Impact of land use-land cover change on spatio-temporal trends in seasonal stream flow and suspended sediment load of Godavari basin from 1969 to 2019

Madhura Chetan Aher* and Sanjay Yadav
SVNIT: Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India
*Corresponding author. E-mail: madhura.aher@gmail.com

ABSTRACT

Assessment of long-term trends in stream flow and sediment load is important for adopting soil and water conservation measures and for predicting morphological changes in rivers. In the present study, detailed quantification of the nature of the trend in stream flow and suspended sediment load of Godavari basin, India is reported for the period of 1969 to 2019. The Mann–Kendall test is used to check the trend of stream flow and sediment load for different seasons, namely, spring, monsoon, post-monsoon and winter. The land use-land cover of the whole basin is prepared for four decades (1980–2020). The maximum and minimum water and sediment discharge is detected in monsoon and winter season, respectively. The stream flow is found to be significantly decreased during monsoon and post-monsoon season. The sediment load is significantly decreased for monsoon and spring season. The nature of trend in sediment load is attributed to the land use and land cover change of the basin. The significant reduction of suspended sediment load is mainly due to increase in water bodies and planned agricultural area. The findings of the research would help to manage water resources as well as sustainable development in the Godavari basin.

Key words: Godavari basin, land use-land cover, sediment discharge, trend, water discharge

HIGHLIGHTS

- The study focuses on long-term seasonal trend of streamflow and sediment load of Godavari basin for the past 50 years.
- 90% of sediment load is carried out in the monsoon season.
- Significant decreasing trend is observed in sediment load at all the stations.
- Land use land cover of the basin is linked with trend.
- Increase in water body and agricultural area is the main reason for the decreasing trend of sediment load.

1. INTRODUCTION

The need for freshwater is constantly increasing due to rapid population growth. Additionally, economic growth is also placing stress on existing water resources in many regions of the world (Vorosmarty et al. 2000; Zhang et al. 2013; Fleskens & Stringer 2014). Rivers not only carry a considerable quantum of water but also the sediment with it. The amount of sediment load carried with the stream flow plays a very important role from various perspectives, such as environmental, economic, and social. Also, sediment contains various nutrients and materials that are essential for healthy ecosystems and agricultural land (Smith et al. 2001; Peng et al. 2010; Apitz 2012). In the second half of the 20th century, environmental changes resulting from intensified human activity have altered many large river systems in the world (Steffen 2004). The assessment of sediment yield and its determining factor is important for sustainable basin management (Parsons et al. 2006; Weinbauer et al. 2009; Zhang et al. 2015; Tripathi et al. 2017). Further, sediment yield is important for the assessment of storage capacity of reservoirs and the effective operation of hydraulic structures. The possible reasons behind altered sediment load of river basins may vary spatially as well as temporally.

In recent decades, climate change and rigorous human actions have significantly influenced natural river systems and substantial attention has been paid to variations in stream flow and sediment transport (Walling 2006; Yang et al. 2006). Many researchers have reported the changes and current trends in the stream flow and sediment flux of the major rivers across the world (Gupta & Chakrapani 2005; Zhang et al. 2009). It has been reported that apparent increasing and decreasing trends
were identified in stream flow and sediment load in many rivers around the world (Milly et al. 2005; Walling 2006; Wang et al. 2012; Fischer et al. 2017; Sinha & Eldho 2018). Further, according to Walling & Fang (2003), historical observations of sediment load (annual) of 145 of the most important world rivers indicates 50% reduction in sediment load. Wang et al. (2007) assess 30% of the reduction in sediment discharge is due to decrease in precipitation, whereas the remaining 70% is attributed to human actions in the river basin. Some of the past studies specify that river systems such as the Yangtze, Amazon, Yellow, Colorado and Nile transport smaller amounts of sediment load due to the erection of dams and temporal change in land use-land cover for, e.g., afforestation and deforestation (Milliman & Meade 1983; Carriquiry & Sanchez 1999; Frihy et al. 2003; Wang et al. 2012). According to several researchers, the land use-land cover changes have been recognized as of the utmost significant reason for the delivery and control of the sediment flux of catchments (Kuhnle et al. 1996; Allan et al. 1997; Bakker et al. 2008; Shi et al. 2013; Sinha & Eldho 2018).

The Gangetic and tropical river systems show significant difference in terms of sediment yield. The Gangetic rivers carry an annual sediment load of 2,390 tonnes/km² and tropical rivers carry an annual load of 216 tonnes/km² (Milliman & Meade 1983). Previous studies reveal that, due to the construction of abundant dams and hydraulic structures, many tropical river basins are subjected to risk in terms of reduced stream flow and sediment flux. For example, the Krishna river basin has experienced a drastic reduction in stream flow and sediment flux in response to the construction of dams and reservoirs and that causes coastal erosion (Bouwer et al. 2006; Biggs et al. 2007; Gamage & Smakhtin 2009). Correspondingly, Narmada River basin has also experienced a drastic reduction in sediment flux to the Arabian Sea due to upstream damming (Gupta & Chakrapani 2005).

The studies mentioned earlier did not address the seasonal trend and variations in stream flow and sediment load and their correspondence with land use and cover change of the Godavari basin. The present study addressed the following research objectives: (i) evaluate the long-term variability and trends in seasonal water and suspended sediment discharge using Mann–Kendall (MK) and Sen’s slope estimator test; (ii) evaluate the percentage change in trend of seasonal water and suspended sediment discharge; (iii) analyse land use and land cover of Godavari basin on the decadal basis of 1980–1989, 1990–1999, 2000–2009 and 2010–2020; (iv) link the water and sediment discharge trends with land use and land cover change.

2. STUDY AREA AND METHODOLOGY

2.1. Study area description

The Godavari River originates in the Western Ghats from Trimbakeshwar village in Nasik district, Maharashtra, India. It is the biggest east-flowing tropical river in India draining into the Bay of Bengal. The Godavari basin covers 9.5% of the total topographical area of India. The basin spreads across the states of Maharashtra, Andhra Pradesh, Chhattisgarh, Odisha, Madhya Pradesh, Karnataka and Puducherry. The Godavari basin is divided into eight sub-catchments, i.e., Upper Godavari sub-basin, Middle Godavari sub-basin, Wainganga sub-basin, Wardha sub-basin, Indravati sub-basin, Pranhita sub-basin, Manjra sub-basin and Lower Godavari sub-basin (Figure 1). The drainage area of the basin is 312,812 km² (CWC 2007). The length and width of the river are 1,465 km and 583 m, respectively. The altitude of the basin ranges between 600 m and 1,200 m. The basin is bounded by the Sahyadri ranges in the Western Ghats and Dandakrayna ranges in the Eastern Ghats. The main tributaries of the Godavari River are Pravara, Majara, Purna, Pranhita, Indravati and Sabri. The extent of the basin is fairly large, hence, contrasting climatic variations are observed throughout the basin, although, due to the limited range of vertical elevation the temperature in the basin does not change significantly with average maximum and minimum temperature of 33.04 °C and 20.63 °C, respectively. The weather in the basin is hotter in the western part in comparison with central, northern and eastern parts. The Dandkaranya region in the eastern part is characterized by a hot and humid climate. The Godavari River is a south-west monsoon-fed river. The whole basin receives 80% of rainfall from the south-west monsoon between June and September. The annual rainfall ranges from 755 mm to 1,531 mm. The crest zone of Sahyadri receives heavy rainfall and the regions which are in the rain shadow receive scanty rainfall. Further, on the eastern side the amount of rainfall carries on increasing. Overall, the rainfall is heavy, irregular and unevenly distributed throughout the basin. In January and February, rainfall differs from less than 0.5 to 55 mm. During March, April and May, rainfall differs from less than 1 to 50 mm. Heavy rainfall is received from June to September. The characteristics of the soil formations are primarily dependent on the nature and intensity of weathering processes. Based on texture, 57.61% of the basin falls under the fine textured followed by rocky category. The significant soil types observed in the basin are black soils, red soils, lateritic soils, alluvium, mixed soils and saline and alkaline soils (CWC 2007). Nearly 64.92% of the basin area is
found to have moderate soil erosion and 24.86% of the basin area has severe erosion in a small area near the Bay of Bengal. The basin area is covered with soil that ranges from extremely productive (28.5%) to a non-productive area of 11.15% (Integrated Hydrological Data Book, Central Water Commission of India).

