



Trend analysis of hydrological parameters of Ganga River

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Abstract

Ganga River basin, being the largest river basin in India, adheres with its social and spiritual importance for the country. Although many studies have been conducted on the Ganga basin, however, trend observed in flow and sediment yield in Ganga River has been scarcely studied. Alteration in flow pattern and sediment transport in rivers brings remarkable impact on river geomorphology and entire ecosystem of the region. The present paper attempts to identify trends observed in Ganga River in terms of annual maximum and annual minimum discharges, water and sediment yield during monsoon season. The trend analysis was accomplished by performing the Mann-Kendall (M-K), Sen's slope, and innovative trend analysis at various gauging sites along the river for the monsoon months. Significance of trend tests were tested at 5% significance level. Innovative trend analysis (ITA) revealed non-monotonicity within the time series and provided more detailed understanding of changes in hydrological changes. While observed annual maximum discharge showed a negative trend at almost all the sites, annual minimum discharge showed positive trend at gauging sites upstream of confluence of Yamuna River. Data of discharge and sediment load for monsoon months also revealed declining trends at most of the gauging sites. Water and sediment yields at all sites except Gandhight showed a negative trend. Decline in trend of sediment and water yield is more pronounced in Western Ganga Plain (WGP) as compared to Eastern Ganga Plain (EGP). Incorporating these trends can be helpful for various water management projects in the future. Both climatic factors and human intervention appear to be responsible for the alteration in flow pattern of Ganga River.

Keywords Trend analysis · Ganga River · Mann-Kendall test · Sen's slope · Innovative trend analysis

Introduction

River systems are important geological agent. The transport of riverine sediment load from the continental land mass to the oceans is an important component of global biogeochemical cycle (Milliman and Meade 1983; Khattab and Merkel 2014). Alteration in climatic conditions directly affect the hydrologic cycle which may be observed in the form of variability of rainfall intensity, timing, or depth. Scientists all over the world are trying to understand the behavior of rivers through the years in view of the increasing anthropogenic and climatic influence (Khazaei et al. 2019). A number of studies have been

conducted to assess the trends in streamflow and sediment yield all over the world (Elouissi et al. 2017; Benzater et al. 2019).

Walling and Fang (2003) conducted trend analysis on 145 rivers around the world of which around 50% of the sediment load records showed statistically significant upward or downward trend. Similarly, Milliman et al. (2008) analyzed the water yield of 137 rivers and reported that more than one third of river presented alteration of more than 30% in water yield. However, total water draining to the global ocean remained constant as the decrease in cumulative discharge from mid-latitude rivers was balanced by the increase in discharge of high-latitude rivers. Lu et al. (2003) analyzed the seasonal time series of discharge and sediment load in several tributaries of Yangtze River, China, the longest river in Asia, and reported remarkable alteration in the hydrological parameters, thereby projecting reasonable concern about flooding and water scarcity in different regions of Yangtze River basin. Rivers in central Japan experienced a significant decline in sediment load over the last few decades; however, during the same period, streamflow did not exhibit any remarkable trend (Siakeu et al. 2004).

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Apart from the abovementioned studies, hydrological behavior of Indian rivers has also been vastly studied (Arora et al. 2014; Subramanian 1996). Abbas and Subramanian (1984) determined the sediment load in River Ganga at Farakka Barrage and found it to be eight times the world average erosion rate as stated by Millimen and Meade (1983). Various levels of aggradation and degradation study have also been conducted in Indian rivers (Roy and Sinha 2007, 2014; Muzzammil et al. 2018; Pandey et al. 2018; Zakwan 2018). Tandon et al. (2006) concluded that in Western Ganga Plains, fluvial sedimentation is strongly affected by variation in monsoonal rainfall regime. In a study regarding sediment flux over Indo-Gangetic plains, Northern Bihar, Sinha and Friend (1994) observed that suspended sediment plot over a 10-year period showed variation from year to year as well as a shift in total sediment discharge from downstream to upstream since 1986. Chakrapani and Saini (2009) studied the temporal variation in sediment in Alaknanda and Bhagirathi Rivers (forming Ganga) and reported large variation in suspended sediment load in monsoon and non-monsoon season.

Although ample work has been performed in terms of geomorphological study of Ganga River, quantitative detection of trend in flow and sediment data of the river has seldom been analyzed. This may be attributed to the absence of large database pertaining to sediment and flow data of the river. This paper aims to apply non-parametric statistical test, namely, the Mann-Kendall, Sen's slope, and innovative trend analysis (ITA), on various gauging sites along the Ganga River to detect presence of significant trend in annual maximum discharge, annual minimum discharge, monthly discharge, water yield, and suspended sediment yield for monsoon months of June to October.

Ganga River basin

With a total length of 2525 km and catchment area of 8,61,542 km², Ganga River is one of the longest rivers in India. Ganga River basin spreads between 73° 2' to 89° 5' E and 21° 6' to 31° 21' N. Rivers Alaknanda and Bhagirathi join at Devprayag to form Ganga which then flows into the Bay of Bengal. The principal tributaries joining the river are Yamuna, Sone, Ghaghara, Gandak, and Kosi. Ganga River caters towards water supply, hydroelectric, irrigation, and drinking water needs. It has a varying climate ranging from tropical, sub-tropical, temperate, to alpine and possesses a mean annual temperature of 24 °C. The basin receives nearly 80% of its total rainfall in the monsoon period of June–October and its average annual rainfall varies from 400 to 2000 mm (Zakwan et al. 2018).

Data set and methodology

Data set

Hydrologic data at various gauging sites along Ganga was procured from Central Water Commission (CWC). Figure 1 shows the location and chainage of these gauging sites. Apart from that, mean discharge and suspended sediment load of the river are also observed at these gauging sites. The mean values are reported as an average over 10 days of the month for the monsoon season June–October. The data used in this study along with the time period of data availability is tabulated in Table 1.

Methodology of trend analysis

The non-parametric Mann-Kendall (Mann 1945; Kendall 1975) and Sen's slope (Sen 1968) were applied in this study to determine presence of trend in flow and suspended sediment load time series. These non-parametric tests do not require data series to follow normal distribution and yet their results are comparable with other parametric trend tests (Yue et al. 2002; Ebadati et al. 2014; Tirkey et al. 2020). MATLAB program was used for obtaining trends through the Mann-Kendall and Sen's slope, while Excel spreadsheet was used for obtaining trends of ITA.

The Mann-Kendall test

The Mann-Kendall test is a statistical test widely used for the analysis of trend in climatologic and in hydrologic time series. According to this test, the null hypothesis H_0 assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis H_1 , which assumes that there is a trend. X_i and X_j are two subsets of data where $i = 1, 2, 3, \dots, n-1$ and $j = i+1, i+2, i+3, \dots, n$.

