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ORIGINAL ARTICLE

# Decadal Response of Dokriani Glacier using High-resolution Hydrological Data, Indian Himalaya

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## ABSTRACT

**Hydrological studies of glaciers in the Indian Himalaya are very important for understanding the melting processes and assessing the influences of climate change. The diurnal variation in the melt-runoff is controlled by the glacial drainage system. To understand the response of such systems continuous monitoring of hydrological and meteorological data is essential. In the present paper, we have studied the high-resolution data for the assessment of hydrological response of Dokriani Glacier in the upper Ganga basin of Garhwal Himalaya. The data were collected for a period of two years (2011-2012) by establishing an Automatic Weather Station (AWS) and discharge gauging site with the provision of automatic water level recorder (AWLR) near the snout of the glacier. A considerable amount of runoff has been observed at nighttime during the glacial ablation with maximum discharge in the evening and minimum in the morning. The depletion of snow from the glacier surface results into exposure of glacier surface ice and reduction in the holding capacity of water in the glacier. Such variations in the physical condition of a glacier attribute to the changes in the hydrological response of the glacier over time. The effect on the hydrological response has also been studied by analyzing diurnal hydrographs for each ablation month. The hydrological response of the glacier becomes faster with the advancement of the ablation season. Significant changes in the hydrological response of the Glacier are observed over a decade.**

## INTRODUCTION

The high-altitude Himalaya is the origin of many important glaciers and rivers that compose the largest freshwater reserve outside the Polar regions and ensure water supply to millions of people living downstream. The Indian Himalayan Region (IHR) accounts for ~9575 glaciers (Raina and Srivastava, 2008; Sangewar et al., 2009). The snow and glacier melt-runoff play a vital role in making all these rivers perennial, whereas the rainfall contribution during the monsoon is critical for storage in various reservoirs. The summer and spring runoff, comprising mostly of snow and glacier melt is a source of water for irrigation, hydroelectric power production, and drinking water supply (Singh and Jain, 2002; Archer et al, 2010; Gan et al., 2015). The melt water replenishes stock ponds, infiltrates the soils, and recharges groundwater (Tiwari and Sain, 2021; Verma et al., 2021). The water yield of a Himalayan basin is higher than an equivalent basin area located in the peninsular India (Singh et al., 2008). This higher water yield in the Himalayan basins is mainly due to the large contribution from the snow and glaciers. Consequently, hydrological studies of Himalayan glaciers become inevitable because of their importance in planning, designing, and operating water resources and hydroelectric power projects (Singh et al., 2010; Mukhopadhyay and Khan, 2014; Kumar et al., 2018, 2021). Therefore, a large number of hydroelectric schemes in the Himalayan states are already operational and many are under construction/envisaged.

Hydro-meteorological records play an important role in understanding the hydrological processes in glacierized catchments (Singh et al., 2008; Kumar et al., 2018). The magnitude of extreme events occurring at higher altitudes is still unknown, because of the unavailability of hydro-meteorological data sets (Allen et al., 2016; Arora et al., 2016; Kumar et al., 2018; Haritashya et al., 2006; Shea et al., 2015). There is an increased demand for hydro-meteorological records at higher altitudes for controlling extreme climatic conditions and hazards. Recent events such as avalanches, debris flows, cloud bursts leading to rain-induced flash floods, glacial and landslide lake outburst floods pose major threats in paralyzing daily life of people living in the IHR (Kumar et al., 2014; 2019, 2021; Sain et al., 2021; Shugar et al., 2021). The snowmelt-runoff and energy balance models depend on meteorological data, and are indispensable for the reliable management and prediction of melt-runoff and melt-rate, respectively (Singh et al., 2010; Kumar, 2011; Braithwaite, 2009). Therefore, it is necessary to better understand the relations between prevailing meteorological conditions and glacier dynamics (Bollasina et al., 2002; Klok et al., 2005; Pellicciotti et al., 2008). The evolution of the sub-glacial drainage system influences discharge and water chemistry in a pro-glacial stream throughout the ablation season (Fountain, 1993; Gordon et al., 1998; Nienow et al., 1998).

The hydrological response of only a few glaciers has been evaluated using continuous high-resolution (hourly) air temperature and discharge records, which indicate that the magnitude and timing of the melt-runoff depend on the glacier dynamics, size, drainage network, seasonal snow cover, ablation, and accumulation area of a particular glacier (Singh et al., 2004; 2010; Srivastava et al., 2014; Azam et al., 2014). In the IHR seasonal snow begins to melt by the end of the winter season (April) and is almost depleted by the end of June. Ice melt contributes significantly, thereafter, through the sub-glacial drainage system during July and August, along with runoff produced by liquid precipitation falling in the basin (Kumar et al., 2018; Verma et al., 2018; Misra et al., 2020).

