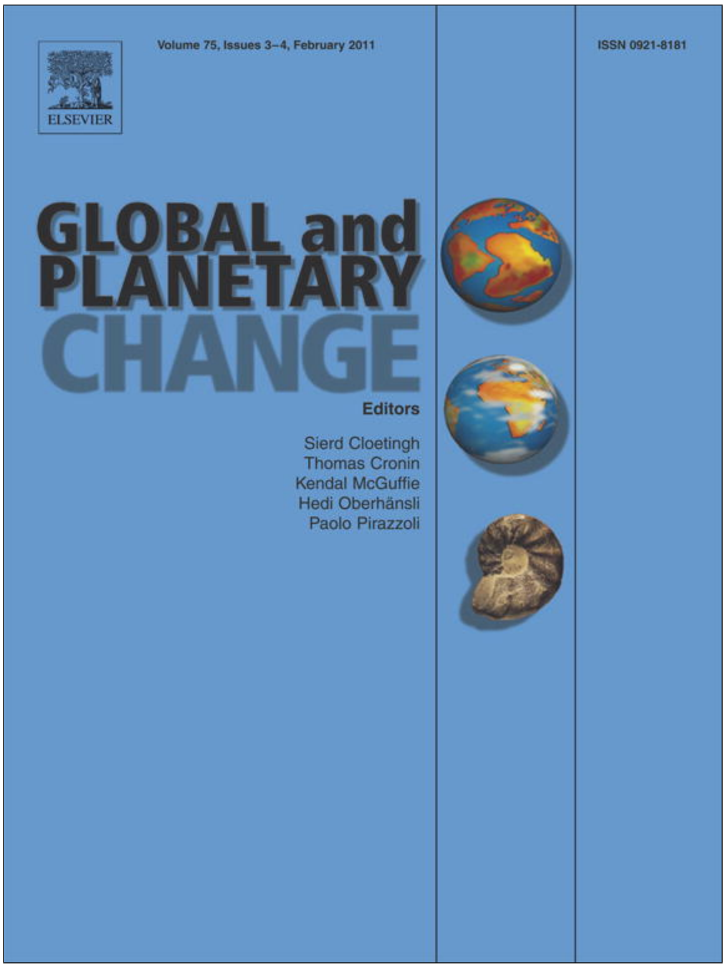
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Recent trends in sediment load of the tropical (Peninsular) river basins of India

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ABSTRACT

The tropical river basins of India are important because of the coastal ecosystem that they sustain and the densely populated economic zones that they serve. This study examines the recent trends in sediment load and also explores the influence of the climatic and human forcing mechanisms on the land–ocean fluvial systems. A large dataset comprised of the sediment time series of different timescale during the period 1986–87 to 2005–06 from 133 gauging stations spreading across tropical river basins of India was analyzed. Results indicate dramatic reductions in sediment load in the tropical river basins, which is beyond the fold of assignable natural variability. Around 88% (62%) of the total 133 gauging stations showed decline in sediment loads in the monsoon (non-monsoon) season. The significant downward trends outnumbered the corresponding upward trends in high proportions for both the seasons. Striking spatial coherence was observed among the significant trends, suggesting the presence of the cross-correlation among the sediment records. The regional trends, which account the spatial correlation, also indicated the widespread nature of the sediment declines. The rainfall, which is characterized by the non-significant decreasing trends and also frequent drought years, is the primary controller of the sediment loads for most of the river basins. It may be inferred that a little change in rainfall towards the deficit side leads to a significant reduction in sediment load. This is due to the diversion and storage of runoff to meet the manifold increases in water requirements for the agriculture and industry. Among the tropical rivers, the maximum reduction in sediment flux has taken place for the Normada River (-2.07×10^6 t/yr) due to the construction of dam. Although the sea level is rising, we speculate that the significant reduction in sediment loads may also have influenced the coastal erosion in recent years. The results of this study can be utilized for the sustainable management of the tropical river basins in the backdrop of a predicted erratic monsoon rainfall and the growing anthropogenic stresses.

1. Introduction

There is a growing body of evidence pertaining to the significant reduction in sediment supply to the global ocean. This is primarily due to the anthropogenic entrapments in dams and reservoirs, which has resulted in noticeable changes in the hydrological, geomorphological, ecological functioning of the river basins (Walling and Fang, 2003; Chakrapani, 2005; Syvitski et al., 2005). Reduction of sediment flux with consequent increases in coastal erosion appears to have serious implications as the coastal zones are economically vital and also densely populated. The rivers draining the Asian continent, which supply a substantial proportion of the global sediment flux and play an import role in the land–ocean linkages (Hu et al., 2001), have drawn considerable scientific attention in recent years due to the evident decreases in sediment flux. Major rivers of China such as the Yellow (Wang et al., 2007), the Yangtze (Zhang et al., 2009), the Pearl (Zhang et al., 2008), and the Mekong (Lu and Siew, 2006) exhibited substantial reduction in sediment supply. Winterwerp et al. (2005) noted serious coastal erosion in the Chao Phraya delta of Thailand, and they attributed this to the dam construction.

The Indian rivers, divided into two broad systems based on the morpho-tectonic difference, show sharp distinction in sediment supply; the Gangetic river system carries annual average sediment of 2390 t (tons)/km^2 from the highly erodible Himalayan range while the tropical (Peninsular) river system carries 216 t/km^2 (Milliman and Meade, 1983). The summer monsoon rainfall during June–September, which is nearly 80% of the annual rainfall, predominantly influences the streamflow, sediment transport and channel morphology of the tropical Indian rivers (Kale, 2002). In contrast, the Gangetic river system experiences a perennial flow regime due to the melting of the glaciers of the Himalayan Mountains during the non-monsoon period. This seasonality of flow in the tropical rivers has led to the construction of multi-purpose dams and reservoirs (Agrawal and Chak, 1991) in order to safeguard the flood prone deltaic region and also to supply water during the drought and non-monsoon period. Although damming the rivers has brought ample societal benefits of the burgeoning population in terms of addressing the water and

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energy crisis, the ecological consequences have received little scientific attention.

A recent study undertaken by the National Institute of Oceanography showed that 23% of the 5423 km mainland coastline of India experienced the coastal erosion. Using remote sensing imageries, Malini and Rao (2004) observed that the landward regression of the Godavari River basin led to evacuation of coastal establishments and loss of mangrove forest. They attributed this coastal erosion to the drastic reduction in sediment supply due the upstream reservoir construction. Further, Bobba (2002) reported the cases of seawater intrusion into the coastal aquifer of the basin. The Krishne River basin, the largest regulated river basin in term of dams and reservoirs in India, experienced coastal erosion due to the drastic reduction in streamflow and sediment flux (Bouwer et al., 2006; Biggs et al., 2007; Gamage and Smakhtin, 2009). Similarly, the upstream damming in the Normada River basin has resulted in significant reduction in sediment flux to the Arabian Sea (Gupta and Chakrapani, 2005). Syvitski et al. (2009) noted that the Mahanadi–Brahmani and Godavari basins were at greater risk to coastal erosion while the Krishna basin was in peril with high accelerated compaction among the major deltas of the world.

The global environmental change programs facilitated by the International Geosphere Biosphere Program (IGBP) Water Group, recommends that studies should delineate the increasing and decreasing sediment load due to human and/or climate change along the fluvial systems (Syvitski, 2003). Most of the studies on the sediment transport have used the time series data of the terminal gauging station or few stations at the mouth of river basin as they reflect the net flux to the global ocean. Nevertheless, there is a need to study the changes in sediment load across the river basin in order to understand the conflicting anthropogenic impacts in term of increases in soil erosion due to the deforestation and agriculture against the entrapments in dams (Syvitski, 2003). A major obstacle to assess the impacts of climate and anthropogenic activity on the global sediment system is the lack of reliable sediment monitoring time series (Dearing and Jones, 2003). In India, the sediment monitoring program with adequate spatial representation of the river basins commenced in the mid-1980s. However, some of the tropical rivers have relatively long time series for a few stations at the mouth of the river, and have also been used for the trend analysis (e.g. Malini and Rao, 2004; Gamage and Smakhtin, 2009).

