Journal of Climate Change, Vol. 7, No. 3 (2021), pp. 45-55.
DOI 10.3233/JCC210018

Hydro-meteorological Correlations of Himalayan Glaciers: A Review

Virendra Bahadur Singh[1], AL. Ramanathan[2]* and Pramod Kumar[3]

[1]Department of Geology, University of Delhi, Delhi - 110007, India
[2]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi - 110067, India
[3]Department of Chemistry, Sri Aurobindo College, University of Delhi, New Delhi - 110017, India
✉ alrjnu@gmail.com

Received March 24, 2021; revised and accepted July 25, 2021

Abstract: This review manuscript addresses hydro-meteorological correlations of various glaciers situated in the Himalayan region. Meteorological parameters influence the discharge pattern of the glacier. A strong correlation has been observed between discharge and air temperature of the studied Himalayan glaciers. Whereas, other meteorological parameters such as wind speed and wind direction etc. were not significantly correlated with the meltwater runoff of different glaciers in this region. In general, variability (Cv) in discharge from the various Himalayan glaciers such as Chhota Shigri and Gangotri glaciers follow the variability (Cv) in the temperature of these glaciers. Maximum variability (Cv) in meltwater runoff from the Chhota Shigri glacier has been reported in the month of September, which might be due to the fast decline in stream runoff and air temperature of the study area during the month of September. A strong relationship has been observed between suspended sediment concentration and temperature of the majority of studied Himalayan glaciers. Such type of result shows that the suspended sediment concentration in the glacial meltwater has increased with rising air temperature in this region.

Keywords: Hydro-meteorological correlations; Meltwater runoff; Air temperature; Suspended sediment concentration; Himalayan glacier.

Introduction

Glacier is one of the important components of the water cycle (IPCC, 2007; Singh et al., 2020). It is a dynamic system that is sliding and creeping slowly from highland region to lowland region (Arora et al., 2019; Mandal and Sharma, 2020). Glaciers are a major source of freshwater that influences different types of natural ecosystems (Rai et al., 2017; Angchuk et al., 2021). They are retreating due to climate change, causing a reduction of snow and ice melt to the headwaters (Marchina et al., 2020). The Himalayas contain one of the richest and biggest mountain ecosystems of the earth with a complex topography and having a large number of mountain glaciers (Kesarwani et al., 2015). The Hindu Kush Himalayan range comprises three main parallel zones, namely Greater Himalaya, Middle Himalaya or Lesser Himalaya (Inner Himalaya) and foothills or the Sub-Himalaya (Pant et al., 2018). The Himalayan cryosphere has contributed significantly to the hydrological budget of various rivers originating from the Himalayan region such as the Ganga (Khan et al., 2017). Generally, high altitude region of the Himalayas experiences warmer climate and the trend of rising temperature in this region is higher than that of the global averages (Shrestha et al., 1999; IPCC,

*Corresponding Author

2014; Ali et al., 2018). On the other hand, the trend of precipitation along with the amount and source of precipitation varies in various regions of the Himalayas (Khan et al., 2018). The monsoonal system, western disturbances and the farrago of orography play a crucial role in governing the pattern of precipitation in the Himalayan region (Singh and Kumar, 1997; Dimri et al., 2015). The majority of glaciers in the region of Indian Himalayas are reported in the Indus basin having 7997 glaciers and the Ganga basin having 1,578 glaciers (Raina and Srivastava, 2008). Himalayan glaciers are a natural reservoir of fresh water for downstream areas (Gardner et al., 2013) and have great scientific and socio-economic importance (Romshoo, 2012).

Hydrology of high altitude region of the Himalayas is complex because of the influence of two atmospheric circulation systems i.e. western disturbances and Asian summer monsoon (Bookhagen and Burbank, 2010). Hydrological investigation of Himalayan glaciers plays a significant role in understanding the response of the glacier to the present climatic condition; this is because the variability in glacial runoff mainly depends on the meteorology of the region (Mandal et al., 2020). Hydrological data in association with various meteorological data (such as rainfall, temperature and humidity) in the glacier catchment are used to know about the dynamics of the generation of glacial runoff at a local scale (Kumar et al., 2020). Changes in the atmospheric temperature are expected to affect the snow or ice melt runoff and stream flow in the catchment of the Himalaya (Immerzeel et al., 2009; Jain et al., 2010). The volume of meltwater draining as runoff from the Himalayan glacier is controlled by the extent of snow above the glacier surface, size of the glacier and strength of the drainage network inside the glacier (Singh et al., 2004). Hydro-meteorological relationship of Himalayan glaciers helps to know about the weather conditions, melting rate, availability of water resources and suspended sediment transportation from the glacierized area (Kumar et al., 2002; Singh et al., 2003, 2005, 2010; Jain et al., 2003; Arora et al., 2014; Srivastava et al., 2014a, b; Kumar et al., 2016a; Singh et al., 2016). Investigations of hydro-meteorological correlation of Himalayan glaciers are difficult due to complex topography and harsh condition of weather in this region. Various literatures are available on the hydro-meteorological correlations of Himalayan glaciers (Singh et al., 1995, 2000, 2004, 2006, 2010; Thayyen et al., 2005; Thayyen and Gergan, 2010; Liu et al., 2010; Singh, 2011, 2016; Singh et al., 2016; Pottakkal et al., 2014; Kumar et al., 2018a; Kumar et al., 2018b; Azam et al., 2019; Mandal et al., 2020; Shukla et al., 2020; Kumar et al., 2020; Ramanathan et al., 2021). The main objective of this review manuscript is to address the hydro-meteorological correlation and interrelationship between suspended sediment concentration (SSC) and load (SSL) with meteorological parameters of the Himalayan glaciers.

