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Full Length Research Paper

Hydro-meteorological correlations and relationships for estimating streamflow for Gangotri Glacier basin in Western Himalayas

Pratap Singh[1*], Amit Kumar[2], Naresh Kumar[3] and Naval kishore[2]

[1] INRM, Consultants, C-23 Hauz Khas, New Delhi, 110 016, India.
[2]Centre of Advanced Study in Geology, Department of Geology, Panjab University, Chandigarh, 160 014, India.
[3] National Institute of Hydrology, Roorkee, Roorkee-247667, India.

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This study investigates the relationships between hydrological and meteorological data collected near the snout of Gangotri Glacier, Indian Himalayas for the different ablation seasons (May - October). The complete analysis employs a hydro- meteorological data series for a period of 7 years (2000 - 2006). The first 5 years data (2000 - 2004) was used for determining correlations, lag-cross-correlations and multivariate regression analyses between daily mean discharge, daily mean temperature and daily rainfall , whereas, last 2 years data (2005 - 2006) was used to simulate the daily discharge using established relationship. Changes in correlations between discharge and meteorological variables, lagged by 0 - 3 days, were determined. 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. The analysis suggests a very high discharge auto-correlation for each individual year and for the combined data series of 5 years. The substantial storage of melt water in the glacier body and its delayed response of the runoff attribute to the high dependency of a particular day discharge on its pervious day's discharge. A comparison of correlations between discharge and temperature, and discharge and rain shows that temperature has a better correlation with discharge series for all the years. To estimate the discharge for Gangotri Glacier basin, multiple linear regression equations were developed separately for each ablation season and a combined data set of 5 ablation seasons. The generalized regression equation developed using stepwise regression approach for the data set of 5 years (2000 - 2004) was adopted to estimate daily mean discharge for 2005 and 2006. For both simulation years, the simulation efficiency was very high (R^2 = 0.96). It is found that discharge of study basin is well represented Q_{i-1} (1-day lagged discharge) and T_i, T_{i-1}, T_{i-2} (0 - 2 days lagged temperature) and R_i (0-day lagged rain). Such relationships can be used for filling the missing discharge data as well as for forecasting of discharge.

Key words: Gangotri Glacier basin, Himalayas, glacierized basins, meteorological variables, estimation of melt-runoff.

INTRODUCTION

Himalayan mountain system acts as natural reservoirs of fresh water, storing precipitation during the winter season, when most precipitation falls as snow. A number of snow storms form thick layers of snow until the warm season releases the melt water into the rivers. The availability of fresh water is directly influenced by the volume of water stored and released from glaciers in the form of melt water from snow and ice. The hydro-meteorological records for the Himalayan rivers are poor. Difficult accessibility, rugged terrains and harsh weather conditions are considered to be the major barrier to establish a good database. Therefore, it is necessary to investigate hydro-meteorological relationships in high-altitude areas (Singh et al., 2000; Archer et al., 2008).

*Corresponding author. E-mail: pratapsingh.iitd@gmail.com.

Such types of relationships between melt water generation and meteorological parameters have been intensively studied worldwide for glaciers and ice sheets (Lang, 1973; Changwei et al., 2006; Barbet et al., 1993). Analysis of hydro-meteorological data helps to understand weather conditions, available water resources of the region, melting and other flow-generation processes, sediment transport processes, and also to give an insight to the problems related to natural hazards, viz: Flash floods, cloudbursts, landslides/rockslides and avalanches (Shcheglova and Chizhov, 1981; Mazari et al., 2004; Naithani et al., 2001; Singh et al., 2003; Jain et al., 2003; Singh et al., 2005; Haritashya et al., 2006). Moreover, such relationships can be used for forecasting of runoff from glacierized basin.

Several investigators have attempted to correlate discharge with meteorological data for glacierized basins. The different regression models developed using hydro-meteorological data are given in Table 1. The review of such investigations show that several studies have been presented using energy balance modeling, many based on regression models, that is, the relationships between hydro-meteorological parameters (Braithwaite, 1995; Hannah and McGregor, 1997; Hannah et al., 2000; Singh et al., 2000; Hodgkins, 2001; Willis et al., 2002; Shea et al., 2005). These studies contribute efforts to understand the seasonal evolution and melt storage of the glacial system (Stenborg, 1970). Kang (1991) simulated daily hydrograph for the Tianshan glacierized basin using multiple regression equations taking the daily air temperature, water vapour and precipitation with time-lag of 0 - 4 days as independent variables. He concluded that the runoff from the glacierized high mountain area can be simulated with the meteorological factors (air temperature, vapor pressure and precipitation) observed at standard meteorological station in the mountains. Similar to this Wolfe and English (1999), performed regression analysis relating daily air temperature, shortwave incoming and net radiation, absorptivity and wind speed to daily glacier discharge. Results show that (i) daily air temperature on the glacier is the only element which shows the best relationship (R^2 = 0.57) with mean discharge on rain- free days,(ii) the best prediction of glacier runoff can be found using a multiple regression equation (R^2 = 0.84) for taking daily air temperature, shortwave incoming and net radiation, absorptivity and wind speed. Singh et al. (2000) and Shea et al. (2005) also established relationship between meteorological variable from the glacierized basins on seasonal basis. The results show that discharge for a particular day is very much dependent on previous day's discharge.

