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DEVELOPMENT OF RELATIONSHIP BETWEEN GLACIER MELT RUNOFF AND METEOROLOGICAL PARAMETERS

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Abstract

In order to assess the predictive significance of the meteorological parameters to forecast the discharge for a high altitude glacierized basin, correlations have been determined between mean daily discharge and precipitation and temperature with a time lag of 0 to 3 days. Dokriani glacier basin located in the Garhwal Himalayas is considered for this purpose. 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. Discharge-auto correlations are also attempted. Meteorological data used were collected by establishing a standard meteorological observatory at an altitude of about 4000m near the snout. In order to get discharge data from the study basin, an automatic water level recorder was installed at the gauging site established just very close to the snout of glacier. Continuous records of discharge were collected for the summer period when intensive melting takes place. The data collected for summer period during last three years (1995-1997) was used for the present analysis.

During the ablation period, the relations between the glacier melt water yield and meteorological parameters are not stationary. Therefore, correlation and auto-correlations have been developed both for monthly and seasonal basis for different years. Discharge auto-correlation was found to be very high for each month and for a season as a whole. It suggests a strong storage and drainage characteristic of the glacier located in the study basin which results in a delayed response of the input available at the glacier surface either in the form of rain or melt water to the runoff at the outlet of the glacier. For different months and seasons, changes in the correlations between discharge and temperature, discharge and rain with different time lags are noticed. Variation in physical features of glacier with time, weather conditions, rainfall and its distribution over the basin have attributed for the changes in correlations. Multiple linear regression equations are developed using discharge as dependent and temperature with lag 0 and 1 day and rainfall with lag 0 and 1 day as independent variables. To arrive at statistical significance of the independent variables in the simple regression equations, stepwise regression approach was used.

1.0 INTRODUCTION

In high mountain basins runoff is derived from various sources like melt water from snow and glaciers in the high altitude elevation zones, melt water and rainfall in the middle to high elevation zones and rainfall in middle to low altitude zones. Thus mountain streams contain mixture of melt water, rainfall and baseflow emanating from ground water. During the summer months, melt water from snow and ice becomes one of the important sources of runoff for mountain streams. The Indus, Ganges and Brahamputra river system, which receive a substantial amount of melt water from the Himalayas, are considered as the life line of the Indian sub-continent. Majority of the rivers originating from Himalayas have their upper catchment in the snow covered areas and flow through steep mountains. Sometimes combination of melt water with rainfall-runoff in the lower part of the mountains generate floods. The storage of precipitation in the form of snow and glaciers in the mountains over a long period provide a large amount of water which regulate the distribution of the river flow in such a way that Himalayan rivers become perennial.

Accurate forecasting of total availability of water and its distribution in time is considered very essential for the management of water resources. Flood control, reservoir operation, agriculture planning, and hydroelectric production are directly related to the management of water resources. A better understanding of glacier melt and drainage processes, availability of required data and analysis technology are the necessary tools in modern predictive techniques. In some countries where snow data are collected through snow surveys, the forecasting of total volume is very satisfactory. For example, in the western Canada prediction of total water availability in the major rivers several months before the melting season i.e. summer months runoff is predicted in spring time. But in the high mountain areas like Himalayas and Tien Shan where such data are not available at all due to various practical reasons, forecasting of total water stored in the basin and its distribution in the form of melt runoff is a very difficult task. Prediction of streamflow from the high mountain areas, where good rainfall occurs in addition to snow and glaciers, becomes very complex. Accuracy of glacier melt runoff forecast depends on the quality of forecasting of meteorological variables. Summer flows deviation from long-term mean is found very helpful in the management of water resources in these regions.

The time-scale considered for forecasting of streamflow is very important. It is related with appropriate duration of forecasting of meteorological variables used in the glacier melt forecasting models. For short-term forecasting of glacier melt runoff, the forecasting interval about length of flow of the melt water from those areas of glacier which contribute most to the daily variation in flow, is considered appropriate. In the alpine glaciers this variation is up to few hours (Lang and Dayer, 1985). The scale of hydropower development also determines the time-scales of glacier melt runoff forecast from a basin. For the countries like Norway and Switzerland, where most of the hydro-electric power is produced by installing small-scale hydropower schemes near the source of snow and ice melt, the forecast on a short-time intervals (hours and days) becomes necessary for efficient operation of these plants. Information on the diurnal fluctuations in the glacier melt runoff needed for the small-scales schemes is obtained by short-term forecasts. Large basin, like the Columbia River basin, with large-scale hydropower generation schemes have enough artificial regulating capacity in reservoirs and, therefore, forecasting of snow and ice melt runoff on daily and seasonal time scales is required to optimize the power production. Forecasting of total water availability for the summer period is considered more useful for hydropower and irrigation usage. 14 hydropower schemes on the main stream of Columbia River are fed by glaciers generating about 6700 kWh annually (Power, 1985, IAHS 149, p.59+). In general a single model does not suit to forecast the streamflow at short intervals (hours/days) and long intervals (weeks /months/seasons)

In the context to India, estimation of the volume of water draining out from the snow and glaciers is needed for assessment and management of Himalayan water resources. Planning of new multipurpose projects on the Himalayan rivers in the country further emphasizes the need for reliable estimate of snow and glacier melt runoff. Limited attempts have been made to assess this contribution in these rivers in detail. Only few hydrological studies are carried out for limited glaciers in the Himalayan region. Thus hydrological data base is very poor for Himalayan glaciers. There is need to establish a data base on the glaciers which may include glacier covered area, runoff, sediment, temperature and other meteorological data in the glaciated regions. Runoff data are required near the snout of the glacier. Application of remote sensing can be made to estimate the glaciated area. In recent years, several projects on the glaciers in the different parts of Himalayas are being executed and attempts are being made to generate a data base on the Himalayan glaciers.

2.0 CHARACTERISTICS OF THE DOKRIANI GLACIER AND ITS BASIN

The Dokriani glacier is a valley type glacier located in Garhwal region of Himalayas. This glacier lies between latitudes 31°49' to 31°52' N and Longitudes 78°47' to 78°51' E. It is situated about 30 km ENE of Bhukki. It originates in the vicinity of Janoli (6633m) and Draupadi ka Danda (5716m) peaks. The melt stream originating from Dokriani glacier is known as Din Gad. It follows a narrow valley and meets Bhagirathi river at Bhukki. 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 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. Area-elevation curves of the whole Dokriani basin and Dokriani glacier are shown in Figure 1. Further altitudinal distribution of basin area and glacier area in the basin is shown in Figure 2. It can be noticed that major part of the glacier is concentrated above 5000m in the basin. The altitudinal distribution of the glaciated area as percentage of total glacier area shows that maximum glacier area (12.86%) lies between altitude range from 5000-5100m, followed by glacier area (12.44%) in the 5100-5200m (Figure 3). In the lower part of the basin, glacier free area is higher than the glaciated area, but upper part of the basin is almost fully occupied by the glacier.

The snout of glacier is situated at an elevation of about 4000 m and covered by huge boulders and debris. The lower portion of the glacier is almost covered by debris. The material of these moraines has been derived from the side of valley mainly by frosting. This glacier is bounded by two large lateral moraines which are about 200 m in height. Besides these two lateral moraines, there are several other lateral moraines observed at different altitude. These different levels of moraines indicate the past extension of the glacier. The remnants of terminal moraines can be observed up to 2 km downstream of Gujar hut which is about 4 km downstream of snout. These are partly covered by grass. The middle part of the glacier is highly fractured and consists of crevasses, moulins, glacier table and ground moraines. The crevasses are found mainly transverse type which are wide and long. Sometimes longitudinal crevasses are also seen along the sides of the glacier.

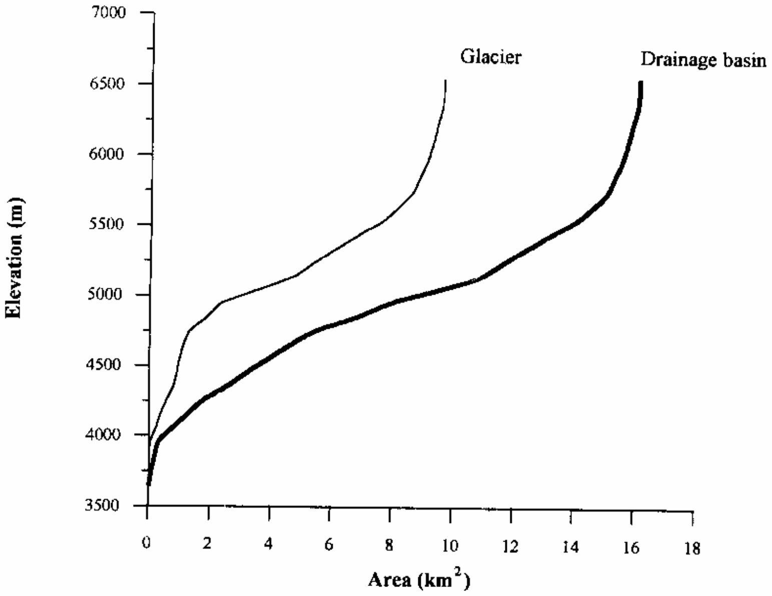

Figure 1: Altitude-area distribution of Dokriani Glacier and its drainage basin

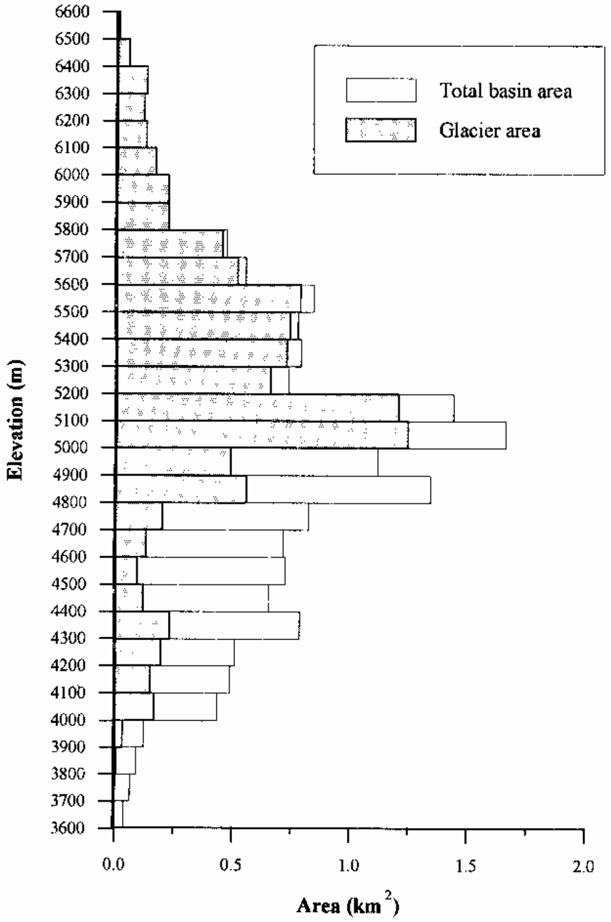

Figure 2: Altitude-area distribution of Dokriani Glacier and its drainage basin.