2.2. Land use and land cover features

The overland flow, pattern of erosion and the quantity and quality of sediment transported along with the water discharge predominantly depends on the present land use and land cover in the basin (Jordan et al. 2005; Valentin et al. 2008). In the current study, satellite images for the years 1980, 1990, 2000, 2010 and 2020 (Landsat 5 and Landsat 7 with 30 m spatial resolution) were categorized according to the Level-1 supervised classification. The entire analysis is carried out in ArcGIS 10.4 and labelled as the land use-land cover pattern within the catchment area (Anderson et al. 1976) (see Figures 2 and 3). The decadal land use-land cover statistics from 1980 to 2020 are provided in the Supplementary material, Tables S1–S9. As per the statistics of year 2020, almost 50% of the basin is covered with forest and other types of vegetation. This coverage of dense forest zone can be seen in the eastern region of the basin and more agricultural land cover is observed in the western part of the basin (see Figure 3). From the year 1980 to 2020 the built-up area gradually increased from 33.8 km² to 2,549 km². The drastic change is observed in all the classes of land use and land cover of the basin.

2.3. Stream flow and suspended sediment discharge features

The daily records of water discharge (m³/s) and suspended sediment concentration (mg/L) at 21 stream gauging stations were collected from Central Water Commission (CWC) of India. The stream gauging stations are located at different sub-basins, such as Middle, Lower, Wardha, Wainganga, Pranhita and Indravati. The details of gauging stations and the data period are presented in Table 1. For different stations the data period varies from 1969 to 2019 (50 years), according to the availability of records. The operations or recording at some of the gauging stations started late (after 1969) and some of the gauging stations have stopped recording, which has led to variation in the data set. The sediment load (t/day) for the
particular cross section is obtained by multiplying the sediment concentration of a particular day by the water discharge \((m^3/s)\) of the same day. For the present study, daily data of water and sediment discharge are grouped into four different seasons, i.e., spring (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February).

**Figure 2** | Land use-land cover map of Godavari basin for the year 1980.

**Figure 3** | Land use-land cover map of Godavari basin for the year 2020.
Kendall test–first to use this test and test statistic distribution was derived by Kendall (Mann 1945; Kendall, 1975). The Mann–Kendall test has been recommended by the World Meteorological Organization (WMO) to measure trends in time series. This is a simple method, can handle missing data, does not need to assume normality and

The non-parametric trend test, i.e., Mann–Kendall, was used to check the trend in the stream flow and sediment discharge from 1969 to 2015. Mann was the first to use this test and test statistic distribution was derived by Kendall (Mann 1945; Kendall 1975). The Mann–Kendall test has been recommended by the World Meteorological Organization (WMO) to measure trends in time series. This is a simple method, can handle missing data, does not need to assume normality and

### Table 1: Description of hydrological stations in the study area

| Sr. No | Hydrological station | Longitude | Latitude | Drainage area (km²) | Data availability | No. of years |
|--------|----------------------|-----------|----------|---------------------|------------------|-------------|
| 1      | Dhalegaon            | 76°21'52" | 19°13'13"| 30,840              | 1971–2019        | 48          |
| 2      | G.R. Bridge          | 76°45'00" | 18°57'00"| 33,934              | 1976–2014        | 38          |
| 3      | Yelli                | 77°28'00" | 19°02'00"| 53,630              | 1978–2011        | 33          |
| 4      | Mancherial           | 79°26'41" | 18°50'08"| 102,900             | 1969–2019        | 50          |
| 5      | Bhatpalli            | 79°30'14" | 19°19'50"| 3,100               | 1969–2019        | 50          |
| 6      | Tekra                | 79°56'49" | 18°58'42"| 108,780             | 1969–2019        | 50          |
| 7      | Kumhari              | 80°10'36" | 21°55'03"| 8,070               | 1988–2019        | 31          |
| 8      | Rajegaon             | 80°15'14" | 21°37'32"| 5,580               | 1990–2019        | 29          |
| 9      | Satrapur             | 79°13'59" | 21°13'00"| 11,100              | 1988–2019        | 31          |
| 10     | Pauni                | 79°38'40" | 20°47'45"| 35,520              | 1969–2005        | 36          |
| 11     | Ashiti               | 79°47'13" | 19°41'12"| 50,990              | 1969–2016        | 47          |
| 12     | Hivra                | 78°19'30" | 20°32'52"| 10,240              | 1990–2016        | 26          |
| 13     | Nandgaon             | 78°49'33" | 20°32'00"| 4,580               | 1988–2016        | 28          |
| 14     | P.G. Bridge          | 78°34'40" | 19°49'03"| 18,441              | 1969–2016        | 47          |
| 15     | Bamni                | 79°22'46" | 19°48'53"| 46,020              | 1969–2019        | 50          |
| 16     | Perur                | 80°22'00" | 18°33'00"| 268,200             | 1969–2019        | 50          |
| 17     | Konta                | 81°23'00" | 17°48'00"| 19,550              | 1969–2019        | 50          |
| 18     | Polavaram            | 81°39'35" | 17°14'45"| 307,800             | 1969–2019        | 50          |
| 19     | Nowrangppur          | 82°31'00" | 19°12'00"| 3,545               | 1969–2006        | 37          |
| 20     | Jagdalpur            | 82°01'30" | 19°06'30"| 7,380               | 1969–2019        | 50          |
| 21     | Putahgudem           | 80°21'00" | 18°49'00"| 40,000              | 1969–2019        | 50          |

The observations revealed that in the spring season the average water discharge varies from 3 m³/s at Dhalegaon station to 241 m³/s at Polavaram station. Similarly, for sediment discharge, the obtained range is from 3 t/day at Kumhari and P.G. Bridge to 10,768 t/day at Rajegaon station. Further, the variations in water and sediment discharge for all the seasons are shown in Table 2.

The statistical analysis revealed that maximum as well as minimum water and sediment discharge is observed during the monsoon season. Monsoon sets in mostly in the second week of June, hence, considerable discharge is observed after the first week, and the minimum water and sediment discharge is observed in the first week of June. The maximum water and sediment discharge values correspond to September because the basin receives the maximum amount of rainfall during this month. All the dams and reservoirs get filled up to the end of September, hence, a considerable amount of water flow is observed in this month. Also, the water and sediment discharge is quite high in the post-monsoon season (see Table 2). The months of December to February are almost dry for the basin, hence, very low water and sediment discharge corresponds to these months. The average water and sediment discharge of Godavari basin during the spring season are 32 m³/s and 742 t/d, during monsoon it is 1,176 m³/s and 1,18356 t/d, during post-monsoon 339 m³/s and 48,794 t/d and during the winter season 56 m³/s and 574 t/d. The maximum sediment yield of 2.35 t/km²/d is observed in the monsoon period.

### 2.4. Methodology

The step-wise procedure adopted in assessing the spatial and temporal trend in water and suspended sediment discharge is included in Figure 4.