The Mann-Kendall S statistic is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(X_j - X_i) \quad (1)$$

$$\text{Sign}(X_j - X_i) = \begin{cases} 1 & \text{if } X_j - X_i > 0 \\ 0 & \text{if } X_j - X_i = 0 \\ -1 & \text{if } X_j - X_i < 0 \end{cases} \quad (2)$$

The variance (σ^2) for the S statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t+5)}{18} \quad (3)$$

Table 1 Data availability period for different gauging sites

Chainage	Gauging site	Discharge			Suspended sediment load (10 daily average)
		Annual maximum	Annual minimum	Average (10 daily)	
0	Garhmukteshwar	1967–2014	1967–2014	1967–2014	1974–2004
147	Kachlabridge	1971–2014	1971–2014	1972–2014	1973–2015
263	Fatehgarh	1972–2014	1972–2014	1972–2014	1978–2015
348	Ankinghat	1968–2014	1968–2014	1968–2014	1977–2014
416	Kanpur	1960–2014	1960–2014	1960–2014	1975–2014
489	Bhithaura	1970–2014	1970–2014	1971–2014	1978–2014
580	Shahzadpur	1960–2014	1960–2014	1960–2014	1963–2014
652	Allahabad	1970–2014	1970–2014	1970–2014	1973–2014
774	Mirzapur	1976–2014	1976–2014	1979–2014	1980–2014
858	Varanasi	1960–2014	1960–2014	1960–2014	1962–2014
1017	Buxar	1960–2014	1960–2014	1960–2014	1996–2015
1165	Gandhighat	1965–2014	1965–2014	1965–2014	1997–2013
1262	Hathidah	1961–2014	1961–2014	1961–2014	1996–2013
1432	Azamabad	1960–2014	1960–2014	1960–2014	1996–2015
1572	Farakka	1960–2014	1960–2014	1960–2014	1995–2014

The standard test statistic Z_s is calculated as follows:

$$Z_s = \begin{cases} \frac{S-1}{\sigma} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sigma} & \text{for } S < 0 \end{cases} \quad (4)$$

where m is the number of unique values (without duplicates) and t_i is the frequency of the i th value. If $|Z_s|$ is greater than $Z_{\alpha/2}$, where α represents the chosen significance level (5% with $Z_{0.025} = 1.96$), then the null hypothesis is invalid implying that the trend is significant.

Sen’s slope estimator

Sen (1968) proposed the non-parametric Sen’s slope statistics. Slope for each pair may be calculated as follows:

$$Q_i = \frac{(X_j - X_k)}{j - k} \text{ where } (j > k) \text{ (for } i = 1, 2, 3, \dots, n) \quad (5)$$

where X_j and X_k are the data values at times j and k ($j > k$), respectively.

Sen’s slope estimator can then be calculated as follows:

$$Q_{\text{med}} = \begin{cases} Q[(n+1)/2] & \text{if } n \text{ is odd} \\ \frac{Q_{n/2} + Q_{(n+2)/2}}{2} & \text{if } n \text{ is even} \end{cases} \quad (6)$$

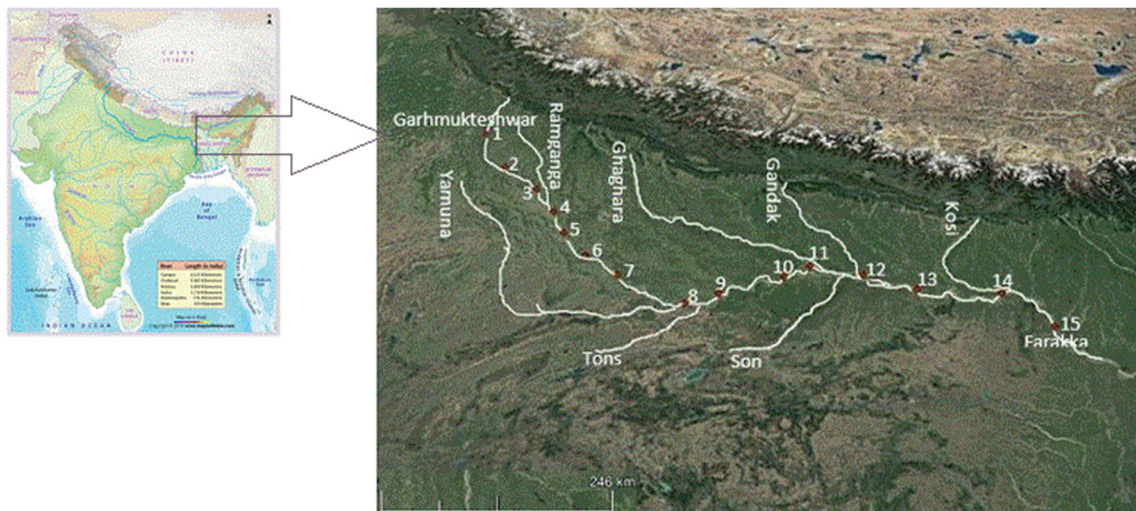


Fig. 1 Various gauging sites along the Ganga River

The Q_{med} sign reflects data trend, while its value indicates the steepness of the trend.

Innovative trend analysis

Şen (2012) presented an innovative trend analysis. The procedure for ITA may be summarized as follows:

- Divide the entire time series into two equal halves.
- Calculate the average of both halves as \bar{Y}_1 and \bar{Y}_2 .
- Arrange both halves of the time series in ascending order.
- Prepare a plot with first half of time series on abscissa and second half series on ordinate. Also plot the 1:1 (45°) line on the same plot. Relative position of scatter point with respect to 45° line demarcates the trend. If all the points lie above the 45° line, it will represent monotonically increasing trend; on the other hand, if all the points lie below the 45° line, it will represent monotonically decreasing trend; otherwise, trend may not be monotonic (Elouissi et al. 2016).

The magnitude of trend may be calculated as follows

$$s = \frac{2(\bar{Y}_2 - \bar{Y}_1)}{n} \tag{7}$$

Confidence limit (CL) of trend may be calculated using the following relationship (Şen 2017):

$$CL_{(1-a)} = 0 + S_{crit}\sigma_s \tag{8}$$

where s_{crit} is the critical slope and σ_s is the standard deviation slope.

$$\sigma_s^2 = \frac{8\sigma^2(1-\rho_{Y_2Y_1})}{n^3} \tag{9}$$

where $\rho_{Y_2Y_1}$ is the cross-correlation coefficient of averages of two halves given by the following:

$$\rho_{Y_2Y_1} = \frac{E(Y_2Y_1) - E(Y_2)E(Y_1)}{\sigma_{Y_2}\sigma_{Y_1}} \tag{10}$$

Figure 2 explains the trend identification process of ITA. Figure 2 shows 1:1 line with first and second half of the time series on either axis. The plot shows low-, moderate-, and high-magnitude event. From the plotted points, the magnitude event trends can be understood distinctly. In this way, innovative trend analysis has an advantage over non-parametric tests, that non-parametric tests only reveal monotonic trend; however, it may be possible that hydrological events of different magnitude may have different trends. As can be observed from Fig. 2, low-magnitude events are trendless, while

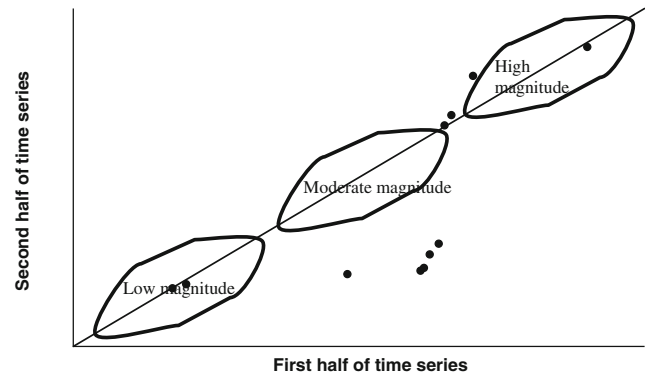


Fig. 2 Graphical representation of innovative trend analysis

moderate-magnitude events show significant negative trend and high-magnitude events show slight positive trend.

Results and discussion

To understand the general behavior of hydrological parameters of Ganga River, time series of annual maximum discharge, annual minimum discharge, monthly discharge, monthly sediment load, water and sediment yield for monsoon season at each gauging site were tested using non-parametric trend tests.