A long-term glaciological data is available for mountain regions around the world including Europe, the USA, South America, Canada, New Zealand, and other mountain ranges (Zemp et al., 2009; Li et al., 2010; Gao et al., 2013; Sun et al., 2015; Andreassen et al., 2016; Li et al., 2016), but a handful of glaciers have been continuously monitored in the IHR (DST, 2012; Srivastava et al., 2014; Kumar et al., 2018). The hydro-meteorological records can be used for various aspects of glaciology such as mass balance, melt-runoff modelling, and particularly for the reconstruction of discharge, tree ring, and ice core chronologies (Verma et al., 2018; Misra et al., 2020; Singh et al., 2021). Therefore, the long-term temperature and precipitation distribution patterns, are required to understand the impact of climate change (minimum 30 years) over the Himalayan glaciers. The gaps in data or lack of continuous long-term records for glaciological studies can be addressed by revisiting and monitoring the glaciers earlier studied by the Geological Survey of India (GSI) or other organizations, institutions, and universities. These studies were usually taken up as short-term projects and were discontinued after the completion of the tenure of the project. A revisit of such a glacier can provide a reasonable estimate of the sustainability of the water yield, sediment dynamics, and melt-rate of the catchment for utilization in the downstream regions. For example, the Dokriani Glacier in the upper Ganga basin of Garhwal Himalaya is being monitored since 1992 by Wadia Institute of Himalayan Geology (WIHG), Dehradun, however, there remains large data gaps in the hydro-meteorological time-series owing to the extreme weather conditions, difficulties in maintenance and operations of gauging sites, and occurrence of small flash flood events that damage the gauging site during the ablation season (May-October). Therefore, keeping in view the difficulties and limitations at high altitude locations, high-resolution (hourly) hydro-meteorological observations were taken up during the ablation season for the years 2011 and 2012, to understand the hydrological response of Dokriani Glacier. Further, the earlier study on Dokriani Glacier during 1995-1998 by the National Institute of Hydrology (NIH), Roorkee, is to be compared to get an overview of the changes in the hydrological response over the last 10-15 years.

## STUDY AREA

Dokriani Glacier is being monitored since 1992 and is one of the most studied glaciers in the IHR. The glacier has been monitored for different aspects including mass balance, geomorphology, meteorology, tree-ring chronologies, hydrochemistry, stable isotopes, hazards, etc. (Dobhal et al., 2021; Kumar et al., 2014; 2018; Dobhal and Mehta, 2010; Verma et al., 2018; Tiwari et al., 2018; Hasnain et al., 2001; Thayyen et al., 2005). It is a compound valley type glacier situated in the upper Ganga basin (UGB, Bhagirathi river), Garhwal Himalaya (31°49' N and 78°47' E) at an elevation of 3965–6200 m asl (Fig. 1).

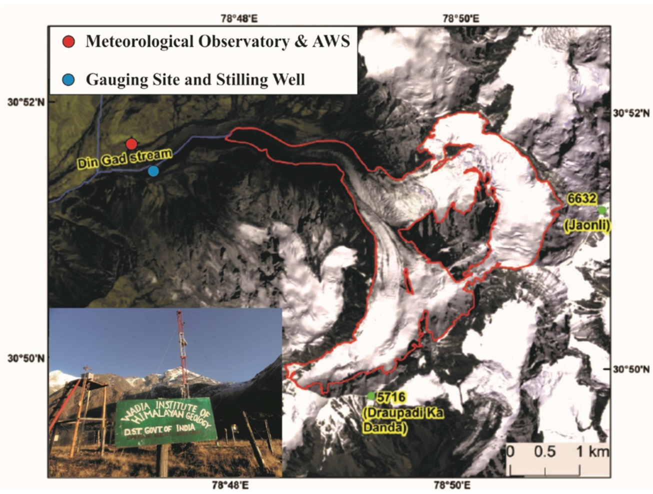


**Fig. 1.** Map showing the study area with locations of conventional meteorological observatory, AWS and gauging site and stilling well for discharge measurement. Inset shows the conventional meteorological observatory and AWS.

The stream originating from Dokriani Glacier is Din Gad, which joins the Bhagirathi river a major tributary of the river Ganga. The glacier is ~5.5 km long and its width varies from ~0.08 km to ~2.5 km. It has a catchment area of ~15 km$^2$ up to the discharge gauging site, of which ~7 km$^2$ is covered with ice and ~4.1 km$^2$ with permanent snow (Singh and Ramasastri, 1999; Kumar et al., 2014). The lower portion of the glacier is covered by supra-glacial debris and lateral moraines (Fig. 2a & b). Material of these moraines is derived from the valley sides through various processes such as debris slides, avalanches, and weathering processes. The glacier is highly fractured and consists of numerous crevasses in the ablation zone.