Study Area

The Hamtah (32º14′16″N and 77°22′16″E), Chhota Shigri (32º13′42″N and 77°30′50″E) and Shaune Garang (31º17′30″N and 78°20′22″E) glaciers are situated in the Western Himalayan region, Himachal Pradesh, India (Sangewar and Shukla, 2009), whereas Dokriani (30º50′-30º52′N and 78º47′-78º50′E), Gangotri (30°43′-31º01′N and 79°00′-79º17′E), Dunagiri (30°33′20″N and 79º53′36″E) and Chorabari (30°46′20.58″N and 79º02′59.38″E) glaciers are situated in the region of Central Himalaya, Uttarakhand, India (Hasnain and Thayyen, 1999; Haritashya et al., 2006; Srivastava et al., 2014a; Kumar et al., 2018a). On the other hand, East Rathong (27°34′54.44″N and 88º06′27.63″E) is located in the region of Eastern Himalaya, Sikkim, India and Rongbuk glacier is situated in the Central Himalayan region, China (Liu et al., 2010; Kumar et al., 2020) (Table 1). The length of Hamtah, Chhota Shigri, Shaune Garang, Dokriani, Gangotri, Dunagiri, Chorabari, East Rathong and Rongbuk glaciers has been found to be 6.0, 9.0, 6.2, 5.5, 30.2, 5.5, 7.5, 7.0 and 18.0 km, whereas the area of these glaciers is observed to be 3.30, 15.7, 4.94, 7.00, 86.32, 2.50, 6.60, 4.80 and 203.0 km^2, respectively (Haritashya et al., 2006; Sangewar and Shukla, 2009; Liu et al., 2010; Azam et al., 2012; Dobhal et al., 2013; Srivastava et al., 2014a; Kumar et al., 2016b; Shukla et al., 2020; Kumar et al., 2020).

The Chhota Shigri glacier geologically lies in the Central Crystallines rocks of Pir Panjal Range of the Western (Himachal) Himalaya (Kumar and Dobhal, 1997). This glacier catchment mainly contains Rohtang gneiss (Kumar et al., 1987; Hasnain et al., 1989). The Dokriani glacier is located on the north of Pindari Trust, which comprises pigmatites, granite, schists, biotite gneiss and calc-silicate rocks (Valdiya et al., 1999). On the other hand, the Shaune Garang glacier situated in the Baspa valley is dominated by the Rakcham group of granite (Dutta et al., 2017). The geology of the Gangotri glacier system contains phyllite, quartzite, mica schist, sericite schist, granite (tourmaline rich), limestone, pyrite etc. (Bhatt, 1963).

Table 1: Details of Himalayan glaciers observed for hydro-meteorological correlations study

Glaciers	*Regions*	*Basin area/area (km^2)*	*References*
Shaune Garang	Himachal Pradesh, India	38.13	Kumar et al., 2018b
Chhota Shigri	Himachal Pradesh, India	34.7	Mandal et al., 2020
Hamtah	Himachal Pradesh, India	3.30	Shukla et al., 2020
Dokriani	Uttarakhand, India	16.13	Singh et al., 2003
Gangotri	Uttarakhand, India	556	Haritashya et al., 2006
Dunagiri	Uttarakhand, India	17.9	Srivastava et al., 2014a
Chorabari	Uttarakhand, India	15.4	Kumar et al., 2018a
East Rathong	Sikkim, India	19.8	Kumar et al., 2020
Rongbuk	Mt. Oomolangma, Central Himalaya, China	298	Liu et al., 2010

Methodology

The velocity-area method has been used for hydrological measurement of Hamtah, Shaune Garang, Chhota Shigri, Dokriani, Gangotri, Chorabari and East Rathong glaciers; whereas various meteorological parameters have been recorded by the automatic weather station (AWS) (Singh et al., 1995, 2006; Singh, 2016; Singh et al., 2016; Kumar et al., 2018 a; Kumar et al., 2018b; Shukla et al., 2020; Kumar et al., 2020). Suspended sediment concentration (SSC) in the stream water has been computed by drying and weighing the suspended glacial sediment accumulated over the filter paper. suspended sediment load (SSL) has been estimated by multiplying glacial runoff with SSC. On the other hand, SSL per unit basin area was used to calculate suspended sediment yield (SSY) of the studied glaciers (Haritashya et al., 2006; Srivastava et al., 2014b; Kumar et al., 2018b; Singh and Ramanathan, 2018; Sharma et al., 2021).

Hydro-meteorological Correlations

Interrelationship between Discharge and Air Temperature

Melt-runoff investigations of Himalayan glaciers are complex to understand because of the limited availability of hydro-meteorological data and high climatic variability in the glacierised region (Srivastava et al., 2014a). Temperature is one of the important factors for controlling the hydrological regimes of Himalayan glaciers (Thayyen and Gergan, 2010). The correlation between discharge and temperature provides key information about the quantity of meltwater runoff and its variation in the glacier environment (Han et al., 2010). Hydro-meteorological correlations of various Himalayan glaciers are shown in Table 2. Strong correlations (R^2=0.71 in 2010, R^2=0.65 in 2011, R^2=0.61 in 2012, R^2=0.61 in 2013 and R^2=0.75 in 2014) were observed between glacier-specific runoff and temperature of Chhota Shigri glacier (Singh et al., 2016; Singh, 2016) (Figure 1 a-d). Such strong relationships between both parameters during the different years show that atmospheric temperature controls the magnitude and variation of discharge in the study area. Location of Chhota Shigri glacier is found in the monsoonal arid transition region of Western Himalaya (Bookhagen and Burbank, 2010) which obtains low rainfall. A major part of glacial runoff in this region is produced from the melting of snow and ice (Singh et al., 2015). Maximum precipitation in the study area was observed in the winter season accounting for 71% of the total annual precipitation, whereas the summer-monsoon season (June, July, Aug. and Sept.) and post-monsoon season (Oct. and Nov.) received low precipitation accounting to 12% and 3% of the total annual precipitation, respectively (Azam et al., 2016). Hence this glacier obtained low precipitation during the ablation season (June-October) which does not significantly influence the melt runoff pattern of the Chhota Shigri glacier (Singh, 2016).