The test statistics obtained for the Mann-Kendall, Sen’s slope test, and ITA for annual maximum and annual minimum discharge at various gauging sites are reported in Tables 2 and 3 respectively. A perusal of Table 2 reveals a significant negative trend in annual maximum discharge at Farakka, Buxar, Varanasi, Mirzapur, Allahabad, Shahzadpur, Kanpur, Fatehgarh, and Garhmukteshwar. It was observed that the slope of first half of the annual maximum discharge time series was much higher than the second half, reflecting decline in the annual maximum discharge. The highest rate of decline in annual maximum discharge was observed at Allahabad followed by Mirzapur and Shahzadpur. At Allahabad, the slope of first half of the time series was around 21,127 m³/s/year which declined to 14,052 m³/s/year. The trend slope obtained for ITA based on Eq. 7 (− 685 m³/s/year) was found to be greater than critical slope (46.98 m³/s/year) reflecting significant trend at 5% significance level. The Mann-Kendall test also revealed significant trend at Allahabad (− 4.73 < − 1.96). These high rates of fall in annual maximum discharge may be attributed to the drying up of River Yamuna as reported by Misra (2010). The decline in discharge in the upstream reach (Garhmukteshwar–Ankinghat) can be attributed to decline in discharge from Gangotri Glacier (Jain 2008).

A positive trend was observed in annual minimum discharge at upstream gauging sites of Garhmukteshwar, Kachlabridge, Fatehgarh, Ankinghat, Kanpur, Bhitaura, and Shahzadpur; however, a negative trend is observed

Table 2 Result of trend tests at various sites for annual maximum discharge

Gauging sites	Annual maximum discharge						
	M-K	ITA					
	Z_s	Sen's slope	First half mean (\bar{Y}_1)	Second half mean (\bar{Y}_2)	Standard deviation (σ)	Trend slope (s)	Critical slope (Scr)
Garhmukteshwar	- 2.40	- 45.99	4885.11	3982.02	1882.19	- 39.26	8.70
Kachlabridge	- 1.13	- 23.80	5823.42	5255.55	2035.86	- 27.09	8.42
Fatehgarh	- 2.90	- 62.29	4619.31	4001.76	2149.99	- 29.41	10.85
Ankinghat	- 1.76	- 63.48	7185.97	5568.13	2793.11	- 77.04	12.19
Kanpur	- 2.95	- 74.08	7681.23	6726.19	3281.95	- 39.79	17.49
Bhitauro	- 1.97	- 73.08	6896.84	6259.51	4201.39	- 30.33	22.37
Shahzadpur	- 5.23	- 133.54	8616.78	4157.99	3675.75	- 185.78	11.99
Allahabad	- 4.53	- 700.38	35,531.12	21,127.23	14,052.62	- 685.85	46.98
Mirzapur	- 3.63	- 601.54	33,788.85	22,054.23	13,564.81	- 617.62	65.81
Varanasi	- 2.45	- 227.28	31,319.52	23,689.52	9972.47	- 317.92	22.47
Buxar	- 2.74	- 177.78	30,804.48	24,932.23	8868.33	- 244.67	37.47
Gandhighat	0.38	73.42	45,353.36	47,114.63	15,111.32	73.39	34.18
Hathidah	- 1.72	- 194.29	52,683.02	47,281.23	11,202.40	- 225.05	21.64
Azamabad	- 0.33	- 37.39	55,362.36	49,762.1	14,177.79	- 233.23	52.45
Farakka	- 3.55	- 465.0	57,852.45	46,904.25	13,125.06	- 457.23	73.37

Italicized values represent significant trend at 5% significance level

downstream towards Allahabad and Buxar. Varanasi showed significant positive trend and an insignificant positive trend was also observed further downstream at Gandhighat and

Hathidah. The highest rate of change in annual minimum observed discharge was found at Fatehgarh followed by Garhmukteshwar and Kachlabridge. Farakka also showed a

Table 3 Result of trend tests at various sites for annual minimum discharge

Gauging sites	Annual minimum discharge						
	M-K	ITA					
	Z_s	Sen's slope	First half mean (\bar{Y}_1)	Second half mean (\bar{Y}_2)	Standard deviation (σ)	Trend slope (s)	Critical slope (Scr)
Garhmukteshwar	4.28	1.33	46.34	81.52	36.86	1.53	0.19
Kachlabridge	3.80	0.21	10.26	15.68	6.69	0.26	0.05
Fatehgarh	2.85	0.22	11.63	20.32	9.30	0.41	0.03
Ankinghat	0.79	0.15	46.24	56.35	23.30	0.48	0.09
Kanpur	1.45	0.22	50.86	52.19	20.66	0.06	0.07
Bhitauro	2.18	0.66	53.01	71.38	24.17	0.87	0.13
Shahzadpur	1.57	0.33	50.26	56.65	28.16	0.27	0.07
Allahabad	- 2.02	- 1.16	192.92	168.34	66.81	- 1.17	0.40
Mirzapur	0.00	- 0.02	179.08	205.16	71.54	1.37	0.68
Varanasi	2.38	1.11	173.23	196.55	62.06	0.97	0.32
Buxar	0.79	0.89	323.44	332.35	125.26	0.37	0.43
Gandhighat	1.57	1.95	1164.41	1405.74	484.82	10.05	0.95
Hathidah	0.33	1.52	1537.81	1688.52	501.07	6.28	1.32
Azamabad	- 0.22	- 0.93	1688.66	1641.07	560.35	- 1.98	1.42
Farakka	- 2.45	- 1.17	223.44	182.35	105.26	- 0.27	0.39

Italicized values represent significant trend at 5% significance level

significant negative trend in annual minimum discharge. Generally, in the Ganga River basin, minimum discharge is observed in the pre-monsoon months (March, April, and May). Zakwan and Ara (2019) reported positive trend in rainfall for the pre-monsoon period which could be the reason behind increase in annual minimum discharge.

Ten daily average discharges were available at fifteen gauging sites for the monsoon period. Using the ten daily data total volumes of water crossing gauging sites in the monsoon period were calculated and trend analysis was performed on the observed water yield at fifteen gauging sites. The results of the Mann-Kendall, Sen's slope, and innovative trend tests are shown in Tables 4, 5, and 6 respectively. Almost all the gauging sites showed a negative trend in terms of sediment yield crossing the gauging sites during the monsoon period with Ankinghat, Kanpur, Shahzadpur, Allahabad, Varanasi, and

Farakka showing significantly negative trend. The upstream gauging sites Garhmukteshwar, Kanpur, and Shahzadpur also showed significant negative trend which may be attributed to decline in discharge from Gangotri Glacier as reported by Jain (2008). Also the annual rainfall received by the region has declined resulting in decline in discharge (Bisht et al. 2018; Zakwan and Ara 2019).

The general trend observed at all the gauging sites except Gandhighat was negative, indicating a lowering of volume of water along the river with time. In line with this general behavior, a significant negative trend with a decrease in rate of 1.1% is observed at Farakka gauging sites. This might be due to the presence of Farakka Barrage in the downstream.