## MATERIALS AND METHODS

### Meteorological Data Collection and Analysis

Meteorological data over the Dokriani Glacier have been collected by establishing a conventional meteorological observatory on a flat surface near the snout of the glacier since 1995 for the ablation season. A permanent Automatic Weather Station (AWS) was installed in June 2011 at Dokriani Glacier base camp (3774 m asl), with the existing conventional meteorological observatory for obtaining round the clock observations throughout the year (Fig. 2c & d).

The conventional observatory and AWS are equipped with instruments and sensors for air temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WD). The list and details of the conventional instruments and AWS sensors are given in Table 1.

The meteorological data, utilized in this study, are for the years 2011 and 2012. The precipitation (rainfall) data were collected manually using an ordinary rain gauge (ORG), calibrated and prescribed by India Meteorological Department (IMD) daily at 08:30 and 17:30 h according to the procedures followed by IMD (Kumar et

**Table 1.** List of sensors installed in the conventional meteorological observatory and AWS

| Conventional Meteorological Observatory (1995-1998 and 2011-12) | | | |
|---|---|---|---|
| Parameters | Sensors | Accuracy | Height |
| Air temperature | Maximum and Minimum Thermometer | As per IMD | 2m |
| | Dry and Wet bulb Thermo-meter | | 2m |
| Wind Velocity | Anemometer (Speed) | | 2m |
| | Wind Vane (Direction) | | 2m |
| Sunshine Hours | Sunshine Recorder | | 1m |
| **Automatic Weather Station (AWS) (2011-2012)** | | | |
| Air temperature | Rotronic Instru. Corp. (PT100-RTD) | ± 0.1°C | 2 m |
| Relative humidity | Rotronic Instru. Corp. (Hygromer IN-1) | ± 0.8% | 2 m |
| Atmospheric Pressure | RM Young (61302V) | ± 0.3 h Pa | 6 m |
| Wind velocity | RM Young (05103) | ± 0.3 m s$^{-1}$, ± 3° | 10 m |
| Data Logger | (CR – 1000) | ± 0.12% | |
| Rainfall | Ordinary Rain Gauge (ORG) | | Surface |

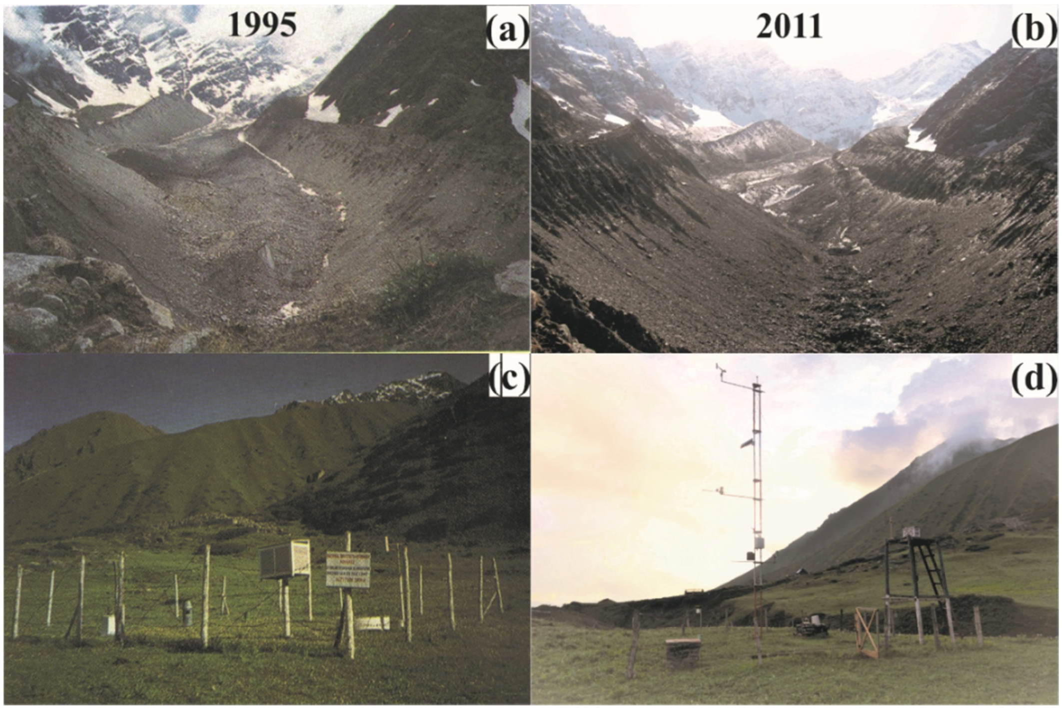


**Fig. 2.** View of snout and ablation zone of Dokriani Glacier in (a) 1995 and (b) 2011, and meteorological observatories established by (c) NIH and (d) WIHG (a & c are from Singh and Ramasastri, 1999).

al., 2014). Further, the meteorological records have been compared to the earlier published study for the period 1995-1998 (Singh and Ramasastri, 1999).