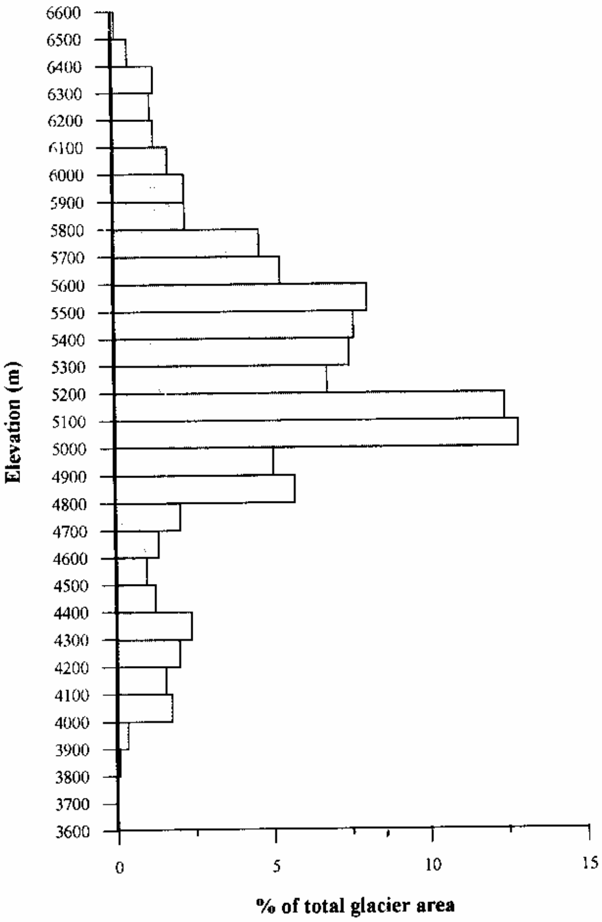

Figure 3: Altitudinal distribution of Dokriani Glacier area as percentage of total area of glacier

There is about 25 km long foot trek to approach the Dokriani glacier. This trek starts from a Bhukki village and passes through thick and dense forest cover. The trek is very difficult one and under rainy conditions it becomes very slippery and risky as well. In general, one night halt is made in between to reach the glacier base camp. The snout of the glacier is about 1 km from the base camp.

2.1 Establishment of Meteorological Observatory

A standard hydrometeorological observatory was set up at about 4000m altitude. This observatory is equipped with the following meteorological instruments.

- Ordinary and self recording raingauge
- Evaporimeter
- Thermograph
- Hygrograph
- Maximum & minimum thermometer
- Dry & wet bulb thermometer
- Anemometer
- Wind vane
- Sunshine recorder

Meteorological observations were made at 0830 hours and 1730 hours. For rainfall observations both ordinary raingauge and self recording raingauge (SRRG) were used. Continuous recording of rain by SRRG provided rainfall intensity. A bimetallic thermograph was used for continuous recording of temperature. Maximum and minimum thermometers were used for observing maximum and minimum temperatures. Hair hygrograph was used for continuous recording of humidity, in addition to this dry bulb and wet bulb temperature observed at 0830 hours and 1730 hours were also used for calculating the humidity. Sunshine duration was observed with the help of shine recorder. U.S. class A pan evaporimeter was used for the measurement of evaporation. Wind observations were made at 0830 hours and 1730 hours and daily average wind velocity was calculated. In 1995 observatory was equipped by only ordinary raingauge and maximum and minimum thermometers, but in 1996 the observatory was strengthened by installing additional equipments as mentioned above.

2.2 Establishment of gauging site

Selection and establishment of the gauging site and observations of streamflow for mountainous rivers are difficult in comparison to the rivers flowing in the plain areas. The gauging at Dokriani glacier melt stream was selected in 1992 after a survey of the melt stream starting from snout to about 2 km downstream was made. The selected gauging site was about 800 m downstream of the snout. The flow was not very much turbulent at this site and most of the boulders were removed from the channel. The site was about 1 km upstream of the confluence of the several small nallahs joining the main stream from southern side. The float travelling length of not more than 8 m was available at the gauging site. A temporary wooden bridge was made over the glacier melt stream. The cross-section area of the channel was determined with the help of this bridge. A graduated staff gauge was installed at the left bank of the stream for observations of water level fluctuations in the melt stream. However, limited hydrological observations on this site were made in 1992 and 1994, but extensive streamflow observations at the glacier melt stream were made since 1995. A stilling well was constructed at the gauging site and an automatic water level recorder was installed for continuous monitoring of the flow in 1995. Daily charts were used for recording the water level fluctuations in the stream. The chart was changed daily at 0900 hours. Hourly manual observations water level were also made during day time.

Velocity-area method was used to estimate flow in the melt stream. Wooden floats were used to compute the velocity of flow and time travelled by the floats was determined with the help of stop watch. For accuracy in velocity the readings were repeated at least three times and an average value was adopted for further computations. In addition to the use of floats for velocity determination a propeller type pigmy current meter was also used for the measurement of velocity. Stage-discharge relationship was established for the gauging site. Later this relationship was used for determining flow only by recording the stage. However, time to time velocity was also ascertained for verification of flow computed using established relationship. In order to assess the transport of suspended sediment through glacier melt stream, every day two samples of suspended sediment were collected and at the same time flow was also measured.

3.0 MELTING OF A GLACIER

As the summer season advances, the seasonal snow deposited in the high altitude regions disappears, except on glaciers, and glacier melt becomes more significant. Estimation of glacier melt runoff is relatively more complex than snow melt runoff because some additional processes are involved in the melting of glaciers. For example, internal movement of glacier ice and sliding of glacier body also produce significant amount of melt runoff from the glaciers. Such incidents are very uncommon in case of snowpack melting. Moreover storage and drainage characteristics are also complex than snowpacks. Evidently, computation of glacier melt runoff requires an understanding of two separate processes namely melt water production and the drainage processes within the glacier. Melting of glacier occurs on surface and base of a glacier. The surface melting is governed by the solar radiation and turbulent energy exchange processes while the basal melting is caused by the energy supplied from the bedrock beneath a glacier. As such snowpack energy balance approach is straight way applicable to the glacier surface using glacier albedo value. Surface melting is seasonal and reach a peak usually in late summer, whereas basal melting fluctuates less markedly and generally exist throughout the entire year. The amount of basal melting varies from glacier to glacier depending upon the geothermal conditions beneath a glacier. In the winter the flow is derived mostly from the basal sources while in summer it is due to surface melting. To estimate basal melt runoff from a glacier, temperature profile of the bedrock and lower part of glacier is required. Additional melting due to internal movement of glacier and glacier sliding is possible when the glacier base is at the pressure melting point. Physical characteristics of a glacier also affect the melt rate, however, it is included in the radiation balance. This leads to different melt rates for valley glaciers and ice sheets. In the case of valley glaciers the long-wave radiation from the unglaciated surrounding slopes enhance the radiation balance at the glacier surface causing higher rate of melt. A good network of micrometeorological instrumentation covering both ablation and accumulation areas glacier surface is needed to extrapolate the point inferences obtained from the middle of a glacier to the general relation of that glacier to its whole environment.

The energy supplied to the glacier through rainfall are not much significant when the glacier is at 0°C, the rain fallen on the glacier surface does not freeze and contribute to melt water drained from the glacier. The rain induced peaks can be noticed almost instantly in the melt water stream emerging out from the glacier, if the glacier is of small size and most of the ice is exposed to rain. On the other hand, snowfall during melt season reduces ablation and a reduction in the overall discharge may be observed lasting several days until the new fallen snow is not completely melted away from the ablation area.

Although insolation reaches a peak in June in the northern Hemisphere, the average albedo of snow covered glacier surface is then relatively high causing a low or moderate melt rate. In July and August, insolation is slightly reduced but the mean albedo of the glacier surface is dropped markedly because old dirty ice is exposed, resulting in higher melt rate than in June (Singh et al., 1997). A year of heavy snow accumulation results in a layer of high albedo snow persisting longer into the summer season and curtailing melt. A dry winter or a hot sunny summer results in increased melt. Thus production of melt water from glaciers tends to compensate for unusually wet or dry, or hot or cold years- a natural regulation of streamflow.

3.1 Effect of debris on glacier melting

One of the very common features of all large glaciers in the Nepal Himalayas, western Himalayas, and Karakoram is that they are covered with debris in their ablation area (Moribayashi and Higuchi, 1977; Fujii and Higuchi, 1977; Nakawo, 1979; Fushimi et al., 1980; Rana et al., 1996). In some cases, there is no debris-free area in the ablation zone of the glaciers in those regions. These glaciers are classified as debris covered glaciers. It is also well established that surface melting of a glacier is influenced by the presence of debris on the glacier body because radiation balance is affected, which inturn influences the melt rate. Further, a change in the thickness of a debris layer over the glacier affects markedly the melt rate of glacier. For example, Zalikhanov (1969) measured that under the layer of moraine of 2-3 cm thickness, 342 mm ice melted; under the layer of 10-12 cm thickness only 261 mm ice melted; and under the layer of 20-25 cm, 189 mm ice melted. Therefore, it is essential to understand the effect of debris cover on ablation of glacier ice for predicting the water supply from such mountain glaciers. Usually, effect of debris cover on the melting of glaciers is not included in the modelling of glacier melt runoff.