The hydro-meteorological study carried out by Mandal et al. (2020) on the Chhota Shigri glacier shows that meltwater runoff has a positive correlation with air temperature (R^2=0.66), incoming long wave radiation (L_{in}) (R^2=0.58) and relative humidity (RH) (R^2=0.39), whereas, on the other side, it has a negative correlation with precipitation (P) (R^2= -0.02) and wind speed (u) (R^2= -0.28) of the study area. The production of meltwater runoff is mainly determined by the presence of heat on the surface of the glacier, hence meltwater runoff showed a strong correlation with

Table 2: Correlation between discharge/glacier specific discharge and air temperature of the Himalayan glaciers

Glaciers	*Locations*	*Years*	*R^2*	*References*
Chhota Shigri	Chandra basin, Western Himalaya	2010	0.71	Singh et al., 2016; Singh, 2016
		2011	0.65	
		2012	0.61	
		2013	0.61	
		2014	0.75	
Hamtah	Chandra basin, Western Himalaya	2000	0.6834	Shukla et al., 2020
		2001	0.701	
		2003	0.6806	
		2004	0.4524	
		2005	0.6071	
		2006	0.6249	
		2007	0.7286	
Shaune Garang	Baspa basin, Western Himalaya	2014	0.6878	Kumar et al., 2018b
		2015	0.7436	
Dokriani	Bhagirathi basin, Central Himalaya	1992	0.89	Singh et al., 1995
Gangotri	Bhagirathi basin, Central Himalaya	2000-2003	0.76	Singh et al., 2006
Chorabari	Mandakini basin, Central Himalaya	2009-2012	0.50	Kumar et al., 2018a
Rongbuk	Central Himalaya, China	2005	0.79	Liu et al., 2010
East Rathong	Rangit basin, Eastern Himalaya	2013-2015	0.93	Kumar et al., 2020; Sharma et al., 2021

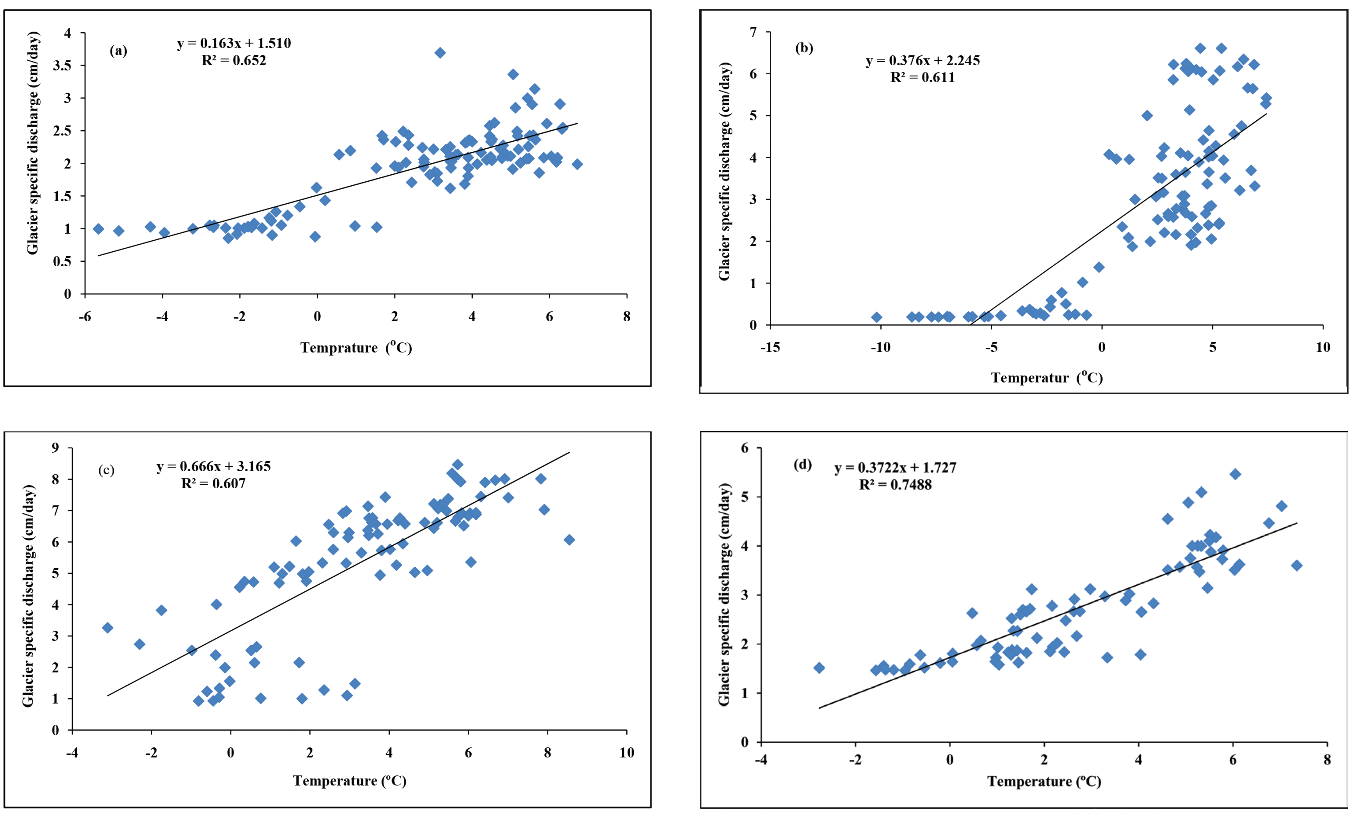

Figure 1: Scatter diagram between glacier specific discharge vs air temperature of the Chhota Shigri glacier for (a) 2011 (b) 2012 (c) 2013 (d) 2014. (*Source:* Singh, 2016)

the temperature of the Chhota Shigri glacier. On the other hand, black-carbon may influence the heat on the surface of a glacier because black-carbon decreases the albedo value of the glacier thus trapping heat. Another study carried out by Azam et al. (2019) on the Chhota Shigri glacier indicates that summer temperature and accumulation of snow during the summer and winter season together regulate the catchment-wide meltwater runoff as well as glacier-wide mass balance in the study area. The scatter diagram between meltwater runoff and air temperature of Hamtah glacier shows the higher value of R^2 (coefficient of determination) (R^2=0.6834 in 2000, R^2=0.701 in 2001, R^2=0.6806 in 2003, R^2=0.4524 in 2004, R^2=0.6071 in 2005, R^2=0.6249 in 2006 and R^2=0.7286 in 2007), indicating a closer association between meltwater runoff and temperature of the investigation area. On the other hand, precipitation is not directly correlated with stream runoff of the Hamtah glacier (Shukla et al., 2020). The strong relationship between discharge and the air temperature was also reported in other Himalayan glaciers such as Shaune Garang, Dokriani and Rongbuk glaciers (Singh et al., 1995; Liu et al., 2010; Kumar et al., 2018b).

