ORIGINAL ARTICLE

Melt Runoff Characteristics and Hydro-Meteorological Assessment of East Rathong Glacier in Sikkim Himalaya, India

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Abstract

Hydro-meteorological records of glacier meltwater are very limited in the Indian Himalayan region, especially in the Sikkim Himalaya. Hydrological data coupled with meteorological parameters (temperature, rainfall and humidity) of a catchment facilitate in understanding the dynamics of glacier's meltwater generation at a local scale. Sikkim Himalaya, an integral part of eastern Himalaya lacks the hydro-meteorological assessment of glacier's meltwater stream. Therefore, hydro-meteorological analysis of East Rathong Glacier was conducted for three consecutive ablation seasons (June–September) from 2013 to 2015. The data record a maximum runoff during the peak ablation month of July and August (~69%), reflecting the seasonal evolution of hydrologic conduits and the expansion of subglacial channels, and the rest runoff observed during June (~10%) and September (~21%). During the study period, the maximum (Q_{max}) and minimum runoff (Q_{min}) of 15.71 and 1.46 m^{3}s^{-1}, respectively were recorded at 17:30 and 9:30 h. The maximum monthly variability in meltwater discharge was recorded in June (Cv = 0.29) and September (Cv = 0.37), which reflects the role of the large extent of seasonal snowfall during early ablation and the seasonal evolution of sub-glacial internal drainage networks in the glacier, respectively. We found that the variability in mean (T_{mean}) and maximum temperatures (T_{max}) has been increased over the subsequent months during the progress of the ablation season with the highest variability in minimum temperature (T_{min}) during the end of the ablation season. The correlation matrix analysis shows significant hydro-meteorological relationships of glacier's meltwater discharge (Q) with the minimum temperature (R^2 = 0.43), maximum temperature (R^2 = 0.93), mean temperature (R^2 = 0.93), Rainfall (R^2 = 0.99) and Relative humidity (R^2 = 0.77), suggesting the substantial meteorological influences in producing meltwater discharge at monthly scale. The present in-situ observation on hydro-meteorological characteristics of East Rathong Glacier can be used effectively for the hydrological modelling of freshwater resources (Glaciers) which further contribute to the freshwater management under a changing climate.

Keywords Meteorological data · Stage-discharge relationships · Glacier's melt runoff · Hydro-meteorological interrelations · East Rathong Glacier

1 Introduction

The Hindu Kush Himalaya (HKH) region is not only the greatest mountain system on the Earth, but also a critically crucial geo-ecological asset of south Asia and also referred to as the 'Third pole' (Bolch et al. 2019). The glaciers of HKH encompass over 4.2 million km^2 area and are the source of ten major river basins. The HKH glaciers cover ~ 59 × 10^3 km^2, out of the world's total of ~ 540 × 10^3 km^2 mountain glacier area (Dyurgerov and Meier 1997, 2005). In the Indian Himalayan Region (IHR), there are ~ 10,000 glaciers excluding the ~ 2000 in Nepalese and Bhutanese Himalaya (Bajracharya et al. 2015; Bajracharya and Shrestha 2011; Raina and Srivastava 2008). It is also

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reported that ~80% of the freshwater supply on Earth originates from the mountain regions (Barry and Chorley 1998) and about half of all human population directly depends on mountain resources, primarily water. Mountains support ~25% of the world's terrestrial biodiversity and nearly half of the world's biodiversity 'hotspots' (Bolch et al. 2019). The resources provided by the mountains include freshwater from the glaciers, hydroelectricity, timber, biodiversity and niche products, mineral resources, recreation, and flood management (Molden and Sharma 2013; Schild and Sharma 2011).

In general, the Himalayan region is experiencing a warmer climate; however, the trend of increasing temperature in the Himalayan region is more than the global averages (Ali et al. 2018; IPCC 2014; Shrestha et al. 1999). Most of the glaciers worldwide including the Himalayan glaciers have been retreating due to rising temperature (Bolch et al. 2012; Gardelle et al. 2013; Kääb et al. 2012; Shea et al. 2015a) except in the Karakoram Range where surging glaciers have been reported (Bhambri et al. 2013; Copland et al. 2011; Quincey et al. 2015). Although in general, the Himalaya is witnessing glacial retreat, however, there are suggestions that the impact of climate change is likely to be more severe in the most critical region like Indus and Brahmaputra basins. These areas have an expanding population and highly depends on irrigation through meltwater (Barnett et al. 2005; Immerzeel et al. 2010). Further, the hydrology of headwater catchments in the Himalaya is expected to be affected significantly by the ongoing changes in temperature and precipitation patterns (Immerzeel et al. 2009).

In the Himalayan region, increased stream and river discharges due to glacier's retreat have played a substantial role causing floods in the downstream areas. Besides the threats imposed by the probability of glacial lake outburst flood (GLOF) due to glacier's retreat (Sharma et al. 2018; Sattar et al. 2020; Bajracharya et al. 2007; Ives et al. 2010; Ashraf et al. 2012; Shijin et al. 2015), high upstream river flow has also contributed to fluvio-tidal floods, inundating the low lying coastal areas during the monsoons (Adnan et al. 2019b; Haque et al. 2018). Also, the increased runoff due to monsoonal precipitation has added to flash floods both in the Himalayan (Dobhal et al. 2013; Allen et al. 2015) and the coastal region (Adnan et al. 2019a).

The ongoing increase in temperature has shown enhanced streamflow of major rivers in the Himalayan region suggesting a positive relationship between climatic variables and the streamflow (Schar et al. 2004; Singh et al. 2006; Singh et al. 2016b; Srivastava et al. 2014). Therefore, it is essential to understand and establish different strategies of flow forecasting for the effective management of water resources in the region (Archer and Fowler 2008). In the Himalaya, the high climate variability, limited data, large uncertainties in climate change projection, and ambiguity on the response of glaciers, suggest an intricate pattern of the impact of climate change on the hydrology of glacierized catchments (Immerzeel et al. 2012). Further, it becomes more troublesome as the meteorological observations at high-altitude regions of the Himalaya are extremely meagre (Shea et al. 2015b; Singh et al. 2016a) that affects the in-situ-based scientific deliberations.

Sikkim Himalaya being an integral part of eastern Himalaya, records ~84 Himalayan glaciers located mostly in west and north districts (Glacier Atlas of Tista Basin-Sikkim Himalaya 2001) covering an area of 883 km^2 that account for 12% of total geographical area (Aggarwal et al. 2017). The records of a widespread increase in temperature from the Sikkim Himalaya are available (Sharma and Shrestha 2016; Telwala et al. 2013); however, the study on temperature-induced effects and the assessment of hydro-meteorological impacts on glaciers are absent. This limitation may be attributed to the harsh climate, rugged and steep terrain, remote location of glaciers and inadequate capacities to carry out in-situ glacio-hydrological investigations. Only a few studies have been conducted in Changme Khangpu glacier during the 1980s and 1990s (Nijampurkar et al. 1985; Nijampurkar and Rao 1993; Puri 1999). Besides, only a few reports on the mass balance of the East Rathong Glacier (Agrawal and Tayal 2015) and glacial hazard assessments of South Lhonak glacial lake (Sharma et al. 2018; Sattar et al. 2019) are available. Sikkim Himalaya is drained by two major rivers (Tista and Rangit). These rivers are significantly contributed by the snowmelt and glacial melt in the higher reaches; despite, the hydro-meteorological processes of the glacier meltwater has not been investigated till date. Data on the contribution of glacier's melt to the streamflow during the melting season in the eastern Himalayan region is minimal and requires an in-depth investigation to understand essential insights of hydrological processes in a global warming perspective in the Sikkim Himalaya. Therefore, the present study aims at characterizing the hydrological responses and their interrelations with the meteorological variables during the three consecutive melt seasons (2013–2015) in East Rathong Glacier. Our primary focus is to understand and address (1) the distribution and variability in the meteorological variables in the glaciated terrain (2) the distribution and variability in glacier melt runoff, and (3) the hydro-meteorological interrelationships between the glacier's melt runoff and meteorological variables.