There are two difficulties in estimating the mean value of ablation under a debris layer extending over a wide area: (i) direct determination of the thermal resistance of the layer in the field which is one of the essential parameters for estimation of ablation, (ii) detailed information on meteorological variables is necessary for the estimation. Nakawo and Young (1982) have shown that the glacier ablation under a debris layer can be estimated from surface temperature and meteorological variables. They have stressed for the necessity of reliable surface temperature data and temperature profile in the debris layer for better results.

3.2 Effective and critical debris thickness

Several field experiments have been conducted to assess the effect of debris on melting rate of glacier. It is observed that a thin debris layer accelerates the ablation rate of the underlying ice, whereas a thick layer retards it as compared with that of natural ice surface (Ostrem, 1959; Fujii, 1977). There is a significant difference in mean seasonal ablation rates between sites of varying debris thickness and also in ablation rates at the same site over time (Mattson et al., 1989). The debris thickness at the which maximum ablation occurs is known as "effective debris thickness". There is a "critical thickness", h_c is defined as the thickness of debris layer at which the ablation rate for debris covered glacier ice is the same as for debris-free ice. It is considered convenient to express the depth of debris layer, h in terms of a thermal resistance R. The critical thermal resistance, R_c corresponding to h_c may be given by the following equation (Nakawo and Takahashi, 1982):

$$R_c = \frac{G(\alpha_0 - \alpha)}{k_0[(k_0 + k_r)\,T_a - G(1 - \alpha_0)]}$$

where, G is the global radiation flux (W m^{-2}), α is the albedo of debris layer, α_0 is the albedo of debris-free layer, k_0 is the degree-day factor for debris-free ice (W m^{-2}°C^{-1}), $k_r = 4\sigma\,(273)^3 = 4.615$ W $m^{-2}K^{-1}$, and T_a is the mean air temperature in °C.

The value of R_c can be determined directly by an experiment in which ablation rates are measured under debris layers with different thickness i.e. different thermal resistance. A comparison of the value of R_c estimated by above described relationship and from direct method has shown reasonable agreement.

Rana et al. (1996) evaluated glacier ablation under debris cover at 30 sites in the ablation area of Lirung Glacier in Nepal. The debris thickness on the experimental plots varied from 0 to 13 cm. The sites were artificially prepared after cleaning away the big bounders from the experimental plots. The meteorological information was collected during the ablation measurements. The albedo of the debris layer and clean ice was 0.11 and 0.40, respectively. Similar to previous observations, it was observed that an increase in the thickness of the debris layer on the clean ice surface initially increased the ablation rate, but it was decreased after reaching the critical debris thickness. At sites with thinner debris thickness than the "effective thickness", the reflectivity of the surface is high thus less incoming energy is used for melting. At higher debris thickness, the energy is used for increasing the temperature of debris material and then conducting for ice melting. The critical thickness and effective ablation varied from day to day depending on the total energy available for melting. The effective debris thickness was determined to be 2.6 cm which provided maximum ablation of 4.5 cm/day. The critical debris thickness at which ablation rate is same as from clean ice is about 9 cm. During the night time, a constant ablation was observed for all thicknesses of the debris. The surface temperature of debris layer increased as debris thickness increased and surface temperature data showed strong diurnal cycle of temperature change at the surface. The individual heat budget components show that radiation heat flux is the main energy source for glacier melt under debris layer. These observations were made on cloudy and humid days. To estimate the mean summer ablation, such observations are needed for clear weather conditions. For the modelling of the melt under debris layer, the portion of the energy transformed into a state of storage in debris material should be taken account. More than 80% of energy received at the surface of 40 cm thick debris layer on a sunny day could be transformed into storage (Mattson and Gardner, 1991).

Khodakov (1978) suggested the following equation for computing melting under debris cover,

$$M_d = \left[\frac{1.3}{1 + 0.2h} \right] \cdot M_0$$

where h is the thickness of debris cover in cm. For central Asia, the following empirical relationship is suggested for estimation of h,

$$h = 80s + 2.9$$

where s is the ratio of the debris covered area to total glacier area.

3.3 Some temperature based empirical relationship

Air temperature above the glacier surface is mostly related with glacier melt runoff either on the daily basis or seasonal basis. Because glacier area does not change as melt season advances, therefore, relationships are least attempted taking area of a glacier into account. Few relationships developed by various investigators for different regions for daily or seasonal basis are produced here. An empirical relation between specific ice melt to mean daily temperature was derived by Young (1980) for Peyto glacier, Alberta, Canada and has the following form:

$$M_r = 1.56 + 5.338\ T_m$$

where M_r is specific melt rate (mm/d), T_m is mean daily temperature (°C). Specific melt per day was calculated for snow free areas of ice and firn for points on a square grid having grid interval of 100m. Environmental lapse rate was used to determine temperature at each point and then applying the above described equation. Based on melt measurements at stake locations, melt in firn area was estimated to be 85% of ice melt for the same elevation. Moreover, it was also assumed that all water derived from ice melt passed the stream gauge the same day. Only half of the melt from the firn area contributed to stream flow on the same day as it was produced. The other half was added to half the calculated firn melt of the next day. It is considered that these assumptions are very reasonable for a glacier the size of Peyto Glacier (13.4 km^2), however, the lags might have to be modified for much larger glaciers.

To develop correlation between different climatological parameters and the runoff on the daily basis from the Nigradsbreen glacier basin, Norway, Lundquist (1982) selected the following climatological parameters for glacial melt computation: precipitation, air temperature, wind speed and humidity. In the first efforts, however, a poor correlation was found between wind speed and humidity and the observed runoff. In the final computations the use of only precipitation and temperature measured at two sites was made and it had very much resemblance with simple degree-day method. The theory that air temperature is a good lumped measured of most of the parameters of importance for ice melt on a basin scales, was also confirmed. As the snow cover shrinked on the glacier surface, the degree day factor for snow was substituted by one for ice (of the order of two to three times larger) to represent the different albedo of ice. Because of an obvious seasonal variation in the value of degree-day factor, a simple cosine transformation was introduced and final melt equation was given as

$$M = D_f \left[1 - \cos \left(2 - \frac{\pi d}{365} \right)^n (T - T_0) \right]$$

where,

M meltwater volume (mm/time step)

D_f degree-day factor (mm/(°C. time step)).

d number of the day counted from 1st January

T actual air temperature

T_0 air temperature at which melting begins

n exponential with value around 2.

The average seasonal melting at the height of equilibrium line M_{equ}(mm) was estimated by the following empirical formula (Krenke, 1973,75, 82)

$$M_{equ} = 1.33 \, (T_{s\,equ} + 9.66)^{2.85}$$

For long-term average seasonal melting it is reduced to

$$M_{equ} = (9.5 + T_{s\ equ})^3$$

where $T_{s\ equ}$ is the mean summer temperature at the equilibrium line at height of 2 m over the glacier surface for summer period (June, July and August) in °C. The mean $T_{s\ equ}$ summer temperature at the equilibrium line is determined with the help of vertical temperature gradient averaged for summer and nearest weather station summer temperature data. Total average ablation on the glacier is considered equal to total ablation at the altitude of equilibrium line. The altitude of equilibrium line is determined from the snowline by terrestrial, airborne, or space observations. This equation has been used in USSR and for majority of glacierized regions of the world in the World Atlas of Snow and Ice Resources. This equation was modified by Khodakov (1978) by including a radiation term in the above equation

$$M_{equ} = (T_{s\ equ} + 1.3\sqrt{R_s} + 4.0)^3$$

where R_s is the short-wave radiation balance for June to August in kcal/cm^2. On the basis of field data it is assumed that

$$R_s = 0.32\ R$$

where R is the total radiation for a summer at the stations situated in non-glacierized areas, varying over the territory of the USSR from 32-62 kcal/cm^2. In the above equation the empirical coefficient of 0.32 accounts for the albedo of the melting firn (0.6), the increase of cloudiness and total radiation of clear sky with altitude.

3.4 Correlations and regression approach

During the ablation period, the relations between the glacier melt water yield and meteorological parameters are not stationary. One of the important reason for such variability is the changes in the storage and drainage characteristics of the glacier with time. Consequently, hydrological parameters of a glacier change with time. Lang (1973) listed such parameters in the following form:

(a) Parameters influencing the melt water yield

(i) Area and distribution of snow cover and glacier ice
(ii) Albedo of snow and ice areas
(iii) An increase in the sensible heat exchange to the glacier surface because of exposition of glacier ice surface due to depletion of snow cover

(b) Parameters influencing the runoff processes:

(i) Runoff delay by the snow cover
(ii) Change in the drainage system of glacier during the ablation season due to action of runoff .

In order to develop a short-term forecast model for a glacierized basin, Lang (1973), Jensen and Lang (1973), and Lang and Dayer (1985) attempted to establish statistical correlations between discharge and meteorological variables including air temperature, T, global radiation, G, actual vapour pressure, e and precipitation, P. Such studies demonstrate the changes in relationship between discharge and meteorological elements when specific seasonal conditions in a glacierized drainage basin change. During the ablation season, the melt rate and hydrological response of basin changes with time due to variations in the extent of snow cover, snow depths, albedo, physical properties of snow and ice and drainage system. Therefore, it is not appropriate to consider the data of whole melt period to establish the correlations. Very accurate assessment of variability in parameters with time is not possible. Assuming that hydrological processes do not change very significantly for a period of few weeks, the ablation season was subdivided into 3 time intervals namely "begin", "summer" and "end" period which on average represented in the following conditions:

Interval 1 (Beginning): representing initiation of melt, main season of snow melt, high percentage of snow coverage and high albedo (about June to July).

Interval 2 (Summer) : representing ablation season of glaciers with maximum discharge, potential melt water supply, improved drainage network (about July and August)

Interval 3 (End): representing end of ablation season, reduced ablation due to low melting conditions, glaciers partly covered with fresh snow (August and September)

The form of precipitation in the basin influences the relationship between discharge and precipitation. One can have a positive or negative effect of precipitation on runoff. The precipitation periods usually show a negative correlation with discharge. In fact, lower parts of drainage area experience precipitation in the form of rain which can compensate for the decrease in melt due to low radiation. In the upper parts of the basin gets solid precipitation which increases the albedo. Reduction of melt rate due to decreased solar radiation during precipitation period and high albedo of freshly fallen snow primarily attribute to the negative correlation between discharge and precipitation. This causes the negative correlation between discharge and precipitation with increasing lag. However under rain events in the basin are responsible to show the positive correlation. Variations in auto-correlation functions of discharges with intervals also suggest changes in the drainage characteristics of glacier.