Consistent with the IGBP Water Group recommendation and a noteworthy background scenario, this study aims (1) to identify and quantify the sediment load trends in the tropical river basins of India; (2) to explore the influence of the rainfall variability and human activity on the fluvial system. The sediment time series of different timescale during the period 1986–87 to 2005–06 from 133 gauging stations spreading across tropical river basins of India were used. The tropical rivers are important because of the economically viable region that they drain and the density of population that they serve. Although the Himalayan river system carries massive sediments, the rivers flow into the Indian Ocean at few points only. The tropical rivers, however, spread all along the coastline, and thus serve several wetland ecosystems. To address the paucity of long time series data, we used the non-parametric statistical methods for a more definitive assessment of the current trends in the land–ocean sediment transfer. To our knowledge, no previous studies have analyzed such a large dataset to depict the patterns of the sediment-load response across the river basins. In general, this study will provide critical inputs for the sound and sustainable management of the coastal zones in the context of the recent increases in the climatic extremes and the human interface. Additionally, the most ambitious mega project of India (i.e. the National River Linking Project (NRLP)) (Misra et al., 2007) can utilize the results of this study to earmark the environmental flow requirements while addressing the emerging water scarcity by transferring the water from the water-surplus basins.

2. An overview of the tropical river basins

The tropical river basins of India (Fig. 1) drain 43% of the total geographical area of 3.23×10^6 km^2, and they cover 46% of the total population of over one billion. Total average annual flow of the tropical rivers is 1869 km^3. Table 1 displays the diverse river basin characteristics of the tropical rivers reflecting the different geology, topography, rainfall, and demography. The Godavari River, the third largest river in term of drainage area after the Ganga and Brahmaputra Rivers of India, flows into the Bay of Bengal along with other major tropical rivers such as the Krishna, Mahanadi, Cauvery, Brahmani, and other east flowing rivers. The Normada is the largest tropical river that flows into the Arabian Sea followed by the Tapi, Mahi, and other west flowing rivers. In general, the sediment load of the tropical rivers draining the central Indian region (Godavari, Normada, Mahanadi, Brahmani, Tapi, Mahi) is much higher than that of the rivers draining the south Indian region (Krishna, Cauvery, Pennar of east flowing rivers).

The magnitude of the sediment flux from the tropical river basins is primary controlled by the rock formation of the basin and channel gradient. The hot tropical climate dominates the Godavari River basin. The western half of the basin is covered by the Deccan Trap, and contributes 50% of the annual sediment load. However, the hard rocks (39%) and sedimentary rock (13%) of the Godavari basin contribute 16% and 33% of the annual sediment load, respectively. The Krishna River basin having the predominant crystalline and basaltic rocks experiences a semi-arid climate. Although the Normada River is the fourth largest among the tropical rivers in term of the drainage area and annual streamflow, it is the second largest river in term of the sediment loads. The climate of the Normada River basin is humid tropical, and most parts of the basin have an elevation of ~500 m above the mean sea level. Further, the Deccan Trap is the major geological formation followed by the sedimentary rocks. The Mahanadi and Brahmani River basins, mostly covered by the Precambian rocks, experience a tropical monsoon climate with the substantial influence of the synoptic disturbances over the Bay of Bangal. Although the annual flow of the west flowing rivers is very high, the sediment load is much less in comparison to that of other river basins.

3. Data and methods

3.1. Data source

The Central Water Commission (CWC), an organization of the Ministry of Water Resources, Government of India, carries out the stream flow, sediment, and surface water quality monitoring activities. The datasets of the sediment loads employed in this study were obtained from the published reports of the CWC (CWC, 2006, 2007). Suspended sediment samples are collected from various marks along the cross-section of the river at the gauging stations using boats or specially designed instruments. The frequency of the sediment observation is daily in the monsoon season (June–September) and once in a week in the non-monsoon season (October–May), because the monsoon season supplies a large proportion of the annual sediment load. The data for the non-observed days is estimated based on the relationship between the observed sediment concentration and weighted mean discharge for the individual years. The analysis of suspended sediment samples provides information on the concentration of three separate size fractions, namely, coarse (>0.2 mm), medium (0.075–0.2 mm) and fine (<0.075 mm), respectively. The sediment concentration (gm/liter) for each group is recorded by passing the water sample through different mesh sieves of the British Standard Size. The discharge-weighted sediment load (t/day) for the river cross-section is obtained by multiplying the concentration by the discharge (m^3/second) on a particular day. These sediment loads are reported in the

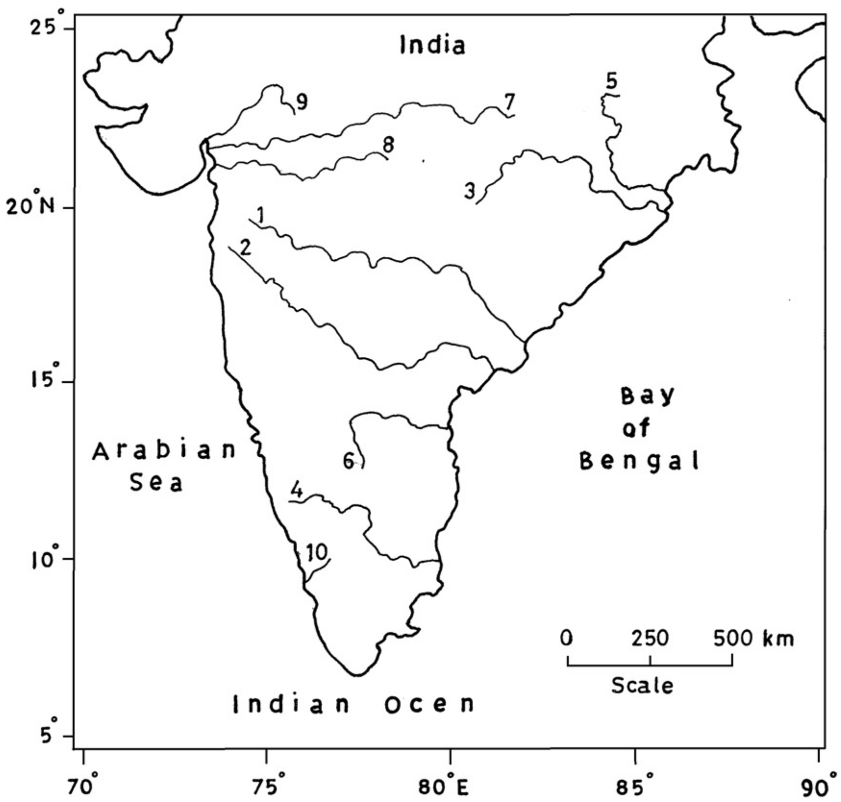

Fig. 1. Location of the tropical (Peninsular) rivers of India. The rivers (1) Godavari, (2) Krishna, (3) Mahanadi, (4) Cauvery, (5) Brahmani, and (6) Pennar (east flowing) drain to the Bay of Bengal whereas the (7) Normada, (8) Tapi, (9) Mahi, and (10) west flowing rivers flow into the Arabian Sea.

10-daily tables from each gauging station, which are subsequently added to find the monthly and seasonal sediment loads.

