water

MDPI

Article

Climatic and Anthropogenic Influences on Long-Term Discharge and Sediment Load Changes in the Second-Largest Peninsular Indian Catchment

Harshada Jadhav [1], Avinash M. Kandekar [1] and Sumit Das [2,*]

[1] Department of Geography, Savitribai Phule Pune University, Pune 411007, India; harshudharma15@gmail.com (H.J.); avikandekar@gmail.com (A.M.K.)
[2] Institute of Hydrogeology, Engineering Geology and Applied Geophysics, Charles University, 12800 Prague, Czech Republic
* Correspondence: sumit.das@natur.cuni.cz

Abstract: In recent decades, understanding how climate variability and human activities drive long-term changes in river discharge and sediment load has become a crucial field of research in fluvial geomorphology, particularly for South Asia's densely populated and environmentally sensitive regions. This study analyses spatio-temporal trends in water discharge (Q_d) and sediment load (Q_s) in the Krishna basin, Peninsular India's second-largest catchment. Using nearly 50 years of daily discharge, sediment concentration, and rainfall data from the Central Water Commission (CWC) and India Meteorological Department (IMD), we applied Mann–Kendall, Pettitt tests, and double mass equations to detect long-term trends, abrupt changes, and the relative influence of climate and anthropogenic effects. Results showed a notable decline in the annual discharge, with 15 of 20 stations showing decreasing trends, especially along the Bhima, Ghataprabha, and lower Krishna rivers. The annual stream flow data showed a 53% decline in the mean Q_d from 26.01×10^9 m^3 $year^{-1}$ before 2000 to 12.32×10^9 m^3 $year^{-1}$ after 2000 at the terminal station. Eight of ten gauging stations showed a significant decrease (p-value < 0.05) in their annual sediment load, with a 76% reduction across the Krishna basin after its changepoint in 1983. The Pettitt test identified a statistically significant downward shift in discharge at seven stations. Double mass plots indicate that anthropogenic factors, such as large-scale reservoirs and water diversion, are the main contributors, accounting for 82.7% of sediment decline, with climatic factors contributing 17.1%. The combined trend analysis and double mass plots confirm these findings, underscoring the need for further study of human impacts on the basin's hydro-geomorphology. This study offers a clear and robust approach to quantifying the relative effects of climate and human activities, providing a versatile framework that can enhance understanding in similar studies worldwide.

Keywords: sediment load; trend analysis; climate change; anthropogenic activities; dam; Krishna

check for updates

Citation: Jadhav, H.; Kandekar, A.M.; Das, S. Climatic and Anthropogenic Influences on Long-Term Discharge and Sediment Load Changes in the Second-Largest Peninsular Indian Catchment. *Water* **2024**, *16*, 3648. https://doi.org/10.3390/w16243648

Academic Editor: Hucai Zhang

Received: 3 November 2024
Revised: 9 December 2024
Accepted: 13 December 2024
Published: 18 December 2024

1. Introduction

Long-term discharge and sediment load trends are essential metrics of riverine health, which respond to both natural and anthropogenic stress [1,2]. The discharge and the amount of transported sediments over a longer time provide insights into how environmental conditions have changed the river's behaviour [1]. Understanding these changes is crucial to developing management strategies for water resources, planning actions aimed at ecological conservation and underlining the sustainable use of territories. Human interventions during recent decades have continued to cause alterations in the river flow and sediment transport [3–7]. Anthropogenic activities have increased fluvial sediment delivery by 215% while there is a decline in ocean-bound sediment by 49% and boosting sediment consumption by over 2500% [8]. Agricultural practises affect the rates at which sediments enter the watershed through soil erosion. Furthermore, constructing impoundments hinders sediment transport because they hold sediments, thus modifying downstream sediment content and inhibiting sediment deposition [9]. Human activities such as water and sand diversions, domestic and industrial water consumption, and river sand mining [10] also intensify the reduction in sediment load [7].