#### 2.4.1. Mann–Kendall test

The non-parametric trend test, i.e., Mann–Kendall, was used to check the trend in the stream flow and sediment discharge from 1969 to 2015. Mann was the first to use this test and test statistic distribution was derived by Kendall (Mann 1945; Kendall 1975). The Mann–Kendall test has been recommended by the World Meteorological Organization (WMO) to measure trends in time series. This is a simple method, can handle missing data, does not need to assume normality and...
is strong against outliers (Hamed 2008). In the hydrological time series, non-normally distributed data are very common; this test when compared to the parametric test like t-test has a higher power (Yue et al. 2002). For a given time series \( X (x_1, x_2, \ldots, x_n) \), null hypothesis \( H_0 \) shows no trend and alternative hypothesis \( H_1 \) represents the presence of either increasing or decreasing trend in the time series.

### Table 2 | Average range of water and sediment discharge

| Parameters                  | Spring       | Monsoon      | Post-monsoon | Winter     |
|-----------------------------|--------------|--------------|--------------|------------|
| Water discharge (m\(^3\)/s) | 3–241        | 74–6,567     | 13–2,129     | 5–382      |
| Sediment discharge (t/d)    | 3–10,768     | 0.39–735,269 | 119–722,340 | 16–4,683   |
The Mann–Kendall trend analysis method is given below:

A standardized test statistic, i.e., $Z$, is calculated as:

$$Z = \begin{cases} 
S - 1/\sqrt{\text{Var}S} & S > 0 \\
0 & S = 0 \\
S + 1/\sqrt{\text{Var}S} & S < 0 
\end{cases}$$

(1)

The positive and negative $Z$ value specifies an upward and downward trend, respectively. The test is carried out at 5% significance level.

Where,

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \text{sgn}(x_j - x_i)$$

(2)

$$\sin (x_j - x_i) = \begin{cases} 
+1 & x_j > x_i \\
0 & x_j = x_i \\
-1 & x_j < x_i 
\end{cases}$$

(3)

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

(4)

2.4.2. Sen’s slope estimator

The non-parametric robust test to detect the monotonic trend in the hydrologic time series is proposed by Hirsch et al. (1982).

The equation is given as:

$$\beta = \text{Median} \left( \frac{x_j - x_i}{j - i} \right) \text{ for } j > i$$

(5)

where, $\beta =$ slope between data points $x_i$ and $x_j$, $x_i =$ data measurement at time $i$, $x_j =$ data measurement at time $j$. A positive value of $\beta$ specifies an ‘increasing trend in the time series’, and the negative value specifies a ‘decreasing trend in the time series’ (Xu et al. 2007).

3. RESULTS AND DISCUSSION

3.1. Trends in seasonal stream flow

Statistical analysis reveals that the stream flow varies largely, across the sub-basins as well as the main stream. The gauging stations located on Lower Godavari basin (eastern-most part of the basin), namely, Konta, Perur and Polavaram show a considerable amount of water discharge in all the seasons. The average water discharge in the spring season for these three stations is 169 m$^3$/s, 68 m$^3$/s and 241 m$^3$/s, respectively. For the same season, all other stations, particularly those located on Middle Godavari basin and Wardha basin, carry a much lower amount of water discharge; as compared with Middle and Wardha basin, Pranhita and Indravati sub-basins show quite a high water discharge for the spring season. Although Godavari River has the maximum rainfall in the monsoon period the basin is spread out to a fairly large extent; hence, spatial as well as temporal variation is observed throughout the basin (Panda et al. 2010). At Polavaram station (Lower Godavari basin) the mean daily discharge during monsoon season is 6,567 m$^3$/s, whereas at Nandgaon station (Wardha basin) daily discharge is 74 m$^3$/s. This significant variation in water discharge is due to spatial and temporal variation in rainfall. In the post-monsoon season, all the stations located on the Lower Godavari sub-basins, i.e., Konta, Perur and Polavaram, reported water discharge of 402 m$^3$/s, 1,607 m$^3$/s and 2,129 m$^3$/s, respectively. In comparison with the spring season, the water discharge during post-monsoon season is high at all the gauging stations. Further, during the winter season, Bhatpalli and Rajegaon stations reported the lowest water discharge of about 5 m$^3$/s, whereas Konta, Perur and Ploavaram stations reported the highest water discharge of 67 m$^3$/s, 136 m$^3$/s and 187 m$^3$/s, respectively. The aforesaid statistics indicate the significant inter-seasonal variability across the entire basin. From the analysis it is observed that as compared with the western and central
part of the basin, the eastern region of the basin exhibits quite heavy water discharge in the river in all four seasons. It is clear from the analysis that the annual water budget of the Godavari River as well as all the sub-basins of the river significantly depends on the south-west monsoon rainfall. The three gauging stations of Middle Godavari basin (Dhalegaon), Pranhita basin (Tekra) and Lower Godavari basin (Polavaram) were selected to analyse the annual variation in stream flow. The selected sub-basins are located in the western, middle and eastern part of the Godavari basin. The mean annual stream flow at Dhalegon, Tekra and Polavaram station is 120.61 m$^3$/s, 3,003.82 m$^3$/s and 6,567.49 m$^3$/s, respectively. The observed variation in stream flow of Middle Godavari, Pranhita and Lower Godavari basin is high. The analysis indicates significant spatial variation in stream flow. The annual variation in stream flow with linear trend is shown in Figure 5.

The non-parametric Mann–Kendall (MK) test and Sen’s slope estimator were applied on daily water discharge at 21 stations. The time series was checked for the presence of serial correlation before application of MK test (Yue et al. 2002). The positive serial correlation in time series has been removed by pre-whitening (Burn & Elnur 2002), and then the MK test (Mann 1945; Kendall 1975) was applied. The result obtained by MK test specifies that 14 out of 21 stations identified a declining trend in the spring season (Table 3). Further significant decreasing trend is reported at Dhalegaon ($Z = -3.30$), G.R. Bridge ($Z = -4.29$), Yelli ($Z = -3.67$), Perur ($Z = -3.54$), Nowrangpur ($Z = -2.48$), Jagdalpur ($Z = -10.15$), Pathagudem ($Z = -10.27$) and Mancherial ($Z = -7.30$) stations, while a significant increasing trend is reported at Konta ($Z = 3.52$), Polavaram ($Z = 2.94$), Tekra ($Z = 2.76$) and Pauni ($Z = 4.03$) stations. The results of Sen’s slope estimator test reported the median of the slope in water discharge during the spring season at Dhalegaon, G.R. Bridge, Yelli, Perur, Nowrangpur, Jagdalpur, Pathagudem and Mancherial is —0.001, —0.002, —0.003, —0.01, —0.003, —0.004, —0.003 and —0.003 mm/day, respectively. On the other hand, Konta and Polavaram exhibit a positive slope of 0.029 and 0.021 mm/day, respectively. The spatially interpolated maps showing trend in seasonal stream flow was prepared for all four seasons (see Figure 6).