The complete datasets are not available to the public domain because of the existing water sharing conflicts among the river basin states. However, the CWC publishes the seasonal stream flow and sediment data in the 'Integrated Hydrological Data Book' after scrutinizing the uncertainty and heterogeneity of the data records. For the research purpose, the complete records can be obtained by following some official norms and regulations. The hydrological year starts at the beginning of June in a given year and extends up to the end of May in the subsequent year. The sediment records with a minimum 10 years of continuous time series were considered for this analysis as the non-parametric statistical tests can handle such short time series. Finally, we could assemble the monsoon and non-monsoon sediment loads of 133 gauging station available at different timescales from 1986–87 to 2005–06 for different river basins. This is the most recent dataset, which adequately represents the tropical river basins of India. The study periods and the number of monitoring sites of the river basins are presented in Table 1. To understand the relationship between the rainfall and the sediment flux, the basin-

Table 1
General information of the tropical river basins of India.

River basin	Latitude and longitude	Drainage area (10^5 km^2)	Length (km)	Annual flow (km^3)	Sediment load (10^6 t)	Annual rainfall (mm)	Population density per km^2	Storage capacity (km^3)	Study period	Gauging stations
Godavari	73° 26′ –83° 07′E to 16° 16′–22° 43′N	3.13	1465	110.5	170	1085	217	31.33	1986–87 to 2005–06	25
Krishna	73° 21′ –81° 09′E to 13° 07′–19° 25′N	2.59	1400	69.8	9.0	800	295	49.55	1986–87 to 2004–05	22
Mahanadi	80° 30′ –86° 50′E to 19° 20′–23° 35′N	1.42	851	66.9	30.7	1360	202	14.21	1993–94 to 2002–03	14
Brahmani	83° 52′ –87° 03′E to 20° 28′–23° 35′N	0.39	799	28.5	20.4	1200	204	5.25	1993–94 to 2002–03	8
Cauvery	78° 09′ –79° 27′E to 10° 00′–11° 18′N	0.87	800	21.4	1.5	800	389	8.87	1986–87 to 2002–03	11
East flowing (11 rivers)	77° 29′ –79° 59′E to 8° 12′–15° 56′N	0.82	–	22.76	–	800	722	3.03	1990–91 to 2003–04	5
Normada	72° 32′ –81° 45′E to 21° 20′–23° 45′N	0.99	1312	45.64	69.7	1180	187	23.6	1986–87 to 2002–03	14
Tapi	72° 38′ –78° 17′E to 20° 05′–22° 03′N	0.65	724	14.9	24.7	1000	245	10.26	1986–87 to 2001–02	8
Mahi	73° 13′ –74° 23′E to 23° 44′–24° 26′N	0.35	583	11.0	9.7	1000	324	4.98	1988–89 to 2001–02	9
West flowing (22 rivers)	73° 15′ –76° 51′E to 8° 43′–19° 10′N	0.30	–	200	–	2400	846	31	1990–91 to 2003–04	17

averaged annual rainfall datasets synthesized by the Indian Institute of Tropical Meteorology were used (Ranade et al., 2007).

3.2. Non-parametric tests

3.2.1. Site-specific trend assessment

The non-parametric Mann–Kendall (MK) statistical test (Mann, 1945; Kendall, 1975), a rank-based method, has been widely used in research studies to assess the monotone trend of hydro-climatic time series. The test is insensitive to the outliers and missing values, and also performs well over the competing class of parametric tests when the data are not normally distributed (Yue et al., 2002). The MK test statistics S is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

where x is the data points at times i and j of a time series of length n. The sgn() is equal to $+1$ if x_j is greater than x_i, -1 if x_j is less than x_i, and 0 if x_j is equal to x_i. For the independent and identically distributed random variables with $n \geq 10$, the test statistics S is approximately normally distributed with the mean and variance given by

$$E(S) = 0, \tag{2}$$

and

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{3}$$

where t_i denotes the number of ties of extent i. The standardized test statistics Z is calculated as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{for} \quad S > 0 \\ 0 & \text{for} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{for} \quad S < 0 \end{cases} \tag{4}$$

Under the null hypothesis of no trend, the Z statistics follow a standard normal distribution. A positive value of Z indicates an upward trend, and a negative value of Z indicates a downward trend. The local significance levels (probability value p) of the Z statistics for each trend can be obtained by

$$p = 2[1 - \Phi(|Z|)] \tag{5}$$

where $\Phi()$ denotes the cumulative distribution function of a standard normal variate. For a very small p value, the trend denotes the systematic component of the data series and has not been caused by the random sampling. The existing trend is assessed to be statistically significant at the significance levels of 5% and 10%, if $p \leq 0.05$ and 0.1, respectively. To quantify the trend, the Kendall slope (β) was estimated by calculating the median of $(x_j - x_i)(j-i)^{-1}$ for all $i<j$.

Although the MK test is robust to the distribution and idiosyncrasies of data, the presence of serial correlation in the time series influences the trend results (Zhang et al., 2001). The positive serial correlation inflates the variance of the MK test statistics, leading to the increased probability of rejecting the null hypothesis of no trend (Von Storch, 1995). The presence of a negative autocorrelation, however, increases the probability of accepting the null hypothesis by reducing the variance of the MK test statistics. Incorporating the modified variance that minimizes the influence of serial correlation (Lettenmaier, 1976; Yue and Wang, 2002), the new MK test statistics can be defined as

$$Z^* = Z\left(\sqrt{\eta^s}\right)^{-1} \tag{6}$$

where $\eta^s = 1 + 2\frac{\rho_1^{n+1} - n\rho_1^2 + (n-1)\rho_1}{n(\rho_1 - 1)^2}$ for the lag-1 autocorrelation (ρ_1).

3.2.2. Regional trend assessment

We adopted the analytical method of assessing the trends at a regional scale proposed by Douglas et al. (2000), which finds the regional average of the MK test statistics as

$$\bar{S}_m = \sum_{k=1}^{m} S_k \tag{7}$$

where S_k is the MK test statistics for the at site k in a region with m sites. Without considering the spatial correlation (i.e. the cross correlation among the variables) of the region, the mean and variance of $\bar{S}_m$ are

$$E\left(\bar{S}_m\right) = 0 \tag{8}$$

$$\operatorname{Var}\left(\bar{S}_m\right) = m^{-1}\operatorname{Var}(S) \tag{9}$$

Subsequently, the standardized test statistics $\bar{Z}_m$ and the significance level p can be calculated using Eqs. (4) and (5). However, if the responses are cross-correlated, as is the case for most of the hydrologic variables, the variance of $\bar{S}_m$in Eq. (9) becomes

$$\begin{aligned} \operatorname{Var}\left(\bar{S}_{mc}\right) &= \frac{1}{m^2}\left[\sum_{k=1}^{m} \operatorname{Var}(S_k) + 2\sum_{k=1}^{m-1}\sum_{l=1}^{m-k} \operatorname{Cov}(S_k, S_{k+l})\right] \\ &= \operatorname{Var}\left(\bar{S}_m\right)\left[1 + (m-1)\bar{\rho}_{k,k+l}\right] \end{aligned} \tag{10}$$

where $\bar{\rho}_{k,k+l} = \frac{2\sum_{k=1}^{m-1}\sum_{l=1}^{m-k}\rho_{k,k+l}}{m(m-1)}$is the average cross-correlation for the region (Salas-La Cruz, 1972; Douglas et al., 2000). The standardized test statistics $\bar{Z}_{mc}$can easily be derived as

$$\bar{Z}_{mc} = \bar{Z}_m\left(\sqrt{1 + (m-1)\bar{\rho}_{k,k+l}}\right)^{-1} \tag{11}$$

4. Results

We computed the location parameters of the sediment load at the last control stations of the basins in order to understand the seasonal and spatial differences. The last control stations at the mouth of the river (outlet) reflect the integrated response of the entire basin. Table 2 indicates that the monsoon season has contributed more than 90% of the annual sediment load. The presence of both the positive and negative Yule–Kendall skewness, which is a resistance measure of the shape of the distribution using the 25th percentile (Q_1), 50th percentile (Q_2), and 75th percentile (Q_3) as $(Q_1 - 2Q_2 + Q_3)/(Q_3 - Q_1)$ (Ferro et al., 2005), suggests the influence of the unusually high and low sediment loads, respectively. Fig. 2 shows that the variability in sediment load is consistent with the rainfall variability as evident from the direct correspondence between the annual sediment flux and the basin-averaged rainfall on an annual scale. Further, the LOWESS (i.e. locally weighted scatter-plot smooth) plots, a robust non-parametric procedure for estimating the regression surfaces (Cleveland and Devlin, 1988), indicate a clear decreasing pattern in both sediment flux and rainfall for most of the tropical river basins (Fig. 2).