In order to determine the predictive significance of different variables, Lang and Dayer (1985) used multiple regression equations with time lag 0 to -5 days. Partial correlation coefficients were also determined. Antecedents runoff (r=0.92) is found a better predictor than the air temperature (r=0.84). Role of antecedent runoff in short interval forecasts smaller basins becomes very important due to less runoff delay from such basins. For the larger basins with prominent delaying characteristics the role of antecedent runoff relatively may not be so important.

To develop statistical relationship between glacier melt runoff and different meteorological parameters and/or their products are considered. An statistical analysis in which temperature (T), precipitation (P) and wind velocity (V) were used as independent variables was made by Ostrem (1972). After a long series of experiments to combine variable, it was concluded that best results were obtained when certain products of temperature and precipitation, another variable would be the product of temperature and wind speed, and in most cases, the temperature itself would be the third variables. The general form of the resulting formula was

$$Q = K + K_1(TV) + K_2(TP) + K_3T$$

where Q is discharge for the next day. However, if each of the meteorological parameters are calculated as running means for two or three days depending upon the size of the glacier, it was possible to predict water discharge approximately two days in advance. This relationship was tested by applying it to previous years observations.

Lang (1980) developed a multi-linear regression equation for prediction of glacier melt runoff. The model operates using forecasted input variables to estimate runoff over time periods of several hours to several days. This model was applied for Alteshgletscher, Switzerland. The area of glacier and drainage basin is 130.5 km^2 and 194.7 km^2 respectively. The altitude range for the glacier is 1446-4195m. The independent variables considered in multi-linear regression equation were air temperature,T, incoming solar radiation, S and precipitation, P. To take into account the storage characteristics of the glacier and non-glacier areas, the runoff terms from previous time steps were also used as independent variables in equation. The form of the multiple regression equation is given as follows (Lang personal communication, 1983):

$$\begin{aligned} R_t = {} & b_0 + b_1R_{t-1} + b_2R_{t-2} + b_3R_{t-3} + b_4T_t \\ & + b_5(T_{t-1} + T_{t-2}) + b_6S_t + b_7(S_{t-1} + S_{t-2}) \\ & + b_8(P.T)_t + b_9(P.T)_{t-1} + b_{10}(P.T)_{t-2} \end{aligned}$$

where R_t is discharge at time t, b_i are coefficients, t-j denotes the observations at previous time step j. Because changes in snow cover over the glacier, albedo and drainage system influences the magnitude and response of the runoff, therefore, the above equation is calibrated for three different intervals of ablation season namely, early, middle and late period. Unreliability in meteorological variables, forecasting, especially is considered a important source of error leading to discrepancy in observed and computed glacier melt runoff. Further, no objective method is found to indicate when recalibration of equation is needed. Dayer (1974) studied the changes in areal average albedo with altitude of snow line for few glaciers. For the basins in which areal average albedo is known, Lang and Dayer

(1985) suggested use of a term of net radiation, $S(1-\alpha)$ in place of S in regression of net radiation equations provides more physically meaningful structure of equation.

Precipitation falling as snow or rain determines the relation of precipitation with discharge. For example precipitation in the form of rain has positive correlation with runoff, whereas precipitation in the form of snow has negative correlation. Therefore, a product of precipitation and temperature as a combined variable rather than taking precipitation alone as a variable was considered. Another possibility may be to take precipitation only for temperatures above freezing point i.e. only liquid part of precipitation which contributes to runoff relatively faster.

4.0 RESULTS AND DISCUSSIONS

4.1 General statistics

A general statistical analysis which includes maximum, minimum, mean and standard deviation (STD) of the observed hydrological and meteorological parameters on the monthly and seasonal basis for different years is given in Table 1 to 3. For a quick comparison of statistics of various variables for different months and seasons results are compiled in Table 4. Data from June to August was used for the statistical analysis of various variables for 1995 and 1996, while for 1997 data was used from June to September. In the study region, highest rainfall is, generally, observed in the month of August followed by July. Depending upon the rainfall events, maximum discharge from the Dokriani glacier basin is observed in July or August. Variations in the mean value of discharge on the monthly basis for different years is caused by the melting conditions and rainfall occurred during that period. Period of maximum temperature varies from year to year, but usually mean temperature is higher in the month of June. Maximum sunshine hours are observed, in June and September. The months of July and August are very humid because of high rainfall during these months. Depending upon climatic conditions, evaporation varies from month to month. As expected, usually maximum evaporation is observed in the month of June. However, no significant variation is noticed in the mean monthly values of evaporation from June to September.

Table 1 General statistics of the daily air temperature, T(°C), rainfall, R(mm), and discharge, Q(cumecs) for 1995

Period	Variable	Maximum	Minimum	Mean	Standard deviation
June, 95	T	16.00	5.00	12.34	2.81
	R	30.00	0.00	5.80	8.14
	Q	7.20	2.80	5.36	1.27
July, 95	T	14.20	9.00	11.27	1.05
	R	30.20	0.00	10.37	8.92
	Q	13.00	6.30	9.38	1.77
August, 95	T	14.80	7.00	10.32	1.98
	R	41.00	0.00	13.64	10.96
	Q	10.90	5.70	8.94	1.25
June-August, 95	T	16.40	5.00	11.30	2.20
	R	41.00	0.00	9.98	9.99
	Q	13.00	2.80	7.92	2.30

Table 2 General statistics of the air temperature, T(°C); rainfall, R(mm); discharge, Q(cumecs); relative humidity, RH(%); sunshine hours, SH(hours); and evaporation, E(mm) for 1996

Period	Variable	Maximum	Minimum	Mean	Standard deviation
June, 96	T	11.00	4.20	8.78	1.85
	R	36.40	0.00	7.23	9.13
	Q	6.50	1.00	3.27	1.86
	RH	94.00	69.00	78.33	7.07
	SH	8.50	0.20	3.70	2.48
	E	3.00	0.20	0.95	0.83
July, 96	T	11.70	5.90	9.13	1.37
	R	29.10	0.00	6.03	7.93
	Q	11.20	3.20	7.47	2.30
	RH	98.00	68.00	86.81	6.76
	SH	6.10	0.00	2.44	1.96
	E	3.80	0.00	1.75	1.11
August, 96	T	11.30	5.90	8.55	1.28
	R	38.00	0.00	13.12	10.86
	Q	11.10	5.70	8.24	1.72
	RH	100.00	81.00	93.48	4.18
	SH	6.50	0.00	1.47	1.83
	E	3.20	0.00	1.12	1.11
June-August, 96	T	11.70	4.20	8.78	1.52
	R	38.70	0.00	8.88	9.82
	Q	11.20	1.00	6.36	2.93
	RH	100.00	68.00	86.29	8.68
	SH	8.50	0.00	2.52	2.25
	E	3.80	0.00	1.28	1.08

Table 3 General statistics of the air temperature,T(°C); rainfall, R(mm); discharge, Q(cumecs); relative humidity, RH(%); sunshine hours, SH(hours); and evaporation, E(mm) for 1997

Period	Variable	Maximum	Minimum	Mean	Standard deviation
June, 97	T	11.50	3.00	7.60	1.89
	R	24.00	0.00	6.12	9.13
	Q	6.50	1.00	3.27	6.04
	RH	94.00	73.00	87.20	5.76
	SH	7.20	0.00	3.38	1.97
	E	3.00	0.40	1.65	0.61
July, 97	T	12.90	8.00	10.94	1.16
	R	35.40	0.00	7.82	10.08
	Q	10.00	2.10	5.30	2.28
	RH	99.00	82.00	90.42	5.63
	SH	9.10	0.00	2.09	2.86
	E	3.90	0.10	1.73	1.07
August, 97	T	12.80	6.80	9.46	1.52
	R	58.00	0.00	9.93	13.40
	Q	24.20	2.70	6.38	3.99
	RH	98.00	90.00	94.36	2.43
	SH	8.40	0.00	2.75	2.66
	E	3.60	0.00	1.38	0.98
September, 97	T	10.30	5.80	8.30	1.22
	R	15.30	0.20	6.30	5.24
	Q	4.20	1.50	2.31	0.84
	RH	81.00	98.00	91.91	3.94
	SH	8.80	0.00	3.92	2.73
	E	3.60	0.00	1.62	0.96
June - September, 97	T	12.90	3.00	9.14	1.96
	R	58.00	0.00	7.64	9.54
	Q	24.20	0.40	3.92	3.23
	RH	99.00	73.00	90.94	5.33
	SH	9.40	0.00	3.27	2.64
	E	3.90	0.00	1.59	0.92

Table 4 General statistics of the air temperature,T(°C); rainfall, R(mm); discharge, Q(cumecs); relative humidity, RH(%); sunshine hours, SH(hours) and evaporation, E(mm) for different years