2 Material and Methods

2.1 Study Area

The East Rathong Glacier (88º 06′ 27.63″ E and 27º 34′ 54.44″ N) with Geological Survey of India (GSI glacial

inventory) ID East-Rathong 007 (Sangewar and Shukla 2009) is a valley type glacier with an average width of ~ 800 m (Fig. 1). The glacier is a south-east facing and is one of the sources of the Rangit river flowing through the west district of Sikkim in Kanchenjunga National Park. The glacier site can be reached after a 3-day trek from Yuksam, the last motorable village in western Sikkim. The main glacier occupies an area of ~ 4.8 km² and has a length of ~ 7 km (altitude range ~ 4600–6700 m asl). The total catchment area of East Rathong Glacier up to the gauging site is estimated to be ~ 19.8 km² (Fig. 1b). The glacier descends from its headwall with a steep gradient, while the slope is moderately gentle in the ablation area (Figs. 1c, 2).

2.2 Measurements of Meteorological Variables

In-situ meteorological observations are crucial in understanding the process of meltwater discharge in any

glacierized area. Hence, a meteorological observatory has been installed at an elevation of 4640 m asl (close to the gauging site) about ~ 0.8 km downstream of the present-day glacier's snout. The observatory is equipped to monitor meteorological variables viz. air temperature, rainfall and relative humidity. The details of the hydro-meteorological sensors used and the frequency of data acquisition is listed in Table 1. Similar hydro-meteorological variables have been used in several studies from other locations in the Himalaya (Kumar et al. 2014, 2016; Shea et al. 2015b; Singh et al. 2006; Singh et al. 2016b). We recorded a series of meteorological data during the ablation seasons (2013–2015) parallel to the records of hydrological variables except for the temperature and humidity data for 24/07/2013 to 23/08/2013 due to malfunctioning of the Thermo-hygrometer sensor. The rainfall data are manually measured with the help of an ordinary rain gauge (ORG) following the guidelines of the Indian Meteorological Department (IMD).
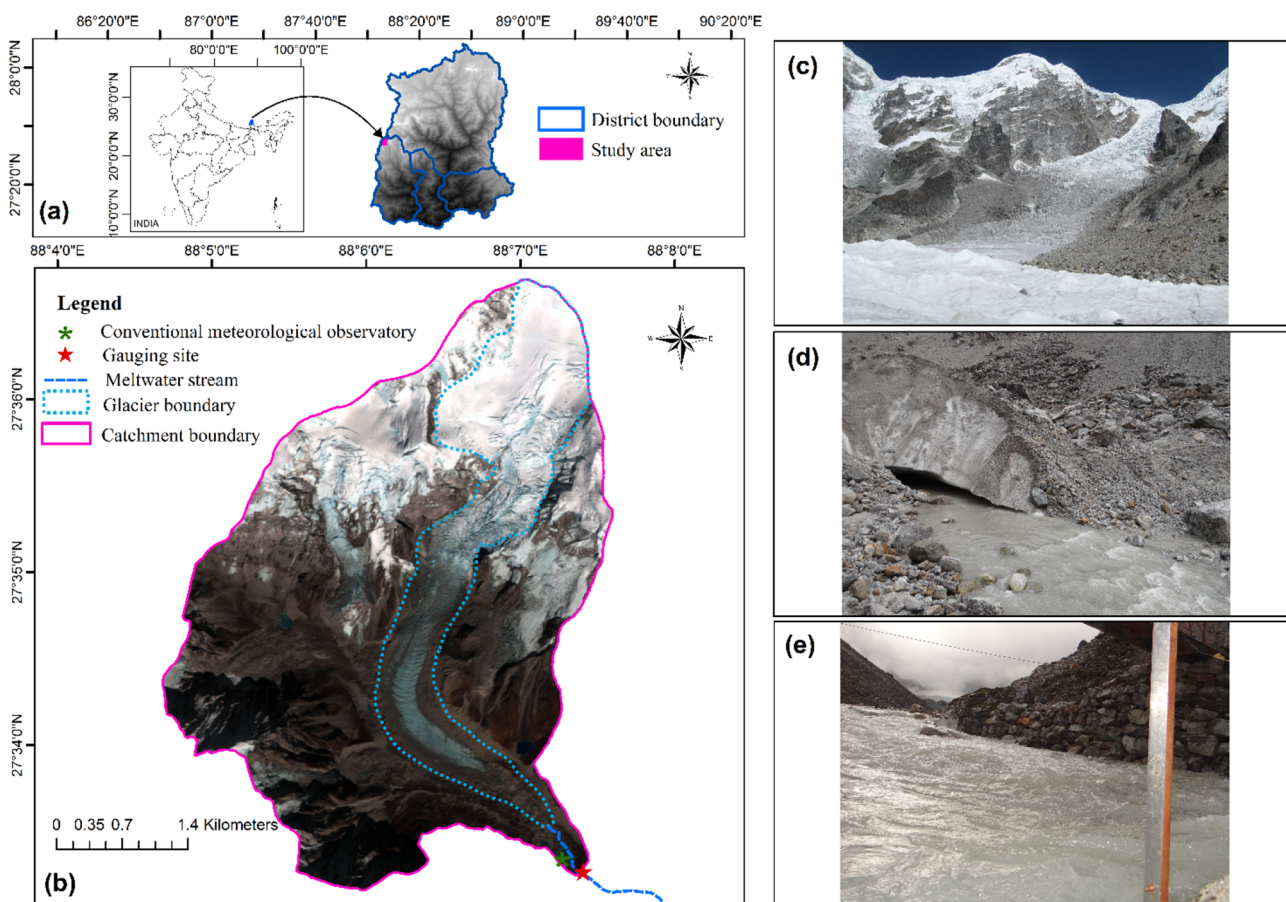

Fig. 1 **a** Study area in Sikkim Himalaya, **b** LISS IV imagery (Source: State Remote Sensing Applications Centre-Sikkim) showing the detail view of study area up to the gauging site, **c** pictorial view of East Rathong Glacier, **d** its snout during 2013 and **e** discharge gauging site below the snout

Fig. 2 Bar chart showing area-elevation distribution of the East Rathong Glacier's catchment. The number in Bar showing percentage distribution of area in different elevation zones
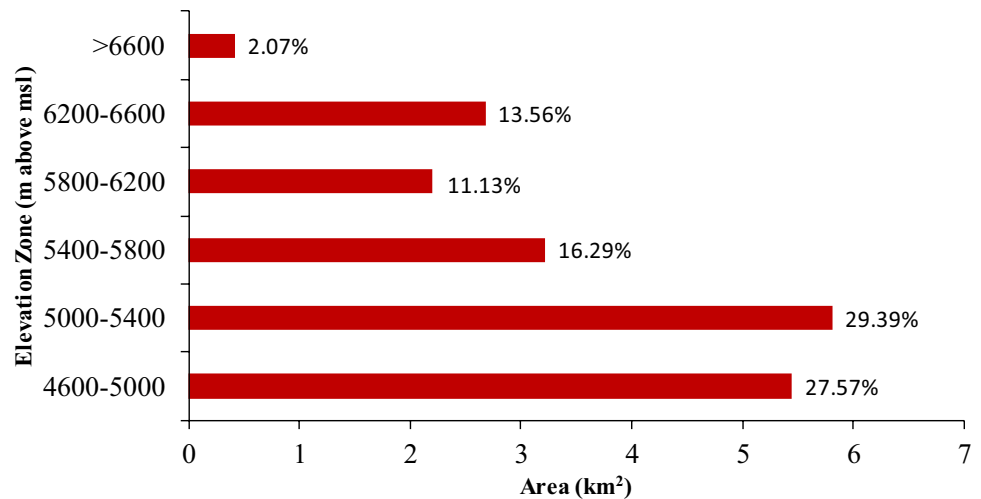