In Himalayas, significant positive relationships established between climatic variables and flow, which suggests the variety of strategies for flow forecasting for the successful management of water resources in the Himalayan region (Archer, 2008). A multiple linear regression model has been successfully used to forecast summer season flows. Schar et al. (2004) suggest that runoff may also be sensitive to fluctuations in mean monthly temperature during October–November and March-April.

Hodgkins (2001) performed time series analysis of meteorological variables, that is, solar radiation, air temperature and wind speed, in order to examine its relationship with proglacial discharge and its variation at diurnal and seasonal scale. The developed regression models showed substantially improved correlations with air temperature and solar radiation. Runoff from Alpine glaciers generally display, increases in daily discharge maximum and range, with superimposed effects from precipitation (Meier and Tangborn, 1961; Smith, 1995; Fountain, 1996; Hannah et al., 2000; Willis et al., 2002; Verbunt et al., 2003). Shea et al. (2005) determined statistically (correlations, multivariate regression and lag cross - correlation) and concluded that early response of ablation season is temperature dominated, whereas, as a melt season progresses radiation discharge response observed as the accumulation area ratio (AAR) decreases. In the present study correlations between discharge and meteorological variables (temperature and rain) have been studied for Gangotri Glacier basin. Discharge auto-correlation also has been determined and its variation with increase in time lag is examined. Multiple linear regression equations have been developed for the Gangotri glacier basin considering air temperature, discharge and rain as function of time-lag (0 - 3 days).

GANGOTRI GLACIER AREA AND DATA COLLECTION

Gangotri Glacier is one of the biggest glaciers in the Indian Himalayas. It lies within the latitudes 30°43′ - 31°01′N and longitudes 79°0′ - 79°17′E. Location map of the Gangotri Glacier system is shown in Figure 1. The snout of Gangotri Glacier is very commonly known as Gaumukh (the mouth of cow). As shown in Figure 1, the Gangotri Glacier system is a cluster of many glaciers comprising the main Gangotri Glacier (length: 30.20 km; width: 0.20 - 2.35 km; area: 86.32 km^2) as the trunk part of the system. The melt-water stream emerging from the snout of the Gangotri Glacier at an elevation of 4000 m a.s.l is known as Bhagirathi River. This river after its confluence with the river Alaknanda is known as river Ganga. Total catchment area of the Gangotri Glacier basin up to the gauging site established downstream, the snout is about 556 km^2, out of which the glacierized area is about 286 km^2. The ablation part of Gangotri glacier is covered with thick supraglacial debris. Details of availability of hydro-meteorological data for different ablation seasons are given in Table 2. The period of collected hydro-meteorological data for each year is referred to ablation season representing the melt period from May to October. For the present study, a standard meteorological observatory (30 × 30 m) was established

Table. 1 Multivariate regression equations developed for different glacier basin.