This indicates a significant decrease of volume of suspended sediment crossing the gauging sites. The rate of decrease of suspended sediment load at Farakka is observed

Table 4 Results of trend analysis of monthly data for Mann-Kendal test

Gauging sites	Quantity	June	July	August	September	October
Garhmukteshwar	Discharge	- 1.17	- 2.88	- 3.01	- 1.10	0.70
	Sediment load	- 2.75	- 2.03	- 1.71	- 0.46	- 0.32
Kachlabridge	Discharge	- 0.61	- 0.90	- 0.42	- 1.05	0.48
	Sediment load	- 0.86	- 0.13	1.45	1.34	2.47
Fatehgarh	Discharge	- 1.09	- 2.01	- 2.13	- 0.86	- 0.54
	Sediment load	- 1.27	- 2.34	- 3.34	- 0.95	0.90
Ankinghat	Discharge	- 1.45	- 2.75	- 2.18	- 0.90	- 0.29
	Sediment load	- 1.92	- 3.82	- 3.77	- 3.04	- 0.25
Kanpur	Discharge	- 0.78	- 2.50	- 1.83	- 1.77	- 1.22
	Sediment load	- 1.88	- 2.53	- 2.57	- 1.71	- 0.83
Bithaura	Discharge	0.13	- 1.19	- 0.94	- 0.84	0.52
	Sediment load	- 1.01	- 0.82	- 1.04	- 1.72	0.57
Shahzadpur	Discharge	- 0.39	- 3.50	- 4.44	- 3.85	- 1.44
	Sediment load	0.43	- 4.93	- 5.82	- 4.90	- 2.39
Allahabad	Discharge	- 2.17	- 3.12	- 3.63	- 3.43	- 1.11
	Sediment load	- 0.48	- 2.74	- 3.24	- 3.08	- 0.29
Mirzapur	Discharge	0.57	- 0.54	- 2.33	- 2.61	- 0.65
	Sediment load	1.36	0.11	- 0.94	- 1.73	0.74
Varanasi	Discharge	0.67	- 1.79	- 2.53	- 2.60	- 1.35
	Sediment load	- 1.04	- 1.65	- 2.77	- 2.14	- 0.43
Buxar	Discharge	0.29	- 1.12	- 2.21	- 1.22	0.13
	Sediment load	1.12	0.14	- 1.12	- 1.12	1.09
Gandhighat	Discharge	0.89	- 0.47	- 0.15	0.03	0.42
	Sediment load	0.61	0.00	0.08	- 0.76	1.44
Hathidah	Discharge	- 0.12	- 0.72	- 1.18	- 0.58	0.42
	Sediment load	0.61	0.15	0.00	- 0.68	- 0.43
Azamabad	Discharge	- 0.48	0.61	- 0.32	0.20	0.52
	Sediment load	- 0.91	- 1.75	- 1.05	- 2.17	- 1.82
Farakka	Discharge	- 0.80	- 1.09	- 2.85	- 2.62	- 0.88
	Sediment load	- 0.03	- 2.30	- 2.56	- 3.21	- 2.76

Italicized values represent significant trend at 5% significance level

Table 5 Sen's slope of trend analysis of monthly data

Gauging sites	Quantity	June	July	August	September	October
Garhmukteshwar	Discharge	- 4.05	- 16.66	- 26.58	- 6.20	1.30
	Sediment load	- 12,856.09	- 67,702.13	- 87,173.17	- 10,179.10	- 695.70
Kachlabridge	Discharge	- 1.18	- 12.14	- 2.14	- 12.87	1.02
	Sediment load	- 532.92	- 2774.14	90,495.23	47,132.16	7422.81
Fatehgarh	Discharge	- 1.73	- 17.95	- 20.88	- 9.53	- 1.88
	Sediment load	- 415.17	- 28,141.29	- 81,928.55	- 19,346.88	766.29
Ankinghat	Discharge	- 2.71	- 25.72	- 39.62	- 12.84	- 1.63
	Sediment load	- 708.71	- 58,108.04	- 152,618.67	- 86,820.97	- 659.95
Kanpur	Discharge	- 0.88	- 18.79	- 30.09	- 24.90	- 5.87
	Sediment load	- 394.17	- 49,084.19	- 141,820.90	- 57,278.76	- 3097.57
Bithaura	Discharge	0.16	- 13.23	- 20.50	- 15.16	3.69
	Sediment load	- 65.86	- 5754.70	- 28,640.50	- 55,073.90	2696.54
Shahzadpur	Discharge	- 0.32	- 22.52	- 70.26	- 54.49	- 7.87
	Sediment load	36.50	- 31,777.76	- 144,149.12	- 82,317.42	- 8564.58
Allahabad	Discharge	- 43.99	- 1037.37	- 3198.83	- 2624.22	- 193.14
	Sediment load	- 511.52	- 98,908.26	- 493,203.15	- 340,687.76	- 4053.39
Mirzapur	Discharge	18.55	- 211.20	- 2994.59	- 2376.66	- 131.29
	Sediment load	1503.62	6734.15	- 238,566.10	- 381,178.09	16,728.03
Varanasi	Discharge	10.43	- 401.98	- 1204.16	- 1457.91	- 183.93
	Sediment load	- 34.55	- 30,454.65	- 381,030.94	- 343,331.16	- 2625.64
Buxar	Discharge	0.47	- 26.64	- 128.10	- 81.85	1.64
	Sediment load	142.72	225.34	- 26,098.53	- 44,982.06	225.00
Gandhighat	Discharge	10.84	- 21.05	- 26.46	6.85	15.75
	Sediment load	26.30	3005.07	21,394.68	- 65,358.47	25,938.80
Hathidah	Discharge	- 1.15	- 46.99	- 96.86	- 53.08	14.20
	Sediment load	935.36	1360.40	- 11,127.80	- 52,566.35	- 11,690.7
Azamabad	Discharge	- 5.70	39.98	- 24.55	14.43	23.56
	Sediment load	- 1858.88	- 39,710.80	- 42,300.40	- 74,546.05	- 18,890.1
Farakka	Discharge	- 18.13	- 103.52	- 382.90	- 381.81	- 62.05
	Sediment load	- 44.11	- 27,956.85	- 120,687.46	- 170,903.79	- 59,152.9

to be 6.2% which might be attributed to the presence of Farakka Barrage while 3.7% decrease in sediment load is observed at Ankinghat and Shahzadpur. Table 7 presents the decadal water yield of monsoon season at various gauging sites of Ganga River. It may be observed that as compared to 1970–1980, the water yield has declined remarkably (13 to 58%) in 2000–2010 at most of the gauging sites except Gandhighat.

Spatial pattern of trends

Trend analysis of sediment yield and water yield of Ganga River reveals a spatial pattern. Analyzing the results reported in Tables 4, 5, and 6 along with Fig. 3, it may be observed that the decline in sediment and water yield was sharper in

Western Ganga Plain as compared to Eastern Ganga Plain. Jain (2008) reported a significant decline in discharge from Gangotri Glacier and concluded that the impact of Gangotri Glacier is effective until Shahzadpur. Decline in discharge of Gangotri Glacier may be considered as the major reason for more pronounced trends in Western Ganga Plain while the decline in discharge of Yamuna River was the major reason for the negative trends observed downstream of Shahzadpur. Spatial trend of annual maximum discharge also reveals a declining trend from Garhmukteshwar to Farakka except Gandhighat. Time series of annual maximum discharge at Gandhighat also revealed an upward trend making it more susceptible to floods. The detailed discussion on monthly trend for each gauging site is provided in the subsequent section. Few graphs obtained from innovative trend analysis have also

