



Comparative analysis of discharge and sediment flux from two contiguous glacierized basins of Central Himalaya, India

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Abstract In the present study, suspended sediment load (SSL), sediment yield and erosion rates in Pindari Glacier basin (PGB) and Kafni Glacier basin (KGB) have been estimated using daily discharge and suspended sediment concentration (SSC) data for three ablation seasons (2017–2019). For this, one meteorological observatory and two gauging sites have been established at Dwali (confluence point), and water samples have been collected twice in a day for high flow period (July to September) and daily for lean period (May, June and October). An area-velocity method and stage-discharge relationship has been established to convert water level into discharge ($\text{m}^3 \text{s}^{-1}$). For estimating SSC (mg/l), collected water samples have been filtered, dried, analysed and confirmed with an automatic suspended solid indicator. Further, SSL, sediment yield and erosion rates have been computed using SSC data. The results reveal that mean annual discharge in PGB ($35.06 \text{ m}^3 \text{ s}^{-1}$) has been found approximately 1.7 times higher than KGB ($20.47 \text{ m}^3 \text{ s}^{-1}$). The average SSC and SSL in PGB have been observed about 396.07 mg/l and 1928.34 tonnes, and in KGB, it is about 359.67 mg/l

and 1040.26 tonnes, respectively. The SSC and SSL have followed the pattern of discharge. A significant correlation of SSC and SSL has been found with discharge in both the glacierized basins ($p < 0.01$). Interestingly, average annual sediment yield in PGB ($3196.53 \text{ t/km}^2/\text{yr}$) and KGB ($3087.23 \text{ t/km}^2/\text{yr}$) have been found almost identical. Likewise, the erosion rates in PGB and KGB have been witnessed about 1.18 and 1.14 mm/yr , respectively. Sediment yield and erosion rates in PGB and KGB have been found in correspondence with other basins of Central Himalaya. These findings will be beneficial for engineers and water resource managers in the management of water resources and hydropower projects in high-altitude areas and in the planning and designing of water structures (dams, reservoirs etc.) in downstream areas.

Keywords Discharge · Suspended sediment concentration · Sediment yield · Erosion rate · Pindari-Kafni glacierized basins · Central Himalaya

Introduction

Glaciers, the prime source of freshwater on earth surface, contribute significantly in generating and transporting water and sediments from mountainous region to oceans via rivers (Jain et al., 2003; Pellicciotti et al., 2010; Wada et al., 2011). It has been estimated that rivers transport about 95% of the total sediments entering the global oceans every year (Li et al., 2020). Among them, glacierized river basins transport enormous silt as compared to

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non-glacierized river basins (Singh et al., 2003; Wada et al., 2011; Zhang et al., 2021). For instance, Himalayan Rivers mainly glacierized in nature, contribute nearly 50% of the total river sediment flux (Stoddart, 1969). The amount of sediment transported by glacierized river basins depends on extent of glacier, nature of bedrock, availability of sediments, slope, energy and meteorological conditions (Kumar et al., 2016; Singh et al., 2006). Besides this, human interferences such as creation of reservoirs, barrages and dams, intrusion in forest lands, deforestation and tilling on high slopes also have a substantial impact on water and sediment flux (Singh et al., 2005). Recently, various studies have reported high sediment yield in glacierized basins due to human driven changes (Panwar et al., 2017; Srivastava et al., 2014a, b). The increased magnitude of sediments in river basins can be a silent threat for river ecology, river hydraulics and water quality in downstream regions (Mao & Carrillo, 2017; Kumar et al., 2020; Rautela et al., 2022). Apart from this, seasonal and inter-annual variability in sediment flux can generate serious problems in the functioning of dams, reservoirs and hydropower projects (Andermann et al., 2012). Annually, the storage capacity of reservoirs is decreasing by 0.5 to 1.0% on account of sedimentation (Rahmani et al., 2018). Similarly, Schleiss et al. (2016) has projected that out of the total available hydropower production capacity of Asia; nearly 80% will be lost by 2035 due to escalation in siltation processes.

Himalayan region, the second largest ice cap outside the polar region, provides considerable flow and sediment load to major river basins of India, i.e. Brahmaputra, Ganga and Indus (Schaner et al., 2012). These river basins produce 75% of their annual runoff and sediment load during monsoon season (June–September) in response to heavy precipitation and ablation (Kumar et al., 2002). Besides, steep valleys, high seismic activities, frequent landslides, avalanches, and continuous retreat in Himalayan glaciers have escalated erosion rates, resulting high sediment yield and load from glacierized catchments (Singh, 2011). A realistic estimation of water and sediment discharge in upstream area is necessary for understanding hydrological behaviour, for designing and development of hydraulic structures and hydropower projects in downstream areas. Moreover, such studies can help water resource administrators and planners in managing adverse climatic conditions (flood and drought) and in reducing hazard risk. Therefore, a lot of interest has been generated among researchers in studying the sedimentological characteristics of Himalayan

River basins (Arora et al., 2014; Haritashya et al., 2006; Jain et al., 2003; Kumar et al., 2014, 2018; Singh, 2011; Singh & Ramanathan, 2018; Singh et al., 2003, 2008a, b). Pindari and Kafni glacier streams, located in Central Himalaya and major tributaries of Alaknanda River, are highly intervened by human activities (development of Devsari, Tharali, Bagoli and Padli dams and hydropower projects) and have almost remained unexplored with respect to comparative analysis of discharge and sediment flux from these basins. Moreover, a faster rate of retreating has been reported in both Pindari (30.74 m/year) and Kafni glaciers (43.73 m/year) in recent years (2011–2018) (Pandey et al., 2022; Panwar et al., 2017). Therefore, present study has been carried out on Pindari and Kafni Glacier basins with following objectives: (i) to assess their discharge, suspended sediment concentration, load, yield and erosion rates, (ii) to examine the relationship of SSC and SSL with discharge and (iii) to compare the SSC, SSL, sediment yield and erosion rates of PGB and KGB with other glacierized basins of Himalayan region.

Study area

The Pindari and Kafni glaciers, located in higher reaches of the Central Himalaya, cover an area of about 9.6 and 3.3 km², respectively. These glaciers having a length of 5.9 km (Pindari) and 4.2 km (Kafni) flow through a faulted valley area. The basins extend between 30°12' 15" to 30°19' 10" N latitudes and 79° 59' 00" E to 80° 01' 55" E longitudes over an altitude range of about 2800 to 6800 m (amsl). Before confluence in Alaknanda River, PGB (111 km²) and KGB (62 km²) drain a total area of about 173 km² up to Dwali and constitute a major part of Pindar valley in Uttarakhand state (Fig. 1). The major peaks found in these basins are Baljuri (5922 m), Panwalidwar (6663 m), Nanda Khat (6611 m), Changuch (6322 m), Nanda Kot (6860 m) and Nanda Bhanar (6236).

The lithology of these glacier basins is characterized by Himalayan crystalline rocks, having diverse erosional and depositional glacio-geomorphological features, related to the Pindari formation of the Vaikrita group (Valdiya, 1999). These basins encompass U-shaped glacial trough, hanging valleys, recessional morainic ridges, kame terraces, debris fans and earth pyramids (Bali et al., 2013). Pindari is a more debris-free and south facing glacier as compared to Kafni (Singh et al., 2020). The two glacier basins experience

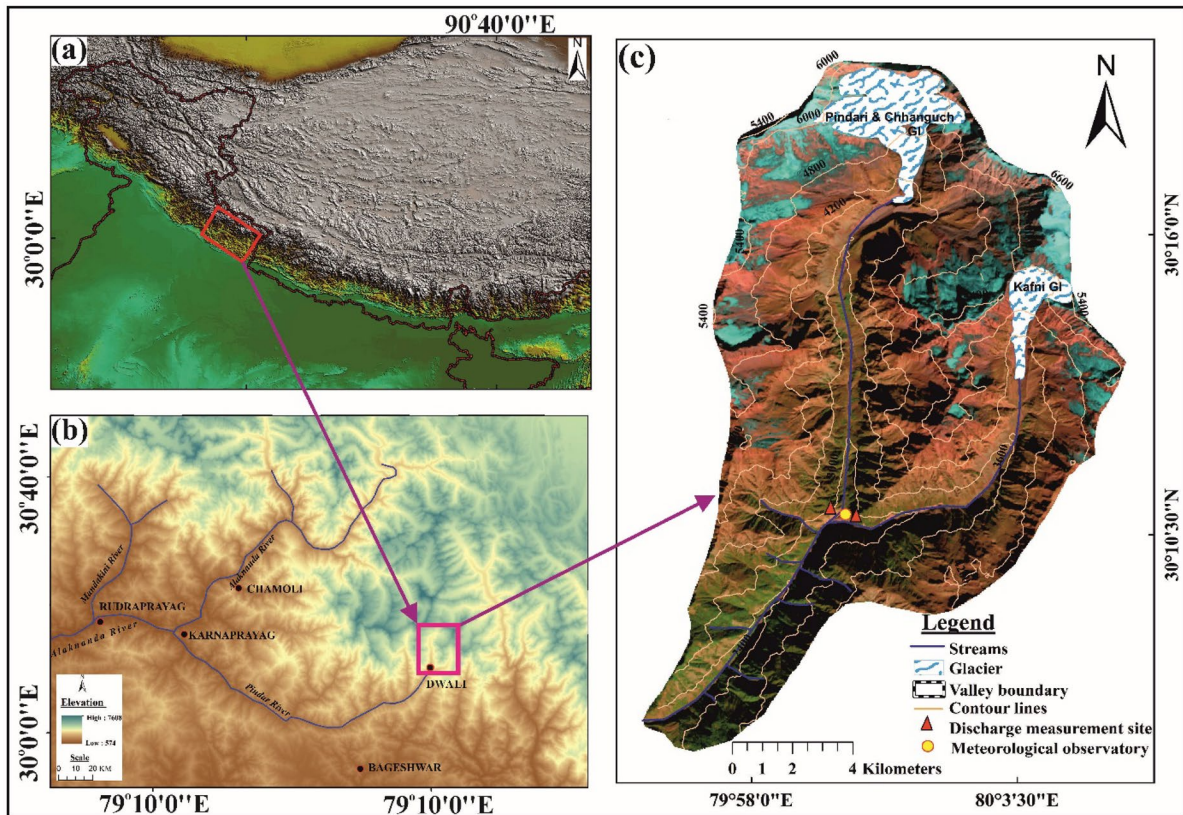


Fig. 1 a Location of study area in Central Himalaya, b contours, discharge site and streams, and c Landsat imagery of study area with discharge sites (red triangle) and meteorological observatory (yellow circle) at Dwali station of the two adjacent Pindari and Kafni glacier basins

long and severe winters along with snowstorm brought by western disturbances (October to March). Temperature in winter falls to negative and varies from -20 to -40 °C and in summer, it reaches up to 30 °C (Pandey et al., 2018, 2022). Being located on the southern slope of Himalaya, the region gets maximum of its rainfall during monsoon season (June to September) (Reczkowska & Joshi, 2016).