**Hydrological Data Collection and Analysis**

A stilling well and temporary gauging site established by the National Institute of Hydrology (NIH), Roorkee in 1995 for continuous monitoring by a mechanical water level recorder (chart type) along with a manual staff gauge is shown in Fig. 3 a & c. The chart of the water level recorder was changed every day at 8:00 h to obtain continuous 24h water level records. The observations were discontinued after 1998. The velocity area method was used to estimate the discharge in the stream. The cross-section of the stream was measured using a graduated staff from the bridge over the stream.

The measurements of cross-sectional area were repeated throughout the ablation season to reduce the errors. A manual stage was placed in the stream cross-section to read the water level. The surface velocity of the stream was measured by throwing floats in the stream for a 10m section and the time required to cover the distance was recorded. For velocity accuracy, the float readings were repeated at least three times and an average value was adopted for actual measurement. The surface velocity was then multiplied by a constant given for Himalayan streams

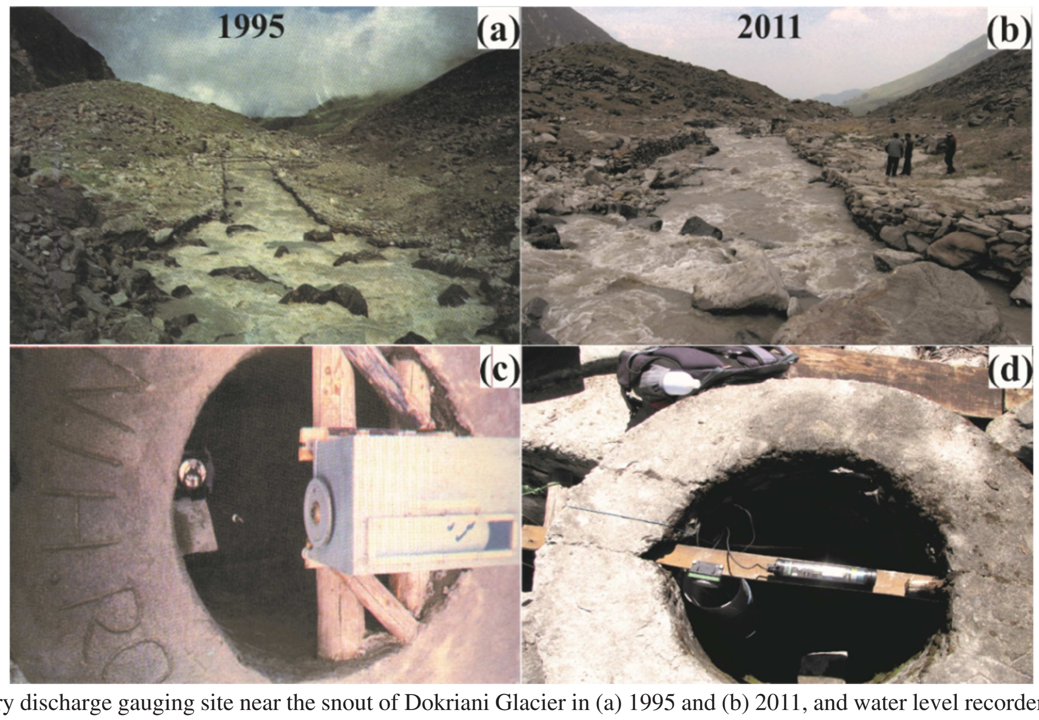


**Fig. 3.** Temporary discharge gauging site near the snout of Dokriani Glacier in (a) 1995 and (b) 2011, and water level recorders installed by (c) NIH and (d) WIHG . (a & c are from Singh and Ramasastri, 1999).