Period	Variable	1995				1996				1997			
		Max	Min	Mean	STD	Max	Min	Mean	STD	Max	Min	Mean	STD
June	T	16.00	5.00	12.34	2.81	11.00	4.20	8.78	1.85	11.50	3.00	7.60	1.89
	R	30.00	0.00	5.80	8.14	36.40	0.00	7.23	9.13	24.00	0.00	6.12	9.13
	Q	7.20	2.80	5.36	1.27	6.50	1.00	3.27	1.86	6.50	1.00	3.27	6.04
	RH	-	-	-	-	94.00	69.00	78.33	7.07	94.00	73.00	87.20	5.76
	SH	-	-	-	-	8.50	0.20	3.70	2.48	7.20	0.00	3.38	1.97
	E	-	-	-	-	3.00	0.20	0.95	0.83	3.00	0.40	1.65	0.61
July	T	14.20	9.00	9.00	1.05	11.70	5.90	9.13	1.37	12.90	8.00	10.94	1.16
	R	30.20	0.00	0.37	8.92	29.10	0.00	6.03	7.93	35.40	0.00	7.82	10.08
	Q	13.00	6.30	6.30	1.77	11.20	3.20	7.47	2.30	10.00	2.10	5.30	2.28
	RH	-	-	-	-	98.00	68.00	86.81	6.76	99.00	82.00	90.42	5.63
	SH	-	-	-	-	6.10	0.00	2.44	1.96	9.10	0.00	2.09	2.86
	E	-	-	-	-	3.80	0.00	1.75	1.11	3.90	0.10	1.73	1.07
August	T	14.80	7.00	10.32	1.98	11.30	5.90	8.55	1.28	12.80	6.80	9.46	1.52
	R	41.00	0.00	13.64	10.96	38.00	0.00	13.12	10.86	58.00	0.00	9.93	13.40
	Q	10.90	5.70	8.94	1.25	11.10	5.70	8.24	1.72	24.20	2.70	6.38	3.99
	RH	-	-	-	-	100.0	81.00	93.48	4.18	98.00	90.00	94.36	2.43
	SH	-	-	-	-	6.50	0.00	1.47	1.83	8.40	0.00	2.75	2.66
	E	-	-	-	-	3.20	0.00	1.12	1.11	3.60	0.00	1.38	0.98
September	T	-	-	-	-	-	-	-	-	10.30	5.80	8.30	1.22
	R	-	-	-	-	-	-	-	-	15.30	0.20	6.30	5.24
	Q	-	-	-	-	-	-	-	-	4.20	1.50	2.31	0.84
	RH	-	-	-	-	-	-	-	-	81.00	98.00	91.91	3.94
	SH	-	-	-	-	-	-	-	-	8.80	0.00	3.92	2.73
	E	-	-	-	-	-	-	-	-	3.60	0.00	1.62	0.96
Whole season	T	16.40	5.00	11.30	2.20	11.70	4.20	8.78	1.52	12.90	3.00	9.14	1.96
	R	41.00	0.00	9.98	9.99	38.70	0.00	8.88	9.82	58.00	0.00	7.64	9.54
	Q	13.00	2.80	7.92	2.30	11.20	1.00	6.36	2.93	24.20	0.40	3.92	3.23
	RH	-	-	-	-	100.0	68.00	86.29	8.68	99.00	73.00	90.94	5.33
	SH	-	-	-	-	8.50	0.00	2.52	2.25	9.40	0.00	3.27	2.64
	E	-	-	-	-	3.80	0.00	1.28	1.08	3.90	0.00	1.59	0.92

4.2 Discharge auto-correlation

The outflow from the glacier consists of the contribution from snow melt, ice melt, baseflow and rainfall, if any. Magnitude of snow accumulation in the preceding winter season, prevailing weather conditions in the melt season, supra, en-glacial and sub-glacial drainage pattern of glacier have an integrated effect on the runoff generated from a glacier. Because of the complex storage and drainage characteristics of the glacier, water generated due to melt on a particular day partially contribute to runoff at the snout on the same day and partially on subsequent days. Monthly distribution of discharge auto-correlation for different years shows that discharge auto-correlation varies from year to year because of changes in melting condition of the glacier, rainfall pattern and storage and drainage characteristics of the basin. As shown in Figure 4 to 9, a strong auto-correlation has been found between daily mean discharge of a day (Q_i) and discharge with a lag from 1 to 3 days (Q_{i-1}, Q_{i-2}, Q_{i-3}). Although discharge has shown good auto-correlation with all considered lags, but auto-correlation for lag 1 day (Q_{i-1}) is relatively higher for all the months and for all the years.

The discharge auto-correlation for the months of June is found to be higher than July and August for different years, suggesting that variations in discharge in the month of June are not very significant. Dominance of delaying characteristics of glacier and little contribution from rain to the streamflow in this month provide a higher discharge auto-correlation. Discharge auto-correlation was poor for June 1995 as compared with corresponding months in the other years. It may be due to climatic conditions or internal structure of the glacier. In July and August, melting from the glacier is at its maximum and rain contribution is also significant due to higher rainfall. Consequently, there is high variability in discharge during the months of July and August due to highly variable contribution from rain to total streamflow. Thus, discharge auto-correlation for July and August is lower than that for June and September. Discharge auto-correlation for the month of September was established only for the year 1997 due to availability of data for this month in 1997 only. It is understood that fair weather conditions contribute more than storage characteristics to an improved discharge auto-correlation for the month of September.

Monthly and seasonal distribution of discharge auto-correlation for different years suggests a maximum auto-correlation coefficient with previous day discharge (Q_{i-1}). Value of maximum discharge auto-correlation with Q_{i-1} varies from 0.61 to 0.97 for different months in different years, while on the seasonal basis it varies from 0.83 to 0.95 for different years. Results show that discharge for a particular day is very much dependent on the previous day discharge. Thus, for the forecasting of discharge for a particular day from the glacierized basin, previous day discharge becomes a significant predictor. Discharge auto-correlation coefficient decreases with an increase in the lag period of discharge both on monthly and seasonal basis (Figure 4 to 9). Reduction in the value of r with an increase in discharge time lag on the monthly basis is higher than that of on the seasonal basis.

4.3 Discharge - temperature correlation

Similar to discharge auto-correlation, a better correlation between discharge and temperature is found in the months of June (Figure 10). In this month, most of the contribution to runoff is from the snow melt (not from ice melt) because glacier body is fully covered with snow at this time and temperature is responsible for the melting of snow. Storage characteristics of the glacier responsible for delaying response of a glacier, have strong effect on runoff generation in the beginning of melting season. Further, fair weather conditions exist for most of time in this months resulting in lower rainfall during this period. Thus, rainfall contribution to the total streamflow is less as compared with snow melt runoff in the month of June. It is understood that a combination of systematic melting conditions and existence of snow over the glacier ice body makes storage character stronger. These factors attribute to an improved discharge auto-correlation for the month of June. Discharge and temperature correlation for June 1995 is different than other two years. It appears that delaying response of the glacier dominates due to storage characteristics in June 1995 than in the same month of 1996 and 1997. Distribution of correlation coefficient for June for different years shows that correlation between discharge and temperature improves with an increase in time lag of temperature from 0 to 3 days for this month. Maximum value of correlation, r=0.78, 0.83, 0.81, is found with T_{i-3}, for 1995,1996 and 1997, respectively.

In the middle of glacier melt season (July and August), contribution from both snow covered area and ice covered area reaches to the outlet of the basin. Melting rate of snow

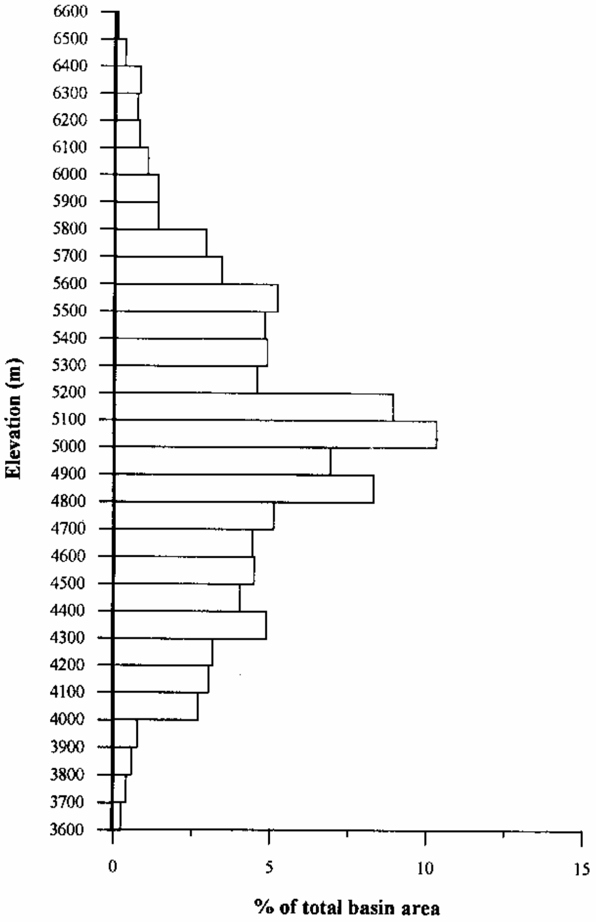

Figure 4: Altitudinal distribution of basin area as percentage of total basin area

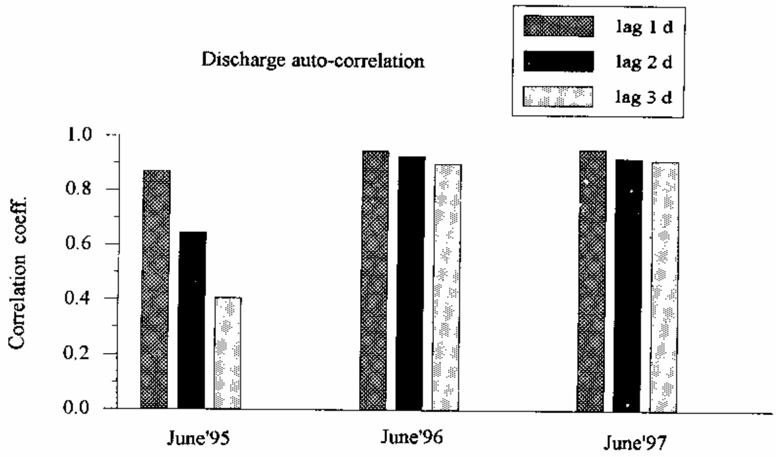

Figure 5: **Discharge auto-correlation coefficient between daily mean discharge and discharge as a function of 1 to 3 days lag for the drainage basin of Dokriani glacier for the month of June for different years.**

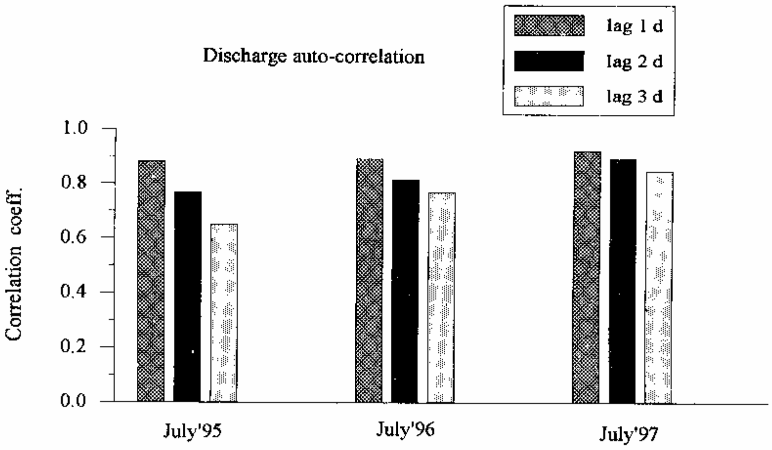

Figure 6: Discharge auto-correlation coefficient between daily mean discharge and discharge as a function of 1 to 3 days lag for the drainage basin of Dokriani glacier for the month of July for different years.