Table 1 Hydro-meteorological (conventional) observatory installed near the gauging site of East Rathong Glacier

Sl. no.	Observations	Instruments/sensors	Frequency
1	Temperature	Thermo-hygrometer (Lutron HT-305)	5:30, 9:30, 13:30 and 17:30 h
2	Rainfall	Ordinary rain gauge	8:30 and 17:30 h
3	Humidity	Thermo-hygrometer (Lutron HT-305)	5:30, 9:30, 13:30 and 17:30 h
4	Water level	Manual water level gauge	5:30, 9:30, 13:30 and 17:30 h
5	Dry and wet bulb temperature	Dry and wet bulb thermometer	5:00 to 23:00 h

Time is in Indian Standard Time (IST) Zone

2.3 Measurements of Hydrological Variables

The data on hydrological variables (water level and flow velocity) have been recorded for the ablation season (June–September) for the years 2013–2015. A water discharge gauging site was established (June 2013) ~ 0.8 km downstream of the present-day East Rathong Glacier's snout at an altitude of ~ 4640 m asl (Fig. 1e). The gauging site was repaired and maintained every year to keep a low turbulent flow. As the geometry of stream bed during ablation season is highly variable due to high erosion and bedload, therefore, water levels were recorded using a manual gauge installed at the gauging site to estimate cross-sectional measurements of the stream (Kumar et al. 2018a). The water velocity measurements (surface velocity) were carried out by float method, where the wooden floats were used to record the float readings, and the readings were repeated five times to increase the data accuracy (Kumar et al. 2014). The average value of the readings was adopted for further computations (Srivastava et al. 2012, 2014). Time taken by float to cross 5 m distance at different points of the cross-section was recorded using a stopwatch. From the time readings of floats, we calculated the average time for further analysis. The Surface velocity was calculated using Eq. 1:

$$Surface\ Velocity = \frac{D}{T_{fd}}, \tag{1}$$

where D is the fixed distance (5 m) and T_{fd} is the time taken by float to cover the fixed distance.

A constant factor of 0.85 was used to compute mean flow velocity from surface velocity, used for Himalayan streams (Bhutiyani 2000; Kumar et al. 2016; Ostrem 1964; Singh et al. 2011). The area-velocity method was used for estimating the discharge in the stream (Kumar et al. 2014). Discharge measurements were carried out four times a day at 5:30, 9:30, 13:30 and 17:30 h. The possibilities of manual errors in the discharge measurements are expected to be ± 5% (Singh et al. 2006; Srivastava et al. 2012).

2.4 Establishment of Stage-Discharge Relationship (Rating Curve)

Consistent measurement on cross-sections of the glacial stream is essential, as river bed geometry is naturally variable owing to the high erosion and bedload observed during the ablation season. Therefore, cross-sectional measurements were carried out using a manual gauge. The rating curves have been established using the continuous values of water level (stage) and discharge throughout the ablation

seasons (2013–2015). The accuracy for a similar type of measurement in the Himalayan region is up to ±10% (Bhutiyani 2000; Kumar et al. 2016; Singh et al. 2006). An empirical relation between discharge and the water level (stage) was developed for East Rathong Glacier for the ablation seasons by fitting techniques (Kumar et al. 2016). The stage-discharge relationship is an essential component to estimate discharge from any other catchment (Guerrero et al. 2012; Kumar 2011; Kumar et al. 2014). The possibilities of error in the rating curve are ±5% observed from similar types of glacierized catchments in other parts of Himalaya (Kumar et al. 2014, 2016; Srivastava et al. 2012).

2.5 Measurements of Variability of Hydro-Meteorological Variables

Both monthly and seasonal variability of hydro-meteorological variables was determined using the daily data collected during the ablation seasons of 2013–2015. We have used the Coefficient of variation (Cv) as a measure of variability (Kumar et al. 2018a; Singh et al. 2006). Cv is the ratio of standard deviation (σ) to the mean (M) that allows dimensionless comparison of variables (Brown 1998).

2.6 Measurements of Hydro-Meteorological Interrelationships

Hydro-meteorological interrelationships of meltwater discharge with meteorological variables at daily as well as the monthly scale were defined by obtaining Correlation coefficient values (R^2) using correlation matrix. Correlation matrix is a useful statistical procedure to measure the strength of relationships between the hydro-meteorological variables. A similar analytical method has been applied in many hydro-meteorological studies in the Himalayan glaciers (Kumar et al. 2016, 2018a, b) to understand the functional relationships between the variables.

3 Results

3.1 Distribution of Meteorological Variables

3.1.1 Air Temperature

Air temperature is one of the critical factors governing the melting process of the glacier (Kumar 2011; Srivastava et al. 2014). Daily variations in T_{max}, T_{min}, and T_{mean} for the ablation seasons of the study area during 2013–2015 is given in Fig. 3. The daily mean T_{min} and T_{max} over the combined ablation season (2013–2015) were ~2.95 °C and ~10.44 °C, respectively, with a T_{mean} of ~7.42 °C (Table 2). During the study period (three ablation seasons), the lowest records

of T_{min} was ~1.0 °C and the highest T_{max} of 15.6 °C was recorded near the snout of East Rathong Glacier. Daily T_{max} was recorded at around 12:00–1.30 h, while the T_{min} was recorded between 5:00–6:00 h. The monthly variation in temperature is given in Fig. 4. The temperature analysis shows that July and August marked a relatively higher temperature than June and September. The monthly mean T_{max} for June–September were recorded as 10.97, 11.20, 10.51 and 9.33 °C, respectively, whereas the monthly mean T_{min} were 4.95, 2.90, 2.93 and 2.01 °C, respectively. The subsequent monthly mean T_{mean} for the consecutive ablation seasons (2013–2015) were recorded as 7.88, 7.80, 7.58 and 6.49 °C, respectively. The year-wise seasonal monthly mean temperature recorded for June–September of 2014 and 2015 were 7.87, 7.72, 7.52 and 6.35 °C and 7.36, 7.50, 7.50 and 6.66 °C, respectively. Subsequently, in the year 2013, the seasonal monthly mean temperature recorded for July–September were 8.91, 8.54 and 5.72 °C, respectively (Fig. 4).

3.1.2 Rainfall

The daily distribution of rainfall during the ablation seasons (2013–2015) is given in Fig. 3. The rainfall records near the snout of East Rathong Glacier demonstrate that July recorded the maximum intensity of rainfall. The maximum rainfall occurred with an intensity of 44.5, 34.75 and 31.25 mm, whereas the minimum rainfall occurred with an intensity of 0.75, 0.25 and 0.25 mm. The daily rainfall amount ranged between 0.25 and 44.5 mm. The seasonal mean rainfall during the year 2013–2015 were 10.88, 10.09 and 9.45 mm, respectively. During 2013, the monthly mean rainfall (June–September) was 8.25, 15.51, 12.34, and 5.04 mm, respectively; and for the year 2014, it was 10.02, 11.63, 9.55, and 7.07 mm, respectively, while for 2015, the mean rainfall was 12.25, 9.06, 11.10 and 7.31 mm, respectively (Fig. 4). The data suggest that the East Rathong Glacier's catchment experienced the maximum amount of rainfall in July (37.04%), followed by August (33.76%). In contrast, during June and September, the rainfall was comparatively lesser (9.96% and 19.24%, respectively). The total seasonal rainfall for the ablation seasons (2013–2015) was 1056, 1019 and 955 mm, respectively, with a total mean rainfall of 1009.83 mm (Table 2). It has also been observed that ~51.58% of total rainfall occurred at night.