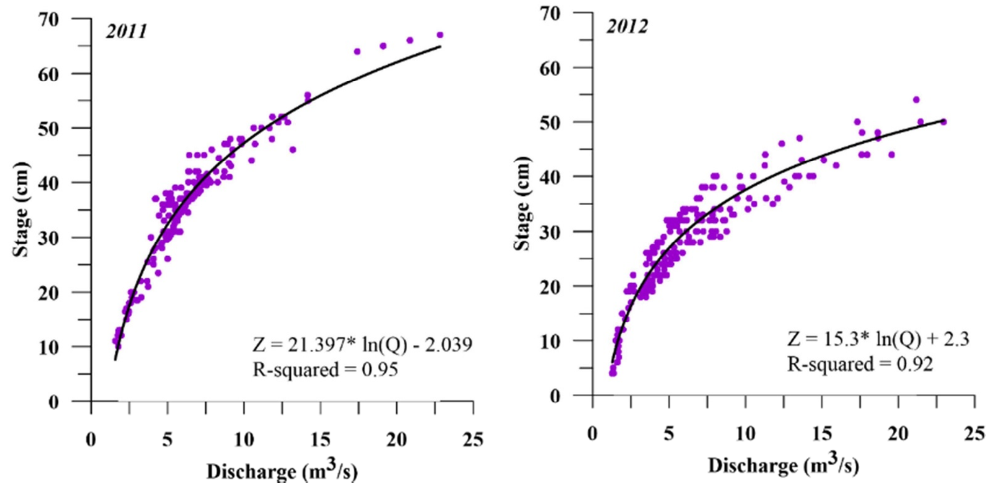


**Fig. 4.** The stage-discharge relationship developed for Din Gad stream (Dokriani Glacier) for the year 2011 and 2012.

to calculate the mean velocity of the stream (Singh et al., 2003; Thayyen et al., 2005). The manual observations were taken at 8:00 and 17:00 h (Kumar et al., 2014).

The existing discharge gauging site (temporary) of NIH was repaired with the use of stone walls and sandbags along the banks of the stream such that all the meltwater flows through the channelized section. The stilling well was operationalized by removing the silt deposited in 2011 and was used to install a digital water level recorder (OTT SE 200 float-operated shaft encoder level sensor and data logger) for high-resolution (hourly) water level records (Fig. 3 b & d). Also, the large boulders transported by the stream were removed from the channel to get laminar flow, as far as possible. A manual staff gauge was also installed for water level readings. The calculation of discharge was carried out using the area-velocity method as described earlier. A rating curve or stage-discharge relationship was developed using high and low flow data for the calculation of discharge with logarithmic equations shown in Fig. 4.

## RESULTS AND DISCUSSION

### Distribution and Variability in Meteorological Conditions

Air temperature records are considered to be the best for the modelling of glacier hydrological processes, especially used as a pre-requisite for snowmelt and energy balance computations. In the present study, the mean monthly values of air temperature were computed from the combined time series for the years 2011-2012. In this study, the average minimum, maximum and mean for the ablation season were observed to be 4.6, 12.8 and 7.7 ºC, respectively for the ablations seasons 2011-2012. The temperatures during the ablation season are much higher than the freezing point, which regulate the melt generation process. Similarly, the mean monthly maximum temperatures for June to September were 14.6, 14.0, 13.6, and 13.4 °C respectively, whereas mean monthly minimum temperatures for these months were 4.8, 7.7, 7.6, and 5.0°C respectively. The maximum and minimum temperatures for the entire ablation season are 18.5° and 0.3ºC, respectively. The monthly distribution of air temperature is given in Table 2. The air temperatures (minimum, maximum and mean) for the years 2011-2012 are comparable to previous studies during 1995-1998 and 2010-2011, with some variations (Singh and Ramasastri, 1999; Kumar et al., 2014). No major difference was observed in the data, collected from conventional and automatic observatories apart from the fact that automatic weather stations provide high-resolution data (hourly or better). The minimum temperature remains positive during the ablation season throughout the diurnal scale (Fig. 5 and 6). In high altitude regions, wind plays an important role in the transport of moisture, formation of clouds and occurrence of precipitation as well as for the melting of glaciers. The monthly mean wind speeds for June to September were 1.5, 1.1, 1.1 and 1.2 km/h, respectively and the average wind speed for the whole season was 1.3 km/h. The maximum wind speed over the entire ablation season was 2.2 km/h, while on the diurnal scale, the maximum recorded wind speed is 2.5 km/h. The mean atmospheric pressure during the ablation season was 645.7 hPa, while the maximum and minimum atmospheric pressure were 650.3 and 642.4 hPa during September and June, respectively. The monthly variations are given in Table 2. The low pressure at the beginning and higher at the end of the ablation season represent the atmospheric conditions for the onset and retreat of the Indian summer monsoon (ISM).