A recent hydrological study carried out by Kumar et al. (2020) on the East Rathong glacier indicates that discharge has a strong interrelation with mean temperature (T_{mean}) (R^2=0.93), maximum temperature (T_{max}) (R^2=0.93) and minimum temperature (T_{min}) (R^2=0.43), RH (R^2=0.77) and rainfall (R^2=0.99) on the monthly scale. On the other hand, discharge also showed a good relationship with rainfall (R^2=0.49) and mean temperature (R^2=0.46) on the daily scale. These results show that the role of mean temperature on the monthly scales is more important than that of mean temperature on the daily scale in regulating the meltwater runoff of the study area. A very good interrelation between discharge and rainfall in the East Rathong glacier on the monthly scale is probably due to the reduction in the variation of both rainfall and meltwater runoff on the monthly scale (Singh et al., 2006). Another hydro-meteorological study carried out by Srivastava et al. (2014a) on the Dunagiri glacier demonstrates that meltwater runoff has a low correlation with air temperature for each ablation period. The R^2 value of 0.51 was observed in discharge-temperature correlation for the selected clear weather days in the Dunagiri glacier. However, meltwater runoff showed an exponential correlation with ablation having a high value of R^2 (0.75), which means meltwater runoff rises exponentially as the ablation rises. On the other hand, ablation showed a high exponential correlation with mean temperature having a value of R^2 (0.79), which means ablation rises exponentially as the mean air temperature rises in the study area. While ablation was not well correlated with precipitation (R^2=0.38).

The correlation between meltwater runoff and air temperature of the Dokriani glacier indicates that air temperature has a good relationship with meltwater runoff for the month of June and September, because of the presence of strong storage characteristics, systematic environment for melting and lower runoff in the study area during these months. While meltwater runoff shows a better correlation with precipitation during the month of July and August, because of the presence of high rainfall and changes in the physical status of the Dokriani glacier during these months (Singh et al., 2000). Another hydrological study carried out by Singh et al. (2006) on the Gangotri glacier shows that the prevailing air temperature controls the magnitude and variation of glacial runoff in the study area. Here much better correlation was observed between mean monthly meltwater runoff and air temperature (R^2=0.76) as compared to daily scale having *an* R^2 value of 0.50. The hydro-meteorological correlation analysis in the Chorabari glacier shows that meltwater runoff is correlated with T_{min} (minimum temperature) (R^2=0.50), whereas it is not or little correlated with T_{max} (maximum temperature) (R^2=0.20) and T_{mean} (mean temperature) (R^2=0.40) during the melt periods (2009-2012). Such types of correlation analysis show that temperature during the night time may play a significant role in the melting of the glacier. Here absorbed incoming solar radiation during the day time by the surface of glacier regulates melting of the glacier during the night time in the form of long wave radiation (Kumar et al., 2018a). Whereas other meteorological parameters such as rainfall, relative humidity, wind speed and wind direction are not better correlated with meltwater runoff in the Chorabari glacier (Kumar et al., 2018a).

Variability in Discharge and Air Temperature

Change in air temperature influences the melting regimes of snow or glacier (Dou et al., 2011). Variation in air temperature occurred on daily, monthly, seasonal and annual levels, which play an important role in changing the discharge pattern of glacial runoff (Mingjie et al., 2013). For the assessment of variability in discharge and air temperature, a coefficient of variation (Cv) is used. Variability (Cv) in stream runoff from the Chhota Shigri glacier generally follows the variability (Cv) in temperature above the glacier surface (Figure 2 a-d). Maximum variability (Cv) in glacial runoff was reported

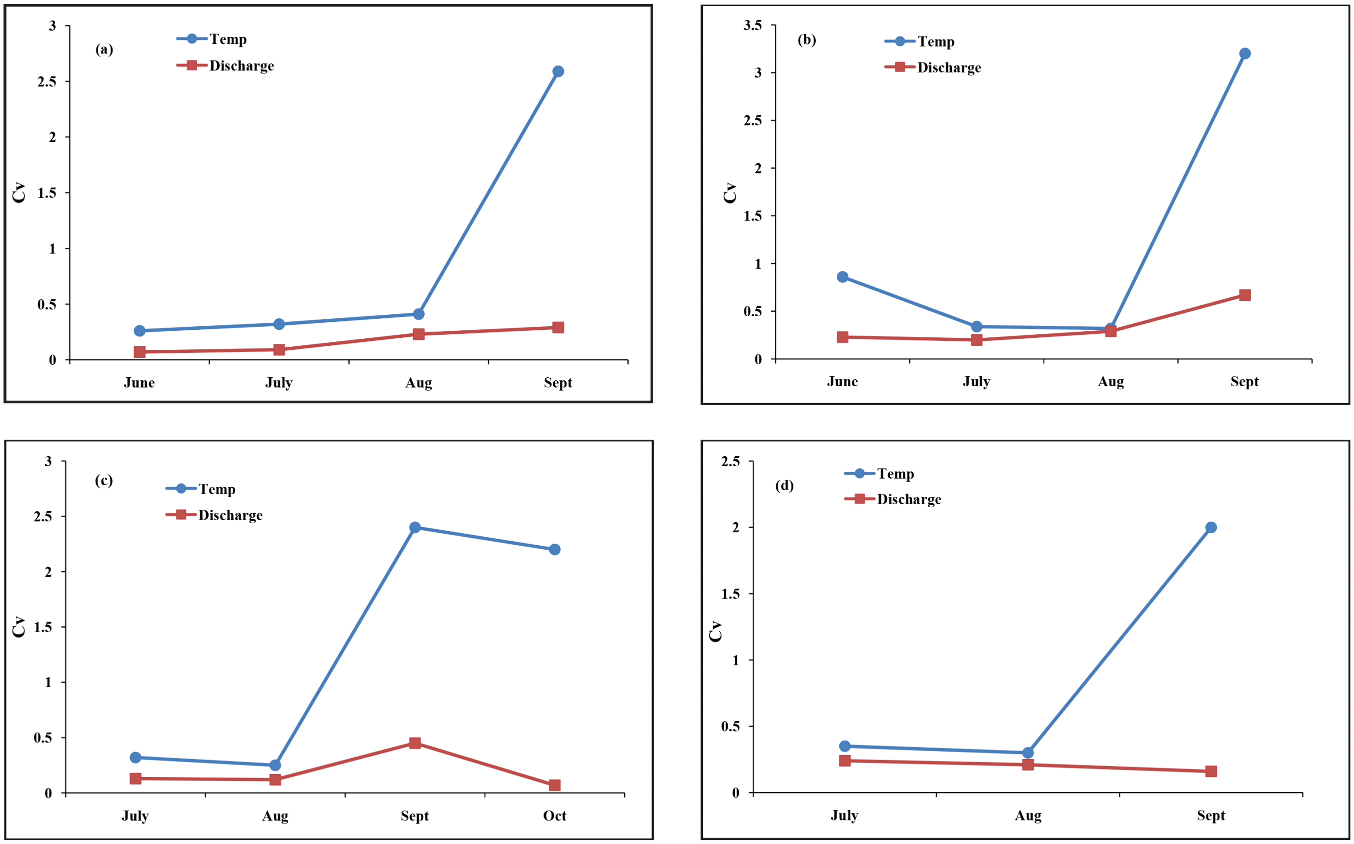

Figure 2: Changes in coefficient of variation (Cv) for discharge and air temperature of the Chhota Shigri glacier during the investigation period (a) 2011 (b) 2012 (c) 2013 (d) 2014. (*Source:* Singh, 2016)