Site/Basin/source	Latitude-Longitude	Equation	R^2
Mikkiglaciaren, Sweden (Stenborg, 1970)	67°25'N, 17°42'E	$Q_i = 0.329 + 0.546Q_{i-1} + 0.035\ \Sigma T_{m+} + 0.0014NRH_i$ *	0.81
Urumqi River basin / Tianshan Mountain Glaciers (Kang , 1991)	43°00′ -44°07′E - 86°45′ -97°56′ E	$Q_c(t) = -1.1114 + 0.0483T_m(t) + 0.0036\sum_{i=1}^{4} T_m(t-i) + 0.1584P_{me}(t) + 0.0446\sum_{i=1}^{4} P_{me}(t-i) + 0.0179P_m(t) + 0.0170\sum_{i=1}^{4} P_m(t-i)$ $Q_c(t) = -2.3370 + 0.1113T_m(t) + 0.0298\sum_{i=1}^{4} T_m(t-i) + 0.2221P_{me}(t) + 0.0550\sum_{i=1}^{4} P_{me}(t-i) + 0.0348P_m(t) + 0.0207\sum_{i=1}^{4} P_m(t-i)$	0.64 0.66
Canadian High Arctic,Ellesmere Island / Quviagiviaa and Nirukikttuq Glacier (Wolfe et al., 1995)	79°33.98′ N- 83°20.48′ W	$Q_i = 0.315T_i \quad 0.00248K_i + 0.000217NRH_i + 0.11767W_i$	0.84
Dokriani glacier, Himalayas (India) (Singh et al., 2000)	30°43′ -31°01′N -79°0′ -79°17′E	$Q_i = -0.671 + 0.901Q_{i-1} + 0.125T_i + 0.016R_i$	0.96
Haig Glacier, Alberata, Canada. (Shea et al., 2005)	50°43′ N - 115°18′ W	$Q_i = 0.386 + 0.630Q_{i-1} + 0.041T_i + 0.0002K_i$	0.87
Gangotri Glacier, Himalayas (India) (Present study)	30°43′ -31°01′N -79°0′ -79°17′E	$Q_i = 7.649 + 0.995Q_{i-1} + 1.450T_i \quad 1.523T_{i-1} \quad 0.710T_{i\ \ 2} + 0.227R_i$	0.94

Q_i = daily mean discharge; Q_{i-1} = discharge lagged by 1 day; $Q_c(t)$=daily mean discharge; T_i = daily mean temperature; T_{i-1} = temperature lagged by 1 day; T_{i-2} = temperature lagged by 2 days; R_i = daily rainfall; T_m=air temperature; T_{md}=air temperature range; P_{me}=Vapour pressure; H_m=relative humidity; P_m=Precipitation; K_i = daily incoming solar radiation; NRH_i= daily net radiation hours; W_i = average daily wind speed.(Discharge in m^3/s; Temperature in °C; Precipitation/rainfall in mm; wind speed in m/s; relative humidity in %;vapor pressure in mb; radiation in W/m^2 /*Langley/d.

Table 2. Availability of hydro-meteorological data for different ablation seasons for Gangotri Glacier basin.

S/No.	Ablation season/Year	Period of data availability
1	2000	9th May - 19th Oct
2	2001	1st May - 20th Oct
3	2002	8th May - 20th Oct
4	2003	9th May - 20th Oct
5	2004	7th May - 14th Oct
6	(2000 - 2004)	9th May - 20th Oct

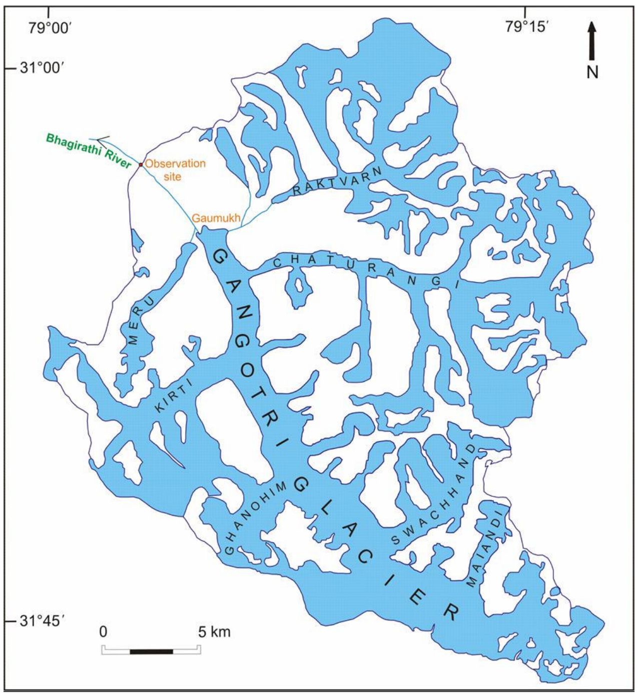

Figure 1. Location of the study area.

at about 3800 m a.s.l near the snout of the Gangotri Glacier. The observatory is located in the valley floor on right bank of the Bhagirathi River, about 3 km downstream to the snout of the glacier and surrounded by steep sloping hills. This observatory was equipped with rainfall and temperature measuring equipments. Standard timings for data collection were according to the practice followed by the India Meteorological Department (IMD). Daily mean temperatures were computed using average of daily maximum and minimum temperatures. Proglacial stream discharge was measured at gauge site near Bhojwasa where a single proglacial meltwater stream is flowing. Continuous monitoring of water level (stage) was done by installing an automatic water level recorder placed in a stilling well. Daily mean discharge was calculated from using developed stage-discharge relationship for each ablation season.