The most typical feature of the study area is the occurrence of rain throughout the ablation season. The monthly total rainfall for the years 2011-2012 at Dokriani Glacier is shown in Table 2. It is observed that the maximum rainfall occurs during August. The maximum daily rainfall recorded over the two ablation seasons is 71.5 mm. The previously published data for the years 1995–1998, shows an average total rainfall of 1041.0 mm during the ablation season (June-September) as compared to 1309.0 mm for 2011–2012. However, rainfall has the highest variability among the meteorological parameters (Kumar et al., 2021). Thus, it would be incorrect to state that the

**Table 2.** Mean monthly distribution of meteorological data during ablation season at Dokriani Glacier for the years 2011-2012

| Months | | Tn (ºC) | Tx (ºC) | Tm (ºC) | WS (km/h) | P (hPa) | R (mm) |
|---|---|---|---|---|---|---|---|
| Jun | Mean | 4.8 | 14.6 | 8.6 | 1.5 | 644.3 | 170 |
| Jul | | 7.7 | 14.0 | 10.1 | 1.1 | 644.9 | 343.2 |
| Aug | | 7.6 | 13.6 | 9.8 | 1.1 | 646.2 | 575.7 |
| Sep | | 5.0 | 13.4 | 8.1 | 1.2 | 647.3 | 197.95 |
| Jun-Sep | | 6.3 | 13.98 | 9.2 | 1.2 | 645.7 | 1309.7 |
| Jun | Max. | 8.1 | 18.5 | 11.0 | 2.2 | 646.9 | 25.5 |
| Jul | | 9.3 | 17.7 | 11.6 | 1.4 | 647.2 | 32.2 |
| Aug | | 9.3 | 16.9 | 11.6 | 1.4 | 648.5 | 71.5 |
| Sep | | 7.8 | 16.3 | 10.7 | 1.6 | 650.3 | 21.6 |
| Jun-Oct | | 9.3 | 18.5 | 11.6 | 2.2 | 650.3 | 71.5 |
| Jun | Min. | 2.0 | 9.0 | 4.5 | 1.1 | 642.4 | 0.15 |
| Jul | | 5.8 | 11.6 | 8.6 | 0.8 | 643.0 | 0.8 |
| Aug | | 5.8 | 10.9 | 8.7 | 0.8 | 643.8 | 1.8 |
| Sep | | 0.3 | 10.7 | 3.8 | 0.9 | 644.6 | 0 |
| Jun-Oct | | 0.3 | 9.0 | 3.8 | 0.8 | 642.4 | 0.0 |

(Tn – Minimum Temperature; Tx – Maximum Temperature; Tm – Mean Temperature; WS – Wind Speed; P – Pressure; R –Total Rainfall)

rainfall has increased as compared to previous records (1995-1998).

**Distribution and Variability in Hydrological Data**

Hydrological records provide information about glacial ablation through the characteristics of water flow. The main sources of runoff from the Dokriani Glacier are derived from the melting of ice, snow and rainfall. The contribution of rainfall in the study region is less as compared to the total discharge. Therefore, most of the meltwater is generated from the melting of ice and snow. The supra-glacial and englacial systems are fragile and respond faster to any changes in the surroundings, while the sub-glacial system is resistant to changes. Discharge variations occur on hourly, daily and annual scales, however, these variations are irregular due to variable weather conditions and extreme events. Changes in discharge on the diurnal scale for different months for the years 2011 and 2012 are depicted in Fig. 7. The minimum, maximum and mean hourly discharge over the ablation seasons 2011 and 2012 were 14.9, 47.4, 32.9 $m^3/s$ and 18.0, 39.9, 29.3 $m^3/s$, respectively. The maximum discharge was observed in July and August for the years 2011 and 2012, respectively. While the minimum discharge was observed during September for both years (Fig. 5 and 6).

Further, it is generally observed that discharge starts rising from May, reaches its maximum in July or August and then starts declining (Srivastava et al., 2014; Kumar et al., 2018). The discharge variation consists of a cycle of rising and falling flow, which is almost flat during the early and later part of ablation season. Rising and falling limbs of the hydrograph become steeper with the advancement of the ablation season and are always steeper than the recession limb (Singh et al., 2003). These variations are also visible in the hourly data collected for the years 2011 and 2012 (Fig. 7). The diurnal variations in the hydrograph as the ablation season progresses are controlled by the changes in the physical features (Schuler et al., 2004). The diurnal fluctuation of discharge in this basin at the beginning of the ablation season is less noticeable. This may be because of the depth and extent of the snow cover in the basin, which reduces the generation of melt-runoff i.e. the snow and glacier melt shows a delayed response because the meltwater has to pass through the snowpack and flows between the snowpack and the ground surface.