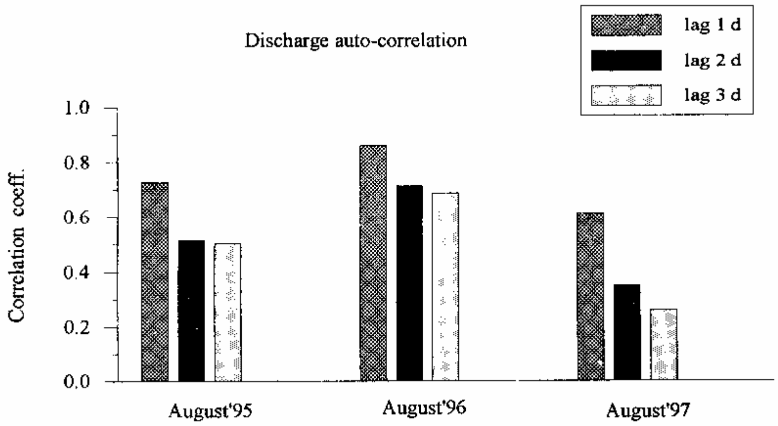

Figure 7: Discharge auto-correlation coefficient between daily mean discharge and discharge as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of August for different years.

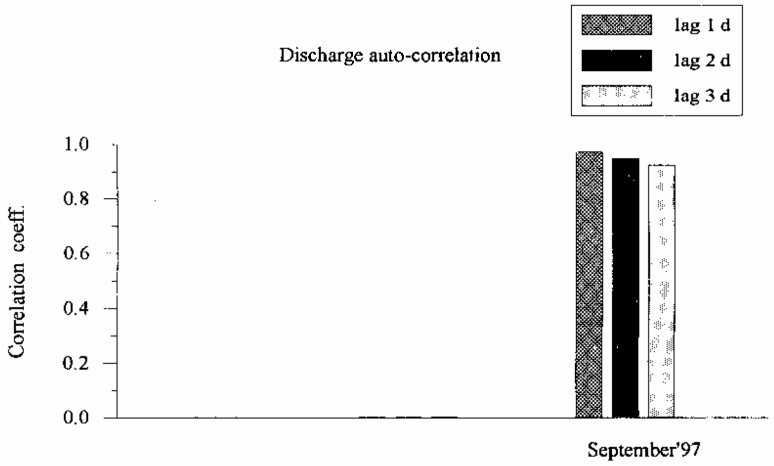

Figure 8: Discharge auto-correlation coefficient between daily mean discharge and discharge as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of September for 1997

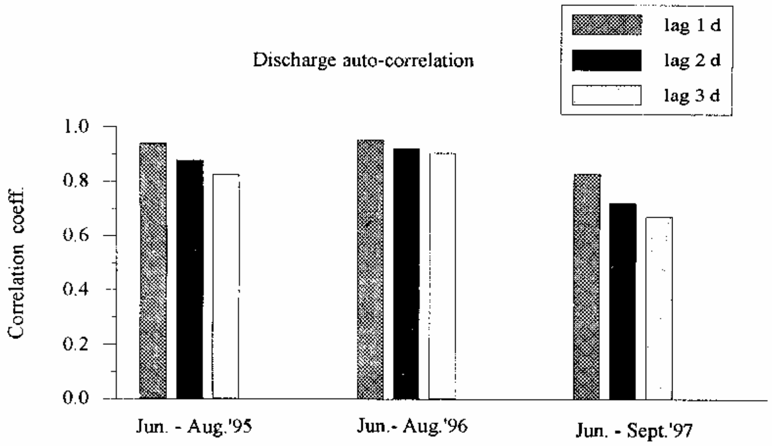

Figure 9: **Discharge auto-correlation coefficient between daily mean discharge and discharge as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the melt season for different years.**

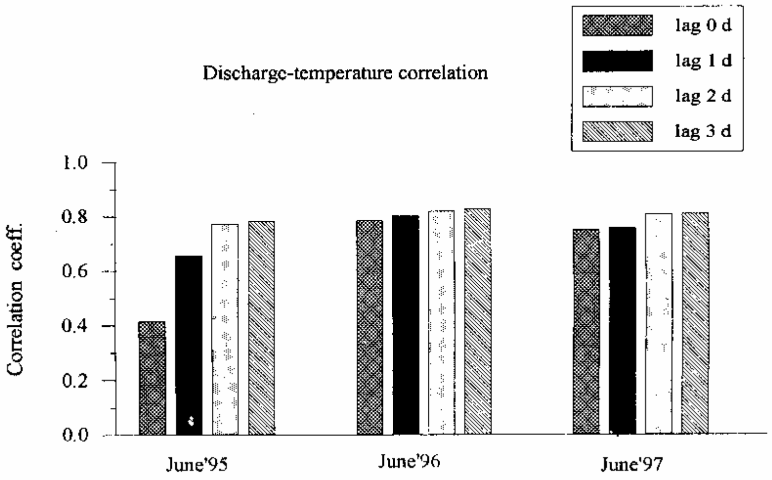

Figure 10: **Correlation coefficient between daily mean discharge and air temperature as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of June for different years.**

and ice are different for a particular temperature. Further, lower and middle part of the glacier is partly covered with debris which has totally different rates of melting. Consequently, under a particular temperature environment, an uneven melting takes place over the glacier surface which may not show a good correlation with temperature. Poorer correlations between discharge and temperature are expected in July and August when rain occurs in the basin and clear weather conditions do not prevail much (Figure 11 and 12). Variation in contribution of rainfall to the total streamflow on bad weather days perturbs the correlation between discharge and temperature. Thus correlation between discharge and temperature becomes very low and that to highly variable in the months of July and August. Discharge and temperature correlation is disturbed for July 1997 because of high rain than in July 1996. The correlation between discharge and temperature for September is shown in Figure 13. For this month, maximum correlation between discharge (Q_i) and temperature is obtained when temperature is considered without any lag i.e. T_i. Correlation coefficient decreases significantly with an increase in time lag of temperature. For example, correlation coefficient reduces from 0.65 to 0.11, when time lag of temperature is increased from 0 to 3 days for this month. It can be noted that trend of variation in correlation of discharge with an increased time lag of temperature for the month of September is opposite to the trend of variation is observed in the month of June.

Seasonal series of discharge and temperature shows a good correlation between discharge (Q_i) and temperature with 0 to 3 days lag (T_i, T_{i-1}, T_{i-2}, T_{i-3}) for 1996 and 1997 (Figure 14). Correlation between discharge and temperature with lag 2 and 3 days (T_{i-2},T_{i-3}) are slightly superior than temperature with a lag of 0 and 1 day (T_i,T_{i-1}). These results suggest that melt water storage and runoff delaying behaviour of the glacier influences the response of the glacier melt runoff. Correlation between discharge and temperature computed on the basis of seasonal series indicates an improvement in correlation coefficient with an increase in time lag of temperature from 0 to 3 days for 1996 and 1997, however, improvement is not very significant. The trend of variation in correlation coefficient with an increase in temperature time lag computed on the basis of seasonal data series matches with the trend of month of June.

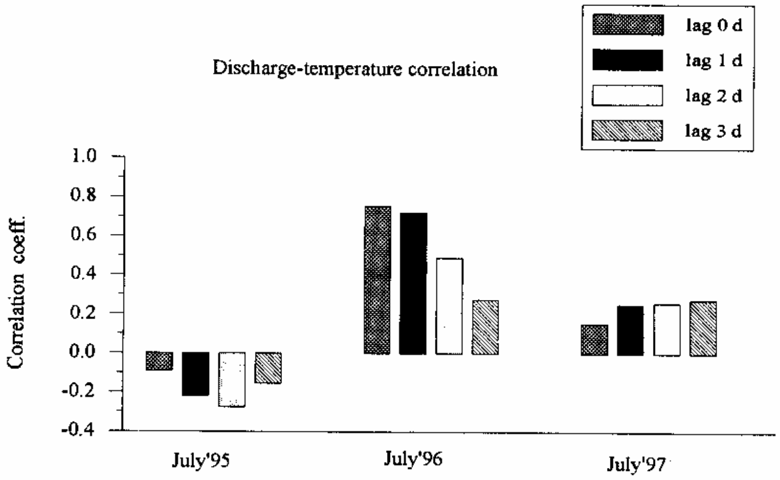

Figure 11: **Correlation coefficient between daily mean discharge and air temperature as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of July for different years.**

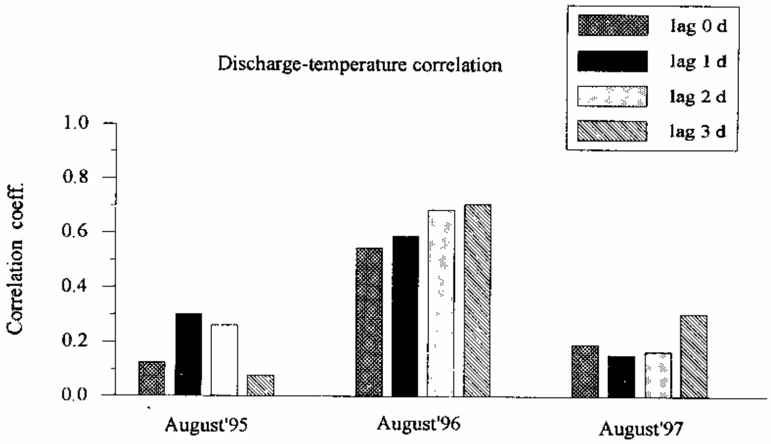

Figure 12: Correlation coefficient between daily mean discharge and air temperature as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of August for different years.