Table 6 Results of ITA of monthly discharge and sediment data

Gauging sites	Quantity	June	July	August	September	October
Garhmukteshwar	Discharge	- 3.46	- 20.03	- 30.39	- 0.20	1.71
	Sediment load	- 177.95	- 886.63	- 1334.25	- 33.18	22.19
Kachlabridge	Discharge	3.08	- 5.93	- 6.54	- 7.31	1.24
	Sediment load	88.81	554.06	1122.7	1086.3	296.63
Fatehgarh	Discharge	0.04	- 6.78	- 12.16	10.70	4.33
	Sediment load	- 2.14	- 316.15	- 1126.1	- 454.77	42.11
Ankinghat	Discharge	- 3.04	- 3.46	- 36.79	- 7.31	1.32
	Sediment load	- 167.90	- 955.25	- 1126.12	- 1744.17	- 11.75
Kanpur	Discharge	- 3.52	- 20.30	- 27.87	- 13.33	- 5.35
	Sediment load	- 3.08	- 574.06	- 1056.85	- 122.50	- 13.20
Bithaura	Discharge	3.63	8.26	- 9.02	2.11	10.97
	Sediment load	4.57	- 19.99	- 840.32	- 1284.11	25.35
Shahzadpur	Discharge	- 2.00	- 29.18	- 85.59	58.85	- 13.97
	Sediment load	- 6.63	- 693.92	- 2210.89	- 1523.45	- 216.89
Allahabad	Discharge	- 0.34	- 62.15	- 221.23	- 177.17	- 21.15
	Sediment load	- 88.97	- 20,895.12	- 78,061.25	- 39,611.12	- 7246.01
Mirzapur	Discharge	12.89	67.84	- 293.96	- 292.54	- 38.53
	Sediment load	506.75	12,289.62	- 12,935.51	- 22,861.52	6784.81
Varanasi	Discharge	1.88	- 49.41	- 147.02	- 153.56	- 34.34
	Sediment load	- 7.01	2145.63	- 45,679.81	- 35,447.12	341.17
Buxar	Discharge	- 3.79	50.50	- 97.16	- 63.18	40.46
	Sediment load	31.90	250.32	- 25,145.20	- 15,201.30	120.23
Gandhighat	Discharge	20.70	18.94	109.38	99.98	3.59
	Sediment load	38.61	36.93	62.53	- 1268.93	143.07
Hathidah	Discharge	- 10.75	- 26.01	- 89.96	- 30.19	- 6.39
	Sediment load	34.03	43.94	266.62	- 935.56	15.70
Azamabad	Discharge	- 21.28	1.64	- 144.21	- 18.56	- 39.41
	Sediment load	- 32.04	- 301.80	- 207.16	- 718.41	32.73
Farakka	Discharge	- 6.03	- 64.72	- 359.36	- 353.41	- 105.82
	Sediment load	180.61	- 25,793.30	- 61,142.32	- 128,920	- 26,393

Italicized values represent significant trend at 5% significance level

been presented in subsequent section, because if all the 180 graphs would have been presented, it would have made the article too lengthy.

Garhmukteshwar

Monthly-trend analysis of discharge presented decreasing trend which was significant during the month of July and August; however, positive trend was observed during October. Sediment load too presented decreasing trend which was significant during the month of June and July. Figure 4a shows the trend of suspended sediment load for the month of July based on ITA. Monotonic decline in the magnitude of suspended sediment load could be observed from Fig. 4a. Similarly, total water yield and sediment yield

during monsoon represent a declining trend at Garhmukteshwar. Decadal monsoon water yield has declined by 36% from 195,990 Mm³ (1970–1980) to 124,806 Mm³ (2000–2010). Construction of CCS barrage in Jansath in 1984 could have led to decline in water and sediment discharge.

Kachlabridge

Monthly discharge generally shows decreasing trend except October. Monthly sediment load generally shows an increasing trend. Total water yield during monsoon season shows a negative trend but the sediment yield represents a positive trend during August, September, and October at Kachlabridge. Decadal monsoon water yield has declined

Table 7 Total water yield during different durations at various gauging sites of Ganga River

Gauging sites	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010
Garhmukteshwar	–	195,990	163,097	160,528	124,806
Kachlabridge	–	165,975	163,285	186,272	144,269
Fatehgarh	–	–	137,241	187,388	124,370
Ankinghat	–	841,510	723,427	738,212	470,738
Kanpur	300,513	276,810	223,267	210,212	183,038
Bhithaura	–	247,473	196,512	168,328	147,003
Shahzadpur	336,770	312,330	226,670	151,758	143,577
Allahabad	–	1,261,104	861,914	885,541	536,108
Mirzapur	–	–	947,754	983,691	583,737
Varanasi	906,247	1,033,778	890,296	872,658	591,507
Buxar	1,117,954	1,026,088	1,007,621	1,142,893	693,168
Gandhighat	2,121,211	1,817,068	2,380,834	1,802,690	2,121,211
Hathidah	2,347,462	2,631,743	2,328,041	2,552,926	2,148,052
Azamabad	2,352,329	3,221,702	2,336,052	2,597,415	2,394,897
Farakka	–	3,412,780	3,158,841	3,004,499	2,397,050

by 13% from 1970–1980 (165,975 Mm³) to 2000–2010 (144,269 Mm³). Figure 5a shows the trend of discharge for the month of July based on ITA at Kachlabridge. Based on Fig. 5a, it can be said that the trends in discharge are not monotonic; instead, magnitude of low discharges is declining trend and the magnitude of high discharges is increasing.

Fatehgarh

Trend analysis of discharge presented decreasing trend which was significant during the month of August. Monthly-trend analysis of sediment load too exhibits a decreasing trend which was significant during the month of July and August; however, positive trend was observed for the month of October. Total water yield and sediment yield during monsoon too represent a negative trend as the river has been divided into a number of channels in the reach.

Ankinghat

Monthly-trend analysis of discharge presented decreasing trend which is significant during the month of July and August. Sediment load too presented decreasing trend which was significant during the month of July and August. Figure 4b shows the trend of suspended sediment load for the month of August. Monotonic decline in the magnitude of suspended sediment load could be observed from Fig. 4b. Total water and sediment yield during monsoon too represent negative trend. Decadal monsoon water

yield has declined by 44% from 841,510 Mm³ (1970–1980) to 470,738 Mm³ (2000–2010). Ramganga River joins Ganga River between Fatehgarh and Ankinghat. Significant decline in discharge of Ramganga mainly due to decline in rainfall has been reported by Kumar (2017). Decline in discharge of Ramganga has been reflected by significant negative trends in discharge at Fatehgarh and subsequent gauging sites of Ganga.

Kanpur

Monthly-trend analysis of discharge presented decreasing trend which was significant during the month of July and August. Sediment load too presented remarkable decreasing trend. A sharp decline in sediment load and discharge can be observed due to construction of Lav Khush Barrage in 1995 just upstream of gauging site. Total water yield and sediment yield during monsoon season also represent negative trend at Kanpur. Decadal monsoon water yield has declined by 34% from 276,810 Mm³ (1970–1980) to 183,038 Mm³ (2000–2010). Figure 5b shows the trend of discharge for the month of August based on ITA at Kanpur. Based on Fig. 5b, it was observed that the magnitude of low discharges is predominantly declining while the magnitude of high discharges has remained almost unchanged.