in the month of September, which may be due to the fast decrease in stream runoff and atmospheric temperature above the surface of the glacier during the given time period (Singh, 2016). In the Gangotri glacier, maximum variability in meltwater runoff was found in the month of May and September, whereas minimum variability in the meltwater runoff was observed in the month of October. Generally, variability in temperature shows a similar trend as the variability in meltwater runoff in the study area (Singh et al., 2006).

Relationship Between Suspended Sediment Concentration (SSC) and Load (SSL) with Meteorological Parameters

Various factors such as meteorological, hydrological and glaciological entities control the erosion and SSL in the glacial environment (Kumar et al., 2018b). The inter-relationship between SSC, SSL and SSY with various meteorological parameters of the Himalayan glaciers is shown in Table 3. A suspended sediment transport study carried out by Singh and Ramanathan (2018) on the Chhota Shigri glacier shows that SSC in the stream water has a strong exponential relationship with temperature during the study in the year 2011 (R^2=0.72), 2012 (R^2=0.74), 2013 (R^2=0.61) and 2014 (R^2=0.70). On the other hand, SSL also shows a very significant exponential relationship with temperature during the study period 2011 (R^2=0.74), 2012 (R^2=0.74), 2013 (R^2=0.61) and 2014 (R^2=0.75). Such types of trends indicate that suspended sediment concentration and load may rise exponentially with the rise in air temperature of the Chhota Shigri glacier. A strong correlation has also been observed between suspended sediment concentration and air temperature of Shaune Garang glacier during the study period 2014 (R^2=0.62) and 2015 (R^2=0.72) (Kumar et al., 2018b).

Another study carried out by Haritashya et al. (2006) on the Gangotri glacier indicates the strong exponential relationship between mean monthly suspended sediment concentration and mean monthly temperature (R^2=0.92) and mean monthly suspended sediment load and mean monthly temperature of the study area (R^2=0.98). Such type of result is due to the high dependency of suspended sediment load on the discharge, which is

Table 3: Inter-relationship between SSC, SSL and SSY with meteorological parameters of the Himalayan glaciers

Glaciers	*Inter-relationship*	*Study periods*	*R^2*	*References*
Chhota Shigri	SSC vs T	2011	0.72	Singh and Ramanathan. 2018
		2012	0.74	
		2013	0.61	
		2014	0.70	
	SSL vs T	2011	0.74	
		2012	0.74	
		2013	0.61	
		2014	0.75	
Shaune Garang	SSC vs T	2014	0.62	Kumar et al., 2018b
		2015	0.72	
Gangotri	SSC vs T_{mean}	2000-2003	0.92	Haritashya et al., 2006
	SSL vs T_{mean}	2000-2003	0.98	
Dunagiri	SSC vs T_{mean}	1985-1989	0.95	Srivastava et al., 2014b
East Rathong	SSC vs T_{mean}	2013-2015	0.91	Sharma et al., 2021
	SSC vs T_{max}	2013-2015	0.90	
	SSL vs T_{mean}	2013-2015	0.91	
	SSL vs T_{max}	2013-2015	0.90	
	SSY vs T_{mean}	2013-2015	0.92	
	SSY vs T_{max}	2013-2015	0.91	
	SSC vs R	2013-2015	0.99	
	SSL vs R	2013-2015	0.99	
	SSY vs R	2013-2015	0.99	

regulated by the temperature of the Gangotri glacier. The very significant exponential relationship has also been observed between mean monthly suspended sediment content and mean monthly temperature (R^2=0.95) of the Dunagiri glacier, indicating suspended sediment content in the stream water increases exponentially as the temperature increases during the ablation periods in the study area (Srivastava et al., 2014b). Another suspended sediment transport study carried out by Sharma et al. (2021) on the East Rathong glacier shows a very significant relationship between SSC and T_{mean} (R^2=0.91), SSC and T_{max} (R^2=0.90), SSL and T_{mean} (R^2=0.91), SSL and T_{max} (R^2=0.90), suspended sediment yield (SSY) and T_{mean} (R^2=0.92) and SSY with T_{max} (R^2=0.91) on a monthly scale. Whereas rainfall (R) also has a strong correlation with SSC (R^2=0.99), SSL (R^2=0.99) and SSY (R^2=0.99) on a monthly scale in the study area. Such types of results show the important role of these meteorological parameters for regulating the suspended sediment transport in the East Rathong glacier.

Conclusions

Hydro-meteorological correlations of Himalayan glaciers play an important role in the distribution of discharge during different melt seasons. The current review paper has mainly discussed the interrelationship between various meteorological parameters such as temperature, precipitation and wind speed etc. with stream runoff from different Himalayan glaciers. Generally, air temperature shows a strong correlation with discharge from the majority of the studied Himalayan glaciers. There exists a strong correlation between glacier-specific discharge and air temperature (R^2=0.71 in 2010, R^2=0.65 in 2011, R^2=0.61 in 2012, R^2=0.61 in 2013 and R^2=0.75 in 2014) of the Chhota Shigri glacier (Singh et al., 2016; Singh, 2016). On the other hand, the close association has also been observed between stream runoff and air temperature of other Himalayan glaciers such as Hamtah glacier (R^2=0.6834 in 2000, R^2=0.701 in 2001, R^2=0.6806 in 2003, R^2=0.4524 in 2004, R^2=0.6071 in 2005,

R^2=0.6249 in 2006 and R^2=0.7286 in 2007) (Shukla et al., 2020), Gangotri glacier (R^2= 0.76) (Singh et al., 2006) and many other (East Rathong and Dokriani) glaciers situated in this region. In general, various Himalayan glaciers such as Chhota Shigri and Gangotri glaciers show a similar trend in the variation (Cv) of meltwater runoff and temperature. Suspended sediment concentration showed a strong relationship with the air temperature of the studied Himalayan glaciers. Further detailed hydro-meteorological studies on the Himalayan glaciers are recommended for a better understanding of hydro-meteorological interrelationship, regulating the magnitude and variation of glacial runoff in the Himalayan region.