Material and methods

Meteorological and hydrological data generation

The PGB and KGB have not any meteorological and stream gauging stations. Therefore, climatic and hydrological characteristics (rainfall, temperature, humidity, water discharge) of both basins have been measured manually. To understand the meteorological conditions

during ablation period (May to October), a meteorological observatory has been established at Dwali, the confluence point of PGB and KGB, in 2017. This observatory contains (i) an automatic data recording system that records data in every 5 min (averaged at sub-hourly scale), (ii) temperature-relative humidity probe with a protected and articulated sensor (AT-RH/TH-P-S/VEC, Roorkee, India) and (iii) tipping bucket type rain gauge (DREL-R, VEC, Roorkee, India).

For discharge (Q) measurement, two individual gauging sites have been established at Dwali station (Fig. 1). Prior to their establishment, a preliminary survey has been conducted to ensure that flow of water in two channels is confined to a single channel. It has been found that KGB flows in a single channel and no other major stream joins it between its outlets and gauging site; whereas PGB is fed by several tiny tributaries such as Ata Gadneve, Pranmata Gad, Kewar, Chopta Gad, Meing Gadhera and Gadhera.

As substantial amount of water and suspended sediments are delivered during high flow months (July to September), the frequency of data collection is higher during these months as compared to lean flow months (May, June and October). Water samples have been collected twice in a day for July to September and daily for May, June and October (Kumar et al., 2018). Flow velocity and water depth have been measured with the help of wooden floats and graduated staff gauges, while the cross-sectional areas of streams have been measured using sounding rods and tape measure (Fig. 2a, b). Further, the width of cross-sectional area has been divided into five equal transects to measure surface flow in each transect. Surface velocity measurements have been multiplied by a factor of 0.90 to convert it into mean flow velocity (Singh et al., 2003). Further, discharge has been calculated using area-velocity method (Buchanan & Somers, 1969), which is mathematically expressed as:

$$Q = k(A \times V) \quad (1)$$

where Q stands for water discharge ($\text{m}^3 \text{s}^{-1}$), k for correction factor (0.9), A represents the cross-sectional area of channel (m^2), and V indicates the velocity of flow.

After calibrating the water levels observed from staff gauge and recorder, a stage-discharge relationship has been established to convert water levels into discharge ($\text{m}^3 \text{s}^{-1}$). Flow measurements may have an inaccuracy up to 5–10% in Central Himalayan region, particularly during the high flow months (July–September) (Haritashya et al., 2006; Singh et al., 2003, 2015; Srivastava et al., 2014a, b).

Measurement of SSC

SSC is the ratio of the weight of dry sediment to the weight of a given volume of water–sediment mixture. For estimating SSC (mg/l), collected water samples have been filtered using whatman-40 ashless filter paper (Fig. 2c) and dried for removing all the moisture stored in sediments. Subsequently, sediment samples have been analysed at Wadia Institute of Himalayan Geology, Dehradun (Kumar et al., 2018). These SSC

Fig. 2 a sampling site, b gauging station, c and d sediment filtration process



measurements have been confirmed with an automatic suspended solid indicator (Model: 3150, VEC, Roorkee, India) (Fig. 2d). Further, SSL, sediment yield and erosion rates have been computed using SSC data.

Estimation of SSL and sediment yield

SSL refers to the amount of sediments moved to downstream through suspension. It mostly comprises of fine-grained, lighter-weight particles such as silt, clay and fine sand that remain in water during transportation. A larger portion of sediments carried in a stream is transported as suspended load. It is measured in tonnes and calculated as:

$$SSL = \text{Discharge} \times \left(\frac{SSC}{\text{Discharge rate}} \right) \quad (2)$$

Sediment yield refers to the amount of sediment removed from per unit area of watershed during a specified time period. This is the consequential effects of erosion, transportation and deposition taking place in the basin. It is measured in tonnes per square km

per annum and is calculated by dividing the total available suspended load to the area of the basin.

$$\text{Sediment yield} = \frac{\text{Total suspended load (tonnes)}}{\text{Area of the basin (km}^2\text{)}} \quad (3)$$

Computation of erosion rates

The erosion rate measures the amount of soil mass lost per unit of time. To compare the erosion rates in basins having different catchment area, same type of areal units (meters, kilometres, feet, yards or miles) is necessary to calculate the rate of erosion. Generally, erosion rates are expressed in mm per 1000 year and computed as:

$$\text{Erosion rate} = \frac{\text{Total sediment load (tonnes)}}{\text{Area of watershed} \times \text{specific gravity}} \quad (4)$$

In this study, the specific gravity of the rocks has been taken as 2.65 (Singh et al., 2008a). The overall methodology adopted in this study has been demonstrated in Fig. 3.

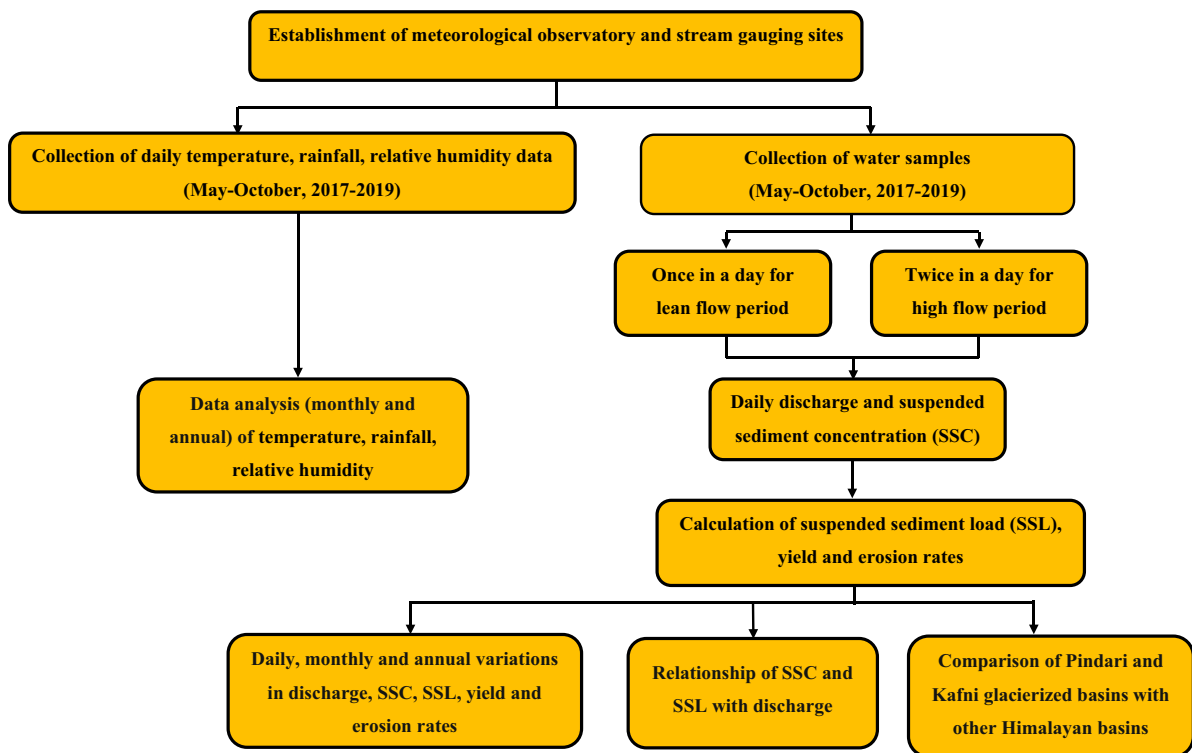


Fig. 3 Methodological steps followed towards the accomplishment of present study

Results and discussion

Meteorological characteristics of PGB and KGB

The meteorological characteristics of PGB and KGB such as average temperature, rainfall and humidity for the ablation period of 2017–2019 have been presented in Table 1. An average of 2106.58 mm rainfall has been recorded in both basins during the study period. The maximum rainfall (2680 mm) has been recorded in 2018, followed by 2017 (1838.90 mm) and 2019 (1800.85 mm). More than two-third (about 67 per cent) rainfall of total ablation period has been reported in July and August months, whereas, October has recorded just about 1 per cent rainfall (Table 1). These results are in correspondence with other studies of Central Himalaya which indicate that rainfall amount in this region is considerably subjected to south-west monsoon (Singh et al., 2006; Kumar et al., 2014; Kayastha et al., 2014; Srivastava et al., 2014a; Joshi et al., 2017).