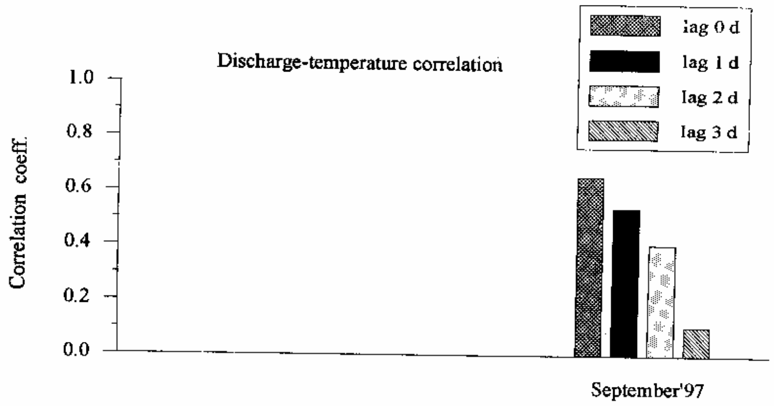

Figure 13: Correlation coefficients between daily mean discharge and air temperature as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of September for 1997

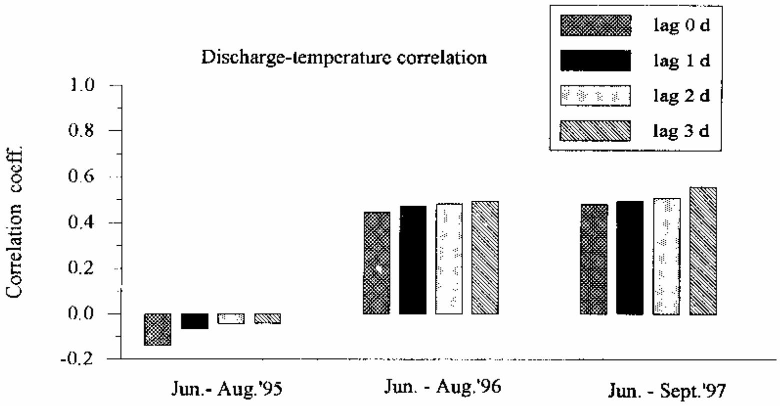

Figure 14 Correlation coefficient between daily mean discharge and air temperature as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the melt period for different years.

4.4 Discharge - rain correlation

The correlation between discharge and rainfall lagged with 0 to 3 days for different months and for whole season for different years is presented in Figures 15 to 19. It is noticed that discharge has a better correlation with rainfall lagged with 1 to 3 days (R_{i-1}, R_{i-2}, R_{i-3}). It can be seen from the results that correlation between discharge and rain is negative for the month of June, 1995 with all lag period of rain, while it is positive for the same months in the years of 1996 and 1997. The form of precipitation and its distribution over the basin also influences the response of precipitation to the runoff. The form of precipitation generally determines whether correlation is positive or negative. When precipitation falls as snow, melting of the glacier is ceased and discharge is reduced. Under such conditions, discharge and precipitation are negatively correlated. On the other hand when precipitation falls in the form of rain over the glacier, a positive correlation with discharge is possible.

In the months of July and August response of rain to streamflow is faster as compared with other months because of changes in physical conditions of the glacier. During this time, glacier ice surface is exposed to large extent. The response of rain is always faster from the ice covered surface as compared with a snow covered surface. Rain falling on a surface covered by snow is first absorbed by the snowpack and released later to the streamflow. Whereas in the case of ice surface, it acts as an impervious surface. Rain is not absorbed in the ice surface, and hence contributes to the runoff at the outlet relatively in a shorter time period. Drainage network within the glacier is improved and well established by July and August which makes response of melt water as well as rain water faster to basin outlet. Thus, lag time of the runoff generated from the rainfall occurred over the ice surface is lower than the rain occurred over the snow surface. Further, in the months of July and August, response of rainfall from the snow free and ice free zones of the drainage basin to runoff is also faster because of soil moisture is saturated during this period. Under such conditions, losses from the rain input are very less and a large portion of input appears as runoff and that too at shorter time interval. Thus, in the months and July and August, a high variability in discharge is caused due to higher rain and its fast response as well. Consequently, correlation between discharge and rain improves for these months as compared with June and September (Figure 16 and 17). An improved correlation is obtained for August 1996 than August 1997 because of higher rainfall in 1996 in this month. A combination of higher temperature and

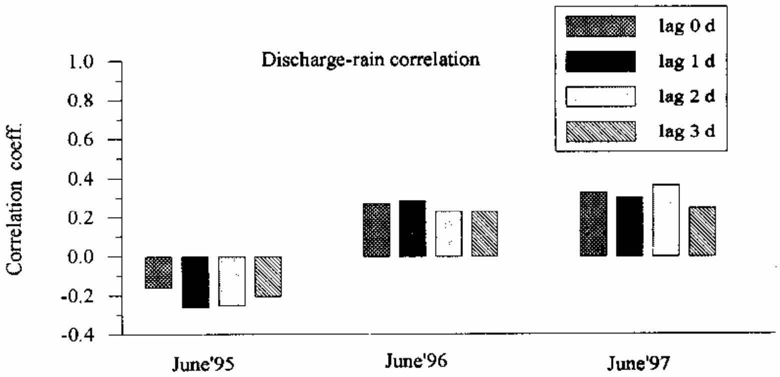

Figure 15: Correlation coefficient between mean discharge and rain as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of June for different years.

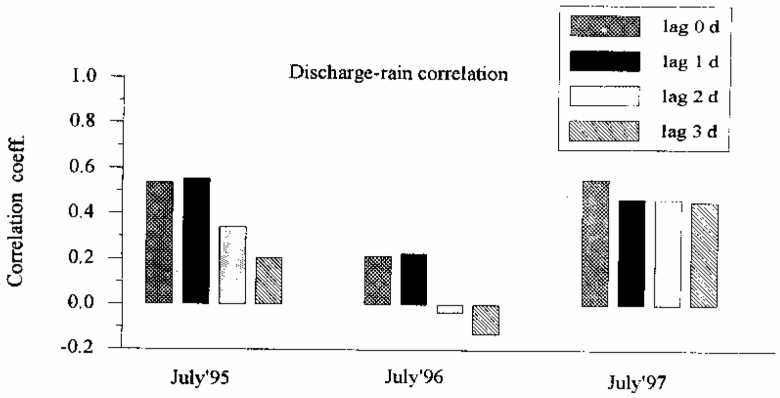

Figure 16: Correlation coefficients detween daily mean discharge and rain as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of July for different years.

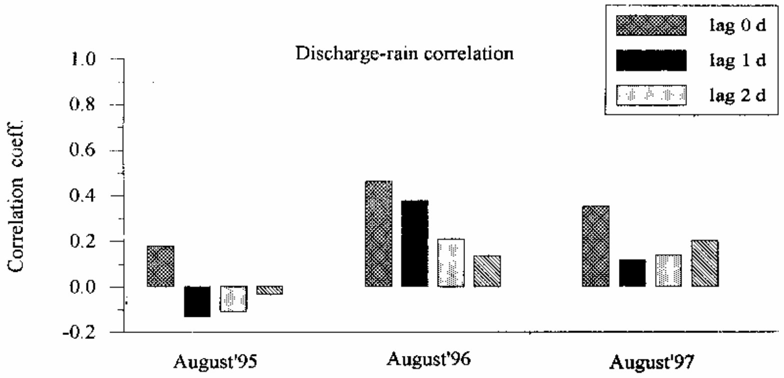

Figure 17: Correlation coefficients between daily mean disharge and rain as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of August for different years

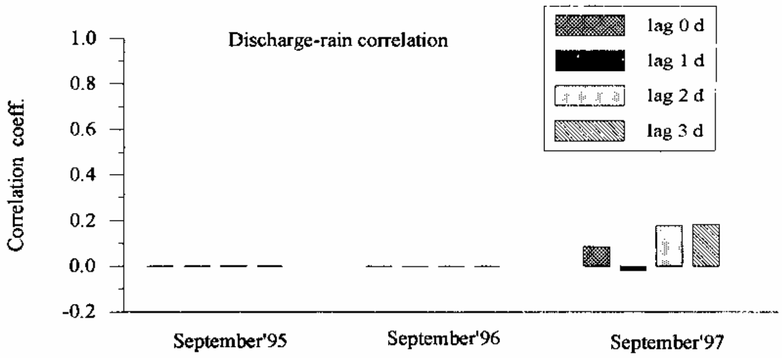

Fig ure 18: Correlation coefficients between daily mean discharge and rain as a function of 0 to 3 days lag for the drainage basin of Dokriani glacier for the month of September for 1997

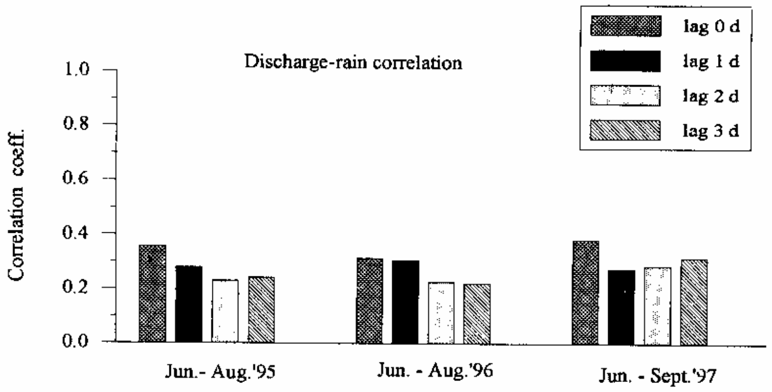

Figure 19: Correlation coefficients between daily mean discharge and rain as a function of 0 to3 days lag for the drainage basin of Dokriani glacier for the melt period for different years.

higher rain shows a better correlation with shorter lag period. For example, in July 1997 correlation between discharge and rain is found better than July, 1996 because of higher temperature and higher rain in July 1997: Higher temperature accelerates the melting of snow accumulated over glacier ice body and exposes more ice covered area making response of rain faster. Rainfall with 0 day lag (R_{i-1}) shows a better correlation with discharge than other lags for the months of July and August. A good correlation between discharge and rainfall with lag of 0 day (R_{i-1}) represents a faster response of rain to the streamflow at the outlet of the basin.