Acknowledgement

Virendra Bahadur Singh acknowledges the UGC (University Grants Commission), Govt. of India under the UGC-Dr. D. S. Kothari Post Doctoral Fellowship scheme [Award No. F.4-2/2006 (BSR)/ES/17-18/0057] for granting him the postdoctoral fellowship. Prof. N. C. Pant is gratefully acknowledged for his valuable suggestion during the critical review of this manuscript.

References

Ali, S.N., Dubey, J., Ghosh, R., Quamar, M.F., Sharma, A., Morthekai, P., Dimri, A.P., Shekhar, M., Arif, M. and Agrawal, S., 2018. High frequency abrupt shifts in the Indian summer monsoon since Younger Dryas in the Himalaya. *Scientific Reports*, **8:** 9287. doi:10.1038/s41598-018-27597-6

Angchuk, T., Ramanathan, A., Bahuguna, I.M., Mandal, A., Soheb, M., Singh, V.B., Mishra, S. and Vatsal, S., 2021. Annual and seasonal glaciological mass balance of Patsio glacier, western Himalaya (India) from 2010 to 2017. *Journal of Glaciology.* doi.:10.1017/jog.2021.60.

Arora, B.R., Dimri, A.P., Dobhal, D.P., Pant, N.C., Sharma, M., Sharma, P., Shukla, S., Ramanathan, AL. and Thamban, M., 2019. The Himalayan cryosphere: Appraisal of climate-glacier inter-linkages. *Proceedings of the Indian National Science Academy*, **85(2):** 319-342.

Arora, M., Kumar, R., Kumar, N. and Malhotra, J., 2014. Assessment of suspended sediment concentration and load from a large Himalayan glacier. *Hydrology Research,* **45(2):** 292-306.

Azam, M.F., Ramanathan, AL., Wagnon, P., Vincent, C., Linda, A., Berthier, E., Sharma, P., Mandal, M., Angchuk, T., Singh, V.B. and Pottakkal, J.G., 2016. Meteorological conditions, seasonal and annual mass balances of Chhota Shigri glacier, western Himalaya, India. *Annals of Glaciology*, **57(71):** 328-338.

Azam, M.F., Wagnon, P., Ramanathan, AL., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J.G., Chevallier, P., Singh, V.B. and Berthier, E., 2012. From balance to imbalance: A shift in the dynamic behaviour of Chhota Shigri Glacier (western Himalaya, India). *Journal of Glaciology*, **58(208):** 315-324.

Azam, M.F., Wagnon, P., Vincent, C., Ramanathan, AL., Kumar, N., Srivastava, S., Pottakkal, J.G. and Chevallier, P., 2019. Snow and ice melt contributions in a highly glacierized catchment of Chhota Shigri Glacier (India) over the last five decades. *Journal of Hydrology,* **574:** 760-773.

Bhatt, B.K., 1963. Preliminary study of the Bhagirathi basin between Uttarkashi and Gomukh. *In:* Proceeding of National Symposium on Himalayan Geology, Calcutta. Geological Society of India. Miscellaneous Publication Number 15, pp. 1-8.

Bookhagen, B. and Burbank, D.W., 2010. Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research*, **115(F3):** F03019. doi:10.1029/2009JF001426

Dimri, A.P., Niyogi, D., Barros, A.P., Ridley, J., Mohanty, U.C., Yasunari, T. and Sikka, D.R., 2015. Western disturbances: A review. *Reviews of Geophysics*, **53(2):** 225-246.

Dobhal, D.P., Mehta, M. and Srivastava, D., 2013. Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India. *Journal of Glaciology*, **59:** 961-971.

Dou, Y., Chen, X., Bao, A. and Li, L., 2011. The simulation of snowmelt runoff in the ungauged Kaidu River Basin of TianShan Mountains, China. *Environmental Earth Sciences,* **62:** 1039-1045.

Dutta, S., Mujtaba, S.A.I., Saini, H.S., Chunchekar, R. and Kumar, P., 2017. Geomorphic evolution of glacier-fed Baspa Valley, NW Himalaya: Record of Late Quaternary climate change, monsoon dynamics and glacial fluctuations. *In:* Pant, N.C., Ravindra, R., Srivastava, D. and Thompson, L.G. (eds), The Himalayan cryosphere: past and present, Special Publications, 462. Geological Society, London.

Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A.,Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R.M., Bolch, T., Sharp, M.J., Hagen, J.O., van den Broeke, M.R. and Paul, F., 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science,* **340:** 85-856.

Han, H., Liu, S., Wang, J., Wang, Q. and Xie, C., 2010. Glacial runoff characteristics of the Koxkar Glacier, Tuomuer-Khan Tengri Mountain Ranges, China. *Environmental Earth Sciences*, **61:** 665-674.

Haritashya, U.K., Singh, P., Kumar, N. and Gupta, R.P.,

2006. Suspended sediment from the Gangotri Glacier: Quantification, variability and associations with discharge and air temperature. *Journal of Hydrology*, **321:** 116-130.

Hasnain, S.I. and Thayyen, R.J., 1999. Discharge and suspended sediment concentration of meltwaters, draining from the Dokriani glacier, Garhwal Himalaya, India. *Journal of Hydrology*, **218:** 191-198.

Hasnain, S.I., Subramanian, V. and Dhanpal, K., 1989. Chemical characteristics and suspended sediment load of meltwaters from a Himalayan Glacier in India. *Journal of Hydrology,* **106:** 99-108.

Immerzeel, W.W., Drooger, P., de Jong, S.M. and Bierkens, M.F.P., 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment,* **113(1):** 40-49.

IPCC, 2007. Climate change 2007-Impacts, adaptation and vulnerability. *In*: Parry M.L. et al. (eds), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, 2014. Climate change 2014: Synthesis report. *In:* Pachauri, R.K. and Meyer, L.A., (eds), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Jain, S.K., Goswami, A. and Saraf, A.K., 2010. Assessment of Snowmelt Runoff Using Remote Sensing and Effect of Climate Change on Runoff. *Water Resources Management,* **24:** 1763-1777.