The basin exhibits decreasing trend in water discharge for the monsoon period as 19 out of 21 stations reported a declining trend (Table 4). Seventeen out of 19 stations reported significant decreasing trend at Dhalegaon, G.R. Bridge, Yelli, Perur, Polavaram, Nowrangpur, Jagdalpur, Pathagudem, Bhatpalli, Tekra, Kumhari, Pauni, Satrapur, Bamni, Hivra, Nandgaon,
Table 3 | Mann–Kendall Z statistics for water discharge

| Sr. No | Station     | Spring | Monsoon | Post-monsoon | Winter |
|--------|-------------|--------|---------|--------------|--------|
| 1      | Dhalegaon   | –3.30  | –9.97   | –10.20       | –5.09  |
| 2      | G.R. Bridge | –4.29  | –10.02  | –7.80        | –4.29  |
| 3      | Yelli       | –3.67  | –15.24  | –5.94        | –5.06  |
| 4      | Konta       | 3.52   | 5.76    | 2.81         | 1.11   |
| 5      | Perur       | –3.54  | –2.16   | –3.78        | –1.78  |
| 6      | Polavaram   | 2.94   | –0.92   | –2.01        | –0.32  |
| 7      | Nowrangpur  | –2.48  | –6.72   | –3.49        | –2.30  |
| 8      | Jagdalpur   | –10.15 | –6.77   | –10.64       | –9.50  |
| 9      | Patahgudem  | –10.27 | –2.89   | –1.62        | –7.55  |
| 10     | Bhatpalli   | 1.80   | –5.68   | –3.72        | 1.37   |
| 11     | Mancherial  | –7.30  | 0.00    | –7.19        | –10.68 |
| 12     | Tekra       | 2.76   | –12.42  | –0.43        | 1.85   |
| 13     | Ashti       | –0.08  | –0.97   | 0.74         | 0.96   |
| 14     | Kumhari     | 0.73   | –3.91   | –1.62        | 3.64   |
| 15     | Pauni       | 4.03   | –2.86   | –0.29        | 2.06   |
| 16     | Rajegaon    | –0.78  | 0.45    | –2.23        | –0.29  |
| 17     | Satrapur    | –1.42  | –5.84   | –0.19        | –0.66  |
| 18     | Bamni       | 0.40   | –4.54   | –7.15        | –0.52  |
| 19     | Hivra       | –1.56  | –9.46   | –5.41        | –1.76  |
| 20     | Nandgaon    | –0.29  | –3.82   | 1.81         | 3.86   |
| 21     | P.G. Bridge | –1.88  | –5.20   | –5.49        | –5.61  |

Bold values indicates the significance at 5%.

P.G. Bridge with Z values of −9.97, −10.02, −15.24, −2.16, −0.92, −6.72, −6.77, −2.89, −5.68, −12.42, −3.91, −2.86, −5.84, −4.54, −9.46, −3.82, −5.20, respectively (Table 3). The Godavari basin receives the maximum rainfall in the monsoon season, and water discharge is highly sensitive to the rainfall. The analysis reveals that significant reduction in the water discharge is noticed during the monsoon period due to shortfall of the rainfall in the western and central part of India. The Sen's slope results are in agreement with MK test results, for all the stations.

The trend analysis results for the post-monsoon season reported significant decreasing trend in water discharge at 13 stations and significant increasing trend at one station. Further, the Ashti (Z = 0.74) and Nandgaon (Z = 1.81) stations indicated a positive trend and the Patahgudem (Z = −1.62), Tekra (Z = −0.43), Kumhari (Z = −1.62), Pauni (Z = −0.29) and Satrapur (Z = −0.19) stations reported a negative trend. During the winter season, 14 stations reported a decreasing trend and seven stations reported an increasing trend in water discharge. Out of seven stations, three stations, namely, Kumhari (Z = 3.64), Pauni (Z = 2.06) and Nandgaon (Z = 3.86), reported significant increasing trend in water discharge.

The percentage change in trend is also analysed from Sen's slope (β) (Yue & Hashino 2003). The percentage change in trend is observed to be negative across the basins. In the spring season the percentage change is negative and greater than 50% at Dhalegaon, G.R. Bridge, Yelli, Perur, Nowrangpur, Jagdalpur, Patahgudem and Mancherial stations; whereas, Polavaram, Konta and Pauni stations exhibit positive change, i.e., 41.22%, 79.31% and 42.96%, respectively. During the monsoon period the basin exhibits a largely negative change in trend. Only two stations, i.e., Jagdalpur (−41.57%) and Nowrangpur (−43.17%), show a highly negative change in trend and the remaining stations indicate moderate change. For the post-monsoon season, a highly negative change in trend was observed at Nowrangpur and Jagdalpur stations with −80.08% and −90.15% and a positive change in trend was observed at Konta (14.94%) and Ashti (4.38%) stations. In the winter season, the basin reported significant negative change in trend for the past 50 years. The Dhalegaon, G.R. Bridge, Yelli, Perur, Nowrangpur, Jagdalpur, Mancherial and P.G. Bridge stations show a drastic negative change in trend of larger than 50%; whereas, Konta, Bhatpalli, Tekra, Ashti, Kumhari and Pauni stations reported a positive change of 28.84%, 26.26%, 12.64%, 9.86%,
91.56%, 18.83% and 96.48%, respectively. The large variation in percentage of change in trend is observed in the spring and winter seasons for all the stations and less variation is observed for monsoon and post-monsoon seasons. The large variation in trend is due to the presence of numerous dams in the catchment area of the basin. To fulfill the water demands of different sectors water is regularly released from the upstream dams. The lesser variation is due to the monsoon rainfall which starts from the middle of June and ends up to the end of September.

3.2. Trends in seasonal suspended sediment load

The preliminary statistical analysis indicates that sediment load varies significantly spatially as well as temporally across the basin. The mean sediment load of Godavari basin in the past 50 years during the spring, monsoon, post-monsoon and winter
The analysis also indicates that 90% of the sediment load was transported in the monsoon season. Further, it is reported that the post-monsoon season followed by monsoon season contributed to the considerable amount of sediment load to the Bay of Bengal. The sediment load is observed to vary from 3 t/day (P.G. Bridge) to 10,678 t/day (Rajegaon) station in the spring season. A considerable amount of sediment flow is recorded in the spring season at Konta (746 t/day), Perur (132 t/day) and Polavaram (507 t/day) stations. As compared with the spring season, significant variation in sediment load is observed at all the stations across the basin in the monsoon period. The minimum and maximum sediment load varies from 0.39 t/day (Dhalegaon) to 735,269 t/day (Polavaram). It is also reported that Lower Godavari sub-basin, located in the eastern region, transports high sediment load of 449,931.66 t/day during the monsoon period and the Middle Godavari basin carried the lowest sediment load of 26,613.13 t/day. The
high sediment load of Lower Godavari basin is due to the good amount of rainfall that the eastern region receives during June to September and also to the lower number of dams in the catchment area. The post-monsoon season also contributes a reasonable amount of rainfall; hence, it is the main season followed by the monsoon season that contributes mean sediment load of 48,794 t/day. The Dhalegaon, G.R. Bridge and Yelli stations reported sediment load of 742,340 t/d, 4,452 t/d and 18,762 t/d, respectively, during the post-monsoon season. In contrast to the monsoon season, Middle Godavari sub-basin carries a good amount of sediment load (255,185 t/d). The Bhatpalli, Mancherial and Tekra stations located on Pranhita sub-basin carried a sediment load of 2,450 t/d, 10,967 t/d and 29,048 t/d, respectively. The Wardha sub-basin carried the lowest sediment load of 5,195 t/d and the reason behind such a low sediment load is the construction of an abundant number of dams in the catchment area. December, January and February, which comprise the winter season, carry very low sediment load of 574 t/d due to a lower amount of water discharge. As compared to the spring season, Konta, Perur, and Polavaram stations (Lower Godavari basin) carry a higher sediment load of 735 t/d, 468 t/d and 844 t/d, respectively, in the winter season. The stations located on Wardha basin, i.e., Bamni, Hivra, Nandgaon and P.G. Bridge, transport an average load of 67 t/d in the winter season. The annual sediment load of three sub-basins, i.e., Middle Godavari, Pranhita and Lower Godavari basins, was analysed to detect the spatial and temporal variations. The observed mean sediment load of Middle Godavari, Pranhita and Lower Godavari basin is 17,766.21 t/d (Dhalegaon), 360,644.41 t/d (Tekra) and 741,750.91 t/d (Polavaram), respectively. The significant spatial variation in the sediment load is observed as the Middle Godavari basin carries a lower sediment load than the Pranhita and Lower Godavari basins. The annual variation in sediment load with linear trend is shown in Figure 7.