Over recent decades, rivers worldwide have significantly reduced sediment loads due to extensive landscape alterations and climate change [11]. Asia was the primary global sediment exporter to ocean before the 1990s, contributing nearly half of the total load, and has recently witnessed a significant decline to 27 ± 1.9% due to anthropogenic factors like dam construction and land-use changes [12]. This substantial decline in riverine sediments, along with their wide-ranging environmental implications, has garnered substantial attention and spurred intensive research efforts over the years [13–17]. During recent decades, human activities have increased global sediment transport by 2.3 ± 0.6 Gt $year^{-1}$ through soil erosion while simultaneously reducing the amount reaching the coastal environment by 1.4 ± 0.3 Gt $year^{-1}$ due to sediment trapping in reservoirs [18]. Large-scale reservoirs and dams on the river channel have curtailed sediment transport to the delta, causing its shrinkage and exacerbating coastal erosion. Deforestation and land cover changes have also been linked to increased mean erosion rates, with studies in the Colombian Andes reporting a significant rise in sediment loads [19].

Krishna basin is the second largest Peninsular riverine system and is one of the most important rivers after Godavari in terms of sediment load and water discharge. Ramesh and Subramanian [20], the classical workers, investigated the trends in sediment load and discharge in the Krishna basin and estimated the sediment yield of 16 t km^{-2} $year^{-1}$ using limited data. The Krishna is one of the most important contributors of sediment to the Krishna–Godavari delta and has experienced substantial erosion and has lost 210 km of coast along the shoreline in the span of 50 years (1965–2015) [21]. Systematic and holistic planning for water and soil management is a concern for Krishna River since it has experienced zero-flow conditions in the past. For proper strategic planning and river management, a comprehensive assessment of sediment trends and their driving forces is much needed. Understanding of spatio-temporal sediment load changes in the Krishna River has been very limited by the data and technical analysis. Therefore, this study aims to address a critical knowledge gap by investigating (i) the long-term trends of sediment load, discharge, and rainfall; (ii) the abrupt changes in hydro-meteorological variables; and (iii) quantifying the influence of climate change and human activities on discharge and sediment load changes.

2. Study Area

Originating in the Western Ghats near Mahabaleshwar, India, the Krishna River travels eastward for around 1400 km, ultimately draining into the Bay of Bengal. This basin encompasses a total catchment area of more than 0.2 billion km^2. The right bank tributaries joining the Krishna are Koyna, Panchganga, Dhoodhganga, Ghataprabha, Malaprabha, and Tungabhadra, whereas Bhima, Dindi, Peddavagu, Halia, Musi, Paleru, Munneru represents its left bank tributaries. This basin exhibits a geologically diverse landscape, characterised by rock formations that include the Deccan Volcanic Province (DVP) in the upstream, Precambrian crystalline rocks of the Peninsular gneissic complex, Dharwar supracrustal, Proterozoic sediments in the middle reach, and deltaic fluvial and coastal sediments of the Quaternary period deposited at the basin's mouth [22,23]. Major land-uses of the Krishna basin include cropland, fallow land, deciduous and scrub forest, grassland, plantations, urban areas, wasteland, and waterbodies. The basin is characterised by intensive agricultural land-use, where cropland comprises the dominant land cover (>80%).

The Krishna basin, characterised by a tropical climate, is strongly shaped by the southwest monsoon, which delivers most of its rainfall. Climate conditions vary across the basin: the western region ranges from per-humid to dry sub-humid. In contrast, conditions become increasingly arid, moving eastward, culminating in a semi-arid to arid climate in the south-central area. Approximately 90% of the basin's annual rainfall falls during the monsoon season, with 70% occurring from June to September [24]. The basin, on average, receives ~900 mm of annual precipitation [22].

Upon reaching the coastal plains near Vijayawada, the Krishna River splits into three distributary channels, forming the main delta lobe, which connects with the Godavari River to create a cohesive delta complex [22]. The eastern part of the Krishna basin and its delta are vulnerable to episodic tropical cyclones resulting from land-ocean interactions in the Bay of Bengal.

3. Data and Methodology

3.1. Data Sources

This study analysed the daily water discharge (Q_d) and suspended sediment concentration (Q_s) data over 45 years (1965–2014) sourced from the Central Water Commission (CWC, New Delhi, India). While the monitoring of suspended sediment concentration at several stations closed around the mid 2000s, most of the stations maintained data until 2014. We selected continuous Q_d data from 20 stations and Q_s data from 10 stations, ensuring that each had a minimum of 20 years of consistent records. The daily data were first examined to exclude missing entries, and then cleaned datasets were used to calculate annual water discharge. The annual sediment load was computed from the suspended sediment concentration. The locations of the gauging stations are shown in Figure 1, and detailed information regarding each station and its study period is listed in Table 1.