METHODOLOGY AND DATA USED

For the present study simple statistical approaches were applied. The analysis of the hydrological and meteorological time series focuses on three components considering a time-lag of 0 - 3 days: (i) Discharge auto-correlation, (ii) discharge-temperature correlation and discharge-rainfall correlation (iii) multivariate regression between discharge, temperature and rainfall.

In the present analysis, as such hydro-meteorological data of 7 years (2000 -2006) have been used. The first 5 years data (2000 - 2004) was used for determining correlations, lag-cross-correlations and multivariate regression analyses between daily mean discharge, daily mean temperature and daily rainfall. Then last 2 years data (2005 - 2006) was used to estimate the discharge using established relationship. The time series for different variables (discharge, temperature and rainfall) were prepared as a function of time-lag of 0 - 3 days for each ablation season of 5 years (2000 - 2004). A combined series of these 5 ablation seasons was prepared by considering all ablation seasons together in chronological order and used in the analysis for developing generalized relationship.

DEVELOPMENT OF CORRELATIONS

Discharge auto-correlation

Discharge auto-correlations determined for different melt seasons as well as for the combined series of 5 seasons (2000 - 2004) are shown in Figure 2. A comparison of discharge auto-correlations for different years indicates that discharge auto-correlation is very high for all the years. The values of discharge auto-correlation for different ablation seasons are given in Table 3. The distribution of discharge auto-correlation with time-lag for different years shows a reduction in autocorrelation with increase in time-lag. It is found that discharge auto-correlation varied from 0.97 - 0.75 for the time-lag from 0 - 3-days. The corresponding values of discharge auto-correlation for the combined discharge series varied from 0.97 - 0.87. Such reduction in discharge auto-correlation may be due to combined effect of melting conditions of glacier, precipitation pattern and water storage and drainage characteristics within the basin. The discharge autocorrelation suggests that, although a good autocorrelation exists for all considered time-lags, the maximum auto-correlation is found with the previous day's discharge (0.97 - 0.92). A high discharge autocorrelation

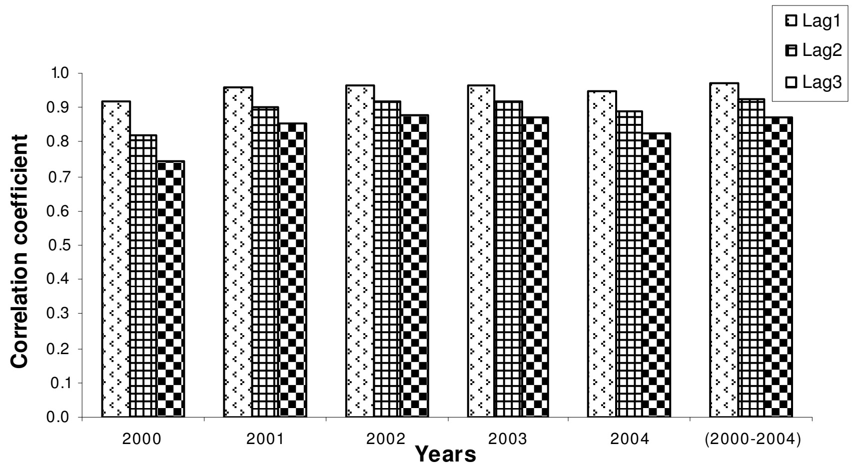

Figure 2. Discharge auto-correlations as a function of time-lag (1-3 days) for the Gangotri Glacier basin.

Table 3. Discharge auto-correlations and standard error (SE) as a function of time-lag (1 - 3 days) for the Gangotri Glacier basin.

Years	Discharge auto-correlation					
	Time-lag					
	1-day		2-day		3-day	
	R^2	SE	R^2	SE	R^2	SE
2000	0.92	0.08	0.82	0.13	0.75	0.16
2001	0.96	0.08	0.90	0.13	0.85	0.16
2002	0.97	0.08	0.92	0.13	0.88	0.17
2003	0.97	0.08	0.92	0.14	0.87	0.17
2004	0.95	0.08	0.89	0.14	0.83	0.17
(2000-2004)	0.97	0.08	0.93	0.13	0.87	0.17

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. It is likely that the dominance of delaying characteristics of the glacier and little contribution from rainfall to the stream-flow. In the present study basin has provided higher discharge auto-correlations. Thus, for the forecasting of discharge from the glacierized basin for a particular day, the previous day's discharge becomes a significant predictor. Singh et al. (2000) also reported such high correlations for Dokriani glacier basin in the Garhwal Himalayas.