The distribution of hourly discharge indicates that maximum discharge is observed in the evening from 1700 to 2200 h and minimum discharge in the morning from 0900 to 1200 h for both years, showing a lag of 5 hours in the timing of maximum discharge over the ablation season (Fig. 7). The time to peak discharge varied from 8 to 10 hours. The previous study for the years 1995-1998 for cloud-free days indicated a lag time of 2 hours and time to peak of 8.5 to 11 hours (Singh et al., 2003). These changes may be attributed to the major morphological changes to the drainage system as well as a significant increase in the supra-glacial debris cover (Fig. 2a & b). It has been observed that melt-runoff delay varies with the intensity and maturity of the snow and firn on the glacier. The occurrence of maximum discharge in streams from glaciers like Dokriani, Dunagiri and Gangotri in the evening suggests that a major part of the meltwater produced during the day reaches the snout/gauging site after few hours (Singh et al., 2003; 2005a, b; 2010; Srivastava et al., 2014). This indicates that the glacier stores a part of the meltwater produced during the day and gradually releases it during the night. Similar findings on meltwater storage characteristics and evolution of englacial and sub-glacial drainage have been reported from glaciers of Norway, Sweden, Tibet, and Canada (Hooke et al., 1988; Hodgkins, 2001; Jansson et al., 2003; Jobard and Dzikowski, 2006; Qiao and Shiyin, 2009; Weigang et al., 2010).

**Hydrological Response with Meteorological Conditions on a Diurnal Scale**

The processes governing the hydrology of glaciers on daily to monthly scales provide limited information on the underlying factors responsible for the complexity in the system. Therefore, the assessment of hourly hydro-meteorological data was done at a daily scale for the entire ablation season. The hourly hydro-meteorological data of the entire ablation season for the years 2011 and 2012 are shown in Figs. 5 and 6, respectively. Multiple peaks of high discharge are

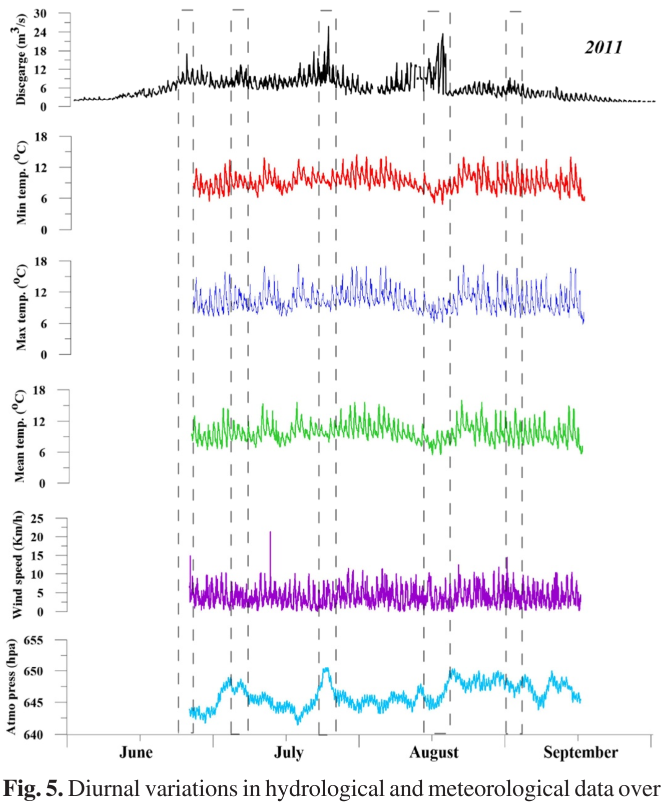


**Fig. 5.** Diurnal variations in hydrological and meteorological data over Dokriani Glacier collected during the year 2011.

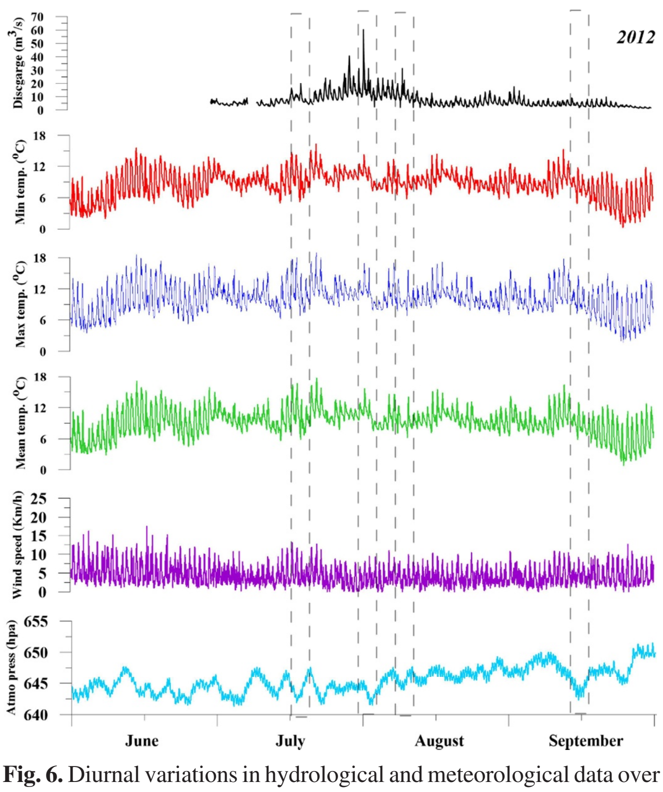


**Fig. 6.** Diurnal variations in hydrological and meteorological data over Dokriani Glacier were collected during the year 2012.