3.1.3 Relative Humidity

Relative humidity of an area depends on temperature and the pressure prevailing in that particular area. In the present study, the daily relative humidity ranged from 63 to 99% during the ablation seasons (Fig. 3). During the study period, the monthly mean relative humidity from June to September was ~78.9, 82.1, 80.1 and 79.0%, respectively
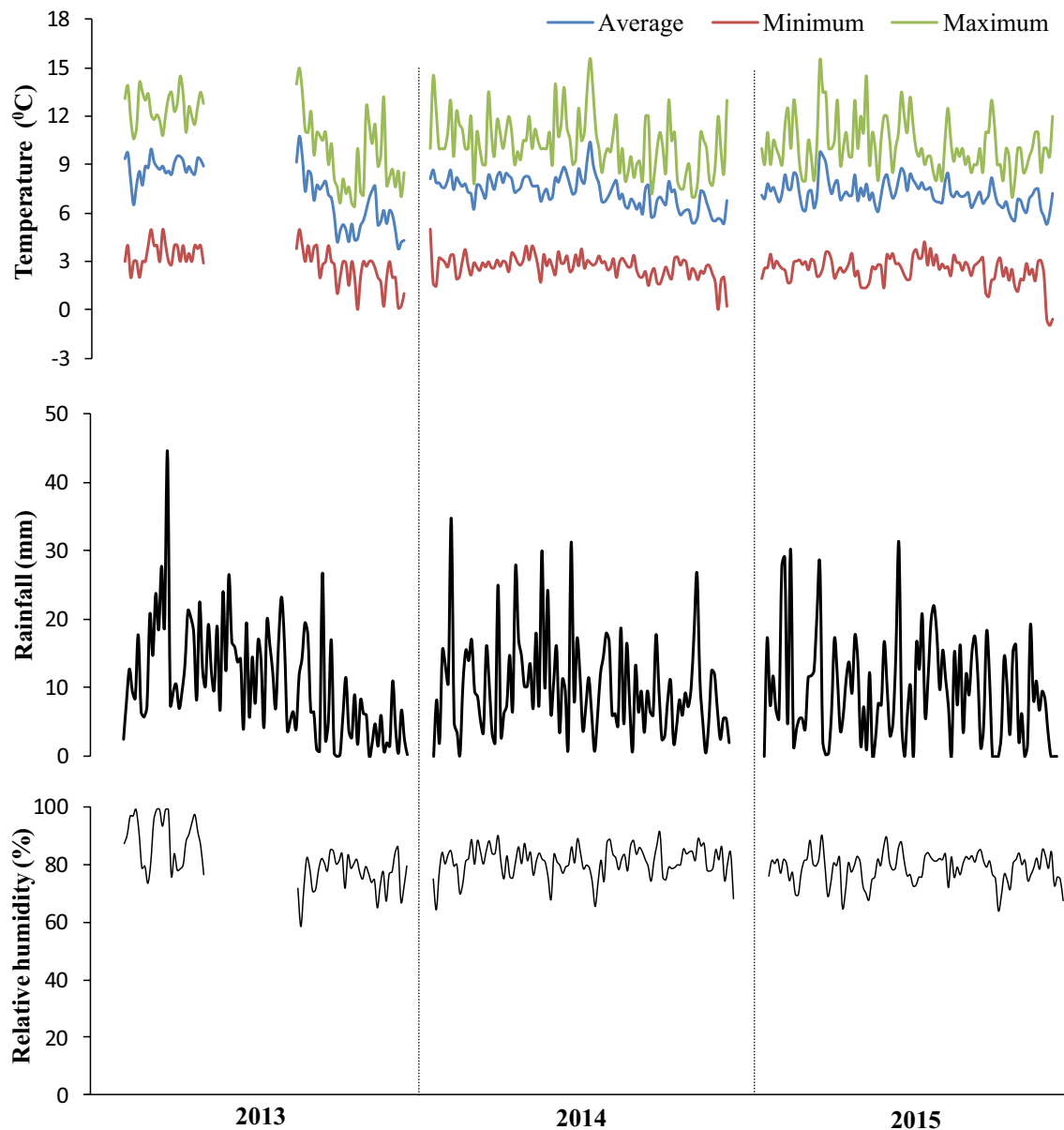
Fig. 3 Daily distributions of meteorological variables below the snout of East Rathong Glacier during the ablation seasons (2013–2015)

(Fig. 4). The mean relative humidity during the ablation seasons of 2013, 2014 and 2015 were recorded to be 81.7, 88.9, and 78.6%, respectively. During the combined ablation season (2013–2015), the mean relative humidity was 80.29% (Table 2). Year-wise monthly mean distributions of relative humidity for June to September were recorded as 94.00, 87.30, 72.84 and 77.79%, respectively in the year 2013. In the year 2014, the relative records of relative humidity were 78.89, 81.36, 81.35 and 81.32% for June to September, respectively. Similarly, relative humidity were 78.92, 77.72, 80.17 and 77.93%, respectively for June to September in the year 2015 (Fig. 4).

3.1.4 Glacier's Meltwater Discharge

Owing to the remote locations and harsh climatic condition of the Himalaya, continuous hydrological records for glacier valley are limited. The daily mean discharges of East Rathong Glacier were ~ 5.32, 6.34, and 7.61 m^{3}s^{-1} for the ablation seasons 2013–2015, respectively. The discharge magnitude revealed that July and August contributed maximum runoff accounting for 35.27% and 33.46%, respectively of the total runoff, followed by June 9.89% and September 21.38%. The discharge magnitude during the start of ablation (June) showed a slow response in producing a discharge

Table 2 Comparison of instrumental high-altitude meteorological datasets in Indian Himalayan region

Glacier	Region	Elevation (m asl)	T_{mean} (°C)	R (mm)	RH (%)	Study period	Reference
East Rathong	EH	~4640	7.42	1009.83	80.29	June–Sept. (2013–2015)	Present study
Chorabari	CH	~3800	8.60	1231.00	81.00	June–Sept. (2011–2012)	Kumar et al. (2018b)
Chorabari	CH	~3800	8.50	1217.00	84.00	June–Sept. (2009–2012)	Kumar et al. (2018a)
Dunagiri	CH	~4200	8.33	174.29	85.66	July–Sept (1984–1989)	Srivastava et al. (2014)
Dokriani	CH	~3850	9.50	1041.00	88.88	June–Sept. (1995–1998)	Singh and Ramasastri (1999)
Dokriani	CH	~3850	8.40	1370.00	–	June–Sept. (2010–2011)	Kumar et al. (2014)
Gangotri	CH	~3800	9.40	260.00	79.00	May–Oct. (2000–2003)	Singh et al. (2005)
*Chhota Shigri	WH	~4863	2.50	$^{\$}117.00	68.00	June–Sept. (2010–2013)	Azam et al. (2016)

T_{mean}, R, and RH are the values for the average temperature, total rainfall and relative humidity respectively, *meteorological variables recorded by Automatic weather station at the elevation of 4863 m asl and $^{\$}$precipitation recorded for the summer monsoon season (June–Sept.) 2013 by the precipitation gauge at elevation of 3850 m asl. EH, CH and WH are eastern Himalaya, central Himalaya and western Himalaya respectively

that is attributed to a lower temperature and fewer rainfall events. During the peak ablation period (July–August), due to the seasonal evolution of hydrologic conduits and the expansion of subglacial channels (Liu et al. 2018), the glacier's melt process tends to increase owing to the rise in temperature with frequent rainfall events, which accelerated the discharge process. However, during the late ablation (September), the decrease in discharge is attributed to lower air temperature (Kumar et al. 2018a). It has been suggested that the glacier subsurface features like englacial and subglacial drainage networks and basal sediments act as storage (Jansson et al. 2003; Singh et al. 2006) that also delays the discharge generation in glacier stream. In the present study, the maximum (Q_{max}) and minimum (Q_{min}) runoff were recorded at 17:30 and 9:30 h, respectively, and are synchronous with the hydrological measurements of glaciers in central and western Himalaya (Singh et al. 2003; 2006; Singh et al. 2016b; Srivastava et al. 2014) (Table 3).