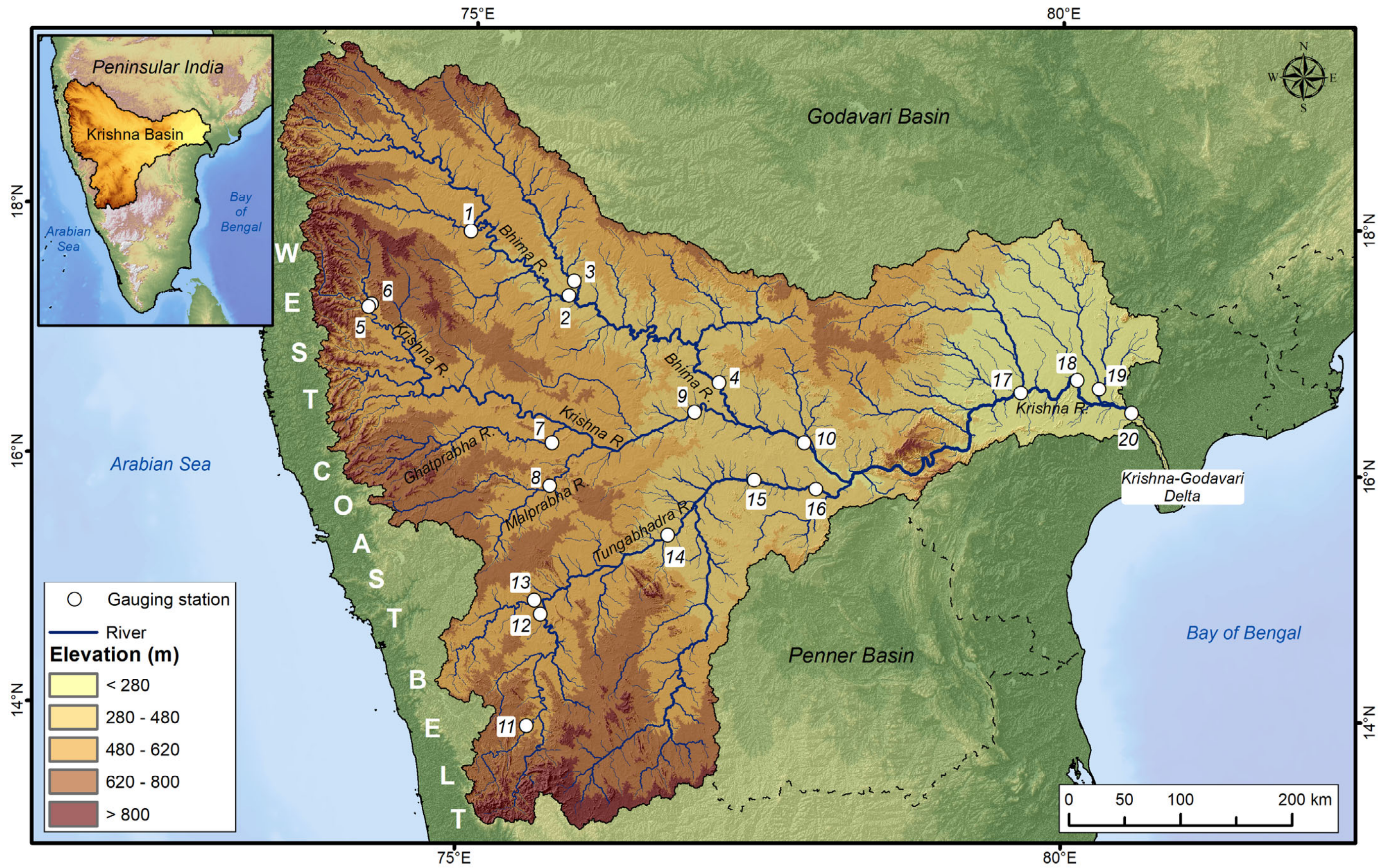

Figure 1. Location map of the Krishna basin and selected gauging stations. Refer to Table 1 for the names of the gauging stations according to the numbers provided in this figure.

Table 1. Hydro-geomorphic characteristics of gauging stations in the Krishna basin (* computed in the present study).