Bithaura

Monthly-trend analysis of discharge presented decreasing trend except for October and early June. Total water yield

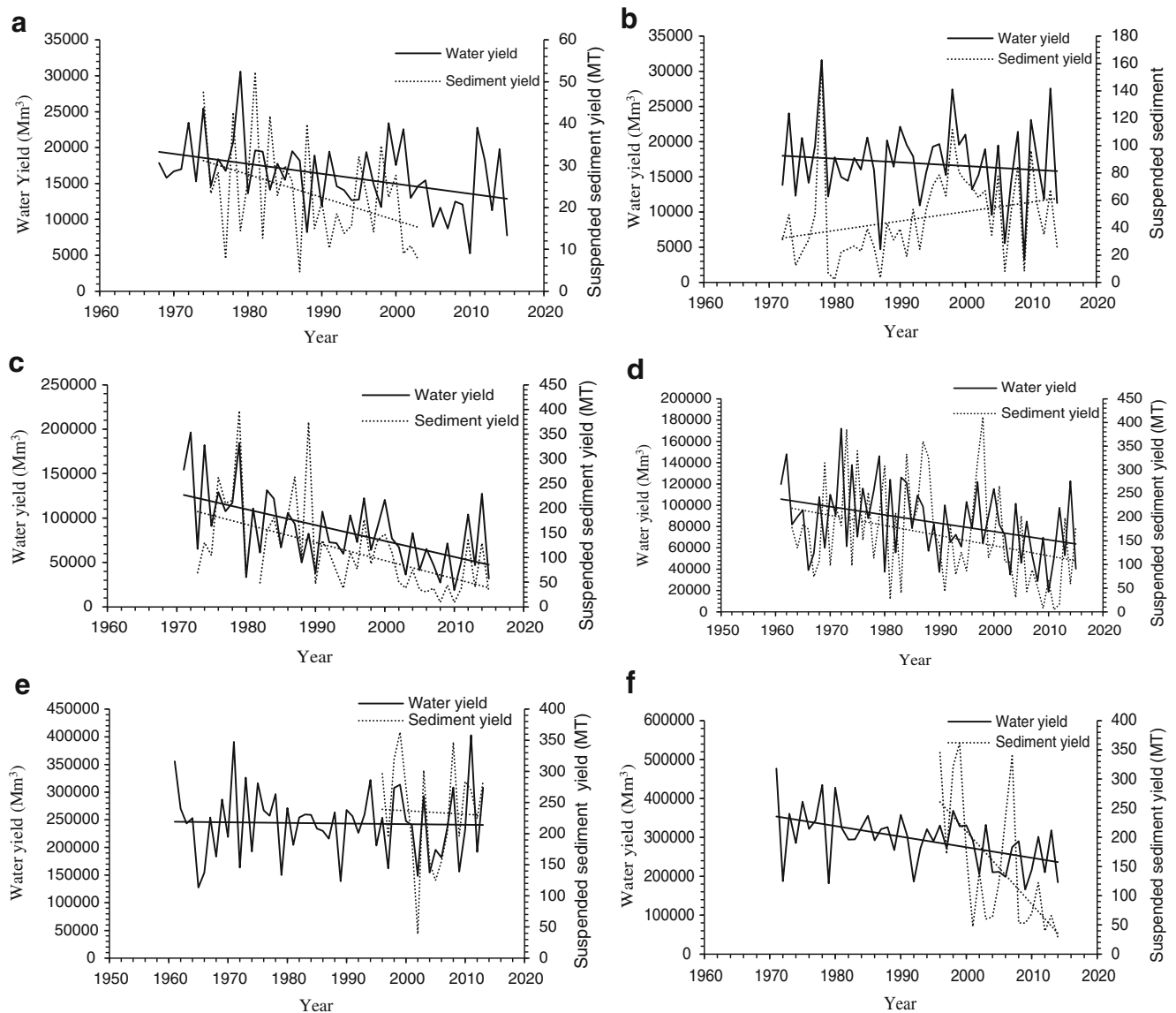


Fig. 3 Trend of water yield and sediment yield at **a** Garhmukteshwar, **b** Kachlabridge, **c** Allahabad, **d** Varanasi, **e** Hathidah, and **f** Farakka

and sediment yield during monsoon season also represent negative trend at Bithaura. Decadal monsoon water yield has declined by 40% from 247,473 Mm³ (1970–1980) to 147,003 Mm³ (2000–2010).

Shahzadpur

Monthly-trend analysis of discharge presented significant decreasing trend. Monthly sediment load presented decreasing trend except for June. Total water yield and sediment yield during monsoon season also represent negative trend at Shahzadpur. Figure 4c shows the trend of suspended sediment load for the month of September based on ITA. Monotonic decline in the magnitude of suspended sediment load could be observed from Fig. 4c. Decadal monsoon water yield has

declined by 54% from 312,330 Mm³ (1970–1980) to 143,577 Mm³ (2000–2010).

Allahabad

Remarkable decrease in discharge and sediment load has been observed from monthly data at Allahabad. Total water yield and sediment yield during monsoon season also represent negative trend at Allahabad. Decadal monsoon water yield has declined by 58% from 1,261,104 Mm³ (1970–1980) to 536,108 Mm³ (2000–2010).

Mirzapur

Decreasing trend was observed in discharge from monthly time series except for the month of June. However, sediment

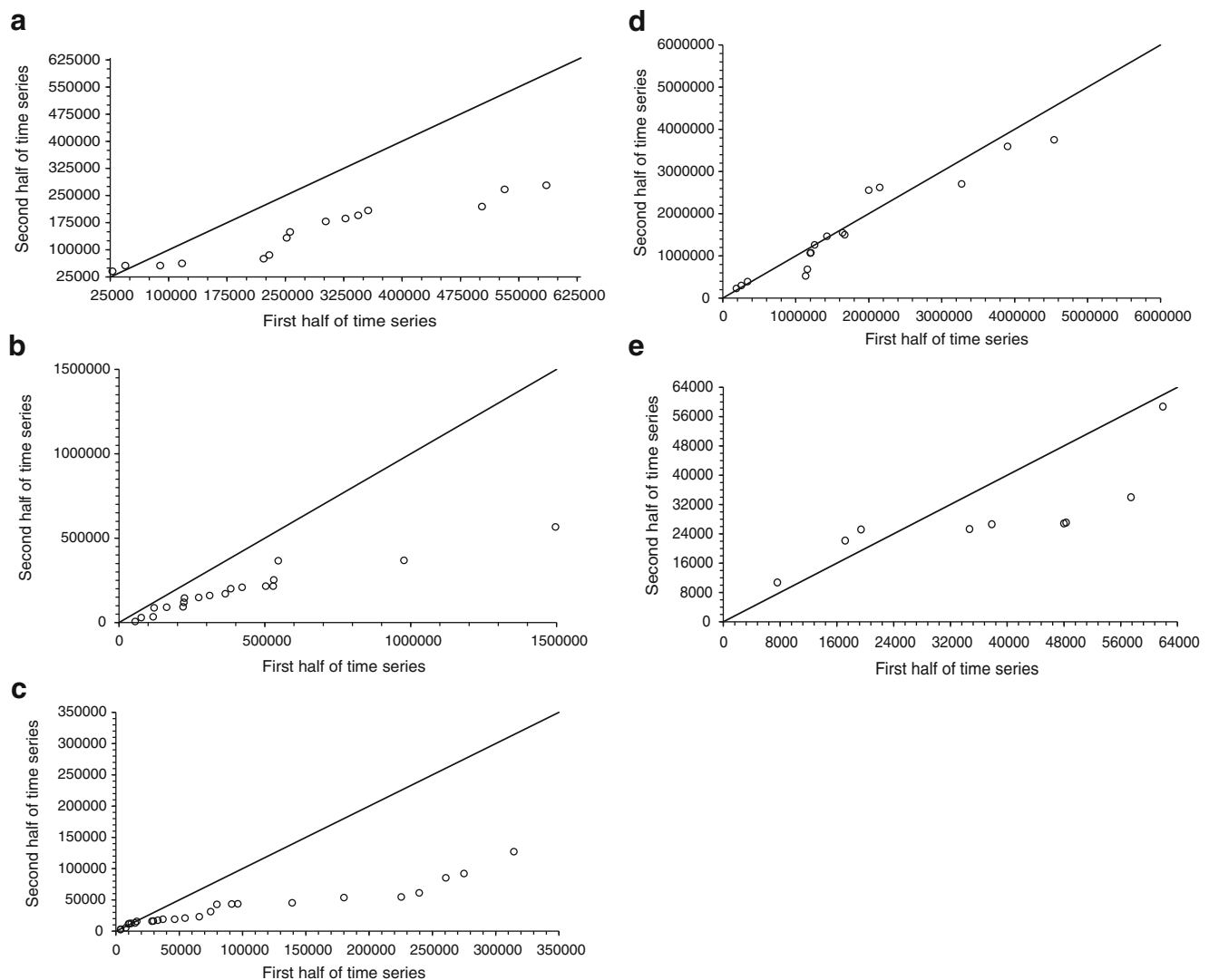


Fig. 4 Trend of suspended sediment load based on ITA at **a** Garhmukteshwar, **b** Ankinghat, **c** Shahzadpur, **d** Mirapur, and **e** Hathidah