The daily mean discharge hydrograph for each ablation season of 2013, 2014 and 2015 was generated using the daily discharge values (Fig. 5). The daily discharge distribution of East Rathong meltwater stream for the ablation seasons (2013–2015) has given some important insights on the variability of meltwater. The overall distribution of discharge showed an increasing trend from June onward and reached its maximum in July–August. The maximum and minimum discharges of 15.71 and 1.46 m^{3}s^{-1}, respectively were recorded with a mean discharge of 6.42 m^{3}s^{-1}. Further, the discharge hydrograph of East Rathong meltwater stream during the ablation seasons showed glacier's melt starts little early than the observed period. The daily mean discharge volume was recorded to be 0.55 MCM (million cubic meter) for East Rathong Glacier during the study period. The monthly mean discharge values observed during the study period for June, July, August, and September were 6.63, 7.35, 6.97, and 4.83 m^{3}s^{-1}, respectively (Table 4).

3.1.5 Stage-Discharge Relationships

In the IHR, many positive stage-discharge relationships have been established for the glacier streams (Kumar et al. 2014, 2016, 2018a; Singh et al. 2006, 2011; Singh et al. 2016b). In the present study, we have also attempted to develop a stage-discharge relationship based on the availability of data for three consecutive ablation seasons (2013–2015) (Fig. 6a–c). Stage-discharge relationships developed for East Rathong meltwater stream show highly significant correlations ($R^2 = 0.95$ for 2013, $R^2 = 0.93$ for 2014 and $R^2 = 0.93$ for 2015). Further, we have tested the consistency and dependency of stage-discharge equations using daily observed discharge values (Fig. 7). The computed daily discharge values were found to be in good agreement with the daily observed discharge ($R^2 = 0.93$ for 2013, $R^2 = 0.92$ for 2014 and $R^2 = 0.91$ for 2015). The results corroborate well with the stage-discharge relationships developed in other Indian Himalayan glaciers (Kumar et al. 2014, 2016, 2018a; Singh et al. 2006, 2011; Singh et al. 2016b). Thus, the present relationships can be used to estimate the melt runoff by considering only the water levels of East Rathong meltwater stream.

3.2 Variability of Hydro-Meteorological Variables

The variability in the hydro-meteorological parameters was analyzed using the Coefficient of variation (Cv) for the daily time series hydro-meteorological data (Table 4). The results show a maximum variability in meltwater discharge during September (Cv = 0.37) followed by June (Cv = 0.29), whereas July and August showed the least. The maximum variability in discharge during September is due to low glacial melts at the end of the ablation season and the evolution of sub-glacial internal drainage networks in the glacier (Swift et al. 2005). The 2nd order variability of discharge (June) is because of the variations in the melting process and
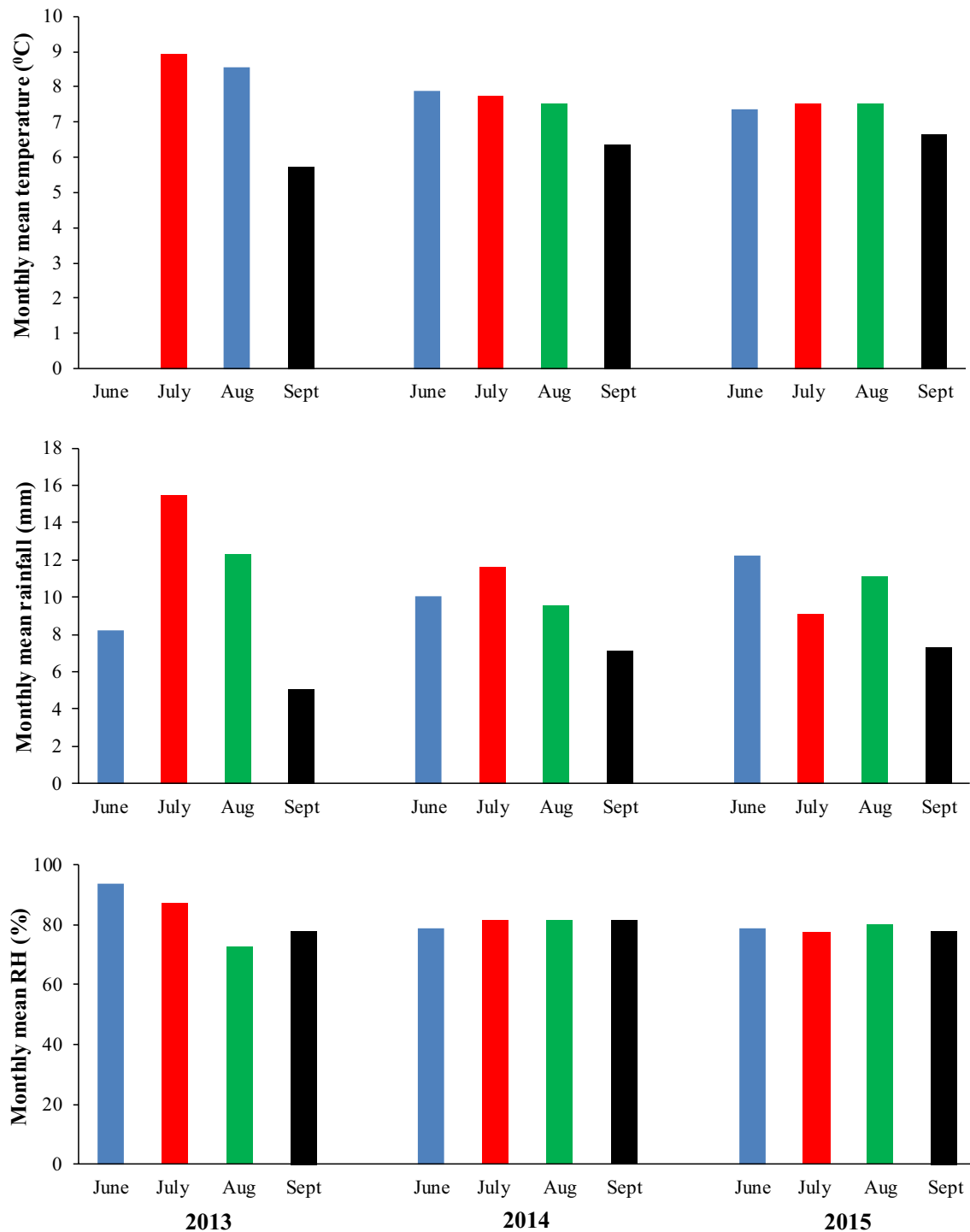
Fig. 4 Monthly distributions of meteorological variables below the snout of East Rathong Glacier during the ablation seasons, June–Sept (2013–2015)

availability of seasonal snow (Singh et al. 2006; Srivastava et al. 2014).