Jain, S.K., Singh, P., Saraf, A.K. and Seth, S.M., 2003. Estimation of sediment yield for a rain, snow and glacier fed river in the western Himalayan region. *Water Resources Management,* **17:** 377-393.

Kesarwani, K., Dobhal, D., Durgapal, A. and Mehta, M., 2015. High altitude meteorology and cloud cover conditions: A study from the Chorabari Glacier Catchment, Central Himalaya, India. *Himalayan Geology*, **36(2):** 134-142.

Khan, A.A., Pant, N.C., Ravindra, R., Alok, A., Gupta, M. and Gupta, S., 2018. A precipitation perspective of the Hydrosphere-cryosphere interaction in the Himalaya. *In:* Pant, N.C., Ravindra, R., Srivastava, D. and Thompson, L.G., (eds), The Himalayan Cryosphere: Past and Present. Geological Society, London, Special Publications, 462, pp. 73-88.

Khan, A.A., Pant, N.C., Sarkar, A., Tandon, S.K., Thamban, M. and Mahalinganathan, K., 2017. The Himalayan cryosphere: A critical assessment and evaluation of glacial melt fraction in the Bhagirathi basin. *Geoscience Frontiers*, **8:** 107-115.

Kumar, A., Gokhale, A.A., Shukla, T. and Dobhal, D.P., 2016a. Hydroclimatic influence on particle size distribution of suspended sediments evacuated from debris-covered Chorabari Glacier, upper Mandakini catchment, Central Himalaya. *Geomorphology,* **265:** 45-67.

Kumar, A., Verma, A., Gokhale, A.A., Bhambri, R., Misra, A., Sundriyal, S., Dobhal, D.P. and Kishore, N., 2018a. Hydrometeorological assessments and suspended sediment delivery from a central Himalayan glacier in the upper Ganga basin. *International Journal of Sediment Research*, **33:** 493-509.

Kumar, K., Miral, M.S., Joshi, V. and Panda, Y.S., 2002. Discharge and suspended sediment in the meltwater of Gangotri Glacier, Garhwal Himalaya, India. *Hydrological Sciences Journal*, **47(4):** 611-619.

Kumar, R., Kumar, R., Singh, S., Singh, A., Bhardwaj, A., Kumari, A., Randhawa, S.S. and Saha, A., 2018b. Dynamics of suspended sediment load with respect to summer discharge and temperatures in Shaune Garang glacierized catchment, Western Himalaya. *Acta Geophysica*, **66:** 1109-1120.

Kumar, R., Sharma, R.K., Pradhan, P., Sharma, N. and Shrestha, D.G., 2020. Melt runoff characteristics and hydro-meteorological assessment of East Rathong Glacier in Sikkim Himalaya, India. *Earth Systems and Environment*, **4:** 567-582.

Kumar, R., Singh, S., Kumar, R., Singh, A., Bhardwaj, A., Sam, L., Randhawa, S.S. and Gupta, A., 2016b. Development of a glacio-hydrological model for discharge and mass balance reconstruction. *Water Resources Management*, **30:** 3475-3495.

Kumar, S. and Dobhal, D.P., 1997. Climatic effects and bedrock control on rapid fluctuations of Chhota Shigri glacier, northwest Himalaya, India. *Journal of Glaciology*, **43(145)**: 467–472.

Kumar, S., Rai, H., Purohit, K.K., Rawat, B.R.S. and Mundepi, A.K., 1987. Multi disciplinary glacier expedition to Chhota Shigri glacier. Department of Science and Technology, Government of India, New Delhi, Technical Report Number 1, pp 1-29.

Liu, W., Ren, J., Qin, X., Liu, J., Liu, Q. and Cui, X., 2010. Hydrological characteristics of the Rongbuk Glacier catchment in Mt. Qomolangma region in the Central Himalayas, China. *Journal of Mountain Science,* **7:** 146-156.

Mandal, A., Ramanathan, AL., Azam, M.F., Angchuk, T., Soheb, M., Kumar, N., Pottakkal, J.G., Vatsal, S., Mishra, S. and Singh, V.B., 2020. Understanding the interrelationships among mass balance, meteorology, discharge and surface velocity on Chhota Shigri Glacier over 2002–2019 using in situ measurements. *Journal of Glaciology*, **66(259):** 727-741.

Mandal, S.T. and Sharma, M.C., 2020. Spatial changes in glaciers between 1965 and 2018 in Tirungkhad watershed, Upper Sutlej Basin, Himachal Pradesh. *Earth Systems and Environment.* doi:10.1007/s41748-020-00159-5.

Marchina, C., Lencioni, V., Paoli, F., Rizzo, M. and Bianchini, G., 2020. Headwaters' isotopic signature as a tracer of stream origins and climatic anomalies: Evidence from the Italian Alps in summer 2018. *Water*, **12:** 390. doi:10.3390/w12020390

Mingjie, G., Tianding, H., Baisheng, Y. and Keqin, J., 2013. Characteristics of melt water discharge in the Glacier No. 1 basin, headwater of Urumqi River. *Journal of Hydrology,* **489:** 180-188.

Pant, N.C., Ravindra, R., Srivastava, D. and Thompson, L.G., 2018. The Himalayan cryosphere: Past and present variability of the 'third pole'. *In:* Pant, N.C., Ravindra, R., Srivastava, D. and Thompson, L.G., (eds), The Himalayan Cryosphere: Past and Present. Geological Society, London, Special Publications, 462, pp. 1-6.

Pottakkal, J.G., Ramanathan, AL., Singh, V.B., Sharma, P., Azam, M.F. and Linda, A., 2014. Characterization of subglacial pathways draining two tributary meltwater streams through the lower ablation zone of Gangotri Glacier, Garhwal Himalaya, India. *Current Science*, **107(4):** 613-621.

Rai, P.K., Mishra, V.N., Singh, S., Prasad, R. and Nathawat, M.S., 2017. Remote sensing-based study for evaluating the changes in glacial area: A case study from Himachal Pradesh, India. *Earth Systems and Environment*, **1(1)**. doi:10.1007/s41748-017-0001-2

Raina, V.K. and Srivastava, D., 2008. Glacier Atlas of India. Geological Society of India, Bangalore.