load presented positive trend during June, July, and October and negative trend during August and September as observed from monthly data. Total water yield and sediment yield during monsoon season also represent negative trend at Mirzapur. Figure 4d shows the trend of suspended sediment load while Fig. 5c shows the trend of discharge for the month of August based on ITA. Figure 5c shows monotonic decrease in the magnitude of discharge while suspended sediment load was trendless. Decline in rainfall in Tons River basin as reported by Bisht et al. (2018) and Yamuna River could have led to decline in water yield.

Varanasi

Monthly-trend analysis of discharge presented remarkable decreasing trend; however, positive trend was observed during June. Monthly sediment loads too presented downward trend except for June. Decadal monsoon water yield has declined by

42% from 1,033,778 Mm³ (1970–1980) to 591,507 Mm³ (2000–2010). Bhatla and Tripathi (2014) reported a significant decline in rainfall over Varanasi which may be the reason behind the decline in discharge at Varanasi.

Buxar

Decreasing trend in discharge was observed during July, August, and September while increasing trend was observed during June and September. Monthly sediment loads too presented downward trend except for June. Total water yield and sediment yield during monsoon season also represent negative trend at Buxar. Decadal monsoon water yield has declined by 32% from 1,026,088 Mm³ (1970–1980) to 693,168 Mm³ (2000–2010). Warwade et al. (2018) reported a decline in monsoon rainfall of over 18% at Buxar which could have led to decline in water yield and other hydrologic parameters.

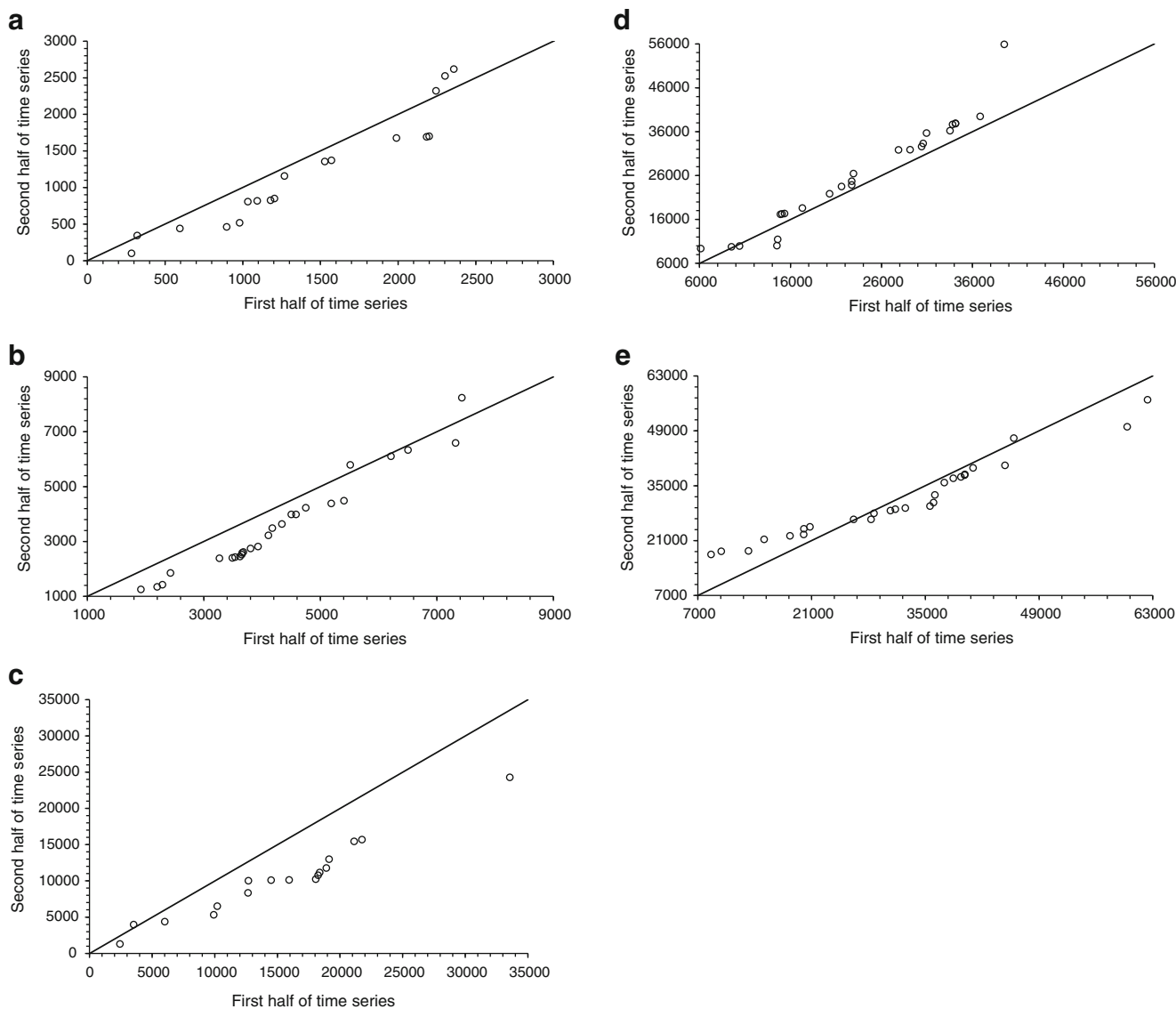


Fig. 5 Trend of discharge based on ITA at **a** Kacalbridge, **b** Kanpur, **c** Mirzapur, **d** Gandhightat, and **e** Azamabad

Gandhightat

Monthly time series shows positive trend during the month of June and October while trends in July, August, and September show mild decreasing trend. Monthly trend of sediment loads represents increasing trend. Total water yield represents an insignificant positive trend while sediment yield represents negative trend at Gandhightat. Rise in annual maximum discharge makes Gandhightat more vulnerable to floods which demands better flood protection and management works to be ensured at Gandhightat. Decadal monsoon water yield has increased by 16% from 1,817,068 Mm³ (1970–1980) to 2,121,211 Mm³ (2000–2010). Between Buxar and Gandhightat, Ghaghara, Sone, and Gandak join the Ganga River. However, trend analysis of available data of these tributaries represents declining trend in general. Figure 5d shows

the trend of discharge for the month of September based on ITA at Gandhightat. Figure 5d shows monotonic increase in the magnitude of discharge.

Singh et al. (2007) reported that the number of rainy days is decreasing in Ganga River basin. Increase in water yield accompanied by reduction in rainy days is reflected in the form of increase in annual maximum discharge at Gandhightat. Increase in annual maximum discharge at Gandhightat makes this region more susceptible to floods.