St. No.	Gauging Station	Q_d Data Range	Q_s Data Range	Upstream Area (km^2)	Mean Q_d (10^9 m^3 Year^{-1}) *	Mean Q_d before 2000 (10^9 m^3 Year^{-1}) *	Mean Q_d After 2000 (10^9 m^3 Year^{-1}) *	Mean Q_s (10^6 Tons Year^{-1}) *	Mean Sediment Yield (Tons km^{-2} Year^{-1}) *
1	Sarati	1966 to 2011	-	7200	1.28	1.36	1.05	-	-
2	Wadakbal	1966 to 2011	1966 to 2005	12,092	0.90	1.03	0.54	3.79	313.77
3	Takli	1966 to 2011	1966 to 2014	33,916	5.47	6.28	3.16	3.86	113.92
4	Yadgir	1966 to 2011	1966 to 2011	69,863	8.84	9.88	5.92	16.14	231.01
5	Warunji	1967 to 2011	1975 to 2005	1890	2.94	2.87	3.16	0.49	258.66
6	Karad	1966 to 2011	1965 to 2014	5462	4.66	4.62	4.75	1.26	231.40
7	Bagalkot	1967 to 1999	-	8610	2.94	-	-	-	-
8	Cholachguda	1983 to 2013	-	9373	0.83	0.92	0.72	-	-
9	Huvinhedgi	1976 to 2011	1976 to 2005	55,150	16.69	18.44	13.20	9.16	166.02
10	K.Agraharam	1986 to 2006	-	132,920	25.37	27.28	20.46	-	-
11	Shimoga	1972 to 2012	1973 to 2012	2831	5.31	5.32	5.29	0.45	159.63
12	Haralahalli	1967 to 2012	-	14,582	7.13	7.44	6.34	-	-
13	Marol	1966 to 2014	-	4901	1.95	1.93	1.98	-	-
14	Oollenur	1972 to 2002	-	33,018	4.89	5.14	2.59	-	-
15	Mantralayam	1973 to 2011	-	67,180	6.78	7.13	5.98	-	-
16	Bawapuram	1966 to 2011	1966 to 2013	67,180	5.48	5.65	4.98	3.68	54.76
17	Pondugala	1976 to 2006	-	221,220	24.05	26.72	14.90	-	-
18	Wadenapalli	1966 to 2011	1967 to 2011	235,544	27.20	30.52	17.80	1.63	6.94
19	Keesara	1966 to 2011	-	9854	1.94	1.96	1.87	-	-
20	Vijayawada	1965 to 2011	1966 to 2005	251,360	22.51	26.01	12.32	3.96	15.75

We collected and analysed rainfall data from the India Meteorological Department (IMD, Pune, India) to examine the hydro-climatic effects on sediment load and discharge. This study utilised pixel-based gridded rainfall data with a resolution of 0.25° × 0.25° covering the period from 1965 to 2020 (55 years) to compute both annual and basin-level rainfall. Additionally, we gathered information on the siltation rates, impoundment years, and completion years of dam constructions from the WRIS-India and the Krishna basin report published by the Ministry of Water Resources, Government of India. The continuous time series data for water discharge, sediment load, and rainfall were analysed using linear regression, the non-parametric Mann–Kendall test, the Pettitt test, and the double mass method to investigate and understand the spatio-temporal changes in discharge and sediment load in the Krishna basin.

3.2. Mann–Kendall Tests

As a non-parametric method, the Mann–Kendall (MK) test is well-suited for trend analysis in monotonic hydro-climatic time series data. Unlike linear regression, the Mann–Kendall test is advantageous for non-normally distributed datasets exhibiting high annual variability or containing missing values. This is because the MK test is robust to outliers and highly skewed data [25]. The MK test was conducted on time series data for water discharge, sediment load, and rainfall to evaluate and detect trends and their significance. A significance level of 0.05 was adopted for this study.