The MK test and Sen’s slope estimator test were applied on suspended sediment load at 21 stations located across the basin, for all four seasons. The results revealed that suspended sediment load of Godavari basin has significantly decreased in the past 50 years. In the spring season, 15 out of 21 stations reported a decreasing trend and six stations reported an increasing trend. Significantly decreasing trend is observed at Dhalegaon (Z = -2.76), G.R. Bridge (Z = -3.29), Yelli (Z = -3.37), Perur

| Table 4 | Nature of trend at different stations for water discharge |
| Sr. No | Station | Spring | Monsoon | Post-monsoon | Winter |
|--------|---------|--------|---------|--------------|-------|
| 1      | Dhalegaon | ↓↓     | ↓       | ↓            | ↓     |
| 2      | G.R. Bridge | ↓↓     | ↓       | ↓            | ↓     |
| 3      | Yelli     | ↓↓     | ↓       | ↓            | ↓     |
| 4      | Konta     | ↑↑     | ↑       | ↑            | ↑     |
| 5      | Perur     | ↓↓     | ↓       | ↓            | ↓     |
| 6      | Polavaram | ↑↑     | ↓       | ↓            | ↓     |
| 7      | Nowrangpur| ↓↓     | ↓       | ↓            | ↓     |
| 8      | Jagdalpur | ↓↓     | ↓       | ↓            | ↓     |
| 9      | Patangudem| ↓↓     | ↓       | ↓            | ↓     |
| 10     | Bhatpalli | ↑↑     | ↓       | ↓            | ↑     |
| 11     | Mancherial| ↓↓     | ↓       | ↓            | ↓     |
| 12     | Tekra     | ↑↑     | ↓       | ↓            | ↑     |
| 13     | Ashti     | ↓↓     | ↓       | ↑            | ↑     |
| 14     | Kumhari   | ↑↑     | ↓       | ↓            | ↑     |
| 15     | Puuni     | ↑↑     | ↓       | ↓            | ↑     |
| 16     | Rajegaon  | ↓↓     | ↑       | ↓            | ↓     |
| 17     | Satrapur  | ↓↓     | ↓       | ↓            | ↓     |
| 18     | Bamni     | ↑↑     | ↓       | ↓            | ↑     |
| 19     | Hivra     | ↓↓     | ↓       | ↓            | ↓     |
| 20     | Nandgaon  | ↓↓     | ↓       | ↑            | ↑     |
| 21     | P.G. Bridge | ↓↓   | ↓       | ↓            | ↓     |

↓, Significant decreasing trend; ↑, significant increasing trend; ↓, decreasing trend; ↑, increasing trend.
Z = 6.25), Nowrangpur (Z = 2.91), Jagdalpur (Z = 5.96), Patahgudem (Z = 3.47), Mancherial (Z = 7.51), Tekra (Z = 2.31) and Bamni (Z = 2.60) stations. Also, a significantly increasing trend is observed at Konta (Z = 6.56), Bhatpalli (Z = 2.81) and Pauni (Z = 4.76) stations (Table 5). The median of slope (β) at Konta, Bhatpalli and Pauni is 0.148, 0.001 and 0.002 mm/day, respectively. The Sen’s slope results are in agreement with MK test results. A drastic reduction in sediment load is observed at all the stations during the monsoon season, where 19 out of 21 stations reported a significant decreasing trend and two stations reported increasing trend in sediment load (Table 6). Konta station (Z = 0.13) indicates an increasing trend and Rajegaon (Z = 3.79) station indicates a significant increasing trend. The Sen’s slope values indicated higher slope at a maximum of stations in the monsoon period, such as at G.R. Bridge, Yelli, Perur, Polavaram, Nowrangpur, Jagdalpur, with β values of −0.014, −0.036, −2.319, −5.428, −0.860, −1.064 mm/day, respectively. Dhalegaon, G.R. Bridge, Yelli, Polavaram, Nowrangpur, Jagdalpur, Hivra and P.G. Bridge reported a significant decreasing trend with Z values of −6.0, −5.36, −4.45, −2.96, −6.85, −11.89, −4.60 and −4.71, respectively. Konta, Pauni and Rajegaon stations reported a significant increasing trend with Z values of 2.98, 2.10 and 2.84, respectively. It is also observed that, as compared with the monsoon, in the post-monsoon season the number of stations showing significant decreasing trends are reduced by eight and the stations showing increasing trend increased by seven. The median of slope at Dhalegaon, G.R. Bridge, Yelli, Polavaram, Nowrangpur, Jagdalpur, Hivra and P.G. Bridge stations is −0.015, −0.011, −0.027, −0.433, −1.262, −0.109, −0.016 and −0.008 mm/day, respectively. In the winter season, 11 stations reported a decreasing trend and 10 stations reported an increasing trend in sediment load of Godavari basin. Dhalegaon (Z = −3.52), G.R. Bridge (Z = −3.82), Yelli (Z = −4.57), Polavaram (Z = −3.53), Jagdalpur (Z = −6.83), Hivra (Z = −4.88) and P.G. Bridge (Z = −2.85) reported a significantly decreasing trend; whereas, Konta (Z = 4.06), Ashti (Z = 2.72), Kumhari (Z = 4.05), Pauni (Z = 5.53), Rajegaon (Z = 2.25) and Rajegaon (Z = 2.83) stations indicated a significant decreasing trend in the winter season. The spatially interpolated maps showing trend in seasonal sediment load were prepared for all four seasons (see Figure 8).

The percentage change in trend of seasonal suspended sediment discharge is reported to be decreasing across the basin. In the spring season the percentage change in trend is observed from −0.001% to 93.03%. Konta, Polavaram, Bhatpalli, Mancherial, Ashti, Kumhari and Pauni stations reported 93.03, 26.97, 0.93, 14.94, 9.33, 5.58 and 38.06% positive change in trend. However, Dhalegaon (−2.44%), G.R. Bridge (−30.05%), Yelli (−15.49%), Perur (−49.78%), Nowrangpur (−18.95), Jagdalpur
Pathagudem (−25.43%), Tekra (−14.27), Rajegaon (−0.001%), Satrapur (−6.67%), Bamni (−4.54%), Hivra (−0.30%), Nandgaon (−0.0009%) and P.G. Bridge (−0.22%) reported a negative change in trend in the spring season. In the monsoon season the percentage change in trend is observed from −28.54% to −0.098%. A further maximum negative change of −17.23% is reported at Jagdalpur station. In the winter season, stations, namely, Dhalegaon, G.R. Bridge, Yelli, Perur, Nowrangpur, Jagdalpur, Pathagudem, Mancherial, Satrapur, Hivra and P.G. Bridge reported positive change in trend and Konta, Polavaram, Bhatpalli, Tekra, Ashti, Kumhari, Pauni, Rajegaon, Bamni and Nandgaon reported negative change in trend. Similar to the water discharge, greater variation in percentage of change in trend is observed in the spring and winter seasons for all the stations and smaller variation is observed for monsoon and post-monsoon seasons. Although Godavari River experiences a good amount of water discharge in the monsoon season, significant reduction in sediment load is observed in monsoon seasons due to the trapping of sediments in the dams. This will have a significant impact on reduction in the storage capacity of dams as well as coastal areas being subjected to severe erosion in the future. Additionally, the direction of flow of water and the amount of sediment flow along with it are linked with each other. The elevation of the catchment area plays an important role in the amount of water flow and the corresponding suspended sediment load that a river transports. The elevation of Godavari basin indicates a considerable range of elevation, varying from 0–246 m to 782–1,677 m. The western part of the basin covering Middle Godavari, Wainganga and Wardha sub-basins has an elevation of 782–1,672 m. It is expected to have a good amount of sediment load to be carried by these three sub-basins, but due to significant temporal variation in some of the classes of land use and land cover (increase in water bodies and agricultural area), the majority of the stations show significant decreasing trend in sediment load. The reduction in sediment load will increase the overland flows and increase the risk of coastal erosion. Syvitski et al. (2009) also reported that the Godavari basin was at greater risk of coastal erosion. For control regions and the management of sediment flows in future, responses to changes in ambient conditions therefore need to be predicted, especially in regions where livelihoods depend on river systems and their natural processes (Fischer et al. 2017).