A high and low seasonal variability ($Cv = 0.34$ and $Cv = 0.18$) in the daily minimum temperature and maximum temperature, respectively, has been reported (Table 4). A

higher variation in the T_{min} during June ($Cv = 0.26$) and September ($Cv = 0.47$) has also been observed. This variability in minimum temperature is expected from the large snow cover and less cloud cover during initial ablation season that allow the penetration of long-wave radiations to reradiate

Table 3 Comparison of mean discharge from the Indian Himalayan glaciers

Glacier	Region	Basin area (km²)	Glacierized area (km²)	Mean discharge (× 10⁶ m³)	Study periods	Reference
East Rathong	EH	19.80	4.81	0.55	2013–2015	Present study
Changme Khangpu	EH	4.5	–	0.19	1979–1985	Puri (1999)
Dunagiri	CH	17.9	2.6	0.20	1984–1989	Srivastava et al. (2012)
Dokriani	CH	15	7	0.49	2010–2011	Kumar et al. (2014)
Chorabari	CH	15.4	6.6	0.37	2009–2012	Kumar et al. (2016)
Gangotri	CH	556	286	3.12	2000–2003	Singh et al. (2006)
Tipra Bank	CH	41.6	13.1	0.67	1981–1988	Puri and Swaroop (1995)
Gara	WH	17	6	0.12	1974–1983	Raina (2009)
Chhota Shigri	WH	45	15.7	0.33	2010	Singh et al. (2016b)
Patsio	WH	7.8	–	0.07	2011–2012	Singh et al.(2015)
Shaune Garang	WH	33.5	–	0.41	1981–1991	Raina (2009)
Triloknath	WH	–	–	0.33	1995–1996	Raina (2009)
Hamtah	WH	–	–	0.38	2000–2006	Raina (2009)
Neh Nar	WH	8.1	–	0.10	1975–1984	Raina (2009)
Siachen	KK	–	–	8.86	1986–1991	Bhutiyani (2000)

EH eastern Himalaya, *CH* central Himalaya, *WH* western Himalaya and *KK* Karakoram

Fig. 5 Daily distributions of discharge (m³s⁻¹) for the ablation seasons (2013–2015) of East Rathong Glacier
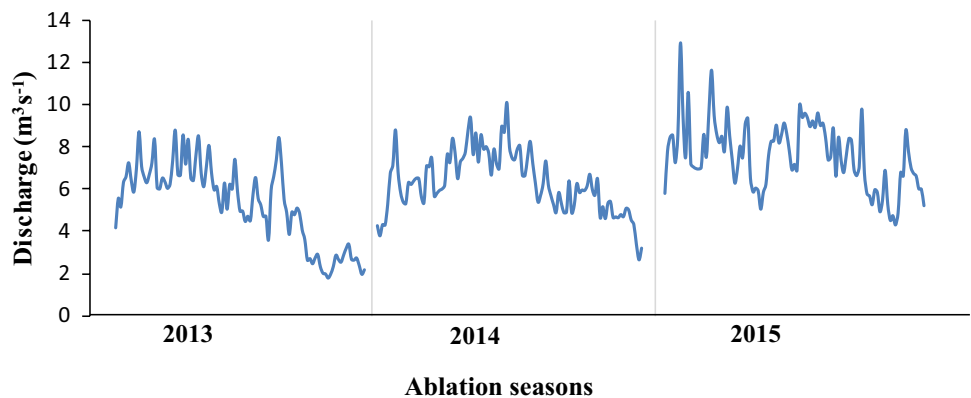

Table 4 The statistical representation of hydro-meteorological variables collected at East Rathong Glacier during the ablation seasons (2013–2015)

Months	June M	July M	Aug M	Sept M	June-Sept M	June σ	July σ	Aug σ	Sept σ	June-Sept σ	June C_v	July C_v	Aug C_v	Sept C_v	June-Sept C_v
Q (m³s⁻¹)	6.63	7.35	6.97	4.83	6.42	1.95	1.21	1.56	1.80	1.89	0.29	0.17	0.22	0.37	0.29
T_{min} (°C)	3.76	2.95	2.95	2.10	2.83	0.74	0.74	0.65	0.99	0.89	0.26	0.25	0.22	0.47	0.34
T_{max} (°C)	11.22	11.21	10.66	9.21	10.49	1.46	1.71	1.85	1.65	1.87	0.13	0.15	0.17	0.18	0.18
T_{mean} (°C)	7.79	7.96	7.66	6.18	7.36	0.72	0.91	0.97	0.99	1.19	0.09	0.11	0.13	0.16	0.16
RH (%)	81.51	81.64	79.86	78.91	80.29	7.66	7.48	5.65	5.48	6.53	0.09	0.09	0.07	0.07	0.08
R (mm)	10.40	12.47	11.00	6.47	9.95	8.74	8.15	6.78	6.15	7.58	0.84	0.67	0.62	0.95	0.76

M Mean, *σ* Standard deviation, *C_v* Coefficient of variation, *Q* Discharge, *T_{min}* Minimum temperature, *T_{max}* Maximum temperature, *T_{mean}* Mean temperature, *RH* Relative humidity, *R* Rainfall
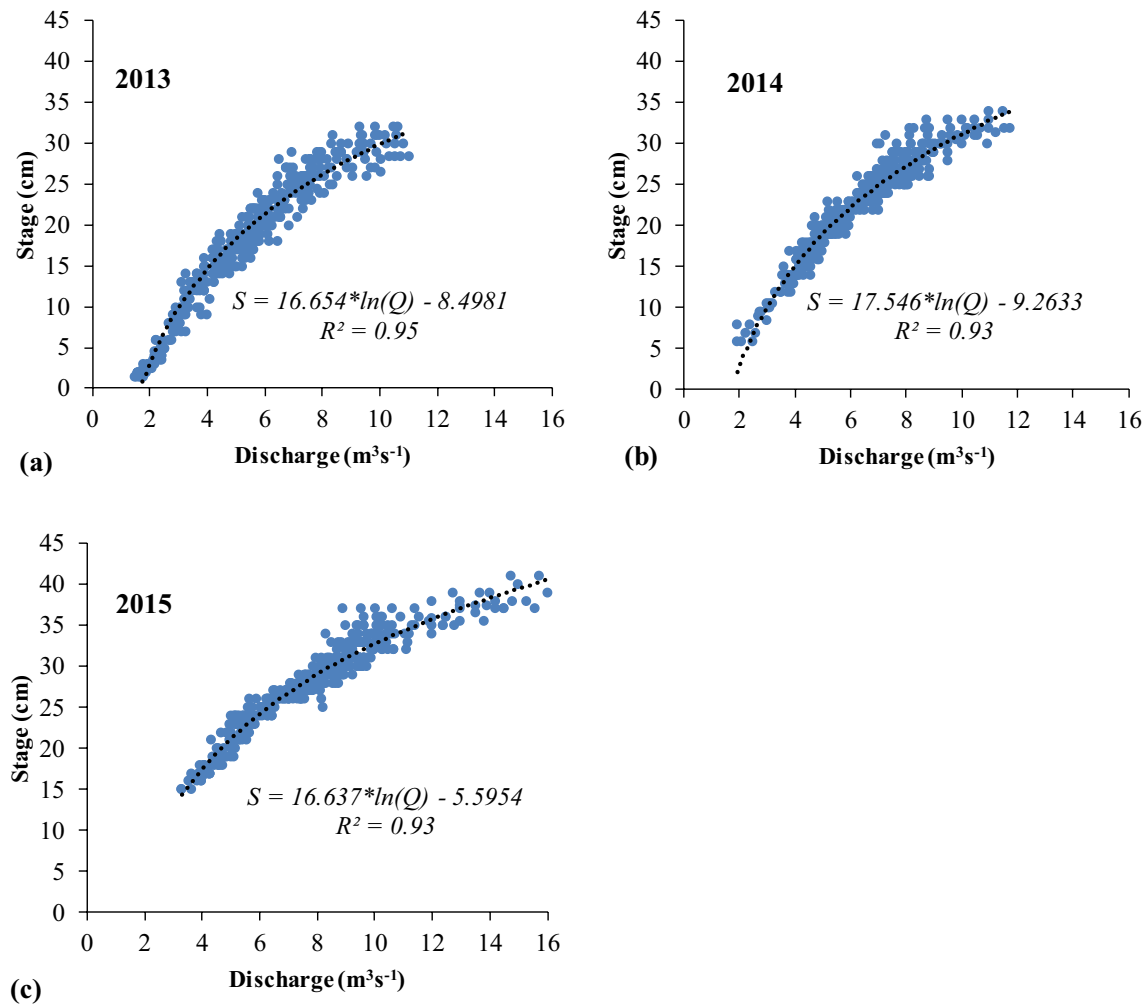
Fig. 6 **a**–**c** The stage-discharge relationships developed for East Rathong Glacier during each ablation seasons (2013–2015). S is the Stage or water level in cm, Q is the discharge in m^3s^{-1} and R^2 is the coefficient of determination