The slope derived from Sen's slope method indicates the trend direction, with its sign showing whether the data trend was positive or negative and its magnitude illustrating the trend's steepness. The calculation of MK statistics was performed as follows:

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

where X_i and X_j re the data points, and i and j represent the time series of length n and:

$$sgn(\varkappa) = \begin{cases} 1 & if\ \varkappa > 0 \\ 0 & if\ \varkappa = 0 \\ -1 & if\ \varkappa < 0 \end{cases} \tag{2}$$

According to the foundational work by Mann [26] and Kendall [27], for a sample size $n \geq 8$, comprising independent and identically distributed random variables, the test statistics S could be approximated with the following mean and variance:

$$E(S) = 0 \tag{3}$$

and

$$\sigma = \frac{\left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j \left(t_j - 1\right)\left(2t_j + 5\right) \right\}}{18} \tag{4}$$

where p represents the number of tied groups in the data and t_j is the number of data values in the extent of j. Following the Z-transformation, the standardised test statistics S is derived as follows:

$$Z = \begin{cases} \frac{S-1}{\sigma}\ if\ S > 0 \\ 0 \quad If\ S = 0 \\ \frac{S+1}{\sigma}\ if\ S < 0 \end{cases} \tag{5}$$

Z attains the standard normal distribution under the null hypothesis of no trend, i.e., $\mu = 0$ and $\delta = 1$. The Kendall's tau τ in close relation with statistics S is given by:

$$\tau = \frac{S}{D} \tag{6}$$

where

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j\left(t_j - 1\right)\right]^{1/2}\left[\frac{1}{2}n(n-1)\right]^{1/2} \tag{7}$$

Since the magnitude of the slope is not calculated in the Mann–Kendall's test, the quantification is pursued by Sen's slope as given by [28,29]:

$$d_k = \frac{\varkappa_j - \varkappa_i}{j - i} \qquad \text{fork} = 1, 2, \ldots\ldots\ldots\ldots, \text{N} \tag{8}$$

where d_k is Sen's slope, X_i and X_j represent the values in the extent of i and j, $(1 \leq i < j \leq n)$. Sen's slope estimator is the median of the N values of d_k which is calculated as:

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & N\ is\ odd \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & N\ is\ even \end{cases} \tag{9}$$

For an odd number of data points N, the sen's estimator computed as $\beta = T_{(N+1)/2}$. For an even number of data points N, it is considered as $\beta = [T_{N/2} + T_{(N+2)/2}]/2$. This non-parametric test allowed for the determination of the direction of the trend. Positive values of β signify an upward trend, whereas negative values indicate a downward trend in the time series.

3.3. Pettitt's Test

Various change detection techniques are available to check the abrupt changepoint in any time series dataset. The Pettitt test, a non-parametric method developed by Pettitt [30], was used in this study to identify abrupt changes (change points) in the prolonged time series data. Numerous studies have utilised the Pettitt test to identify shifts in climatic and hydrological patterns [31–35]. This non-parametric method tests the null hypothesis (H_0), and computational statistical methods are as follows:

$$K_T = max|U_{t,T}| \tag{10}$$

where

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(\varkappa_i - \varkappa_j) \tag{11}$$

The statistic $U_{t,T}$ is analogous to a Mann–Whitney U test, used to compare if the two subsamples $X_1, \ldots\ldots, X_t$ and $X_{t+1}, \ldots, X_T$ originate from the same population. The statistic $U_{t,T}$ is considered for all integer values of t such that $1 < t < T$ [30].

The position of KT represents the point of change in the time series, which indicates its statistical significance. The tests were performed at a significance approximately at *p*-value of ≤ 0.05:

$$p \simeq 2exp\left(\frac{-6K_T^2}{T^3 + T^2}\right) \tag{12}$$

The statistical analyses were conducted using XLSTAT software with a significance level 0.05.

3.4. Double Mass Curves

The double mass curve is commonly used for assessing the consistency in long-term hydrological and meteorological data trends [36]. This study applied it to analyse the relationships between correlated variables, allowing us to differentiate the impacts of climatic changes from human activities. A stable, linear trend in the curve suggests a dependency on hydro-climatic conditions, while deviations or changes in the slope indicate shifts, potentially due to external factors. This method also smooths time series data, reducing random fluctuations to reveal underlying trends [37]. By comparing precipitation against discharge and sediment load for both natural and impacted periods, we examined changes in regression slopes, helping to identify shifts in the relationships between these variables over time.

3.5. Quantification of the Relative Contributions of Climate Change and Human Activities

Double mass curves, paired with linear regression, were used to assess how climate and human activities have influenced changes in sediment load, with the Pettitt test identifying specific transition years as breakpoints. By using precipitation as a climate proxy, this approach is helpful in clarifying the quantitative impact of climate variation on hydrological patterns.