### Table 5 | Mann–Kendall Z statistics for suspended sediment discharge

| Sr. No | Station     | Spring | Monsoon | Post-monsoon | Winter |
|--------|-------------|--------|---------|--------------|--------|
| 1      | Dhalegaon   | −2.76  | −5.44   | −6.00        | −3.52  |
| 2      | G.R. Bridge | −3.29  | −9.02   | −5.36        | −3.82  |
| 3      | Yelli       | −3.37  | −18.69  | −4.45        | −4.57  |
| 4      | Konta       | 6.56   | 0.13    | 2.98         | 0.098  |
| 5      | Perur       | −6.25  | −3.35   | −1.78        | −1.57  |
| 6      | Polavaram   | 1.08   | −1.97   | −2.96        | 0.24   |
| 7      | Nowrangpur  | −2.91  | −6.24   | −6.85        | −3.53  |
| 8      | Jagdalpur   | −5.96  | −10.43  | −11.89       | −6.83  |
| 9      | Pathagudem  | −3.47  | −2.02   | 0.36         | −0.75  |
| 10     | Bhatpalli   | 2.81   | −4.10   | −1.62        | 0.72   |
| 11     | Mancherial  | −7.51  | −4.76   | −1.24        | −1.37  |
| 12     | Tekra       | −2.32  | −2.86   | 1.29         | 0.08   |
| 13     | Ashti       | 1.15   | −2.384  | 0.51         | 2.72   |
| 14     | Kumhari     | 1.89   | −3.763  | −0.26        | 4.05   |
| 15     | Pauni       | 4.76   | −2.791  | 2.10         | 5.53   |
| 16     | Rajegaon    | −0.22  | 3.799   | 2.84         | 2.25   |
| 17     | Satrapur    | −0.81  | −7.690  | −0.27        | −0.74  |
| 18     | Bamni       | −2.60  | −3.140  | −1.36        | 0.45   |
| 19     | Hivra       | −1.87  | −7.888  | −4.60        | −4.88  |
| 20     | Nandgaon    | −0.21  | −2.139  | 1.65         | 2.83   |
| 21     | P.G. Bridge | −1.42  | −3.478  | −4.71        | −2.85  |

Bold values indicates the significance at 5%.
3.3. Decadal variations in land use and land cover and its linkage with trend of stream flow and suspended sediment discharge

The land use and land cover maps were prepared for four decades, i.e., 1980–1989, 1990–1999, 2000–2009 and 2010–2019 for the Godavari River Basin. The selected classes of land use and land cover were built-up area, agricultural area, water bodies, fallow/uncultivated land, rocky/barren, land/dry riverbed and forest patches/other vegetation. The fallow/uncultivated land is the predominant land use-land cover class in the Godavari basin. The rocky/barren land was the predominant land use-land cover class during 1980–1989, that occupied 58% of the total area (see Figure 2). However, considerable reduction in barren land to 7.7% is reported during 2010–2020, thus, a total decline of 50.3% is reported during 1980–2020. Forest cover was the second predominant class during 1980–1989, with coverage of 23.1% of area; whereas, during 2010–2020, forest area decreased from 23.1% to 15.9% (see Table 7). The fallow/uncultivated land is the predominant land use-land cover class in the Godavari basin. The rocky/barren land was the predominant land use-land cover class during 1980–1989, that occupied 58% of the total area (see Figure 2). However, considerable reduction in barren land to 7.7% is reported during 2010–2020, thus, a total decline of 50.3% is reported during 1980–2020. Forest cover was the second predominant class during 1980–1989, with coverage of 23.1% of area; whereas, during 2010–2020, forest area decreased from 23.1% to 15.9% (see Table 7). The fallow land area increased from 11.9% to 58% during 1980–2020. Similarly, agricultural land is reported as increased from 6.5% (during 1980–1989) to 16.1% (during 2010–2020). It is reported that the aforesaid decreases in barren land and forest cover are covered by agricultural area. Similarly, the built-up area across the basin has rapidly increased from 0.01% (during 1980–1898) to 0.8% (during 2010–2020). The built-up area is reported to be increased consistently after 1990 and the same trend is continued up to 2020. The percentage area of water bodies in terms of water storage structures in the catchment area also increased consistently from 0.5% to 1.5% during 1980–2020. The water bodies increase doubled from 0.5% to 1% during 1990–1999 and a consistent increase in area is reported in 2000–2009 and 2010–2020 (see Figure 9).

It is observed that the water discharge and sediment load decreased significantly from 1969 to 2019 across the Godavari basin. The drastic change in land use and land cover class was also noticed during 1980 to 2020. The change in land use and land cover class over the period of 40 years has a considerable impact on the stream flow and sediment load of the basin. To correlate the impact of land use-land cover change with the stream flow and sediment load, it is important to study and

### Table 6 | Nature of trend at different stations for sediment discharge

| Sr. No. | Station   | Spring | Monsoon | Post- monsoon | Winter |
|---------|-----------|--------|---------|---------------|--------|
| 1       | Dhalegaon | ↓      | ↓       | ↓             | ↓      |
| 2       | G.R. Bridge | ↓      | ↓       | ↓             | ↓      |
| 3       | Yelli     | ↓      | ↓       | ↓             | ↓      |
| 4       | Konta     | ↑      | ↑       | ↑             | ↑      |
| 5       | Perur     | ↓      | ↓       | ↓             | ↓      |
| 6       | Polavaram | ↑      | ↓       | ↓             | ↑      |
| 7       | Nowrangpur| ↓      | ↓       | ↓             | ↑      |
| 8       | Jagdalpur | ↓      | ↓       | ↓             | ↓      |
| 9       | Patahgudem| ↓      | ↓       | ↑             | ↓      |
| 10      | Bhatpalli | ↑      | ↓       | ↓             | ↑      |
| 11      | Mancherial| ↓      | ↓       | ↓             | ↓      |
| 12      | Tekra     | ↓      | ↓       | ↑             | ↑      |
| 13      | Ashti     | ↑      | ↓       | ↑             | ↑      |
| 14      | Kumhari   | ↑      | ↓       | ↓             | ↑      |
| 15      | Pauni     | ↑      | ↓       | ↑             | ↑      |
| 16      | Rajegaon  | ↓      | ↑       | ↑             | ↑      |
| 17      | Satrapur  | ↓      | ↓       | ↓             | ↓      |
| 18      | Bamni     | ↓      | ↓       | ↓             | ↑      |
| 19      | Hivra     | ↓      | ↓       | ↓             | ↑      |
| 20      | Nandgaon  | ↓      | ↓       | ↑             | ↑      |
| 21      | P.G. Bridge | ↓      | ↓       | ↓             | ↓      |

↓, Significant decreasing trend; ↑, significant increasing trend; ↓, decreasing trend; ↑, increasing trend.

Journal of Water and Climate Change Vol 13 No 2, 1039
analyse the long-term or historical records. Hence, 50 years of records of water discharge and suspended sediment discharge were checked to determine the trend and variability in the seasonal time series. The seasonal time series of water discharge and suspended sediment discharge also elaborates the effect of climatic parameters particularly, rainfall pattern, on the trend and variability. From the analysis of decadal changes in land use-land cover class it is observed that some of the land use-land cover classes are reduced and increased drastically from 1980 to 2020, while some of the land use-land cover classes are increased gradually in the catchment area. Now these considerable and/or consistent reductions as well as increase in some of the classes have a direct impact on erosion pattern, stream flow, overland flow, quality and quantity of sediments.