back to the atmosphere, which develops variations (Kumar et al. 2018a). The maximum variability ($Cv = 0.76$) in the study period (2013–2015) was shown by the rainfall indicating the more considerable variations in rainfall than any other hydro-meteorological variables. The months of June ($Cv = 0.84$) and September ($Cv = 0.95$) showed the highest variability in rainfall. In contrast to all, the relative humidity showed the least variations during the study period.

3.3 Hydro-Meteorological Interrelationships

We have used correlation matrix to estimate the functional relationships of meltwater discharge with meteorological variables. The correlations between meltwater discharge (Q) and meteorological variables at monthly and daily scale for the ablation seasons (2013–2015) is shown in Table 5a–b. The analysis revealed a strong hydro-meteorological relationships of meltwater discharge (Q) with T_{min} ($R^2 = 0.43$),

T_{max} ($R^2 = 0.93$), T_{mean} ($R^2 = 0.93$), Rainfall ($R^2 = 0.99$) and RH ($R^2 = 0.77$) at monthly scale, compared to daily scale. On a daily scale, the mean temperature ($R^2 = 46$) and rainfall ($R^2 = 0.49$) showed a strong relationship with meltwater discharge. The results suggested a significant role of meteorological variables in controlling the meltwater discharge. The correlation between T_{min} and Q was significant ($R^2 = 0.35$ for daily scale and $R^2 = 0.43$ for monthly scale), which indicates that the temperature during the night may play a considerable role in producing meltwater discharge. Further, our results suggested that the role of monthly T_{mean} is more significant ($R^2 = 0.93$) than daily T_{mean} ($R^2 = 0.46$) in controlling the meltwater discharge. Also, a very strong correlation was observed between T_{max} and Q at monthly scale ($R^2 = 93$) throughout the ablation seasons (2013–2015). The relationships between Q and Rainfall have been found highly significant for both daily ($R^2 = 0.49$) as well as monthly scales ($R^2 = 0.99$) (Table 5a–b). A very strong correlation between Q with Rainfall in monthly
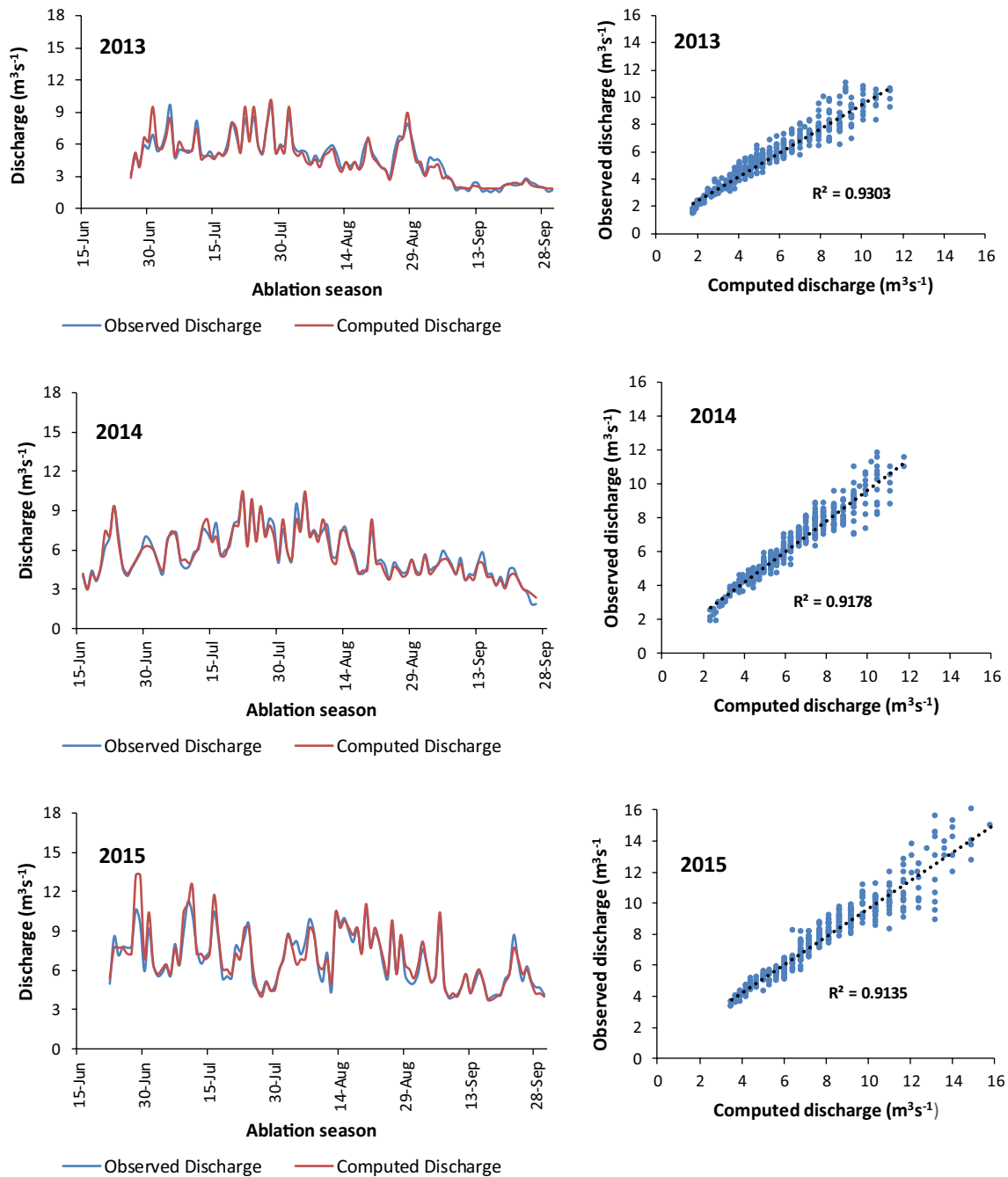
Fig. 7 The observed discharge *versus* computed discharge in the three ablation seasons (2013–2015). R^2 values are given in the figures

scale is likely due to the decrease in variations of both discharge and rainfall at the monthly scale (Singh et al. 2006).