The temperature in PGB and KGB varies between 11.17 (October) and 17.31 °C (July) with a mean temperature of 14.71 °C (Table 1). The months of July and August have recorded slightly higher temperature than others. Similarly, mean humidity has been found comparatively high in these months. The average humidity has ranged between a minimum of 59.14% in October to a maximum of 87.59% in August with an average of 73.14% during 2017–2019 (Table 1). Similar climatic characteristics have been witnessed in other basins of Central Himalaya (Singh et al., 2006; Kumar et al., 2014; Kayastha et al., 2014; Srivastava et al., 2014a; Joshi et al., 2017; Kumar et al., 2018; Singh et al., 2020; Pandey et al., 2022).

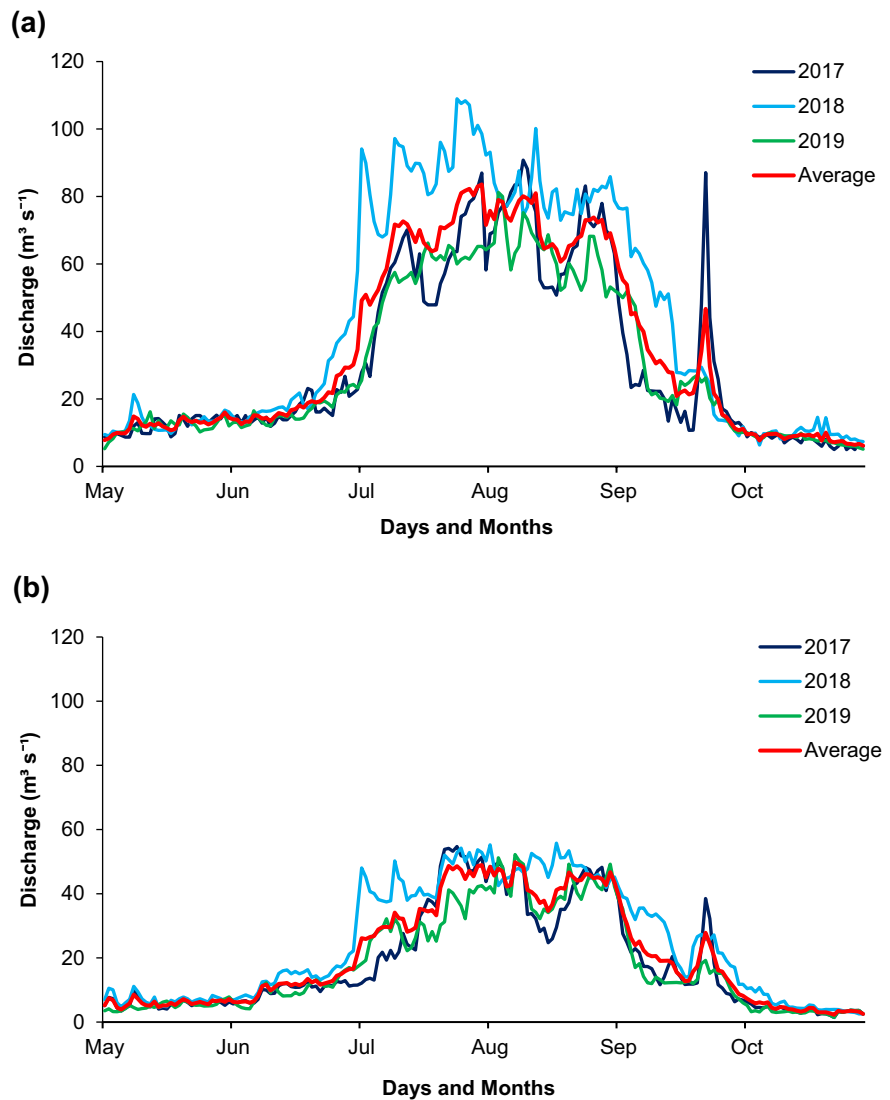
Variations of discharge in PGB and KGB

Daily, monthly and annual variations of discharge in PGB and KGB during 2017–2019 have been shown in Fig. 4 and Table 2. A very high fluctuation in mean daily discharge has been recorded in both basins. The mean daily discharge in PGB has ranged between 6.15 and 83.58 m³ s⁻¹, whereas, in KGB, it has ranged from 2.26 to 49.83 m³ s⁻¹ during 2017–2019 (Fig. 4). The PGB has recorded maximum discharge of 108.96 m³ s⁻¹ on July 25, 2018, and minimum of 4.98 m³ s⁻¹ on October 29, 2017. Similarly, in KGB, maximum (55.76 m³ s⁻¹) and minimum

Table 1 Meteorological conditions over Pindari and Kafni glacierized basins during 2017–2019

Month	2017			2018			2019			2017–2019			
	Average temp. (°C)	Average humidity (%)	Monthly rainfall (mm)	Average temp. (°C)	Average humidity (%)	Monthly rainfall (mm)	Average temp. (°C)	Average humidity (%)	Monthly rainfall (mm)	Average temp. (°C)	Average humidity (%)	Average rainfall (mm)	Rainfall (%)
May	10.45	57.51	109.10	13.36	61.89	103.40	3.86	11.56	58.50	57.15	11.90	89.88	4.32
Jun	15.16	60.58	207.20	16.47	78.94	349.60	13.04	14.26	72.54	228.80	15.30	261.87	12.34
Jul	16.06	89.97	600.00	18.17	81.45	1024.00	38.21	17.69	83.71	537.30	17.31	720.43	33.56
Aug	16.98	87.63	613.80	16.87	87.94	720.00	26.87	16.92	87.21	700.00	16.92	677.93	33.04
Sept	15.30	82.59	306.40	15.92	79.17	429.20	16.01	15.70	67.20	259.60	15.64	331.73	15.70
Oct	13.50	60.68	2.40	9.56	58.51	53.80	2.01	10.46	58.24	18.00	11.17	24.73	1.05
Mean	14.58	73.16	306.48	15.06	74.65	446.67	-	14.43	71.62	300.14	14.71	351.10	-
SD	0.33	15.10	253.72	3.12	11.70	371.46	-	2.91	12.41	268.89	2.58	292.00	-

Fig. 4 Daily variations in discharge **a** Pindari and **b** Kafni glacierized basins during 2017–2019



($1.43 \text{ m}^3 \text{ s}^{-1}$) discharge have been recorded on August 18, 2018, and October 24, 2017, respectively.

The mean monthly discharge in PGB has varied from $8.59 \text{ m}^3 \text{ s}^{-1}$ in October to $71.55 \text{ m}^3 \text{ s}^{-1}$ in August, while in KGB, it has fluctuated between $4.40 \text{ m}^3 \text{ s}^{-1}$ (October) to $43.68 \text{ m}^3 \text{ s}^{-1}$ (August). The maximum ($88.80 \text{ m}^3 \text{ s}^{-1}$) and minimum ($7.95 \text{ m}^3 \text{ s}^{-1}$) discharge in PGB have been recorded in July (2018) and October (2017), respectively, whereas KGB has experienced a maximum discharge of $48.09 \text{ m}^3 \text{ s}^{-1}$ in August 2018 and a minimum of $3.46 \text{ m}^3 \text{ s}^{-1}$ in October 2019. Further, both glacierized basins have experienced their peak discharge in August month and minimum in October which is almost in correspondence with rainfall occurrence, but PGB has

exceptionally reported maximum discharge in July 2018 due to occurrence of very high rainfall over the basin in this month. Approximately, two-third of the annual discharge of PGB and KGB has been recorded in July and August months (Table 2).

The mean annual discharge in PGB and KGB during 2017–2019 have been found about $35.06 \text{ m}^3 \text{ s}^{-1}$ and $20.47 \text{ m}^3 \text{ s}^{-1}$, respectively (Table 2). It has been found approximately 1.71 times higher in PGB than KGB. Both glacierized basins have observed comparatively higher annual discharge in the year 2018 ($42.72 \text{ m}^3 \text{ s}^{-1}$ and $24.49 \text{ m}^3 \text{ s}^{-1}$) as compared to 2017 ($31.84 \text{ m}^3 \text{ s}^{-1}$ and $18.79 \text{ m}^3 \text{ s}^{-1}$) and 2019 ($30.30 \text{ m}^3 \text{ s}^{-1}$ and $18.01 \text{ m}^3 \text{ s}^{-1}$), respectively. These inter-annual variations in discharge are driven by changes

Table 2 Mean monthly discharge from Pindari and Kafni glacierized basins during 2017–2019

Month	2017			2018			2019			2017–19					
	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni			
	Discharge (m ³ s ⁻¹)	%	Discharge (m ³ s ⁻¹)	Discharge (m ³ s ⁻¹)	%	Discharge (m ³ s ⁻¹)	Discharge (m ³ s ⁻¹)	%	Discharge (m ³ s ⁻¹)	Discharge (m ³ s ⁻¹)	%				
May	12.13	6.35	5.82	5.17	12.94	7.06	4.81	11.77	6.48	5.12	4.74	12.28	5.96	6.00	4.91
Jun	16.75	8.77	10.01	8.90	22.28	13.72	9.34	16.26	8.94	10.11	9.36	18.43	8.80	11.28	9.20
Jul	57.01	29.84	33.22	29.53	88.80	44.49	30.28	54.69	30.09	30.32	28.08	66.83	31.53	36.01	29.29
Aug	70.06	36.67	40.94	36.17	81.22	48.09	32.73	63.38	34.87	42.00	38.89	71.55	34.41	43.68	35.93
Sept	27.15	14.21	18.82	16.73	41.38	27.76	18.89	27.52	15.14	16.98	15.73	32.02	15.17	21.19	17.12
Oct	7.95	4.16	3.95	3.51	9.67	5.80	3.95	8.15	4.48	3.46	3.20	8.59	4.14	4.40	3.55
Mean	31.84	-	18.79	-	42.72	24.49	-	30.30	-	18.01	-	35.06	-	20.47	-
SD	25.95	-	16.15	-	33.77	17.81	-	22.89	-	14.97	-	26.76	-	15.88	-

in rainfall over this region (Table 1). More than 80% of the total annual rainfall and discharge have been recorded in monsoon months (Tables 1 and 2). Similarly, Kayastha et al. (2014) and Joshi et al. (2017) have reported that during south-west monsoon period, Pindar and Kafni rivers flow up to the danger level and become violent because more than 80% discharge of these basins is rainfall dominated. Furthermore, discharge results of Pindar and Kafni basins are incongruent with several other basins of Himalayan region (Singh & Jain, 2002; Kumar et al., 2002; Jain et al., 2003; Haritashya et al., 2006; Thayyen & Gergan, 2010; Arora et al., 2014; Kayastha et al., 2014; Joshi et al., 2017; Kumar et al., 2018).

