relationship developed for the records of a particular month over the years may result in an average value for the regression coefficient. Applications of such relationships to forecast the flow for an independent year show much variation between the forecast value and observed flows. However, consideration of the time series of the variables for the two different seasons provides a regression equation which gives less variation between forecast and observed streamflow values.

CONCLUSIONS

Discharge autocorrelation, and correlations between discharge and temperature, and discharge and precipitation are determined for Dokriani Glacier basin for each summer month separately and for the melt season as a whole. The seasonal distribution of discharge autocorrelation suggests that, although a good autocorrelation exists for all the considered time lags, maximum autocorrelation is observed with the previous day's discharge (Q_{i-1}) for all months and the whole season. The results show that discharge for a particular day is very much dependent on the previous day's discharge. Thus, for the forecasting of discharge from the glacierized basin for a particular day, the previous day's discharge becomes a significant predictor. The high discharge autocorrelation throughout the melt season indicates the dominance of storage characteristics on the response of runoff from the glacierized basin. Discharge autocorrelation decreases with an increase in the lag period of discharge both on a monthly and a seasonal basis.

Correlations varied from month to month because of changes in weather conditions and physical characteristics of the glacier. The occurrence of higher rainfall in July and August reduces the discharge–temperature correlation, but increases the discharge–precipitation correlation. Discharge–temperature correlations were at a maximum in June and September. Occurrence of lower rainfall, a systematic melting environment and stronger storage characteristics are responsible for higher correlations for these months. However, a better correlation between discharge and temperature is expected for the highly glacierized basin throughout the melt period, but this was not the case for the Dokriani Glacier basin. In July and August, a variability in discharge is caused by higher rainfall and its fast effect on streamflow. This results in a better correlation between discharge and precipitation for July and August compared with June and September. A reduction in this correlation for September may be due to the occurrence of precipitation as rainfall in the lower part of glacier basin and as snowfall in the upper reaches. In general, the maximum correlation is found with the rainfall of the same day (R_i) for the seasonal series, suggesting the maximum contribution of rainfall to runoff on the same day. Multiple linear regression equations developed for the Dokriani Glacier basin separately for each month and for the whole melt season were used to compute the streamflow for an independent year (1997). The results show that the seasonal regression equation provided better results than the monthly regression equations.

A comparison of correlations between the same parameters for the Dokriani Glacier basin in the Himalayas and the Z'mutt Glacier basin in the Alps indicates that, for both basins, the maximum discharge autocorrelation was obtained with Q_{i-1} throughout the melt period (i.e. discharge from the highly glacierized basins is very much dependent on the previous day's discharge). A similar decrease in the trend of discharge autocorrelation with an increase in time lag is observed for both glacier basins. A good correlation between discharge and temperature is observed for the Z'mutt Glacier basin for the whole melt period, while, for the Dokriani Glacier basin, it is good for the beginning and end of the ablation season. The runoff delaying behaviour of the Dokriani Glacier basin is more prominent than that of the Z'mutt Glacier basin at the beginning of the melt season. The storage characteristics of the Dokriani Glacier are reduced at the end of the ablation season, while for the Z'mutt Glacier, they remain dominant during this period. In general, for both glacier basins, the maximum correlation is found with the same day precipitation (R_i).

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