Table 2
Summary statistics of the sediment flux (10^6 t) at the river basin outlets in the monsoon and non-monsoon seasons.

Basin	Period	Season	Mean	Standard deviation	Minimum	Q_1	Median	Q_3	Maximum	Yule–Kendall skewness
Godavari at Polavaram	1986–87 to 2005–06	Monsoon	57.72	38.36	19.40	28.42	46.71	72.26	158.58	0.17
		Non-monsoon	0.22	0.22	0.01	0.10	0.14	0.22	0.94	0.30
Krishna at Vijaywada	1986–87 to 2004–05	Monsoon	1.64	2.31	0.00	0.17	0.67	2.31	9.71	0.53
		Non-monsoon	0.10	0.16	0.00	0.01	0.04	0.13	0.65	0.65
Mahanadi at Tikarpara	1993–94 to 2002–03	Monsoon	11.78	15.79	1.99	3.03	6.98	10.53	55.05	−0.05
		Non-monsoon	0.67	0.38	0.07	0.38	0.73	0.95	1.24	−0.21
Brahmani at Jenapur	1993–94 to 2002–03	Monsoon	6.32	4.55	1.68	3.07	5.77	6.95	15.70	−0.39
		Non-monsoon	0.27	0.17	0.01	0.13	0.26	0.37	0.56	−0.07
Cauvery at Mausiri	1986–87 to 2002–03	Monsoon	0.25	0.25	0.03	0.13	0.16	0.38	0.88	0.73
		Non-monsoon	0.10	0.07	0.03	0.04	0.07	0.13	0.26	0.38
Pennar at Chennur	1990–91 to 2003–04	Monsoon	1.78	1.73	0.22	0.32	0.94	3.02	4.94	0.54
		Non-monsoon	0.05	0.10	0.00	0.01	0.03	0.04	0.40	−0.62
Normada at Garudeshwar	1986–87 to 2002–03	Monsoon	19.04	16.18	1.67	4.71	15.15	29.09	51.51	0.14
		Non-monsoon	0.06	0.07	0.00	0.02	0.03	0.06	0.20	0.60
Tapi at Sarankheda	1986–87 to 2001–02	Monsoon	19.38	14.85	4.69	7.65	18.23	22.75	54.79	−0.40
		Non-monsoon	0.08	0.21	0.00	0.00	0.00	0.03	0.83	0.83
Mahi at Khanpur	1988–89 to 2001–02	Monsoon	2.08	1.84	0.01	0.09	1.87	3.07	6.00	−0.20
		Non-monsoon	0.04	0.09	0.00	0.00	0.00	0.00	0.27	0.00
Nethravathi at Bantwal	1990–91 to 2003–04	Monsoon	1.19	0.72	0.32	0.65	1.16	1.52	2.77	−0.17
		Non-monsoon	0.01	0.02	0.00	0.01	0.01	0.02	0.06	0.45

Q_1: 25th percentile; Median (Q_2): 50th percentile; Q_3: 75th percentile.

The MK trend results summarized in Fig. 3 indicate that the decreases in sediment load predominate over the corresponding increases in high proportions for both the monsoon and non-monsoon seasons. Around 88% (62%) of the total 133 gauging stations across river basins showed declines in sediment load in the monsoon (non-monsoon) season. Around 27% and 42% of the total stations experienced significant decreases at the 0.05 and 0.1 levels, respectively in the monsoon season in comparison to that of 11% and 17% in the non-monsoon season. However, the significant increasing trends are infrequent or non-existent in the monsoon season (Fig. 3). It is interesting to note the presence of some upward trends in the non-monsoon season, although it contributes only a small fraction of annual sediment load. Fig. 4 presents the location maps of the significant trends ($p \leq 0.1$) in the monsoon and non-monsoon seasons. In general, an abundant decrease in sediment load was observed in the tropical river basins. The spatial distribution of the significant trends reveals noticeable patterns, suggesting the presence of cross-correlation among the sediment records. In the monsoon season, the significant downtrends have occurred across the tropical river basins with some concentration in the southern parts (Fig. 4a). In the non-monsoon season, however, the increasing trends are concentrated in the northwestern parts (i.e. Normada–Tapi–Mahi basin) (Fig. 4b). The decreasing trends tend to occur more towards the eastern parts (i.e. rivers flowing to the Bay of Bengal) of the study area.

Table 3 provides evidence that a major proportion of the total gauging stations showed significant decreasing trends for some of the major fluvial transporting river basins. In the Godavari basin, 16% and 36% of the total of 25 gauging stations experienced significant reduction at the 0.05 and 0.1 levels, respectively in the monsoon season. It is interesting to note that all the 22 gauging stations of the Mahanadi–Brahmani River basins showed decreases in sediment load in the monsoon and non-monsoon season. However, the significant reductions have occurred in 13% and 36% of the stations in the monsoon season at the 0.05 and 0.1 levels, respectively. The abundance of the decreases in sediment load is evident in the Krishna River basin as 59% and 73% of the 22 gauging stations exhibited significant reduction in the monsoon season at the 0.05 and 0.1 levels, respectively. In the Cauvery and east-flowing river basin, the decreases in sediment load were observed in 80% of the 16 gauging stations, although a few of them were statistically significant. Among the river basins flowing to the Arabian Sea, around 21% of the 14 gauging stations of the Normada River basin showed significant decreases in sediment load in the monsoon season at the 0.05 level. Further, the declining trend was observed in 87% of the 17 stations of the Tapi–Mahi River basin in the monsoon season. However, it is interesting to note the occurrence of increasing trends in more than 60% of the stations of these basins in the non-monsoon season. For the west-flowing rivers, around 94% of the 17 gauging stations were having decreasing trends in the monsoon season. However, the significant reduction in sediment load was observed in 29% and 52% of the stations at the 0.05 and 0.1 levels, respectively.

The spatial distribution of the significant trends ($p \leq 0.1$) shows the definite patterns even for the individual river basins, indicating the dependency among the sediment loads (Fig. 4). For example, most of significant decreases in sediment load are observed in the western catchments of the Godavari basin, whereas they are concentrated in the northwest parts of the Mahanadi–Brahmani River basins. Table 4 also indicates the presence of cross and serial correlations in sediment time series. In order to examine the overall pattern in a basin, we assessed the regional trend, which takes into account the spatial correlation among the sediment records. In the monsoon season, the regional trend in sediment load of the Godavari, Krishna, Mahanadi–Brahmani, Cauvery, Mahi, east-flowing and west-flowing river basins exhibited significant ($p \leq 0.1$) declining pattern (Table 4). This suggests the widespread (basin-wide) nature of the decreasing trends. However, the monsoon season reductions of the Tapi basin are localized as evident from the non-significant regional trends. In the non-monsoon season, it is interesting to note the basin-wide increases in sediment load of the Normada and Tapi River basins in contrast to an overall decreasing pattern for most of the basins. Based on the degree of correspondence with the rainfall (Table 5), we discuss the impacting factors of the sediment trends in the following sub-sections.