Apart from above, a high variability has been detected in annual streamflow in both PGB (0.76) and KGB (0.78) during 2017–2019 (Table 3). However, PGB has witnessed a continuous decline in annual variability since 2017, i.e. 0.81 (2017), 0.79 (2018) and 0.75 (2019); but in KGB, the minimum variability (0.73) has been detected in 2018, followed by 2019 (0.85) and highest (0.86) in 2017. Considering the months, the lowest variability has been reported in August month and highest in September (except in October 2018 in KGB).

Variations of SSC in PGB and KGB

In general, sediment concentration largely depends on the volume of stream flow. The higher the stream flow, the greater will be the sediment concentration, but in glacier fed rivers, the main sources of sediment generation are weathering of moraines and rocks, channel system, bedrock system and glacier system (Arora et al., 2014; Rautela et al., 2022). The mean daily, monthly and annual SSC in PGB and KGB have been presented in Fig. 5 and Table 4. The mean daily SSC in both basins has varied largely, i.e. from 91.03 to 967.83 mg/l in PGB and from 61.97 to 900.17 mg/l in KGB (Fig. 5). The PGB has witnessed maximum SSC (1200 mg/l) on July 16, 2018, and minimum (70.1 mg/l) on October 31, 2019. Similarly, maximum (1022.20 mg/l) and minimum (60 mg/l) SSC in KGB have been witnessed on July 22, 2018, and October 26, 2018, respectively (Fig. 5). This may be attributed to occurrence of maximum and minimum water discharge in PGB and KGB basins during these months as increased discharge generates more suspended sediments in glacierized basins (Arora et al., 2014; Kumar et al., 2018; Lu et al., 2022).

The mean monthly SSC has ranged from 113.49 (May) to 791.26 mg/l (August) in PGB and from 80.94

(October) to 737.85 mg/l (August) in KGB during 2017–2019 (Table 4). The maximum monthly SSC in both PGB (974.11 mg/l) and KGB (933.89 mg/l) have been recorded in July 2018 due to occurrence of high rainfall and resultant discharge in this year (Fig. 6 and Table 1). Nearly two-third amount of SSC has been recorded in peak monsoon months (July and August) (Table 4).

The average SSC has been found about 396.07 mg/l in PGB and 359.67 mg/l in KGB during 2017–2019 (Table 4). When this amount of SSC is compared with discharge in both basins, it has been found that the amount of SSC is comparatively higher in KGB than PGB. The SSC amount difference within two adjacent valleys may be attributed to glacier coverage, steepness and roughness of streams, location of the sediment sources and variation in travel distance from sediment source to gauging station (Arora et al., 2014). The maximum SSC in PGB has been observed in 2018 (441.66 mg/l), followed by 2017 (387.99 mg/l) and minimum (358.56) in 2019. Similar pattern has been observed in occurrence of SSC (409.04, 353.67, 316.30 mg/l) in KGB. This indicates that SSC is directly

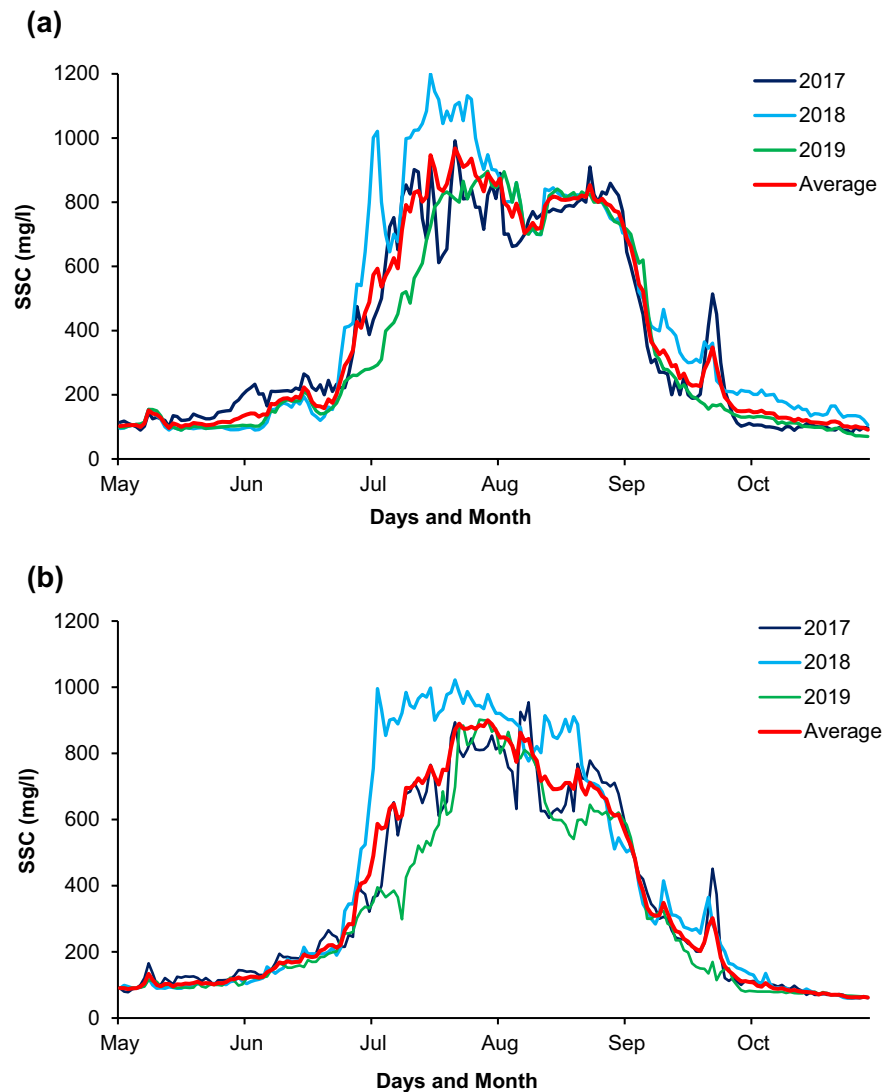
linked with occurrence of rainfall and resultant discharge in PGB and KGB (Fig. 6 and Table 1). Besides, the factors such as temperature, weathering, slope and amount of eroded material also play a decisive role in determining SSC amount in these basins (Bisht et al., 2018). Under the effect of high temperature, humidity and intense precipitation in ablation season, both debris-free and debris-covered glaciers are exposed to high erosion and melting rates which further intensify the concentration of sediment (Kumar et al., 2018; Bisht et al., 2018; Rautela et al., 2022). Further, the results of this study are in correspondence with other studies conducted in several Himalayan River basins (Arora et al., 2014; Bisht et al., 2018; Kumar et al., 2018; Pandey et al., 2018; Singh et al., 2005).

The annual variability in SSC in both basins, PGB (0.77) and KGB (0.81), has been found high and almost identical during 2017–2019 (Table 3). However, a continuous increase has been witnessed in annual variability in SSC in PGB since 2017, i.e. 0.76 (2017), 0.79 (2018) and 0.83 (2019), but in KGB, it has been found highest (0.85) in 2018, followed by (0.83) 2019 and

Table 3 Coefficient of variation (CV) in monthly and annual discharge, SSL and SSC in both glacierized basins

Year	Month	Pindari Glacier			Kafni Glacier		
		Discharge	SSC	SSL	Discharge	SSC	SSL
2017	May	0.21	0.18	0.36	0.24	0.17	0.37
	Jun	0.23	0.30	0.55	0.23	0.34	0.50
	Jul	0.29	0.20	0.44	0.46	0.23	0.60
	Aug	0.16	0.08	0.17	0.19	0.13	0.29
	Sep	0.62	0.52	1.12	0.49	0.46	0.94
	Oct	0.24	0.07	0.29	0.33	0.21	0.53
2018	May	0.22	0.15	0.38	0.23	0.09	0.28
	Jun	0.42	0.67	1.18	0.29	0.51	0.82
	Jul	0.14	0.16	0.25	0.14	0.08	0.18
	Aug	0.08	0.07	0.11	0.07	0.15	0.18
	Sep	0.53	0.39	0.86	0.30	0.33	0.61
	Oct	0.18	0.19	0.26	0.50	0.28	0.80
2019	May	0.20	0.16	0.25	0.23	0.09	0.26
	Jun	0.23	0.30	0.51	0.35	0.33	0.67
	Jul	0.22	0.33	0.45	0.24	0.35	0.56
	Aug	0.12	0.07	0.14	0.13	0.15	0.24
	Sep	0.47	0.64	1.12	0.49	0.57	1.18
	Oct	0.18	0.20	0.34	0.32	0.07	0.37
2017		0.81	0.76	1.23	0.86	0.79	1.31
2018		0.79	0.79	1.19	0.73	0.85	1.16
2019		0.75	0.83	1.23	0.85	0.83	1.31
Average (2017–2019)		0.76	0.77	1.17	0.78	0.81	1.20

Fig. 5 Daily variations in SSC **a** Pindari and **b** Kafni glacierized basins during 2017–2019



lowest (0.79) in 2017. Considering the months, the lowest variability has been reported in August and highest in September in both glacierized basins (except in June 2017 in KGB).