Ramanathan AL., Mandal, A., Mohd, A.F., Angchuk, T., Mohd, S., Kumar, N., Pottakkal, J. G., Vatsal, S., Mishra, S. and Singh, V.B., 2021. Interrelationships among mass balance, meteorology, discharge, and surface velocity on Chhota Shigri Glacier over 2002-2019 using in-situ measurements. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11598, https://doi.org/10.5194/egusphere-egu21-11598, 2021.

Romshoo, S. A., 2012. Indus River Basin. Common concerns and the roadmap to resolution. New Delhi: European Union sponsored publication, Centre for Dialogue and Reconciliation (CDR).

Sangewar, C.V. and Shukla, S.P., 2009. Inventory of the Himalayan glaciers: A contribution to the International Hydrological Programme. An Updated Edition, Kolkata: Geological Survey of India (Special Publication 34).

Sharma, R.K., Kumar, R. and Shrestha, D.G., 2021. Suspended sediment dynamics and associated hydro-meteorological interrelations in East Rathong Glacier, Eastern Himalaya, India. *Materials Today: Proceedings,* doi:10.1016/j.matpr.2021.01.082.

Shrestha, A.B., Wake, C.P., Mayewski, P.A. and Dibb, J.E., 1999. Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *Journal of Climate,* **12(9):** 2775-2786.

Shukla, S.P., Mishra, R. and Kumar, A., 2020. Glacier melt water characteristics of Hamtah Glacier, Lahaul and Spiti District, Himachal Pradesh, India. *In:* Goel, P.S., Ravindra, R. and Chattopadhyay, S. (eds), Climate change and the white world. Springer Nature Switzerland, pp. 169-185.

Singh, A.T., Sharma, P., Sharma, C., Laluraj, C.M., Patel, L., Pratap, B., Oulkar, S. and Thamban, M., 2020. Water discharge and suspended sediment dynamics in the Chandra River, Western Himalaya. *Journal of Earth System Science*, **129:** 206. doi:10.1007/s12040-020-01455-4

Singh, P. and Kumar, N., 1997. Effect of orography on precipitation in the western Himalayan region. *Journal of Hydrology*, **199(1-2):** 183-206.

Singh, P., Haritashya, U.K. and Kumar, N., 2004. Seasonal change in meltwater storage and drainage characteristics of the Dokriani Glacier, Garhwal Himalayas (India). *Hydrology Research,* **35(1):** 15-29.

Singh, P., Haritashya, U.K., Kumar, N. and Singh, Y., 2006. Hydrological characteristics of the Gangotri Glacier, central Himalayas, India. *Journal of Hydrology,* **327:** 55-67.

Singh, P., Haritashya, U.K., Ramasastri, K.S. and Kumar, N., 2005. Diurnal variations in discharge and suspended sediment concentration, including runoff-delaying characteristics of the Gangotri Glacier in the Garhwal Himalayas. *Hydrological Processes,* **19:** 1445-1457.

Singh, P., Kumar, A., Kumar, N. and Kishore, N., 2010. Hydro-meteorological correlations and relationships for estimating streamflow for Gangotri Glacier basin in Western Himalayas. *International Journal of Water Resources and Environmental Engineering*, **2(3):** 60-69.

Singh, P., Ramasastri, K.S., Kumar, N. and Arora, M., 2000. Correlations between discharge and meteorological parameters and runoff forecasting from a highly glacierized Himalayan basin. *Hydrological Science Journals,* **45(5):** 637-652.

Singh, P., Ramasastri, K.S., Kumar, N. and Bhatnagar, N.K., 2003. Suspended sediment transport from the Dokriani Glacier in the Garhwal Himalayas. *Hydrology Research,* **34(3):** 221-244.

Singh, P., Ramasastri, K.S., Singh, U.K., Gergan, J.T. and Dobhal, D.P., 1995. Hydrological characteristic of Dokriani Glacier, Garhwal Himalaya. *Hydrological Sciences Journal,* **40(2):** 243-257.

Singh, V.B., Ramanathan, AL., Mandal, A. and Angchuk, T., 2015. Transportation of suspended sediment from meltwater of the Patsio Glacier, Western Himalaya, India. *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences,* **85(1):** 169-175.

Singh, V.B. and Ramanathan, AL., 2018. Suspended sediment dynamics in the meltwater of Chhota Shigri glacier, Chandra basin, Lahaul-Spiti valley, India. *Journal of Mountain Science,* **15(1):** 68-81.

Singh, V.B., 2011. Hydro-meteorological and hydro-geochemical characteristics of Chhota Shigri Glacier, Lahaul-Spiti Valley, Himachal Pradesh, India. M.Phil dissertation, Jawaharlal Nehru University, New Delhi.

Singh, V.B., 2016. Hydrological characteristics and solute dynamics of meltwater draining from Chhota Shigri glacier, Western Himalaya, India. Ph.D thesis, Jawaharlal Nehru University, New Delhi.

Singh, V.B., Ramanathan, AL. and Pottakkal, J.G., 2016. Glacier runoff and transport of suspended sediment from the Chhota Shigri glacier, Western Himalaya, India. *Environmental Earth Sciences,* **75:** 695. doi:10.1007/s12665-016-5271-8

Srivastava, D., Kumar, A., Verma, A. and Swaroop, S., 2014a. Analysis of climate and melt-runoff in Dunagiri Glacier of Garhwal Himalaya (India). *Water Resources Management,* **28:** 3035-3055.

Srivastava, D., Kumar, A., Verma, A. and Swaroop, S., 2014b. Characterization of suspended sediment in meltwater from glaciers of Garhwal Himalaya. *Hydrological Processes,* **28:** 969-979.

Thayyen, R.J. and Gergan, J.T., 2010. Role of glaciers in watershed hydrology: A preliminary study of a "Himalayan catchment". *The Cryosphere,* **4:** 115-128.

Thayyen, R.J., Gergan, J.T. and Dobhal, D.P., 2005. Monsoonal control on glacier discharge and hydrograph characteristics. A case study of Dokriani glacier, Garhwal Himalaya, India. *Journal of Hydrology*, **36(1-4):** 37-49.

Valdiya, K.S., Paul, S.K., Chandra, T., Bhakuni, S.S. and Upadhyay, R.C., 1999. Tectonic and lithological characterization of Himadri (Great Himalaya) between Kali and Yamuna rivers, central Himalaya. *Himalayan Geology,* **20(2):** 1-17.