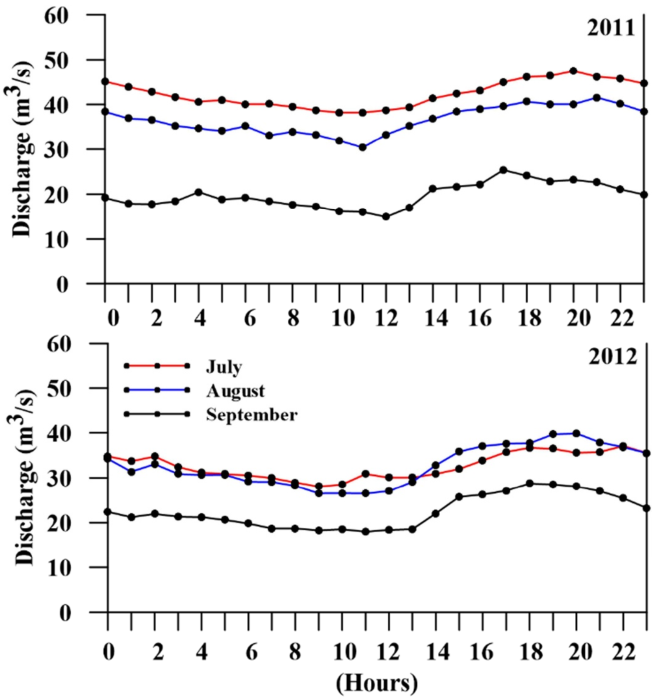


**Fig. 7.** Mean monthly diurnal variations in the discharge of Dokriani Glacier for the years 2011 (top) and 2012 (bottom). The 0 h represents midnight and the last point is 2300 h of the same day.

observed in both years, which have been discussed in detail to understand the control of meteorological parameters on the hydrological response of the Dokriani Glacier.

Although the unavailability of hourly rainfall severely hampers the interpretation of the hydrological data at an hourly scale, the authors utilize atmospheric pressure as a proxy for any major storm or rainfall event. It is evident from the analysis that most of the high discharge peaks correspond to low-pressure values in the region, either preceding or at the same time (Fig. 5 & 6). The high discharge peaks during the year 2011 are observed on 26th June (1800 h), 7th July (1900 h), 25th July (2100 h), 18th August (0900 h) and 1st September (0400 h). The event of 25th July corresponds to high pressure, however, a major low pressure is preceding the event with the lowest air pressure of the ablation season. Further, the delay in the hydrological response is visible in the early and mid-ablation season as compared to the end of the ablation season. Diurnal variations in discharge followed diurnal variations in temperature with a certain lag. The air temperature was the most important factor along with cloud conditions.

Similarly, for the year 2012 the high discharge peaks are observed on 20th July (2100 h), 30th July (2100 h), 2nd August (1900 h) and 10th August (1900 h). These events also correspond to the low pressure and high-temperature conditions leading to higher rate of melting and a short lag-time. While a rapid reduction in discharge was observed on 16th September (0700 h), this rapid reduction in the discharge towards the end of the ablation season could be due to low-temperature conditions or snowfall event. Also, a change from clear skies to overcast conditions may result in the reduction of the ablation rate with an immediate reduction in the daily peak discharge during the early and late ablation season (June and September).

## CONCLUSIONS

The hydrological response of Dokriani Glacier during the ablation season has considerable variations from previous studies carried out 12-15 years before, with an increase in the lag-time as well as time to peak discharge. Such changes could be attributed to the recession of the glacier, increase in debris cover as well as other morphological changes in the drainage system of the glacier. The maximum number of high discharge peaks are observed during the late evening or night-time, indicative of meltwater generation and flow that regulate the evolution of the glacier drainage system and meteorological conditions. The hydrological response of the glacier is observed at monthly and daily scales using high-resolution (hourly) data sets, while these characteristics of the glacier response are weakened using coarser data sets. Further, several extreme events like heavy rainfall, flash floods, etc., are not distinguished in the manual data sets. To better understand the runoff generation trends and their year-to-year variability, a long-term continuous discharge observations are required including observations on the energy balance components (e.g. short-wave, long-wave and net radiation) over the glacier surface. It is suggested that a broader database must be established for the Dokriani Glacier, using a non-contact water level recorder (radar-based), as there is uncertainty in the measurement of discharge with contact type water level recorders.

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