5. Discussion

5.1. Impacts of rainfall (climate) variability

The observed changes in sediment load of the tropical rivers of India reflect the impacts of the recent climate variability and its interaction with the anthropogenic activities as the study period represents the post-dam construction scenario for most of the river basins. The rainfall is the primary controller of the sediment flux to the adjacent ocean in the Godavari, Mahanadi, Cauvery, Brahmani, Tapi, Mahi River basins as evident from the significant correlations at the

0.05 level (Table 5). Table 1 also indicates that the storage capacity in dams and reservoirs in these basins is less in comparison to their annual flow, suggesting the minimal anthropogenic diversions. Further, the east-flowing and the west-flowing rivers are not impacted by the dams and reservoirs as evident from the low storage capacity and high annual rainfall (i.e. for the west-flowing rivers), although the sediment flux is weakly correlated with the rainfall for the Nethravathi and Pennar Rivers. The highest reduction in sediment flux (-1.40×10^6 t/yr) to the Bay of Bengal was observed at the last control station Polavaram of the Godavari River basin (Table 5). Further, the Mahanadi River experienced a significant ($p\leq0.1$) decreasing trend of -0.95×10^6 t/yr at the last control station Tikerpara, whereas the Brahmani River experienced a non-significant decreasing trend of -0.42×10^6 t/yr at Jenapur. The sediment flux to the Arabian ocean from the Tapi River also showed a significant ($p\leq0.1$) decreasing trend of -0.57×10^6 t/yr followed by a non-significant trend of -0.12×10^6 t/yr from the Mahi River at their respective outlets. In general, the decreases in sediment flux can be attributed to the decreases in rainfall. However, none of the river basin experienced significant decreasing trend in rainfall (Table 5). The LOWESS plots (Fig. 2) also suggest the substantial reduction in sediment flux in correspondence to a modest decreasing pattern in rainfall for most of the river basins.

Although several rivers show the basin-wide declines in sediment load, the trend of the sediment fluxes to the adjacent ocean from the outlets of these basins are not statistically significant. This suggests that the sediment fluxes are either stable or no apparent trend is observed due to the interaction of the changes in opposite direction.

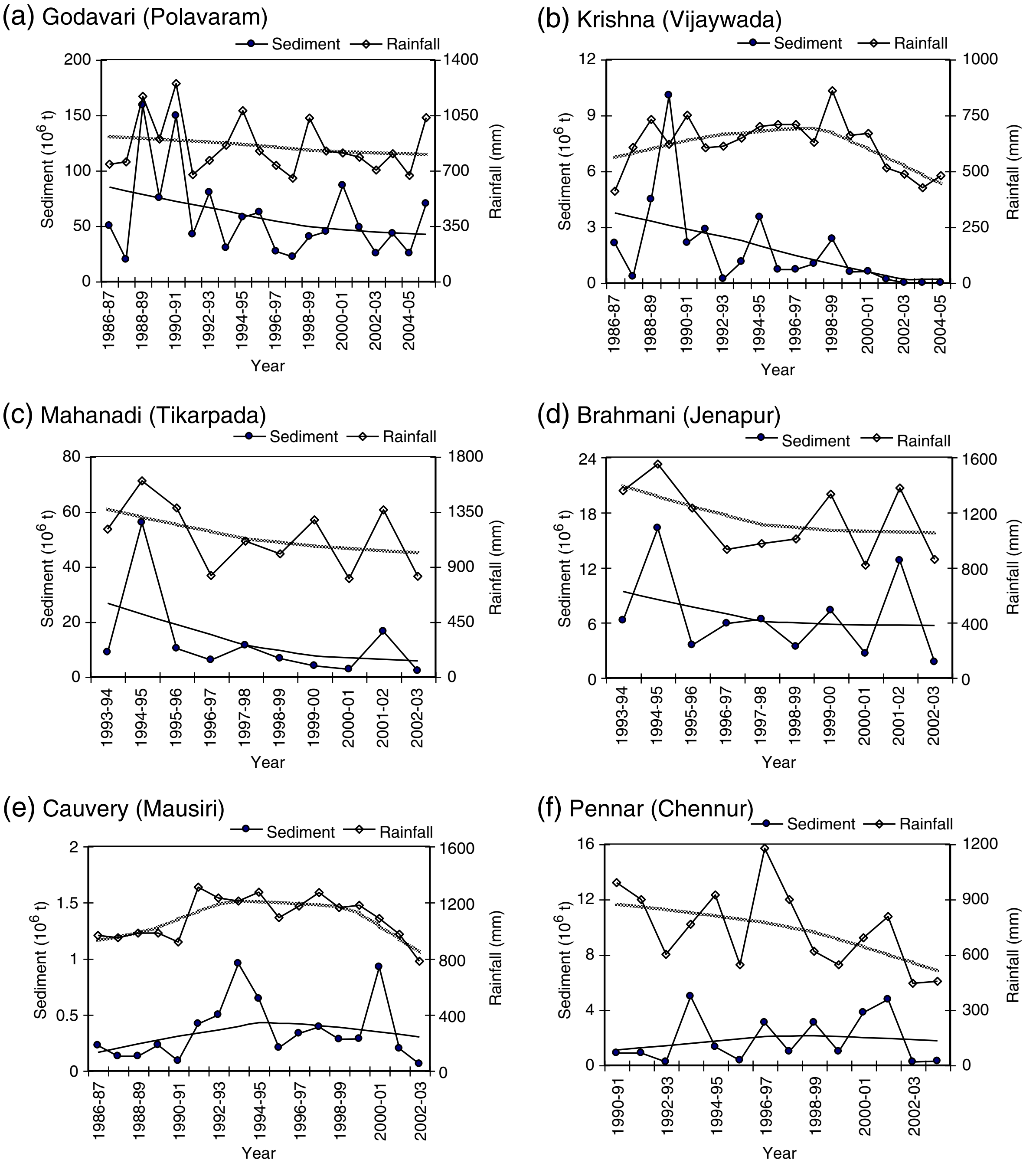

Fig. 2. Correspondence between the annual sediment flux (at the last gauging station) of the tropical rivers and the basin-averaged rainfall. The robust LOWESS plots (thick and thin lines) indicate a clear decreasing pattern in both sediment flux and rainfall for most of the river basins.