Discharge-temperature correlation

Correlations established between discharge and air temperatures with a time-lag of temperature from 0 - 3 days (T_i, T_{i-1}, T_{i-2}, and T_{i-3}) are shown in Figure 3. The values of discharge-temperature correlation for each ablation season and combined data series are given in Table 4. The analysis shows that discharge is well correlated with temperature for each ablation season. It is found that for all the years discharge-temperature correlation decreased with increase in time-lag. The value of discharge-temperature correlation varied from 0.81 - 0.40 for a time-lag from 0 - 3 days. The highest correlation between discharge and temperature was obtained with temperature of 0-day time-lag. In other words, discharge of a particular day has shown highest correlation (0.81) with temperature of the same day. The combined series of discharge and temperature also show a good correlation (0.76 - 0.66) with temperature having time-lag from 0 - 3 days. As such a good correlation has been found between discharge (Q_i) and temperature (T_i, T_{i-1}, T_{i-2}, and T_{i-3}) for all the years, showing important role of temperature in producing runoff in the glacierized basin.

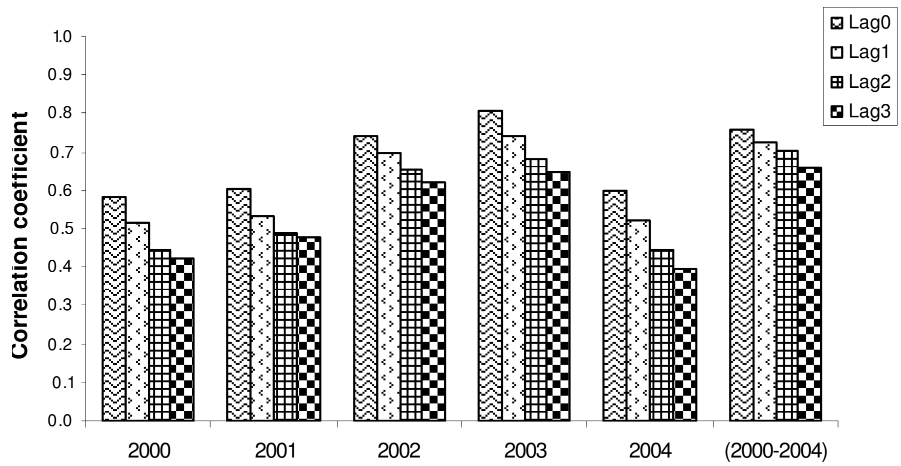

Figure 3. Correlation between daily mean discharge and temperature as a function of time-lag (0-3 days) for the Gangotri Glacier basin.

Table 4. Correlation between daily mean discharge and temperature as a function of time-lag (1 - 3 days) for the Gangotri Glacier basin.

Years	Discharge-temperature correlation							
	Time-lag							
	0- day		1- day		2- day		3- day	
	R^2	SE	R^2	SE	R^2	SE	R^2	SE
2000	0.58	0.08	0.52	0.08	0.45	0.08	0.42	0.08
2001	0.60	0.08	0.53	0.8	0.49	0.08	0.48	0.08
2002	0.74	0.08	0.70	0.08	0.65	0.08	0.62	0.08
2003	0.81	0.08	0.74	0.08	0.68	0.08	0.68	0.08
2004	0.60	0.08	0.52	0.08	0.44	0.08	0.40	0.08
(2000 - 2004)	0.76	0.08	0.73	0.08	0.70	0.08	0.66	0.08

Discharge-rainfall correlation

The correlations between discharge and rainfall with time-lags between 0 and 3 days (R_i, R_{i-1}, R_{i-2}, R_{i-3}) for different ablation seasons were developed. The values of discharge and rain correlations for each ablation season and combined data series are given in Table 5 and presented in Figure 4. For the study basin the correlation between discharge and rainfall are found poor and highly variable for all the years. No consistent change in correlation between discharge and rainfall was found with increase in time-lag. In general, discharge was positively correlated with rainfall, except year 2002. A negative correlation is possible when rainfall occurs near the snout and low temperature conditions prevail. Such weather conditions allow for snowfall over the major part of glacier, which ceases the melting of glacier and in turn reduces discharge. The examination of rainfall and temperature data for the year 2002 showed that the magnitude of temperature during rainfall event was very low, which might have resulted in snowfall over the glacier, giving negative correlation for this year.