4 Discussion

Local meteorological information is a prerequisite to comprehend and characterize the hydro-meteorological characteristics of any glacierized area (Kumar et al. 2014). To understand the regional meteorological setting, we have analyzed the available high altitude meteorological datasets (i.e., above 3800 m) for the ablation seasons in the IHR (Table 2). Comparison of our data with other glacierized basins of the central and western Himalayan region (Azam et al. 2016; Kumar et al. 2014, 2016, 2018a; Singh and Ramasastri 1999; Singh et al. 2005; Srivastava et al. 2014) shows a similar pattern of mean temperatures with central Himalayan glaciers during the ablation season (Table 2). Further, as per the

Table 5 Correlation matrix for major hydro-meteorological variables in East Rathong Glacier during the ablation seasons (2013–2015) at daily (a) and monthly scale (b)

(a) Daily scale						
2013–2015	Q	T_{min}	T_{max}	T_{mean}	R	RH
Q	1.00					
T$_{min}$	0.35	1.00				
T$_{max}$	0.21	0.10	1.00			
T$_{mean}$	0.46	0.51	0.82	1.00		
R	0.49	0.39	− 0.07	0.14	1.00	
RH	0.16	0.33	− 0.30	− 0.07	0.42	1.00
(b) Monthly scale						
2013–2015	Q	T_{min}	T_{max}	T_{mean}	R	RH
Q	1.00					
T$_{min}$	0.43	1.00				
T$_{max}$	0.93	0.64	1.00			
T$_{mean}$	0.93	0.73	0.98	1.00		
R	0.99	0.44	0.95	0.93	1.00	
RH	0.77	0.71	0.95	0.89	0.80	1.00

Q Discharge, T_{min} Minimum temperature, T_{max} Maximum temperature, T_{mean} Mean temperature, R Rainfall, RH Relative humidity

available instrumental records in IHR and the present study, the rainfall distribution ranged between 117 and 1370 mm in the different high altitudinal glacierized zones. The comparison of the present rainfall data (East Rathong Glacier) with other high altitude sites (central and western Himalaya) suggests that the rainfall distribution of East Rathong Glacier is found almost similar to Chorabari and Dokriani glaciers (above 1000 mm) of central Himalayan region (Kumar et al. 2014, 2016, 2018a; Singh and Ramasastri 1999) during the summer (Table 2). The eastern Himalayan region is primarily influenced by the Bay of Bengal branch of the Indian summer monsoon (ISM) during summer and the northeast monsoon in winter (Pathak et al. 2010). The ISM mainly governs the hydrology of eastern Himalaya in summer, and the mid-latitude westerlies further contribute to the glacier budget (Benn and Owen 1998; Lang and Barros 2004; Mani 1981). The study suggests a significant influence of ISM over the eastern Himalaya and some parts of central Himalaya; however, the impact keeps on decreasing towards the western and north-western Himalaya. Accordingly, the glaciers like Dunagiri, Gangotri and Chhota Shigri show relatively lesser ISM precipitation, thereby suggesting a progressive decrease in the ISM rainfall along the south-north and east–west gradients. Previous studies from the IHR (western, central and eastern Himalaya) have revealed that the high altitude mean relative humidity ranged between ~ 68.0 and 88.8% (Table 2). On a regional scale, the mean relative humidity pattern of East Rathong Glacier is similar to that of Chorabari and Gangotri glaciers (Kumar et al. 2016, 2018a; Singh et al. 2005). The differences in relative humidity for

the different climatic zones are likely due to the variations in air temperature caused by elevation, orography and cloud cover conditions of the region.

It has been observed that the average discharge volumes draining of the Indian Himalayan glaciers (Karakoram, western, central and eastern Himalaya) are highly variable (Table 3). In the present study, the daily mean discharge volume for East Rathong Glacier is calculated as 0.55 MCM. Glaciers like Dunagiri has a similar catchment area; however, the discharge is substantially lower, while, it is comparable with the Dokriani glacier. These variations in glacial discharge in Indian Himalaya is ascribed to the location of the glacier area concerning the influence of ISM. The low discharge of the Dunagiri Glacier is accordingly attributed to its geographical setting in rain shadow zone (Kumar et al. 2018a), where precipitation during summer is orographically controlled, leading to scanty monsoon precipitation (Singh et al. 2016a). This effect is more pronounced in the case of Chhota Shigri Glacier (western Himalaya), and a low ISM precipitation has been implicated (Azam et al. 2016) (Table 2). Hence, the heterogeneity in glacier's meltwater discharges is not only governed by the size of the glacier valley but is significantly governed by other meteorological factors like temperature and precipitation. The orographic controls on precipitation and local geographical conditions of the glacier-like elevation, orientation, slope, and aspect also have significant control on the streamflow.

The relationships between meltwater generation and meteorological parameters have been intensively studied for glaciers and ice sheets worldwide (Barbet et al. 1993;

Braithwaite 1995; Changwei et al. 2006; Hannah and McGregor 1997; Hannah et al. 2000; Hodgkins 2001; Lang 1973). The investigation of hydro-meteorological relationships in high altitude areas is essential to have an in-depth knowledge of hydrological responses of the glaciers (Archer and Fowler 2008; Singh et al. 2000) towards the meteorological impacts. However, in the eastern Himalayan region (India), such studies are scarce, and the present study is a step in that direction. Our analysis showed that meteorological variables (T_{min}, T_{max}, T_{mean}, Rainfall and RH) plays a considerable role in producing meltwater discharge (Q) in East Rathong Glacier stream. Interestingly, T_{min} during the night is found significantly related to daily as well as monthly discharges. Further, the glacier absorbs the incoming solar radiation during the day, and at night, the long-wave radiation controls the glacier melt process (Kumar et al. 2018a). The results of the present investigation are consistent with the hydro-meteorological relationships of meltwater discharges reported from the central Himalayan region (Kumar et al. 2018a; Singh et al. 2006). Strong correlations were found between Q and Rainfall for both the daily as well as the monthly scale that confirms a considerable amount of rainfall during summer governs the glacier's melt process in the East Rathong river basin, Eastern Himalaya (Table 2).

5 Conclusions

In Himalaya, many studies about the impact of climate change based on in-situ observations are limited to the lower altitudes that cannot be used for a better understanding of high altitudinal glacierized zones. The present study based on in-situ hydrological characteristics coupled with meteorological conditions is the first systematic record of East Rathong Glacier in Sikkim Himalaya that provides essential insights into meltwater generation processes during the consecutive three ablation seasons (2013–2015). Most importantly, the study suggests a more significant role of air temperature, rainfall and humidity in producing the meltwater discharge that confirms significant meteorological controls on the meltwater generation in East Rathong Glacier.

Till date, the limited interventions in the hydro-meteorological study of glaciers in Sikkim Himalaya require the attention of policymakers and research-based institutions to develop capacity in carrying out glaciological studies for further understanding on a long term basis. Due to limits imposed by steep terrain and harsh weather conditions, the availability of field-based data are scarce in Sikkim Himalaya. Besides, insufficient high altitude meteorological observatories is a matter of concern, which needs particular attention. These constraints add to the uncertainties and restrict the detailed understanding on impacts of climate change in glacio-hydrology in the region. Therefore,

a systematic long-term monitoring of glaciers is required for in-depth knowledge of glacier's melt process in the area. In Indian Himalayan region, under the eight National missions of the National Action Plan on Climate Change (NAPCC), the National Mission for Sustaining the Himalayan Ecosystem (NMSHE) and the National Mission on Strategic Knowledge for Climate Change (NMSKCC) have been coordinated by the Ministry of Science and Technology (GoI) from the year 2010. These missions focus mainly on building capacities, creating institutional networks, carrying out the research on strategic knowledge and identifying the knowledge gaps, related to climate change impacts in the IHR (DST 2010a, b). Thus, a better understanding of the effects of climate change on high altitude Himalayan catchments can be expected in the near future. Accordingly, the present study in East Rathong Glacier basin can also contribute to these nationally coordinated missions. It can be beneficial to carry out predictions on the future availability of glacier's meltwater flow in the study basin that can support in developing policies and strategies to cope with the climate change impacts in future. At a local level, the present study can be effectively used for the hydrological modelling of freshwater resources (Glaciers) required to the hydrologists, scientists and policymakers for high altitude freshwater management under a changing climate. Still, for the entire Himalayan region, comprehensive understanding of meltwater characteristics and hydro-meteorological conditions is always essential at different climatic zones.

Compliance with ethical standards

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