Variations of SSL in PGB and KGB

The variations in daily, monthly and annual SSL in PGB and KGB have been presented in Fig. 7 and Table 5. The average daily SSL in both basins has been found highly variable over the ablation season. It has varied between 49.49 tonnes/day and 6761.55 tonnes/day in PGB and between 13.55 tonnes/day and 3789.54 tonnes/day in KGB (Fig. 7). The PGB has recorded

highest SSL about 10,657.28 tonnes/day on July 25, 2018, and KGB (4593.11 tonnes/day) on July 22, 2018 (Fig. 7). These variations may be attributed to different lithological conditions, size, debris coverage and drainage pattern (Kumar et al., 2018; Singh et al., 2016). Apart from this, morainic and fluvio-glacial deposits found in the Pindar and Kafni Valleys may further increase the sediment discharge during ablation season (Reczkowska & Joshi, 2016).

Mean monthly SSL in both PGB and KGB have been found highly variable during the study period, i.e. 93.09 tonnes/day in October to 4889.20 tonnes/day in August (PGB) and from 33.51 tonnes/day (October) to 2822.36 tonnes/day (August) in KGB (Table 5). The SSL starts

Table 4 Mean monthly SSC in Pindari and Kafni glacierized basins during 2017–2019

Month	2017			2018			2019			2017–2019						
	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni				
	SSC (mg/l)	%	SSC (mg/l)	%	SSC (mg/l)	%	SSC (mg/l)	%	SSC (mg/l)	%	SSC (mg/l)	%				
May	13.07	5.63	114.51	5.41	102.70	3.89	99.44	4.07	107.06	4.99	98.92	5.23	113.49	4.84	104.29	4.90
Jun	246.51	10.62	211.78	10.01	220.78	8.36	215.03	8.80	176.39	8.23	186.13	9.84	214.56	9.07	204.31	9.55
Jul	742.79	32.00	677.73	32.03	974.11	36.88	933.89	38.20	648.76	30.26	590.37	31.21	788.55	33.05	734.00	33.81
Aug	780.21	33.61	730.37	34.52	797.19	30.19	800.99	32.76	796.37	37.14	682.19	36.06	791.26	33.65	737.85	34.45
Sept	322.76	13.90	298.55	14.11	384.03	14.54	309.87	12.67	311.84	14.54	259.57	13.72	339.54	14.33	289.33	13.50
Oct	98.32	4.24	82.70	3.91	162.16	6.14	85.55	3.50	103.59	4.83	74.57	3.94	121.36	5.07	80.94	3.78
Mean	387.99	-	353.67	-	441.66	-	409.04	-	358.56	-	316.30	-	396.07	-	359.67	-
SD	294.12	-	277.63	-	349.54	-	348.29	-	298.21	-	263.69	-	306.46	-	290.13	-

to rise from June onwards, reaching its maximum at the end of July and the mid of August, and then begins to decline towards the end of ablation season (Fig. 7). The maximum monthly SSL in PGB (7569.48 tonnes/day) and KGB (3604.24 tonnes/day) has been recorded in July 2018 which may be attributed to intense precipitation events resulting high erosion, landslide and avalanches on steep slopes (Table 5). Nearly 85% of the total annual SSL of PGB and KGB have been delivered in July and August months. The average annual SSL in PGB (1928.34 tonnes/day) has been found approximately 1.9 times higher than KGB (1040.26 tonnes/day). The mean annual SSL has been recorded maximum in 2018 followed by 2017 and 2019. SSL has also shown a correspondence with discharge, i.e. increase (decrease) consistently with increase (decrease) in discharge amount in both basins (Fig. 8).

Apart from above, a high variability has been observed in average annual SSL in PGB (1.17) and KGB (1.20). These results reveal that variability in SSL in PGB and KGB has been found identical to Gangotri and Chhota Shigri glaciers (1.1 each) (Haritashya et al., 2006; Singh et al., 2018) and less to Dokriani glacier (1.4) (Singh et al., 2003). The annual variability in SSL has varied from 1.19 (2017) to 1.23 (2019) in PGB and from 1.16 (2017) to 1.31 (2019) in KGB. This variability has been found higher when compared with the variability of SSL in Alpine glaciers ($C_v=0.22$) (Collins, 1990) and Norwegian glaciers ($C_v=0.22-0.48$) (Ostrem, 1975). The lowest variability has been observed in August, whereas the highest in September (except in October 2018 in KGB).

Sediment yields from PGB and KGB

Sediment yield is the measurement of sediment drained from a catchment during a specific period of time (Kumar et al., 2018). The average annual sediment yield in PGB and KGB has been found about 3196.53 tonnes km⁻² yr⁻¹ and 3087.23 tonnes km⁻² yr⁻¹, respectively (Table 6). These estimated sediment yields are considerably greater than the average global sediment yield (150 tonnes km⁻² yr⁻¹) and the Indian subcontinent (327 tonnes km⁻² yr⁻¹). With comparison of other Himalayan glacier basins, sediment yield from these basins has been found very high as compared to Pastio (132 tonnes km⁻² yr⁻¹), Siachen (707 tonnes km⁻² yr⁻¹), Chhota Shigri (1689 tonnes km⁻² yr⁻¹) and Gangotri (2863 t km⁻² yr⁻¹) and less than Chorabari (4064 tonnes km⁻² yr⁻¹) (Arora et al., 2014; Bhutiyani, 2000; Haritashya et al., 2006;

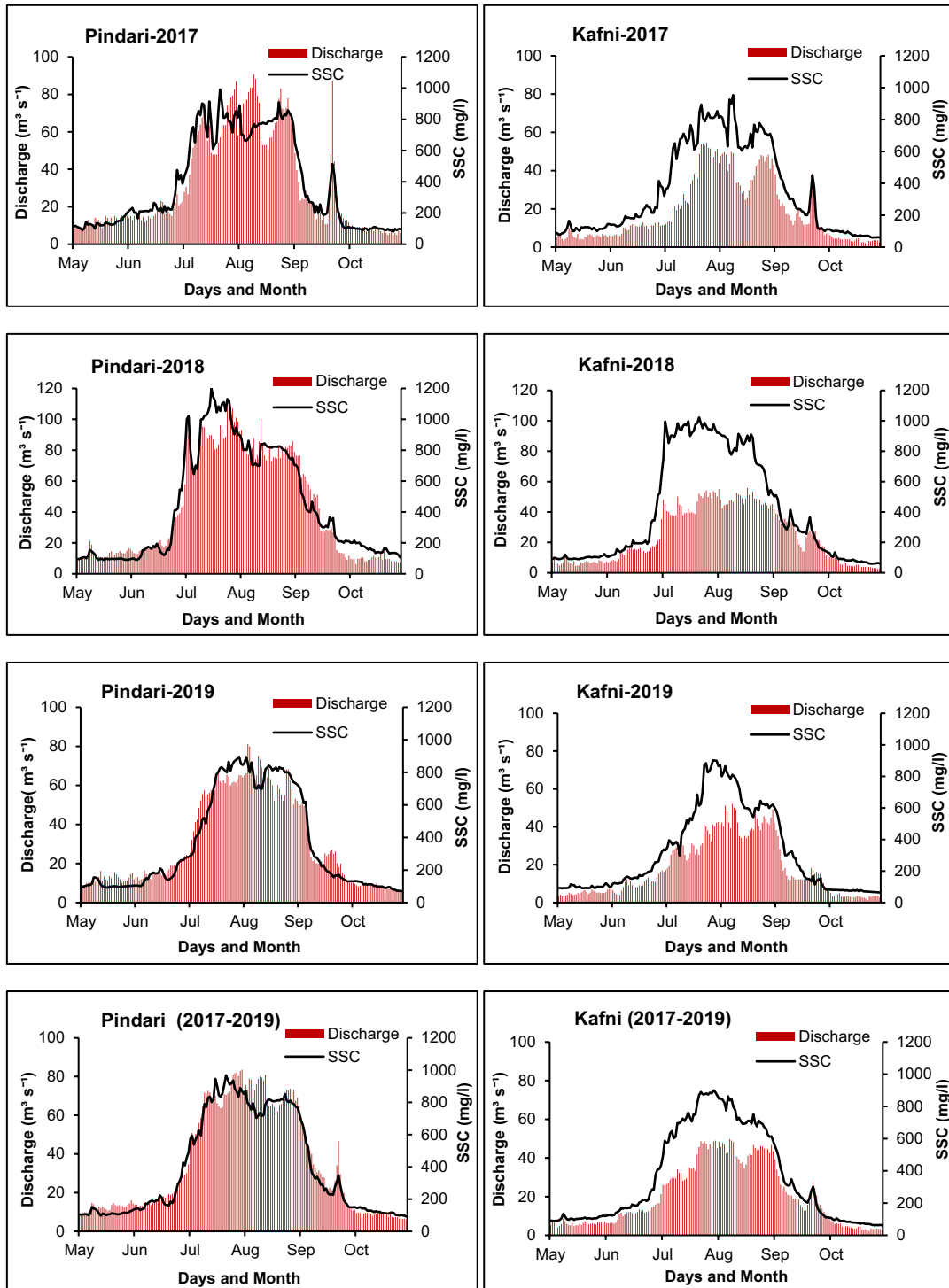
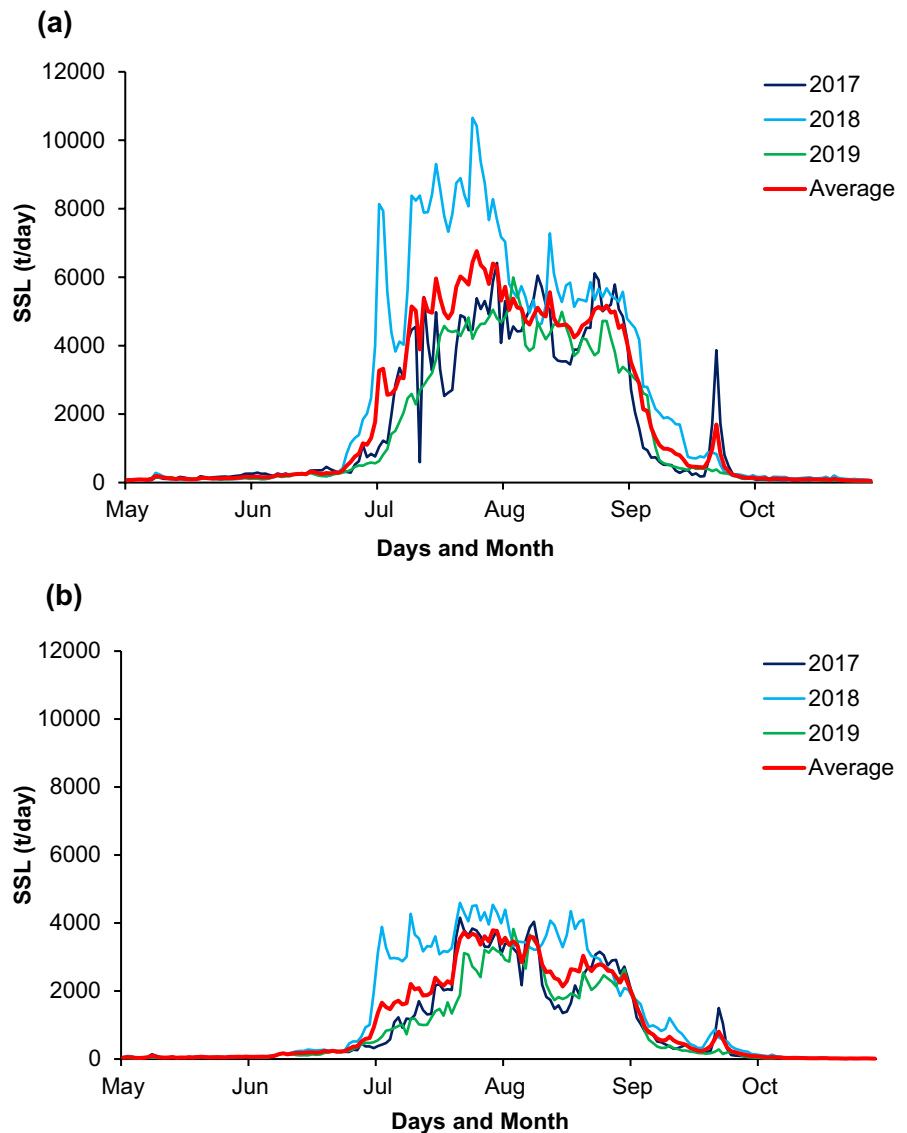