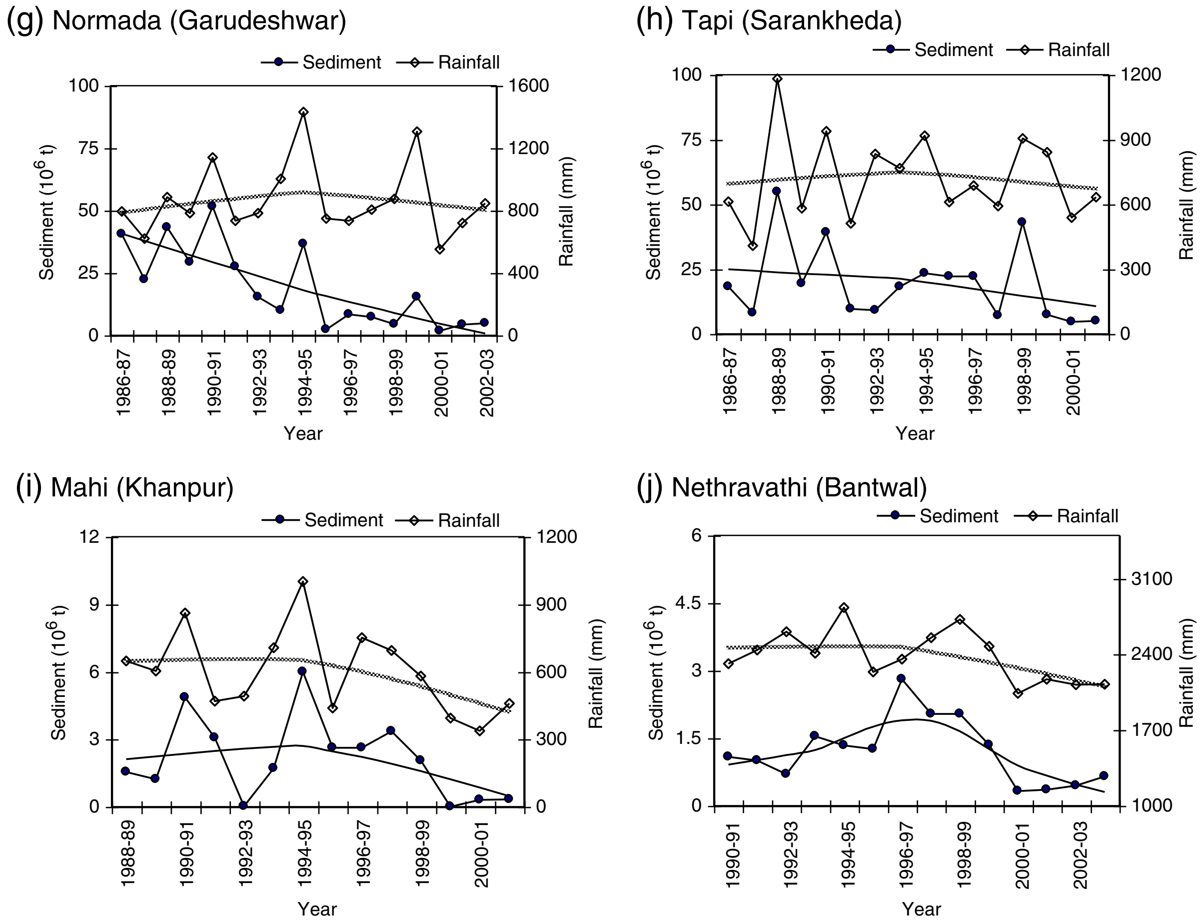

Fig. 2 (*continued*).

Fig. 2 provides evidence that the presence of high interannual variability in terms of the dry and wet years have obscured the underlying patterns in rainfall and sediment flux in most of the basins. The monsoon rainfall not only meets the water requirement of the predominant rain-fed agriculture in India but also recharges the groundwater that is used for irrigation and human consumption in a large scale. Therefore, a small deficit or skewed distribution in rainfall triggers the anthropogenic intervention in terms of the rainfall conservation and storage of runoff in the reservoirs in order to meet the amplified water demands in a drought year. For example, the Godavari River basin is heavily farmed with a cultivable area that encompasses 60% of the basin area, and two crops are grown due to assured irrigation from the major dams and reservoirs in the basin. It can be noticed that the sediment supply has reduced substantially during the drought years, which can be attributed to the diversion of the streamflow for the irrigation, drinking water and industrial water requirements. This is also the case for the Mahanadi, Brahmani, Cauvery, Mahi, and Tapi River basins. Therefore, the observed declines in sediment loads reflect the impacts of the frequent dry and deficit rainfall years and their interaction with the anthropogenic activities during the study periods.

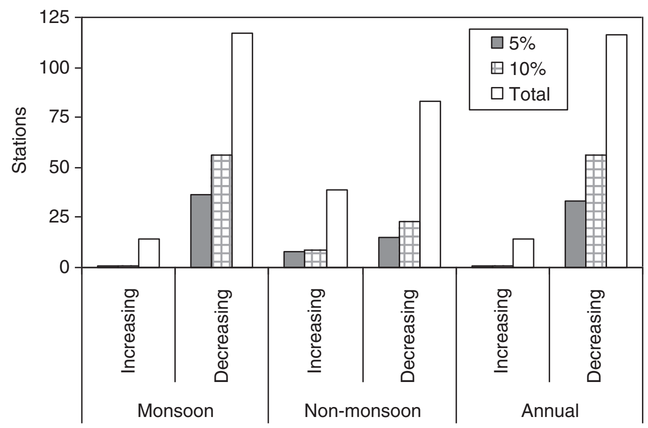

Fig. 3. The monsoon, non-monsoon, and annual sediment load trends in the tropical river basins of India. The gauging stations experiencing decreases in sediment load outnumber the corresponding increases in high proportions. The presence of significant decreasing trends at the 0.05 and 0.1 levels is also prominent irrespective of the seasons.

5.2. Impacts of dams and reservoirs

The Krishna and Normada River basins are highly regulated as a major portion of their annual runoff is earmarked for multifarious uses like electricity generation, irrigation and urban water supply (Table 1). Therefore, the correspondence between the rainfall and sediment load is critically distorted (Table 5). In the Krishna River basin, the stored water irrigates 3.2×10^4 km^2 area (i.e. 16% of the cultivable land) of the basin, and also produces 1947 MW of electricity annually. In addition, the reservoirs supply a large proportion of the drinking and domestic water requirements of the Hyderabad city with a population of 7 million. Therefore, the anthropogenic stresses appear to play a dominant role in comparison to the climate (rainfall) variability as the city population is increasing alarmingly along with the agriculture. The sediment flux at the outlet of the river basin (Vijaywada) to the Bay of Bengal exhibited significant ($p\leq0.05$) decreasing trend of -0.14×10^6 t/yr in