Hathidah

Monthly-trend analysis of average discharge too presented decreasing trend except for the month of October. Sediment load also presented decreasing trend except for the month of June and October. Figure 4e shows the trend of suspended

sediment load for the month of September based on ITA. Figure 4e clearly shows non-monotonic trend in suspended load. Magnitude of low sediment load is increasing; on the other hand, moderate- and high-magnitude sediment loads are declining, resulting in overall declining trend in suspended sediment load. Total water yield and sediment yield during monsoon also represent negative trend at Hathidah. Decadal monsoon water yield has declined by 18% from 2,631,743 Mm^3 (1970–1980) to 2 148,052 Mm^3 (2000–2010).

Azamabad

Discharge data generally represent upward trend except for the month of June and August. Monthly sediment loads represent a predominant negative trend. Total water yield and sediment yield during monsoon season also represent negative trend at Azamabad. Decadal monsoon water yield has declined by 25% from 3,221,700 Mm^3 (1970–1980) to 2,394,900 Mm^3 (2000–2010).

Figure 5e shows the trend of discharge for the month of September based on ITA at Azamabad. Figure 5e shows a non-monotonic trend in discharge. At Azamabad, the magnitude of low discharges is increasing; on the other hand, magnitude of high discharges is increasing while the magnitude of moderate discharges has remained unaltered over the period of time.

Farakka

The discharge and sediment load data represent predominantly negative trend at Farakka. Total water yield and sediment yield during monsoon season also represent negative trend at Farakka. Decadal monsoon water yield has declined by 30% from 3,412,780 Mm^3 (1970–1980) to 2,397,050 Mm^3 (2000–2010).

Above results indicate that discharge and sediment load are generally decreasing along the Ganga during monsoon season. In Western Ganga Plain, it has been observed that discharge shows upward trend during the month of October. At Farakka, the discharge and sediment load represent the downward trend which may be associated with construction of Farakka Barrage.

In most of the cases, the alteration in sediment yield of rivers has been associated with trapping of sediment load by construction of dams and effective soil erosion control measures (Zhang et al. 2007; Xu and Milliman 2009; Yang et al. 2015; Guo et al. 2018). On the other hand, fluctuation in water yield has been correlated with the alteration of rainfall in river basins (Pham et al. 2019; Tandon et al. 2006; Guo et al. 2018). However, in large river basin, interpretation of hydrologic changes is very difficult because of variety of land surface condition, spatial climatic variation, and human activities (Ives and Messerli 1990; Hofer 1993; Lu et al. 2003).

Supply of sediment load and discharge is triggered by monsoon rains in Ganga River (Zakwan et al. 2018). Monsoon season in the Ganga River basin starts in the month of June, intensifies during July and August, and starts to retreat from mid-September (Zakwan and Ara 2019). Significant negative trends were observed in sediment load and discharge during July and August at most of the gauging sites, thereby deteriorating overall sediment and discharge yield of Ganga River in monsoon. Although sediment and discharge yield of Ganga River depends on large number of factors, yet, decline in monsoon rainfall in Ganga River basin as reported by Bera (2017) may be considered as the major reason. Significant decline in annual rainfall in this region was also reported by Sharma and Ojha (2018) and Sharma et al. (2019). Sharma and Ojha (2018) also detected that the change point in rainfall pattern was 1992 or earlier. Moreover, Moors et al. (2011) and Shrestha et al. (2017) reported an increasing trend in temperature in the Ganga River basin leading to enhanced evaporation rates and decline in discharge.

Ganga basin has also observed significant surge in population and industrial activities, resulting in decline in forest cover and increment in built-up area, thereby contributing to alteration in hydrological response of Ganga basin (Shukla et al. 2017). Surge in industrial activities along with rising population has led to construction of dams, barrages, and canal across the Ganga and its tributaries to encounter the increased requirements of energy and food, leading to alteration in flow. Ganga basin is also experiencing a significant increase in construction activities which has led to increased rate of mining from Ganga River and its tributaries which is adversely affecting the morphology of the river (Barman et al. 2019; Park et al. 2020). The flow of the river is also influenced by rituals. Comparative pictures of Ganga, before and after the 21-day COVID-19 lockdown, are also evidence of human intervention with the natural system of Ganga River.

Hence, it may be concluded that both climate change and human intervention have contributed to changes in flow pattern and sediment flux in the Ganga River basin. Generally, it is assumed that sediment load is directly proportional to discharge through power law; therefore, decline in sediment flux with decline in discharge is obvious.

Ganga River basin being the largest and most populous basin of India is the source of livelihood of millions of people. Alteration in flow pattern of Ganga River would have far-reaching socio-economic consequences for the entire region. Many cities lying on the bank of Ganga River have already started experiencing shortage of water during the summer season. Decline in groundwater table has also been common in many parts of the river basin over the past few years. With increased effluents from industries, water quality in the region has declined remarkably, thereby affecting aquatic life and self-cleansing capability of the river. Sarkar et al. (2012) have reported that many species of fishes, earlier found in Ganga

River, have become extinct. Sarkar et al. (2012) also reported an overall decline in the fishes in Ganga River which has led to a huge loss to fisheries sector. Decline in discharge as observed in the present study would also lead to decline in hydropower production of hydropower stations of the country.

Despite numerous measures to rejuvenate and manage Ganga River, the health of the Ganga is declining at an alarming rate basically because restoration of Ganga River requires an integrated approach which requires combined efforts of hydrologists, geomorphologists, ecologists, environmental experts, social workers, politicians, and most essentially local people. Ganga River is marked by diverse geographical, climatic, and morphological setting (Sinha et al. 2017). In this regard, Ganga River management strategy would essentially involve diverse rejuvenation measures for different reaches. As an example, Roy and Sinha (2014) and Zakwan et al. (2018) reported that bankfull discharge is a rare event in Western Ganga Plain and Ganga River is subjected to deep incision in this region, but around Patna, bankfull discharge is a frequent event and this section of Ganga requires special attention from the prospect of flood protection works.

Conclusion

Trend analysis was performed using the Mann-Kendall, Sen's slope, and innovative trend tests of different hydrologic parameters at various gauging sites located on the Ganga River. It was observed that almost all the parameters, like annual maximum and annual minimum discharges, sediment and water yield crossing gauging sites during monsoon, showed a negative trend at 5% significance level indicating a fall in all the parameters with time. The presence of significant negative trend at gauging sites downstream of Yamuna from Allahabad to Buxar calls for detailed study of the behavior of the major tributary Yamuna. A significant negative trend in discharge and sediment yield was observed at Farakka which may be attributed to the presence of barrage at the location. Contrary to the general negative trend, Gandhighat exhibit a positive trend behavior for annual maximum and annual minimum discharge, average discharge, and sediment load. Innovative trend analysis could reveal trends of different magnitudes of events; in this way, its application is certainly advantageous over the traditional Mann-Kendall and Sen's slope tests.

Hydrology of large river basin such as Ganga is influenced by various land surface condition, spatial climatic variation, and human activities and as such, it is very difficult to ascertain a particular reason for alteration in flow pattern. However, as evident from the present and earlier studies, both climatic factors (changes in the rainfall and temperature) and human intervention (changes in land use pattern, demographic changes, industrial activities, construction of hydraulic structures) have influenced the flow pattern of Ganga.

Ganga River is marked by diverse geographical, climatic, and morphological setting. In this regard, Ganga River management strategy would essentially require integrated approach with emphasis on diverse rejuvenation measures for different reaches of Ganga River.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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