Fig. 6 Daily pattern of discharge and SSC in Pindari and Kafni glacierized basins during 2017–2019

Fig. 7 Daily variations in SSL **a** Pindari and **b** Kafni glacierized basins during 2017–2019



Kumar et al., 2018; Singh et al., 2015, 2016). In PGB, sediment yield has been observed maximum in 2018 (4334.09 tonnes km⁻² yr⁻¹), followed by 2017 (2752.82 tonnes km⁻² yr⁻¹) and minimum in 2019 (2502.68 tonnes km⁻² yr⁻¹), respectively. Similar pattern in the sediment yield has been observed in KGB, maximum (4056.65 tonnes km⁻² yr⁻¹) in 2018 and minimum (2415.38 tonnes km⁻² yr⁻¹) in 2019 (Table 6). The annual variation in sediment yield may be attributed to variation in climatic conditions (rainfall, temperature), amount of water discharge,

snow cover and sediment mobilization processes over these basins (Kumar et al., 2018; Rautela et al., 2022).

However, average annual SSL in PGB (354,814.56 tonnes) has been found about twice than KGB (191,407.84 tonnes), whereas the difference in annual sediment yield from two basins (3196.53 tonnes km⁻² yr⁻¹ and 3087.23 tonnes km⁻² yr⁻¹, respectively) is only 0.03 times (Table 6). Remarkably, steeper slopes and steep stream gradient in KGB support large sediment yield (Singh et al., 2008a,

Table 5 Mean monthly SSL in Pindari and Kafni glacierized basins during 2017–2019

Month	2017			2018			2019			2017–2019						
	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni	Pindari		Kafni				
	SSL (t/day)	%	SSL (t/day)	%	SSL (t/day)	%	SSL (t/day)	%	SSL (t/day)	%	SSL (t/day)	%				
May	140.37	1.51	58.33	1.04	116.93	0.75	61.21	0.75	108.92	1.21	43.91	0.91	122.07	1.06	54.48	0.88
Jun	372.72	4.01	192.34	3.43	540.29	3.47	285.66	3.51	260.26	2.89	178.40	3.68	391.09	3.4	218.80	3.53
Jul	3666.49	39.43	2117.32	37.78	7569.48	48.57	3604.24	44.23	3253.94	36.15	1646.36	33.93	4829.97	42.01	2455.97	39.6
Aug	4110.78	44.21	2625.69	46.85	5597.05	35.91	3346.24	41.07	4359.77	48.44	2495.14	51.43	4889.20	42.53	2822.36	45.51
Sept	940.67	10.12	580.86	10.36	1625.15	10.43	802.75	9.85	942.00	10.47	465.22	9.59	1170.61	10.18	616.28	9.94
Oct	68.22	0.73	29.71	0.53	135.93	0.87	48.31	0.59	75.12	0.83	22.51	0.46	93.09	0.81	33.51	0.54
Mean	1660.67		939.99		2614.59		1366.91		1509.77		813.88		1928.34		1040.26	
SD	2034.86		1228.53		3102.92		1587.59		1863.37		1067.30		2246.74		1249.11	

b). Also, the debris-cover area of Kafni glacier (22.5%) is larger than the Pindari glacier (7.62) (Garg et al., 2017).

Erosion rates in PGB and KGB

Himalayan glacierized regions are facing high erosion rates mainly due to active glaciers, steep valleys, avalanches, high tectonic activities, landslides and high rainfall (Arora et al., 2014). The mean annual erosion rates in both the glacierized basins have been found very high and almost identical (1.18 mm/yr in PGB and 1.14 mm/yr in KGB) (Table 6). The annual erosion rate in the years 2017, 2018 and 2019 has been quantified as 1.02, 1.61 and 0.93 mm/yr for PGB and about 1.03, 1.50 and 0.90 mm/yr for KGB. The erosion rates in Central Himalayan basins have been found more than 1 mm/yr. The estimated erosion rates of PGB and KGB are in correspondence with other findings of the Central Himalaya (Arora et al., 2014; Haritashya et al., 2006; Kumar et al., 2016, 2018; Singh et al., 2003, 2014; Srivastava et al., 2014a).

Relationship of SSC and SSL with discharge in PGB and KGB

The simultaneous demonstration of discharge-SSC (Fig. 6) and discharge-SSL (Fig. 8) clearly show that SSC and SSL have followed the pattern of discharge; maximum in July and August, and minimum in May and October. SSC and SSL have started to rise quickly since mid of June and reach to their maximum in August. Additionally, plotted SSC and SSL values against discharge have revealed a significant relationship between discharge-SSC and discharge-SSL (Figs. 9 and 10). The coefficient of determination (R^2) between discharge and SSC in PGB (0.88, 0.89 and 0.93) and KGB (0.89, 0.88 and 0.89) during study period reveals that this relationship has become stronger with time in PGB and remains same in KGB (Fig. 9). Likewise, relationship between discharge and SSL has been found stronger in both PGB (0.94, 0.93 and 0.95) and KGB (0.96, 0.90 and 0.91) reflecting the substantial impacts of climatic factors (temperature and rainfall events) on water discharge and resultant sediment load (Fig. 10). Various studies have reported such high positive correlation between discharge, SSC and SSL in Gangotri, Chorabari, Dokriani, Dunagiri and Panchachuli glacier basins (Haritashya et al., 2006; Srivastava et al., 2014a; Bisht et al., 2018; Kumar et al., 2018; Rautela et al., 2022).