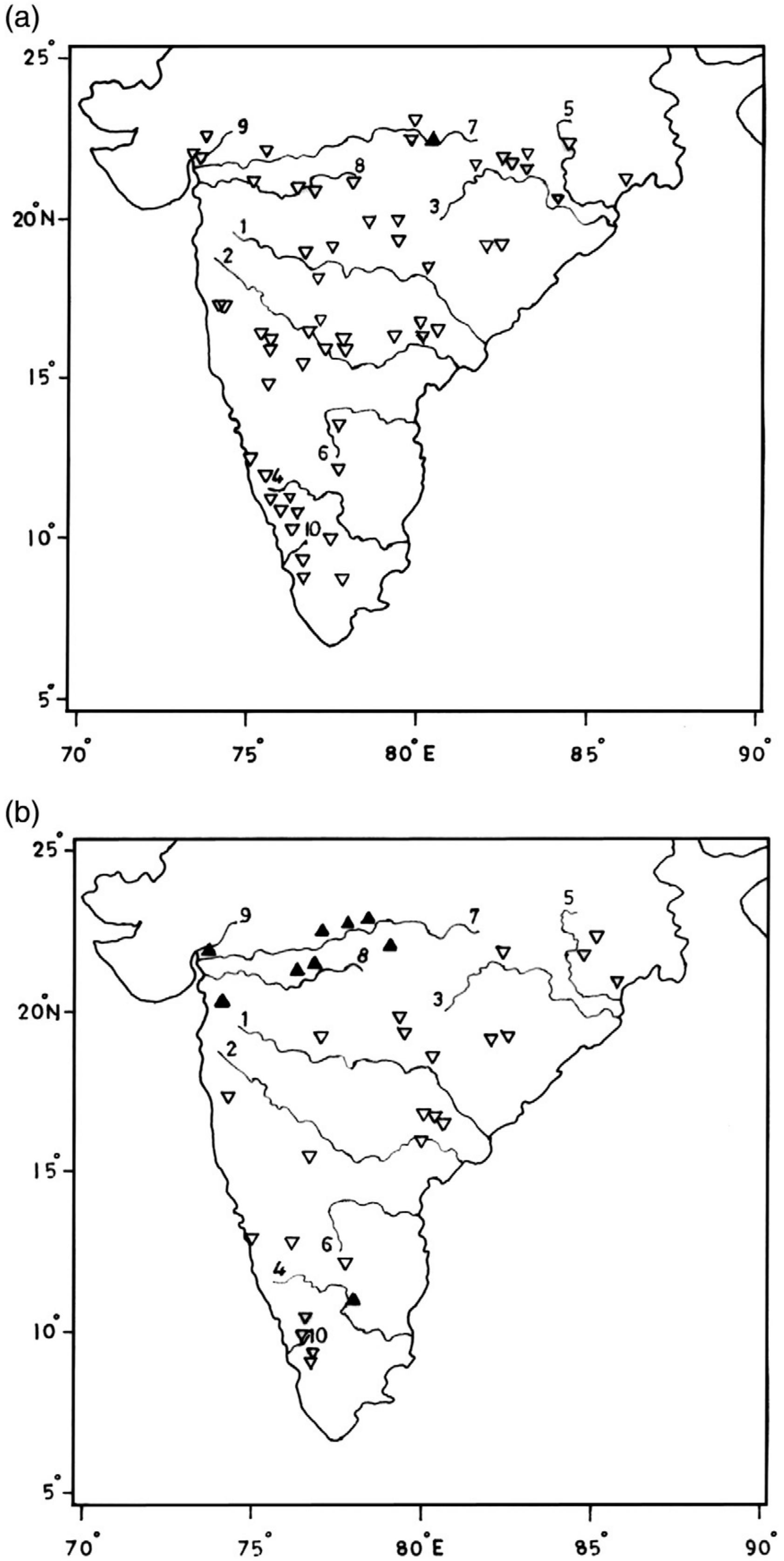

Fig. 4. Spatial distribution of the significant ($p \le 0.1$) trends in sediment load of the tropical river basins of India in the (a) monsoon and (b) non-monsoon seasons. The occurrence of trends in group suggests the presence of the cross-correlation. The monsoon season, which supplies more than 90% of the annual sediment load, experiences widespread declining trends (inverted triangles) in sediment load. Few gauging stations show increases (filled triangle) in the non-monsoon season.

Table 3
Significant trends in sediment load of the tropical river basins in the monsoon and non-monsoon seasons.

River basin	Stations	Significance level	Monsoon		Non-monsoon	
			Increase	Decrease	Increase	Decrease
Godavari	25	0.05	0	4	0	4
		0.1	0	9	0	6
Krishna	22	0.05	0	13	0	5
		0.1	0	16	0	6
Mahanadi–Brahmani	22	0.05	0	3	0	1
		0.1	0	8	0	4
Cauvery and East-flowing	16	0.05	0	3	1	3
		0.1	0	4	1	3
Normada	14	0.05	1	3	5	0
		0.1	1	4	5	0
Tapi	8	0.05	0	3	1	0
		0.1	0	4	2	0
Mahi	9	0.05	0	2	1	0
		0.1	0	2	1	0
West-flowing	17	0.05	0	5	0	2
		0.1	0	9	0	4

correspondence to a non-significant decreasing trend in the basin rainfall. The recent decreases in sediment flux, which is even close to zero in some years, are due to the steady decrease in rainfall starting from the year 1997–98 (Fig. 2b). This suggests that almost all the rainfall of the basin have been captured in the reservoirs during the drought years. Further, it appears that much of the rainfall in the following normal year or even wet year have been used for refilling the deficits in the previous drought year.

The Normada River basin, which was supplying the largest volume of sediment to the Arabian Sea, experienced an abrupt reduction in sediment flux (Fig. 2g). The average sediment flux at the last control station Garudeshwar during the period 1986–87 to 1994–95 was 30.7×10^6 t/yr. This decreased to 6×10^6 t/yr during the period 1995–96 to 2002–03. Over the study period, the sediment supply dropped significantly ($p \le 0.05$) at the rate of -2.07×10^6 t/yr in correspondence to a non-significant rainfall trend. This trend can be attributed to the construction of the Sardar Sarovar dam, which entraps around 60–80% of the sediment loads (Gupta and Chakrapani, 2005). Although the Sardar Sarovar dam with a reservoir capacity of 3.7 km^3 renders immense societal benefits, the observed trend suggests that the anthropogenic regulation has altered the natural fluvial system of the basin. In general, coastal ecosystem develops resilience to the gradual trends in the hydroclimatic variables. However, the occurrence of abrupt

Table 4
Regional trends in sediment load with cross-correlation $\left(\bar{Z}_{mc}\right)$ in the tropical river basins.

Basin	Season	Gauging stations	Mean correlation		Regional trends	
			Serial	Cross	$\bar{Z}_{mc}$	*p*-value
Godavari	Monsoon	25	−0.04	0.22	−2.25	0.024
	Non-monsoon		−0.01	0.21	−1.96	0.050
Krishna	Monsoon	22	0.25	0.33	−3.98	0.000
	Non-monsoon		0.00	0.18	−1.97	0.050
Mahanadi–Brahmani	Monsoon	22	−0.20	0.44	−1.65	0.099
	Non-monsoon		−0.01	0.27	−1.84	0.066
Cauvery	Monsoon	11	0.15	0.23	−1.72	0.086
	Non-monsoon		0.07	0.12	−0.81	0.420
East-flowing	Monsoon	5	0.16	0.16	−2.91	0.004
	Non-monsoon		0.03	0.10	−2.76	0.006
Normada	Monsoon	17	−0.01	0.29	−1.17	0.241
	Non-monsoon		0.08	0.26	2.58	0.010
Tapi	Monsoon	8	−0.15	0.44	−1.35	0.178
	Non-monsoon		0.01	0.27	1.85	0.064
Mahi	Monsoon	9	0.06	0.34	−1.83	0.068
	Non-monsoon		0.05	0.06	1.36	0.174
West-flowing	Monsoon	17	0.26	0.40	−3.03	0.002
	Non-monsoon		−0.07	0.25	−1.56	0.119

reduction in streamflow and sediment flux can fundamentally alter the ecosystem function. The future research needs to examine the potential ecosystem responses to the abrupt shift in fluvial system. Further, the increases in sediment load in the non-monsoon season, which is widespread as evident from the regional trend results, could be attributed to the recent increases in the baseflow (Gupta and Chakrapani, 2007).

5.3. Coastal erosion and the future scenario

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change predicted that the global warming induced sea level rise along with the rainfall variability may aggravate the coastal ecosystem of the densely populated Asian river basins (Cruz et al., 2007). As the sea level is rising in the Indian coast (Unnikrishnan and Shankar, 2007), the simultaneous reduction in sediment supply observed in this study appears to have made the basins more vulnerable to the coastal erosion. The pristine Godavari River (i.e. the pre-dam scenario) was the 9th largest sediment transporting river on a global scale with an annual flux of 170×10^6 t. In the post-dam scenario, however, this has reduced substantially to 56.76×10^6 t during the period 1990–1998 (Malini and Rao, 2004). Our results reveal that the widespread declining tendency is still continuing in both the Godavari and Krishna River basins. Further, both the basins are prone to the global warming induced sea level rises (Rao et al., 2008). All these factors are likely to have caused the coastal erosion as evident from the loss of the mangrove vegetation and also the displacement of the human habitation (Malini and Rao, 2004; Gamage and Smakhtin, 2009).

Among the major deltas of the world, the Godavari and Krishna River basins are also identified as the basins at risk to coastal erosion where the reduced aggradation no longer keeps up with the local sea-level rise (Syvitski et al., 2009). With a reserve of 1060×10^6 t of hydrocarbon resources (Rao, 2001), both the basins are also prone to the coastal subsidence due to the extraction of natural gas from the underlying sediments. Further, the numerical modeling provides evidence of the sea water intrusion into the coastal aquifers due to the human activities and the sea-level changes (Bobba, 2002). Therefore, the proposed Polavaram project, which will link the water surplus Godavari River at Polavaram to the Krshna River at Vijaywada in order to meet the growing water requirements of the Krishna basin (GOI, Government of India, 1999b; Bharati et al., 2009), may further aggravate the coastal ecosystem.