REGRESSION RELATIONSHIP AND ITS USE FOR ESTIMATION OF STREAMFLOW

Antecedent discharge, temperature and rainfall are used as important variables to represent the discharge from the study basin. To estimate daily streamflow from the Gangotri Glacier basin, multiple regression equations were developed separately for each melting season (2000 - 2004) and for the combined series of 5 melt seasons. Stepwise regression technique has been used to identify important variables for estimating the discharge of Gangotri Glacier basin. 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 11 independent variables namely, Q_{i-1}, Q_{i-2},

Table 5. Correlation between daily discharge and rain as a function of time-lag (0 - 3 days) for the Gangotri Glacier basin.

Years	Discharge-rain correlation					
	Time-lag					
	1- day		2- day		3- day	
	R^2	SE	R^2	SE	R^2	SE
2000	0.15	0.08	0.02	0.08	0.01	0.080
2001	0.16	0.08	0.100	0.08	0.08	0.08
2002	-0.12	0.08	-0.08	0.08	-0.08	0.08
2003	0.30	0.08	0.31	0.08	0.31	0.08
2004	0.06	0.08	0.08	0.08	0.09	0.08
(2000 - 2004)	0.003	0.08	0.02	0.08	0.05	0.08

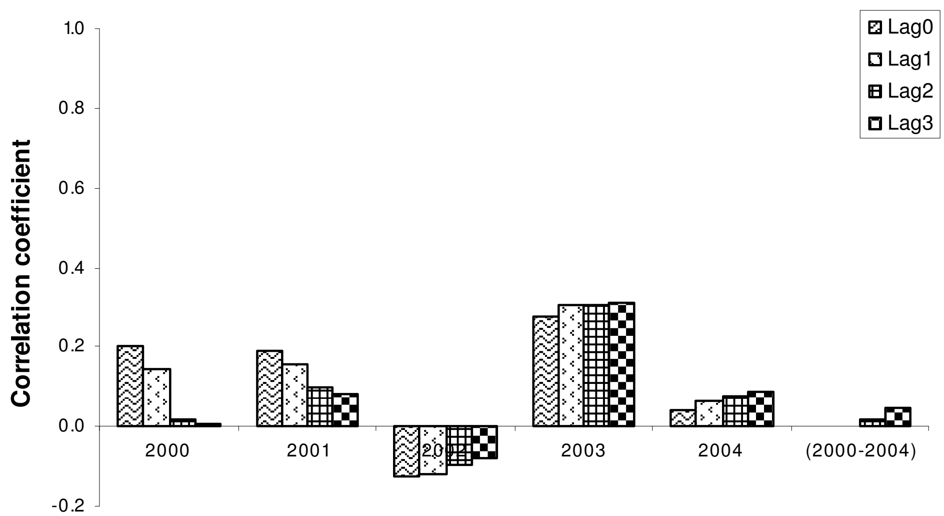

Figure 4. Correlation between daily discharge and rainfall (R) as a function of time-lag (0 - 3 days) for the Gangotri Glacier basin.

Q_{i-3}, Ti, T_{i-1}, T_{i-2} T_{i-3} and R_i, R_{i-1} R_{i-2} R_{i-3} respectively, were used as independent variables.

The resulting multiple regression equations obtained through stepwise regression and corresponding values of correlation for each year and for the combined series of all 5 seasons is given in Table 6. It can be noted that some of the variables were dropped in the regression equations due to their statistical insignificance determined by stepwise regression approach. A high value of R^2 varied between 0.90 and 0.98 for all the five (5) ablation seasons, showing that discharge data is well represented by these equations. For the combined series also a very high value of R^2 (0.94) was obtained.

The regression equations developed were used to estimate daily streamflow for two independent years (2005 and 2006). The estimation of discharge was made using generalized regression equation developed from combined data series of 5 ablation seasons. A comparison of computed and observed daily streamflow for 2005 and 2006 is given in Figure 5a and 6a. Figure 5b and 6b shows that computed value of discharge is very close to matched with estimated values of the models during the years 2005 and 2006. Using the generalized regression equation for computing discharge, the value of R^2 was obtained as 0.96 for both years (2005 and 2006).

CONCLUSIONS

Discharge auto-correlations and correlations between discharge and temperature, and discharge and rainfall are determined for the Gangotri Glacier basin for 5 ablation seasons (2000 - 2004) separately and for the combined series of 5 seasons. The seasonal distribution

Table 6. Regression equations developed for the Gangotri glacier basin using stepwise regression approach (2000 - 2004) and combined flow series.