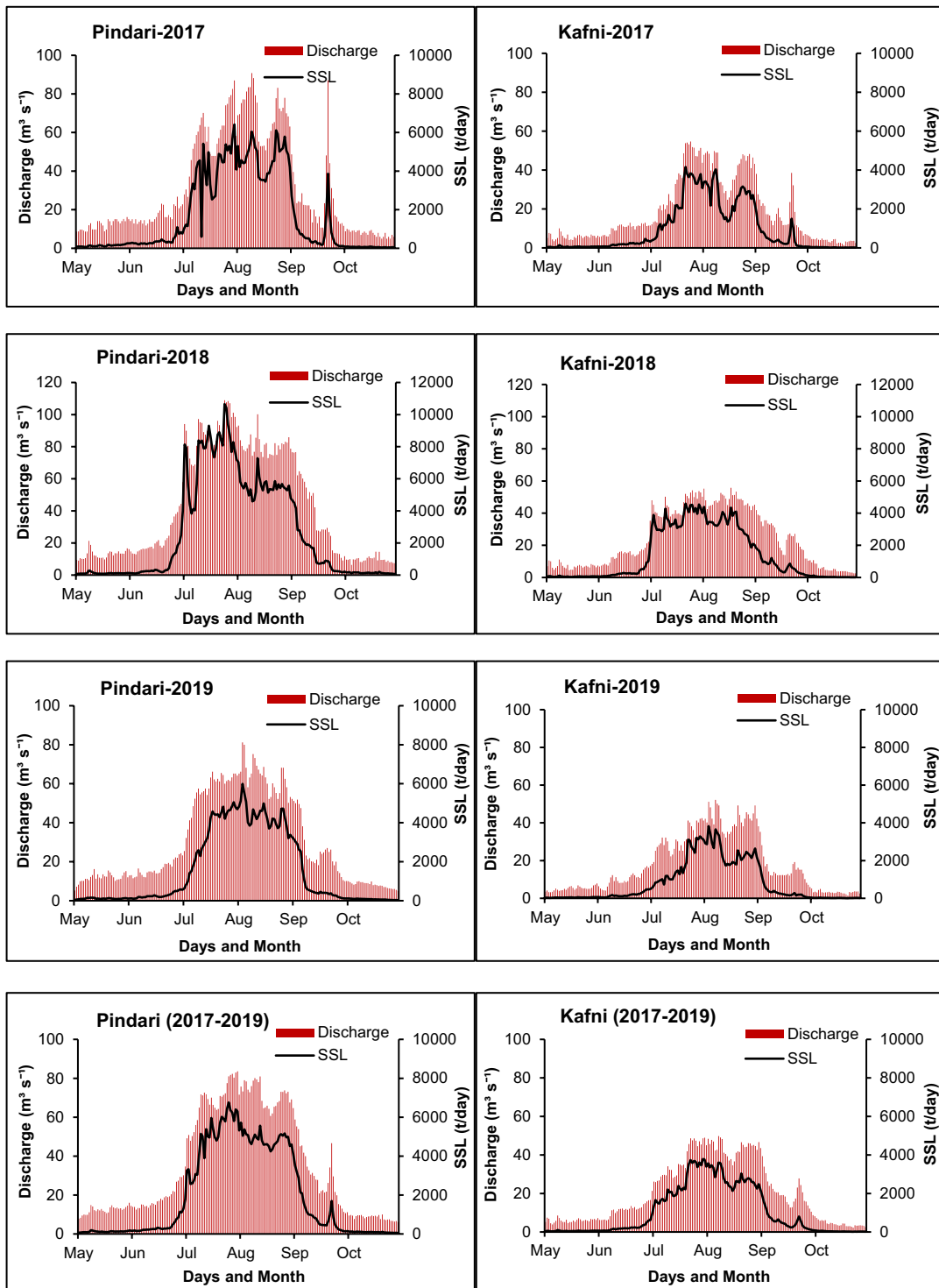


Fig. 8 Pattern of daily discharge and SSL in Pindari and Kafni glacierized basins during 2017–2019

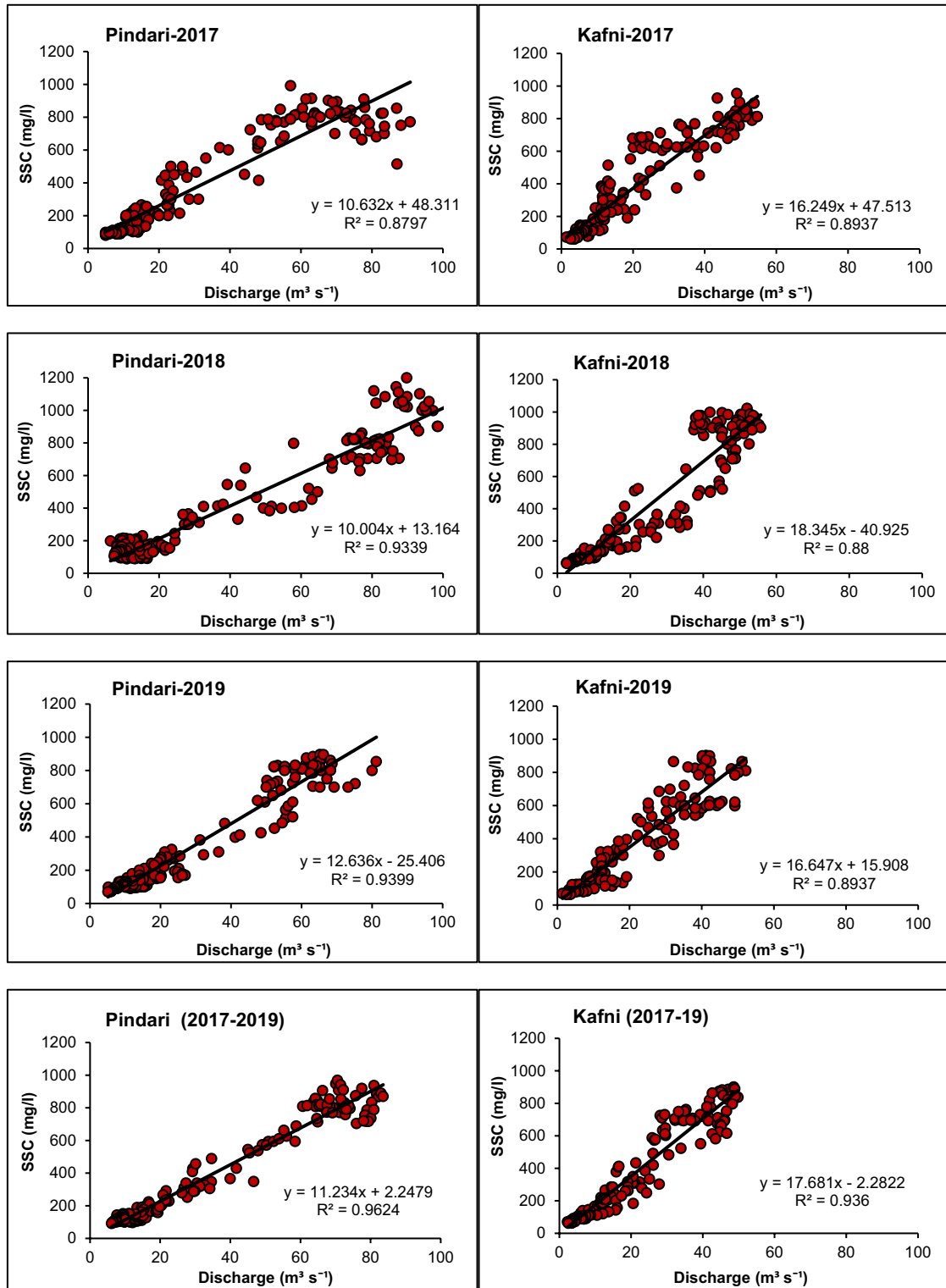


Fig. 9 Relationship of SSC with discharge in Pindari and Kafni glacierized basins during 2017–2019

Table 6 Annual sediment yield and erosion rate in Pindari and Kafni glacierized basins during 2017–2019

Year	PGS			KGS		
	Total sediment load (tonnes)	Sediment yield (t km ⁻² yr ⁻¹)	Erosion rate (mm yr ⁻¹)	Total sediment load (tonnes)	Sediment yield (t km ⁻² yr ⁻¹)	Erosion rate (mm yr ⁻¹)
2017	305563.38	2752.82	1.02	172958.48	2789.65	1.03
2018	481084.21	4334.09	1.61	251512.26	4056.65	1.50
2019	277797.73	2502.68	0.93	149753.67	2415.38	0.90
2017–2019	354815.11	3196.53	1.18	191408.14	3087.23	1.14

Comparison of SSC, SSL, sediment yield and erosion rates of PGB and KGB with other Himalayan basins

A number of studies have inferred that SSC, SSL, sediment yield and erosion rates differ by order of magnitude in different Himalayan basins (Haritashya et al., 2006; Arora et al., 2014; Kumar et al., 2016; Singh & Ramanathan, 2018; Rautela et al., 2022). Mean daily SSC in PGB (396.07 mg/l) and KGB (359.67 mg/l) has been found comparatively higher than Western Himalayan glacier basins (370 mg/l in Chhota Shigri glacier and 38.5 mg/l in Pastio glacier) but lower than other Central Himalayan glacier basins (1310.3 mg/l by Gangotri glacier and 1188.7 mg/l by Chorabari glacier) (Table 7). These variations are

associated with differences in basin area, slope, surface characteristics, amount and intensity of rainfall (Arora et al., 2014). For example, despite of having been less basin area, Mandakini (15.4 km²) and Bhagirathi in Dokriani (16.3 km²) glacierized basins have witnessed high SSC amount which reflect the contribution of steepness, rocks and soil characteristics in generating SSC (Haritashya et al., 2006; Kumar et al., 2018).