The Mahanadi and Brahmani River basins are also highly vulnerable to the coastal erosion as both the deltas are sinking at a faster rate than that of the sea level rise (Syvitski et al., 2009). The long-term dataset available for the Tikarpara gauging station at the outlet of the Mahanadi River to the Bay of Bengal indicated a significant ($p \le 0.05$) declining sediment flux of -0.62×10^6 t/yr for the period 1980–81 to 2007–08. The observed reductions in sediment load appear to have exerted substantial influence on the coastal ecosystem as evident from the accelerated erosion hazards (Kumar et al., 2010). Further, the storms and severe cyclones developed over the northwest Bay of Bengal hit both the river basins more frequently than any other tropical river basins of India (Mascarenhas, 2004). This leads to frequent inundation of the coastal region. For example, the super cyclone in 1999 with a tidal surge of 8–10 m destroyed the coastal ecosystem, leading to serious socio-economic crisis (Mirza, 2003). In addition, the loss of the protective vegetation along the coast has made the deltas more vulnerable to even small tides. In the Brahmani River basin, the ENVIS (Environmental Information System of the wetland ecosystem of India) reported that the reduction in streamflow due to the construction of dam has increased the salinity of the Bhitarkanika estuary, leading to retardation of growth in mangrove forest. In order to sustain the ecological barrier, the requirement of the minimum environmental flow has also been highlighted.

Table 5
Trends in annual sediment load at the outlets of the tropical rivers and in basin rainfall.

River basin	Sediment trend			Rainfall trend			Correlation coefficient (*r*)
	Z^*	*p*-value	β (t/yr)	Z^*	*p*-value	β (mm/yr)	
Godavari at Polavaram	−1.02	0.308	−1.46	−0.91	0.363	−4.93	0.76[a]
Krishna at Vijaywada	−2.27	0.023	−0.14	−0.43	0.667	−6.49	0.25
Mahanadi at Tikarpara	−1.72	0.085	−0.95	−1.50	0.134	−42.61	0.72[a]
Cauvery at Mausiri	0.33	*0.371*	0.01	0.03	0.488	0.86	0.60[a]
Brahmani at Jenapur	−1.40	0.162	−0.42	−1.19	0.234	−43.42	0.80[a]
Penner (East flowing) at Chennur	0.26	0.397	0.01	−1.85	0.064	−30.12	0.31
Normada at Garudeshwar	−2.28	0.023	−2.07	−0.11	0.912	−0.60	0.40
Tapi at Sarankheda	−1.81	0.070	−0.57	−0.07	0.944	−1.17	0.76[a]
Mahi at Khanpur	−0.69	0.490	−0.12	−1.55	0.121	−20.30	0.81[a]
Nethravathi (West flowing) at Bantwal	−0.39	0.697	−0.05	−1.16	0.246	−26.78	0.52

[a] Significant correlation coefficient between the annual sediment load and the rainfall at the 0.05 level; β denotes the trend magnitude.

Besides the rainfall, the synoptic scale disturbances such as the storms and severe cyclones over the Indian Ocean influence both the sediment load and coastal erosion of the Indian coast. Particularly, the floods in the central India, which supply large proportion of the sediment loads in the Mahanadi–Brahmani, Godavari and Krishna River basins, are primarily associated with the cyclonic storms and depressions developed over the Bay of Bengal during the monsoon season. Recent studies show that the weakening of atmospheric dynamical parameters and the tropical easterly jet has led to the suppression of monsoon depressions in the Bay of Bengal (Dash et al., 2004). However, the rise in sea surface temperature (SST) has led to the intensification of the severe cyclonic storms in the non-monsoon seasons (Singh, 2007). We speculate the partial impacts of both the phenomenon in terms of the reduced sediment load in the monsoon season and the increased inundation in the non-monsoon season. The timing of the flood also influences the sediment loads as the high flows during the beginning of the monsoon season carry large quantity of sediment, and it decreases thereafter due to the vegetation cover. There are occasions when the Godavari has transported more than 7×10^6 t in a day (Vaithiyanathan et al., 1988). Further, when the adjacent ocean is stormy in term of the large tidal force, the high runoff creates new flood zones particularly in the flat deltas of the Godavari, Mahanadi and Brahmani Rivers due to the resistance of the Bay of Bengal to drain the flow, leading to the reduction in sediment flux.

Although there is limited evidence available regarding the impacts of climate change on the sediment loads (Walling and Fang, 2003), our result suggest that the anthropogenic control on the fluvial load is primarily associated with the climatic stresses. The early monsoon rainfall in India and the number of rainy days, which are important for the sediment loads, show decreasing trend (Ramesh and Goswami, 2007). Simultaneously, most of the tropical river basins have been experiencing an increasing trend in temperatures (Singh et al., 2008). The declining trends in sediment loads are spread across the river basins irrespective of the presence of dams and reservoirs. This indicates that the sediments are not only trapped in big reservoirs but also the soil and water conservation measures are intensified to meet the challenges of the frequent droughts. To support the burgeoning population and the developmental goals, the reservoirs that are in construction and those under consideration of construction will capture an additional annual flow of 184 km^3 (CWC, Central Water Commission (2006, 2007). The proposed interlinking of rivers will further reduce the sediment supply to the ocean (Misra et al., 2007). Therefore, the coastal erosion is likely to be accelerated if the current trends in sediment load continue well into the future.

6. Conclusions

Based on a large dataset comprised of the monsoon and non-monsoon sediment time series of different timescale during the period 1986–87 to 2005–06 from 133 gauging stations of the tropical river basins of India, this study investigated the trends in sediment load using the non-parametric statistical procedures. Results reveal clear signals of the declines in sediment load, which can be attributed to the impacts of the recent climate variability and its interaction with the anthropogenic activities. The observed variability in sediment load are in consistent with the rainfall variability for most of the basins (e.g. Godavari, Mahanadi, Cauvery, Brahmani, Tapi, Mahi River basins) as evident from the significant correlation coefficients. The sediment fluxes to the adjacent ocean at the outlets of these basins and also the average basin rainfall showed non-significant decreasing trends. This is due to the presence of high interannual variability in rainfall in terms of dry and wet years, which may have obscured the underlying patterns in both the rainfall and sediment flux. Highly regulated river basins such as the Krishna and Normada River basin exhibited significant reduction in sediment flux at the basin outlets, indicating the anthropogenic impacts in terms of stream flow storage and diversion. The Normada River, which was supplying the largest quantity of sediment to the Arabian Sea, also showed an abrupt reduction in sediment flux from 30.7×10^6 t/yr to 6×10^6 t/yr with an overall trend of -2.07×10^6 t/yr due to the construction of the Sardar Sarovar dam.

The observed significant downward trends in sediment load, which outnumbered the corresponding upward trends in high proportions for both the seasons, were found to spread across the river basins irrespective of the presence of the dams and reservoirs. This indicates that the sediments are not only trapped in big reservoirs but also the soil and water conservation measures are intensified to meet the challenges of the frequent droughts and the decreasing rainfall patterns. Strong spatial patterns were also observed among the significant trends, suggesting the presence of the cross-correlation among the sediment records. The regional trend, which accounts the spatial correlation, indicated significant reductions in the monsoon season for most of the river basins. This suggests the widespread nature of the sediment load declines. It may be assumed that the impacts of the proposed dams and the water conservation practices to deal with the climatic stresses will continue to reduce the sediment load. Based on our results, which identified the regions and locations of the significant reduction in sediment loads, policy measures need to be undertaken for the environmental flow requirements in order to safeguard the ecology and geomorphology of the densely populated deltas of India. Further research is required to quantify the relative contributions of different factors that influence the sediment trends and variability.

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