The majority of barren lands and forest lands were transformed into well-organized agricultural lands during 1980–2020. A consistent increase in built-up area or urban development occurred in the catchment area of the Godavari basin. This consistent increase from 0.01% to 0.8% leads to increased overland flows as well as improved sediment load of the basins. While

Figure 8 | Spatial distribution of seasonal sediment discharge trend: (a) spring, (b) monsoon, (c) post-monsoon, (d) winter. (continued.)
Trend analysis revealed significant decreasing trend in water discharge as well as sediment discharge, this is due to consistent increase in the water storage structures in the sub-basins. These water storage structures act like check dams within the catchment. Hence, although increased built-up areas could have an effect on increased sediment load, due to the trapping of significant sediments in the reservoirs, the majority of the stations reported significant decreasing trend of sediment discharge. Nearly 90% of the sediment load of the Godavari basin is transported during the monsoon season and the majority of the stations (19 out of 21) are reported with significant reduction in sediment discharge. This significant reducing trend is due to the combined effect of rainfall and land use-land cover changes during the study period. The water bodies in all the sub-basins are constantly increased after 1990 from 1,622 km² to 3,492 km², also the agricultural area is increased from 20,312 km² to 63,086 km². The forest area is decreased from 72,172 km² to 50,630 km² and fallow/uncultivated land area
Table 7 | Decadal change in land use-land cover statistics of Godavari basin

| Land use-land cover class (percentage change) | 1980–1989 | 1990–1999 | 2000–2009 | 2010–2019 |
|---------------------------------------------|-----------|-----------|-----------|-----------|
| Built-up area                               | 0.01      | 0.5       | 0.7       | 0.8       |
| Agriculture                                 | 6.5       | 7.1       | 20.8      | 16.1      |
| Water bodies                                | 0.5       | 1.0       | 1.2       | 1.5       |
| Fallow land/Uncultivated                    | 11.9      | 39.5      | 25.8      | 58.0      |
| Rocky/Barren land/Dry riverbed              | 58.0      | 22.3      | 30.0      | 7.7       |
| Forest patches/Other vegetation             | 23.1      | 29.5      | 21.5      | 15.9      |
| Total                                       | 100       | 100       | 100       | 100       |

Figure 9 | Decadal changes in land use-land cover in Godavari basin.
is increased from 37,220 km² to 151,103 km². However, these decreases in land cover are replaced by planned agricultural area which, in turn, resist the sediment load from the catchment. The percentage distribution in the nature of seasonal water discharge and sediment discharge trend at 21 stations is represented in Figures 10 and 11.

4. CONCLUSION

The long-term spatial and temporal trends in water discharge and suspended sediment load during the spring, monsoon, post-monsoon and winter seasons has been analysed at finer spatial scale for Godavari basin, India. The nature of trends has been examined using non-parametric MK test and Sen's slope estimator test. The decadal analysis of land use and land cover is performed for the period of 1980 to 2020. The trends in water discharge and sediment load have also been connected with the land use and land cover pattern of the basin. The key findings of this study are summarized as follows.

The inter-seasonal variation in the stream flow is large across the sub-basins as well as the main stream. As compared with Middle Godavari basin, Wardha basin, Wainganga basin, Pranhita and Indravati basin, Lower Godavari basin show considerable amounts of water discharge in all four seasons. During the post-monsoon season, water discharge is quite high at all the gauging stations. From the analysis it is observed that, as compared with western and central parts of the basin, the eastern part of the basin exhibits quite heavy water discharge particularly during the monsoon season. Godavari River basin receives the maximum rainfall in the monsoon season, and water discharge is highly sensitive to the rainfall. Thus, the annual water budget of Godavari River, as well as all the sub-basins of the river, is significantly dependent on the south-west monsoon rainfall. The large variation in percentage of change in trend is observed in spring and winter seasons for all the stations and little variation is observed for monsoon and post-monsoon seasons. The large variation in trend is due to the presence of numerous dams in the catchment area of the basin and lesser variation is due to the monsoon rainfall which starts from the middle of June and ends up to the end of September.

The sediment load varies significantly spatially as well as temporally across the basin. The analyses also indicate that 90% of the sediment load was transported in the monsoon season. Further, it is testified that the post-monsoon season followed by monsoon contributed a considerable amount of sediment load to the Bay of Bengal. It is also reported that Lower Godavari sub-basin, which is located in the eastern region, transports a high sediment load of 449,931.66 t/day during the monsoon period and Middle Godavari basin and Wardha basin carry the lowest sediment load of 26,613.13 t/day and 5,195 t/day, respectively. The high sediment load of Lower Godavari basin is due to the good amount of rainfall that the eastern
region receives during June to September and to a smaller number of dams in the catchment area. The post-monsoon season also contributes a fair amount of rainfall and, hence, it is the main season that contributes average sediment load of 48,794 t/day over the last 50 years. The drastic reduction in sediment load is observed at all the stations for the monsoon period. Similar to the water discharge, greater variation in percentage of change in trend is observed in the spring and winter seasons for all the stations and smaller variation is observed for the monsoon and post-monsoon seasons. Although Godavari River experiences a good amount of water discharge in the monsoon season, significant reduction in sediment load is observed in monsoon seasons, due to the trapping of sediments in the dams. This will have significant impact on reduction in storage capacity of dams as well as coastal areas being subjected to severe erosion in the future. The significant change in land use-land cover is noticed during the 1980–2020 period. During this period, forest cover and barren land area decreased and built-up area, water bodies and planned agricultural area are increased. Such drastic reduction and/or increase in land use-land cover are due to rapid urbanization and industrialization. The drastic changes in land use-land cover would have a significant impact on water discharge and sediment discharge. Significant reduction in water discharge and sediment discharge is observed across the basin due to increased planned agricultural area and consistent increase in water storage structures in the catchment area. Due to increased built-up areas, overland flows are also increased and most parts of the basin are subjected to floods in the monsoon and post-monsoon seasons. The adverse impact of anthropology, mainly land use-land cover changes, on river morphological characteristics can be reduced by implementing certain regulatory measures such as preventing mining activities, afforestation, prevention of extraction of natural sand form river beds, promoting green culture and implementing sediment management policies in the basin area.

DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Allan, D., Erickson, D. & Fay, J. 1997 The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology* **37** (1), 149–161.

Anderson, J. R., Hardy, E. E., Roach, J. R. & Witmer, R. E. 1976 A land use and land cover classification system for use with remote sensor data. United States Geological Survey. Available at: https://pubs.usgs.gov/pp/0964/report.pdf (accessed 13 January 2022)

Apitz, S. E. 2012 Conceptualizing the role of sustaining ecosystem services: sediment-ecosystem regional assessment (SecoRA). *Science of the Total Environment* **415**, 9–30.

Bakker, M. M., Govers, G., van Doorn, A., Quetier, F., Chouvardas, D. & Rounsevell, M. 2008 The response of soil erosion and sediment export to land-use change in four areas of Europe: the importance of landscape pattern. *Geomorphology* **98** (3–4), 213–226.

Biggs, T., Gaur, A., Scott, C., Thenkabail, P., Gangadhara Rao, P., G huma, M. K., Acharya, S. & Turrall, H. 2007 *Closing of the Krishna Basin: Irrigation, Streamflow Depletion and Macroscale Hydrology*. IWMI Research Report 111. International Water Management Institute, Sri Lanka.

Bouwer, L. M., Aerts, J. C. J. H., Droogers, P. & Dolman, A. J. 2006 Detecting long-term impacts from climate variability and increasing water consumption on runoff in the Krishna river basin (India). *Hydrology and Earth System Sciences* **10**, 703–715.