Year	Multiple regression equations	R^2
2000	$Q_i = 1.593 + 0.911Q_{i-1} + 2.787T_i - 0.789T_{i-1} - 1.611T_{i-2} + 0.487R_i$	0.90
2001	$Q_i = 11.389 + 1.009Q_{i-1} + 0.195T_i - 2.085T_{i-1} + 0.630T_{i-2} + 0.658R_i$	0.94
2002	$Q_i = 3.507 + 1.005Q_{i-1} + 2.096T_i - 1.326T_{i-1} - 1.227T_{i-2} + 0.136R_i$	0.96
2003	$Q_i = 9.281 + 1.044Q_{i-1} + 1.582T_i - 2.167T_{i-1} - 0.895T_{i-2} + 0.724R_i$	0.98
2004	$Q_i = 11.649 + 1.018Q_{i-1} + 0.752T_i - 1.266T_{i-1} - 0.867T_{i-2} + 0.304R_i$	0.95
(2000 - 2004)	$Q_i = 7.649 + 0.995Q_{i-1} + 1.450T_i - 1.523T_{i-1} - 0.710T_{i-2} + 0.227R_i$	0.94

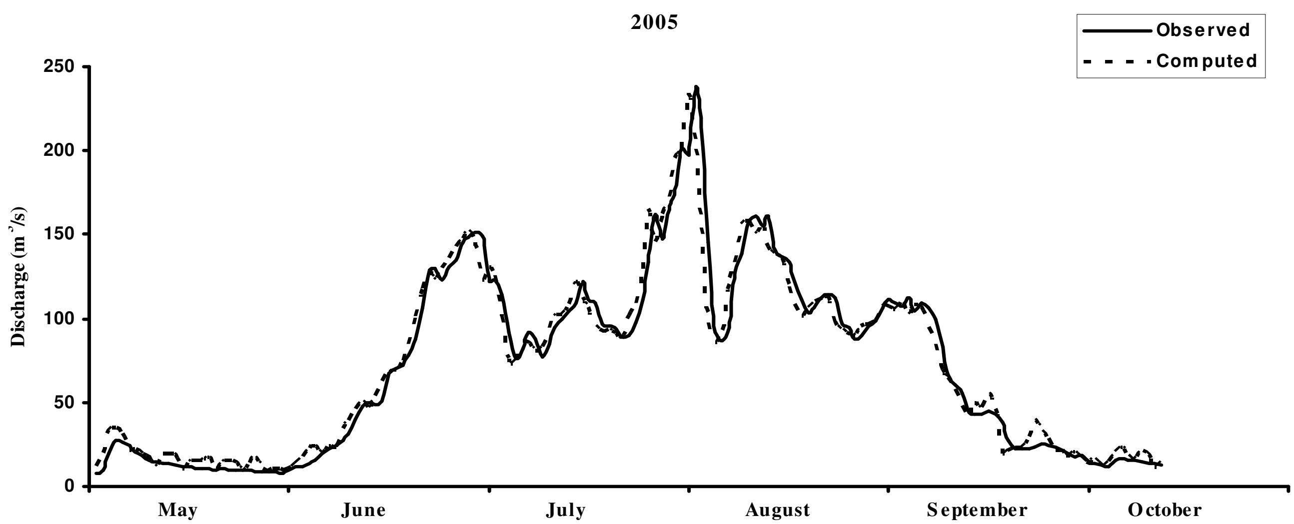

Figure 5a. Observed and computed discharge at near the snout of Gangotri Glacier during the year 2005.