For September, rainfall with a lag of 2 and 3 days (R_{i-2}, R_{i-3}) has shown relatively a higher correlation in comparison to rainfall with a lag of 0 and 1 day (R_i, R_{i-1}) (Figure 18). During this period melting freezing process also adds to delaying response of the rain because of starting of cold weather. The value of correlation coefficient is reduced significantly for this month. It may be due to occurrence of precipitation as rainfall in the lower part of glacier basin and as snowfall in the upper reaches of the basin.

Seasonal series of discharge and rain from June-August has shown a positive correlation is observed between discharge (Q_i) and rainfall lagged from 0 to 3 days (R_i, R_{i-1}, R_{i-2}, R_{i-3}). As shown in Figure 19, in general, maximum correlation, r=0.35, 0.31 and 0.38 for 1995, 1996 and 1997, respectively, is found with lag 0 day (R_i) for seasonal series.-In other words, it shows maximum contribution of rainfall to runoff on the same day.

4.5 Development of multiple linear regression equations

Keeping in view the availability of meteorological data in the high altitude region of Himalayas, discharge from the Dokriani glacier basin was correlated with two meteorological variables namely, temperature and rain using multiple regression approach. The regression equations were developed considering the possible climatic factors which may influence the runoff. Multiple regression equations were developed separately for each month of melt season and for whole season of glacier melt. However, a long series data is required for developing such regression equations for any basin, but in the present study data for only three summer seasons for the years 1995, 1996 and 1997 were available. Therefore, limited data were used for developing regression equations for the study basin. In order to constitute the data series for a particular month, data of that month for different years was arranged in sequence. For example, data series for the month of June was constituted by arranging June 1995, 1996 and 1997 data in sequence.

Discharge from the basin was used as dependent variable and temperature with lag 0 and 1 day (T_i, T_{i-1}) and rainfall with lag 0 and 1 day (R_i, R_{i-1}) as independent variables. Thus, four independent variables were used to develop the regression equations. Regression equations and corresponding values of correlation coefficient for different months and for the complete melt season is given in Table 5. Highest correlation coefficient is found for the month of June followed by September. It is lower for both July and August. As such there is not much difference in correlation coefficient for the month of July and August, but it is lowest for August. Such equations can be used for forecasting of streamflow from the high altitude glacierized basin, provided input data are available.

For the month of June, the regression coefficient of temperature lagged with 1 day (T_{i-1}) is higher than that of the same day temperature (T_i). It is because of the fact that the snowmelt resulted due to temperature of previous day significantly contributes to the runoff during the month of June. For other periods mentioned in the Table 5, the regression coefficient for the same day temperature is larger than that of 1 day lagged temperature. For the month of September, the regression coefficient of the same day rainfall variable is negative which may be attributed to precipitation in the form of snow in the upper reaches of the catchment.

In order to arrive at statistically significant regression equations, stepwise regression has been carried out using above mentioned 4 independent variables. Resulting regression equations are given in Table 6. It can be noticed that when stepwise regression approach was followed, same day temperature has been dropped from the simple regression equation of month of June. It suggests that temperature lagged with 1 day (T_{i-1}) plays more important role than same day temperature in generating discharge from the basin for the month of June. It is quite possible due to stronger storage characteristics because large extent of glacier surface is covered by snow in this month. Conversely, same day temperature is found more important than same day temperature for the month of July, August and September. Both rainfall terms, R_i and R_{i-1}, have been retained in the stepwise regression equations for the months of June, July and August, while they are dropped for the month of September. For the month of September, only same day temperature was considered a appropriate variable using stepwise regression approach. Variables in the seasonal multiple regression equations are not changes even after stepwise regression. Because of removal of some terms in the monthly regression equations due to stepwise regression, correlation coefficients are slightly reduced for all months.

Table 5 Monthly and seasonal regression equations developed for the Dokriani glacier basin using simple regression approach

Period	Regression equations	Corr. Coeff. (r)	Standard error of estimate
June	$Q_i = -3.355 + 0.131\ T_i + 0.507\ T_{i-1} + 0.042\ R_i + 0.048\ R_{i-1}$	0.863	1.126
July	$Q_i = 1.535 + 0.474\ T_i + 0.055\ T_{i-1} + 0.095\ R_i + 0.090\ R_{i-1}$	0.553	2.292
August	$Q_i = -0.578 + 0.500\ T_i + 0.208\ T_{i-1} + 0.097\ R_i + 0.042\ R_{i-1}$	0.522	2.441
September	$Q_i = -2.466 + 0.357\ T_i + 0.208\ T_{i-1} - 0.013\ R_i + 0.022\ R_{i-1}$	0.689	0.676
June - September	$Q_i = -3.456 + 0.462\ T_i + 0.324\ T_{i-1} - 0.108\ R_i + 0.092\ R_{i-1}$	0.631	2.602

Table 6 Monthly and seasonal regression equations developed for the Dokriani glacier basin using stepwise regression approach

Period	Regression equations	Corr. Coeff. (r)	Standard error of estimate
June	$Q_i = -3.174 + 0.622\ T_{i-1} + 0.039\ R_i + 0.048\ R_{i-1}$	0.860	1.132
July	$Q_i = 1.368 + 0.437\ T_i + 0.094\ R_i + 0.090\ R_{i-1}$	0.552	2.280
August	$Q_i = -0.036 + 0.653\ T_i + 0.103\ R_i + 0.037\ R_{i-1}$	0.522	2.440
September	$Q_i = -1.437 + 0.451\ T_i$	0.654	0.653
June - September	$Q_i = -3.456 + 0.462\ T_i + 0.324\ T_{i-1} - 0.108\ R_i + 0.092\ R_{i-1}$	0.631	2.602

5.0 CONCLUSIONS

Discharge auto-correlation, correlation between discharge and temperature, discharge and rainfall are attempted for each month of summer season separately and for the melt season as a whole for different years. Correlation and auto-correlation coefficients vary from year to year for a period because of changes in weather conditions and physical characteristics of the glacier. Occurrence of higher rainfall in the months of July and August lowers down the discharge auto-correlation, and correlation between discharge and temperature, but improves the discharge and rainfall correlation. Discharge auto-correlation, discharge and temperature correlation are observed to be maximum in the months of June and September. Occurrence of lower rainfall, systematic melting environment, stronger storage characteristics are responsible for this higher correlation for these months. Monthly and seasonal distribution of discharge auto-correlation for different years suggests that although discharge auto-correlation is very good with all considered lags, but auto-correlation for lag 1 day (Q_{i-1}) is relatively higher for all the months and for all the years. On the monthly basis, maximum discharge auto-correlation with Q_{i-1} ranged from 0.61 to 0.97 for different years, while on the seasonal basis it varied from 0.83 to 0.95. It shows that for the forecasting of discharge for a particular day from the glacierized basin, previous day discharge becomes a significant predictor Discharge auto-correlation coefficient decreases with an increase in the lag period of discharge both on monthly and seasonal basis. However, reduction in the value of r with an increase in discharge time lag on the monthly basis is higher than that of on the seasonal basis.

For the month of June, correlation between discharge and temperature improves with an increase in time lag of temperature from 0 to 3 days. Maximum value of correlation, r=0.78, 0.83, 0.81 for 1995,1996 and 1997, respectively, is found with T_{i-3} for this month. In contrast, for the month of September, maximum correlation between discharge and temperature was obtained when temperature was considered without any lag i.e. T_i. Correlation coefficient decreases significantly with an increase in time lag of temperature for this month. For example, correlation coefficient reduces from 0.65 to 0.11, when time lag of temperature is increased from 0 to 3 days for this month. It can be noted that trend of variation in correlation of discharge with an increased time lag of temperature for the month of September is opposite to the trend of variation observed in the month of June. Seasonal series of discharge and temperature shows an improvement in correlation coefficient with an increase in time lag of temperature from 0 to 3 days for 1996 and 1997, but improvement is not very significant. The trend of variation in correlation coefficient with an increase in temperature time lagcomputed on the basis of seasonal data series matches with the trend of month of June. Generally, correlation between discharge and temperature were poor for the month of July and August because of rain during these months. However, a better correlation between discharge and temperature is expected for the highly glacierized basin through out the melt period, but this was not the case for this glacierized basin. It is understood that significant amount of rainfall in the peak melt period in the study region was responsible for reduction in the correlation between discharge and temperature.

Because melt water or rain water storage characteristics of the glacier dominate in the month of June, therefore, discharge has a better correlation with rainfall lagged with 1 to 3 days (R_{i-1}, R_{i-2}, R_{i-3}). In the months of July and August, a high variability in discharge is caused due to higher rain and its fast response as well. Consequently, correlation between discharge and rain improves for these months as compared with June and September. For September, rainfall with a lag of 2 and 3 days (R_{i-2}, R_{i-3}) has shown relatively a higher correlation in comparison to rainfall with a lag of 0 and 1 day (R_i, R_{i-1}). During this period melting freezing process also adds to delaying response of the rain because of starting of cold weather. The value of correlation coefficient is reduced significantly for this month. It may be due to occurrence of precipitation as rainfall in the lower part of glacier basin and as snowfall in the upper reaches of the basin. In general, maximum correlation, $r=0.35$, 0.31 and 0.38 for 1995, 1996 and 1997 respectively, is found with the rainfall of same day (R_i) for the seasonal series. It indicates maximum contribution of rainfall to runoff on the same day.

Multiple linear regression equations are developed separately for each month and for whole season of glacier melt. Discharge is used as dependent variable and temperature with lag 0 and 1 day (T_i, T_{i-1}) and rainfall with lag 0 and 1 day (R_i, R_{i-1}) as independent variables. Independent variables used in the regression equations were selected keeping in view the availability of meteorological data easily in the Himalayan region. Considering these variables, highest value of correlation coefficient was found for the month of June followed by September, and a low value for July and August. In order to obtain the statistical significance of the meteorological variables, stepwise regression was also made. Such equations can be used for forecasting the discharge from the high altitude basin where most of the contribution arrived from glacier melt runoff.

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