Burn, D. H. & Elnur, M. A. H. 2002 Detection of hydrologic trends and variability. *Journal of Hydrology* **255** (1), 107–122. https://doi.org/10.1016/S0022-1694(01)00514-5.

Carriquiry, J. D. & Sanchez, A. 1999 Sedimentation in the Colorado river delta and upper Gulf of California after nearly a century of discharge loss. *Marine Geology* **158** (1–4), 125–145.

CWC 2007 *Integrated Hydrological Data Book (Non Classified River Basins)*. Hydrological Data Directorate, Central Water Commission, New Delhi, India.

Fischer, S., Pietron, J., Bring, A., Throslund, J. & Jarsjo, J. 2017 Present to future sediment transport of the Brahmmaputra river: reducing uncertainty in predictions and management. *Regional Environment Change* **17** (2), 515–526. DOI 10.1007/s10113-016-1059-7.

Fleskens, L. & Stringer, L. C. 2014 Land management and policy responses to mitigate desertification and land degradation. *Land Degradation and Development* **25** (1), 1–4.

Frihy, O. E., Debes, E. A. & El Sayed, W. R. 2003 Processes reshaping the Nile delta promontories of Egypt: pre- and post-protection. *Geomorphology* **53** (3–4), 263–279.

Gamage, N. & Smakhtin, V. 2009 Do river deltas in east India retreat? A case of the Krishna Delta. *Geomorphology* **105** (4), 533–540.

Gupta, H. & Chakrapani, G. J. 2005 Temporal and spatial variations in water flow and sediment load in Narmada River Basin, India: natural and man-made factors. *Environmental Geology* **48** (4), 579–589.

Hamed, K. H. 2008 Trend detection in hydrologic data: the Mann-Kendall trend test under the scaling hypotheses. *Journal of Hydrology* **349** (3–4), 350–365.
Hirsch, R. M., Slack, J. R. & Smith, R. A. 1982 Techniques of trend analysis for monthly water quality data. *Water Resources Research* **20** (6), 727–732.

Jordan, G., Van Rompaya, A., Szilassi, P., Csillag, G., Mannaerts, C. & Woldai, T. 2005 Historical land use changes and their impact on sediment fluxes in the Balaton basin (Hungary). *Agricultural Ecosystems and Environment* **108** (2), 119–133.

Kendall, M. G. 1975 *Rank Correlation Methods*. Charles Griffin, London, UK.

Kuhnle, R. A., Bingner, R. L., Foster, G. R. & Grissinger, E. H. 1996 Effect of land use changes on sediment transport in Goodwin Creek. *Water Resources Research* **32** (10), 3189–3196.

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica* **13** (3), 245–259.

Milliman, J. D. & Meade, R. H. 1983 World-wide delivery of river sediment to the oceans. *Journal of Geology* **91** (1), 1–21.

Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. 2005 Global pattern of trends in stream flow and water availability in a changing climate. *Nature* **438** (7066), 347–350.

Panda, D. K., Kumar, A. & Mohanty, S. 2010 Recent trends in sediment load of the tropical (Peninsular) river basins of India. *Global and Planetary Change* **75** (3), 108–118. doi: 10.1016/j.gloplach.2009.07.002.

Parsons, A. J., Wainwright, J., Brazier, R. E. & Powell, D. M. 2006 Is sediment delivery a fallacy? *Earth Surface Process and Landforms* **31** (10), 1325–1328.

Peng, J., Chen, S. L. & Dong, P. 2010 Temporal variation of sediment load in the Yellow River basin, China, and its impacts on the lower reaches and the river delta. *Catena* **83** (2–3), 135–147.

Shi, Z. H., Ai, L., Li, X., Huang, X. D., Wu, G. L. & Liao, W. 2015 Partial least-squares regression for linking land-cover patterns to soil erosion and sediment yield in watersheds. *Journal of Hydrology* **498**, 165–176.

Sinha, R. K. & Eldho, T. I. 2018 Effects of historical and projected land use/cover change on runoff and sediment yield in the Nethravati river basin, Western Ghats, India. *Environmental Earth Sciences* **77** (3), 11.

Smith, S. V., Renwic, W. H., Buddemeier, R. W. & Crossland, C. J. 2001 Budget of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. *Global Biogeochemical Cycles* **15** (3), 696–707.

Steffen, W. 2004 *A Planet Under Pressure, Global Change and the Earth System*. Springer, New York, USA.

Svysitsky, I., Kettner, A. & Overeem, I. 2009 Sinking deltas due to human activities. *Nature Geosci.* **2**, 681–686. https://doi.org/10.1038/ngeo629.

Tripathi, A., Kumar, N. & Chauhan, D. K. 2017 Understanding integrated impacts of climate change and pollution on Ganges River system: a mini review on biological effects, knowledge gaps and research needs. *SMJ Biology* **3** (1), 1017.

Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J. P., Chaplot, V., de Guzman, T., de Rouw, A., Janeau, J. L., Orange, D., Phachomphonh, K., DuyPhai, D., Podwojewski, P., Ribolzi, O., Silvera, N., Subagyon, K., Thiébaux, J. P., Duc Toan, T. & Vadari, T. 2008 Runoff and sediment losses from 27 upland catchments in Southeast Asia: impact of rapid land use changes and conservation practices. *Agricultural Ecosystems Environment* **128** (4), 225–238.

Vorosmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2000 Global water resources: vulnerability from climate change and population growth. *Science* **289**(5477), 284–288.

Walling, D. E. 2006 Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology* **79** (5–4), 192–216.

Walling, D. E. & Fang, D. 2003 Recent trends in the suspended sediment loads of the world's rivers. *Glob. Planet. Chang.* **39** (1–2), 111–126.

Wang, Z. Y., Li, Y. T. & He, Y. P. 2007 Sediment budget of the Yangtze River. *Water Resources Research* **43**, W04401. doi: 10.1029/2006WR005012.

Yang, Z., Wang, H., Ye, B., Liu, F., Wang, J. & Wang, J. 2012 Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. *Earth Surfaces Processes* **36** (6), 1398–1412.

Weinbauer, M. G., Bettarel, Y., Cattaneo, R., Luef, B., Maier, C., Motegi, C., Peduzzi, P. & Mari, X. 2009 Viral ecology of organic and inorganic particles in aquatic systems: avenues for further research. *Aquatic Microbial Ecology* **57**(3), 321.

Xu, Z. X., Li, J. Y. & Liu, C. M. 2007 Long-term trend analysis for major climate variables in the Yellow River basin. *Hydrological Processes* **21**(14), 1935–1948.

Yang, Z., Wang, H., Saito, Y., Milliman, J. D., Xu, K., Qiao, S. & Shi, G. 2006 Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: the past 55 years and after the Three Gorges Dam. *Water Resources Research* **42**(4), W04407.

Yue, S. & Hashino, M. 2003 Temperature trends in Japan: 1900–1996. *Theoretical Applied Climatology* **75** (1–2), 15–27.

Yue, S., Pilon, P., Pinney, B. & Cavadias, G. 2002 The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes* **16**(9), 1807–1829.

Zhang, B. Q., Wu, P. T., Zhao, X. N., Wang, Y. B., Gao, X. D. & Cao, X. C. 2013 A drought hazard assessment index based on the VICPDSI model and its application on the Loess Plateau, China. *Theoretical and Applied Climatology* **114**(1–2), 125–138.

Zhang, H., Zhang, L., Zhu, R. & Liu, C. 2009 Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resources Research* **45**, 1–9.

Zhang, H. Y., Shi, Z. H., Fang, N. F. & Guo, M. H. 2015 Linking watershed geomorphic characteristics to sediment yield: evidence from the Loess Plateau of China. *Geomorphology* **234**, 19–27.

First received 11 May 2021; accepted in revised form 3 November 2021. Available online 20 December 2021.