Further, PGB (1928.3 tonnes/day) and KGB (1040.3 tonnes /day) have delivered comparatively higher amount of SSL than Mandakini (513.8 tonnes/day) and Bhagirathi (447.0 tonnes/day) glacierized basins but comparatively lesser than Gangotri glacierized basin (10,392.0 tonnes/day) (Table 7). The SSL directly responses to

Table 7 Estimated SSC and SSL in different glacierized basins of the Himalayas

Glacier	Basin/region	Basin area (km ²)	Mean daily SSC (mg/l)	Mean daily SSL (t/day)	Observation period	Source
Pindari	Alaknanda River/ Central Himalaya	111.0	396.1	1928.3	(May–Oct, 2017–2019)	Present study
Kafni	Alaknanda River/ Central Himalaya	62.0	359.1	1040.3	(May–Oct, 2017–2019)	Present study
Chorabari	Mandakini/Central Himalaya	15.4	1,188.7	513.8	(June–Sept., 2009–2012)	Kumar et al. (2018)
Dokriani	Bhagirathi/Central Himalaya	16.1	656.2	447.0	(June–Sept., 1995–1998)	Singh et al. (2003)
		15.0	2,324.0	-	(June–Sept., 2010–2011)	Kumar et al. (2014)
Dunagiri	Dhauliganga/ Central Himalaya	17.9	229.0	47.0	(July–Sept., 1984–1989)	Srivastava et al. (2014a)
Gangotri	Bhagirathi/Central Himalaya	556.0	1310.3	10,392.0	(May–Sept., 2008–2011)	Arora et al. (2014)
Patsio	Chandra-Bhaga/ western	7.8	38.5	2.8	(Sept., 2011–2012)	Singh et al. (2015)
Chhota Shigri	Chandra/Western Himalaya	45	370.0	135.0	(May–Oct., 2010)	Singh and Ramanathan (2018)

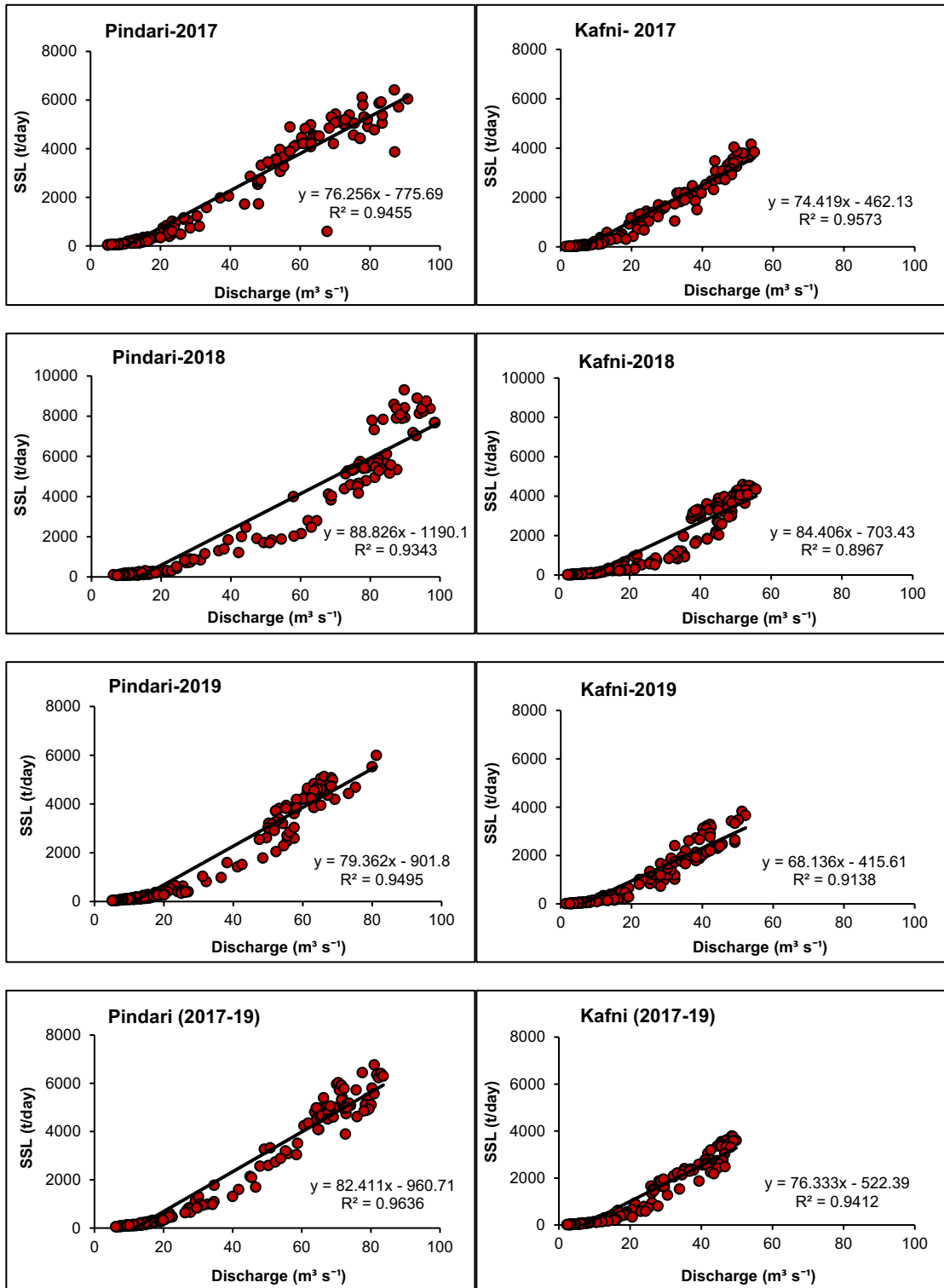


Fig. 10 Relationship of SSL with discharge in Pindari and Kafni glacierized basins during 2017–2019

Table 8 Estimated sediment yield and erosion rate in different glacierized basins of the Himalayas

Glacier/river	Region	Basin area (km ²)	Sediment yield (t/km ² /yr)	Erosion rate (mm/yr)	Observation period	Source
Pindari	Alaknanda River/ Central Himalaya	111.0	3196.53	1.18	(May–Oct, 2017–2019)	Present study
Kafni	Alaknanda River/ Central Himalaya	62.0	3087.23	1.14	(May–Oct, 2017–2019)	Present study
Chorabari	Mandakini/Central Himalaya	15.4	4064.3	1.5	(June–Sept., 2009–2012)	Kumar et al. (2016)
Dokriani	Bhagirathi/Central Himalaya	16.1	2800	1.0	(June–Sept., 1995–1998)	Singh et al. (2003)
Dunagiri	Dhauliganga/ Central Himalaya	17.9	296.3	-	(July–Sept., 1984–1989)	Srivastava et al. (2014a, b)
Gangotri	Bhagirathi/Central Himalaya	556.0	2863	1.0	(May–Sept., 2008–2011)	Arora et al. (2014)
Tons river basin	Chandra/Western Himalaya	34.7	3001	1.1	(May–Oct., 2011–2014)	Singh and Ramanathan (2018)
Tons river basin	Garhwal Lesser Himalaya	41.2	894	0.33	(Jan–Dec, 2008–2011)	Chauhan et al. (2017)
Punatsangchhu river basin	Bhutan/Eastern Himalaya	6271	377	0.28	1992–2008	Choden (2009)

amount of discharge, e.g. PGB and KGB have delivered high amount of SSL as compared to Mandakini and Bhagirathi owing to larger drainage area and resultant discharge in these basins. Several scholars have reported similar results from the glacierized river basins of Western Himalaya (Table 7).

Sediment yield reported from different glacierized basins of Himalayan region have revealed that Central Himalaya produce more sediment as compared to Western, Eastern and Lesser Himalaya because higher erosion rates have been observed in Central Himalaya (more than 1 mm/yr). The erosion rates in PGB (1.18 mm/yr) and KGB (1.14 mm/yr) have been found almost identical to other basins of Central Himalaya except Bhagirathi (1.8 mm/yr), but comparatively higher than the Eastern (0.28 mm/yr) and Lesser (0.33 mm/yr) Himalayan glacierized basins (Table 8).

Conclusions

In this study, discharge, SSC, SSL, sediment yield and erosion rates in PGB and KGB have been estimated for three ablation seasons (2017–2019). The results of this study reveal that annual discharge in PGB and KGB differs slightly, e.g. minimum (30.30 m³ s⁻¹ and 18.01

m³ s⁻¹) and maximum (42.72 m³ s⁻¹ and 24.49 m³ s⁻¹). PGB has witnessed approximately 60% (1.7 times) higher discharge than KGB. More than 80% of the total annual discharge has been recorded in monsoon months for both basins. However, a large variation has been detected in monthly discharge in PGB (8.59 m³ s⁻¹ in October to 71.55 m³ s⁻¹ in August) and KGB (4.40 m³ s⁻¹ in October to 43.68 m³ s⁻¹ in August). Both the basins have witnessed their peak discharges in August almost in correspondence with occurrence of rainfall. Interestingly, the mean annual variability of discharge has decreased over the study period in PGB and KGB. Also, SSC and SSL have fluctuated largely and have increased (decreased) with an increase (decrease) in rainfall and resultant discharge. SSL has been found approximately 1.9 times higher in PGB than KGB, but no large difference has been observed in annual sediment yield. The mean annual variability in SSC has increased over a period of time, but has remained almost same in SSL. The erosion rates observed in PGB (1.18 mm/yr) and KGB (1.14 mm/yr) have been found higher than the other basins of Himalayan region. Also, a significant correlation of SSC and SSL with discharge has been detected in both basins (*p* < 0.01). The major limitation of this study is that due to inaccessibility, harsh climatic conditions and rugged topography, the

observations have been recorded only for three ablation seasons which is not considered hydrologically sufficient. However, an increase in the frequency of records can provide better inferences regarding discharge, SSC, SSL, sediment yield and erosion rates in these basins. For future prediction of water resources and freshwater availability in Central Himalaya, development of a long hydro-meteorological dataset is needed. Moreover, there is a need to conduct research on energy balance in both glacier valleys for determining the causal factors of glacier retreating.

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Author contribution Pankaj Chauhan designed and conceived the research idea, conducted field experiment and analysed the initial data. Jyoti Sharma and Pankaj Bhardwaj did literature review, prepared figures and tables and wrote the initial draft. Manish Mehta and Rouf Ahmed Shah provided suggestions and edited the manuscript. Omvir Singh took the lead in writing and edited the final version of the manuscript. Kalachand Sain provided overall guidance and suggestions for improvement of manuscript. All authors reviewed the manuscript. The listed authors have made a significant contribution to warrant their being part of authorship and have approved the work.

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Data availability All data included in this study are available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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