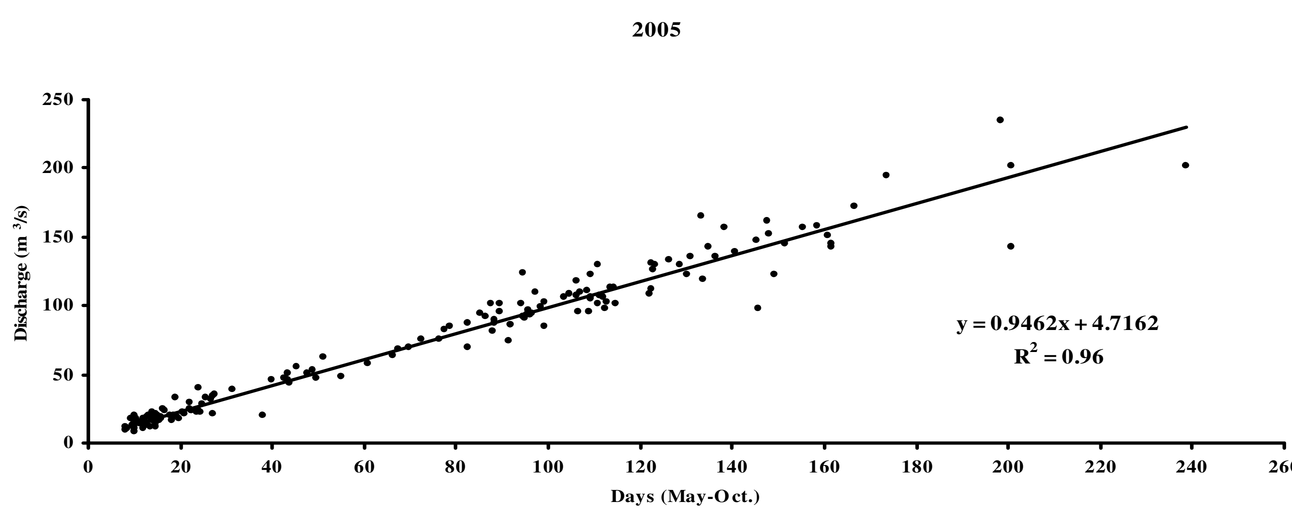

Figure 5(b). Correlation between observed and estimated discharge at Gangotri Glacier during 2005.

Figure 6 (a). Observed and computed discharge at near the snout of Gangotri Glacier during the year 2006.

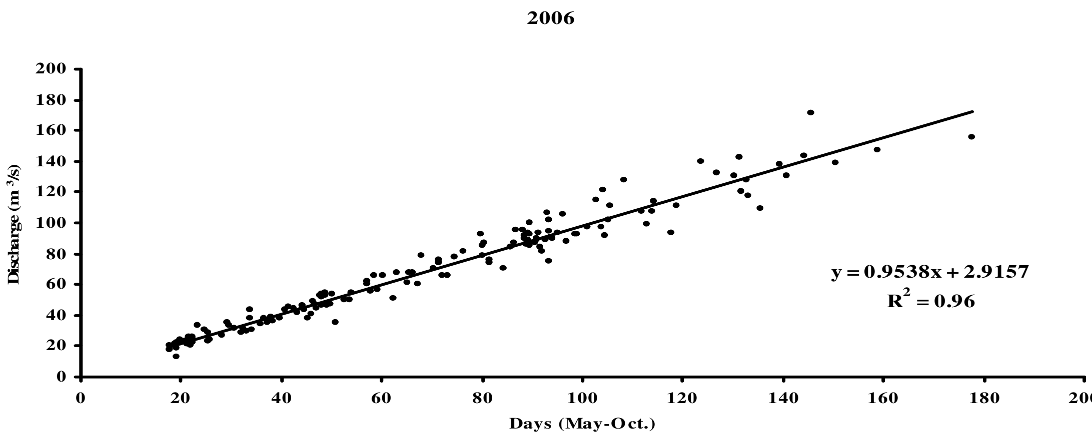

Figure 6(b). Correlation between observed and estimated discharge at Gangotri Glacier during 2006.

of discharge auto-correlation suggests that, although a good auto-correlation exists for all the considered time lags, maximum auto-correlation (0.92 - 0.97) is observed with the previous day's discharge (Q_{i-1}) and for the combined series as well (0.97). It suggests that discharge for a particular day is highly dependent on the previous day's discharge. Therefore, for the estimation/forecasting of discharge from the glacierized basin for a particular day, the previous day's discharge becomes a significant predictor. The high discharge auto-correlation indicates the dominance of storage characteristics on the response of runoff from the glacierized basin. Discharge auto-correlation decreases with an increase in the lag period of discharge.

As such the discharge and temperature with time lag from 0 - 3 days were found to be reasonably well correlated. The highest correlation was found with same day temperature, which varied from 0.60 - 0.80 for different years. For the combined series the highest correlation between discharge and same day temperature was 0.76. Like discharge auto correlation, correlation between discharge and temperature also decreased with increase in lag in temperature. Poor and inconsistent correlation was found between discharge and rainfall for all the year.

Multiple linear regression equations developed for the Gangotri Glacier basin separately for each year and for the combined series of 5 years. Stepwise regression approach was used to identify the statistically significant parameters for computing discharge from the basin. It was found that discharge of a particular day (Q_i) is well represented by the regression equation having Q_{i-1}, T_i, T_{i-1}, T_{i-2}, and R_i. The established equation using combined series was used to compute discharge for 2 independent years (2005 and 2006). For both years discharge was computed with high accuracy ($R^2 = 0.96$). The results show that the developed regression equation can be used for computing discharge once its input variables are available.

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