The change point identified by double mass curves allows the time series to be divided into two phases: a reference period before the change point, representing predominantly natural conditions, and an anthropogenic period afterwards, marked by increased human impact on sediment load. While human activities might have influenced the sediment load to some extent in the reference period, their impact is considered minor compared to the changes in the anthropogenic period. The double mass curves of cumulative rainfall and cumulative sediment load suggest that the sediment has a stable linear relationship for the baseline period, emphasising the hydro-climatic dependency responsible for the overall trend and variability of sediment load. By focusing on a baseline period within the reference interval characterised by minimal anthropogenic disturbance, the natural variability of the sediment load can be more accurately assessed, enabling the significant impact of increased human activities on subsequent sediment load trends to be isolated. This method provides a quantitative view of how each factor has contributed to the observed changes in sediment dynamics over time. For example, the regression equation (Figure S1) developed from the annual rainfall and annual sediment in the reference period stated below was used to estimate the relative contribution of rainfall on the sediment variability of the Krishna basin at Vijayawada (Equation (13)):

$$y = 0.0243x - 11.052 \ (R^2 = 0.36; p = 0.0001) \tag{13}$$

$$y = 0.0353x + 0.3254 \ (R^2 = 0.09; p = 0.0001) \tag{14}$$

$$y = 0.0252x - 5.1197 \ (R^2 = 0.16; p = 0.0001) \tag{15}$$

$$y = 0.0118x - 2.9235 \ (R^2 = 0.19; p = 0.0001) \tag{16}$$

where x and y represent the annual precipitation and sediment load in the reference period.

The Linear Equations (14), (15), and (16) were developed for Yadgir, Huvinhedgi, and Bawapuram, representing the Bhima, upper Krishna, and Tungabhadra sub-basins, respectively, to capture precipitation's influence on the sediment load during the reference period.

The linear regression model from the reference period was then applied to the anthropogenic period using precipitation data. By comparing the average sediment load from the reference period with the predicted sediment load during the anthropogenic period, the difference quantified the sediment load changes attributed to human activities. The equations for evaluating the percent contribution of the climate change (ΔQ_P) and human intervention (ΔQ_H) in altering sediment load are as follows:

$$\Delta Q_{CH} = Q_s - Q_p \tag{17}$$

$$\Delta Q_{CP} = Q_s - Q_r \tag{18}$$

$$Q_C = Q_{CH} + Q_{CP} \tag{19}$$

$$\Delta Q_H = \frac{\Delta \mathrm{Q_{CH}}}{\mathrm{Q_C}} \times 100 \tag{20}$$

$$\Delta Q_P = \frac{\Delta \mathrm{Q_{CP}}}{\mathrm{Q_C}} \times 100 \tag{21}$$

where ΔQ_H and ΔQ_P represent the relative contribution of anthropogenic activities and climate change in altering sediment load, respectively. Sediment changes due to human interventions (ΔQ_{CH}) are calculated as the difference between the average sediment observed during the anthropogenic period (Q_s) and the sediment predicted based on precipitation during that period (Q_p). Sediment changes attributed to climate variability (ΔQ_{CP}) are determined by subtracting the sediment load estimated by precipitation in the anthropogenic period (Q_s) and the average sediment load in the reference period (Q_r). The total sediment change (Q_C) represents the combined impact of climate (ΔQ_{CH}) and human influences (ΔQ_{CP}).

A positive change reflects an increase relative to the reference period, while a negative change indicates a decrease. Similarly, a positive percentage signifies that the direction of change aligns with the overall trend, whereas a negative percentage indicates a change in the direction opposite to the total trend [35].

4. Results

4.1. Temporal Trends in Discharge (Q_d) and Sediment Load (Q_s)

Krishna's annual average water discharge varies from 2.94 × 10^9 m^3 $year^{-1}$ at Warunji to 22.51 × 10^9 m^3 $year^{-1}$ at the terminal station, Vijayawada. From 1966 to 2011, the Krishna basin showed a pronounced decline in the annual discharge trend (Figure 2). The stream flow data of 45 years reveals that among 20 gauging stations, 15 witnessed decreasing trends in discharge (8 significant at 0.05 significance level). In contrast, five stations showed an insignificant increasing trend (Table 2). The stations Pondugala, Wadenapalli, and Vijayawada experienced the most significant declines in annual water discharge, with rates of 0.77 m^3 $year^{-1}$, 0.53 m^3 $year^{-1}$, and 0.53 m^3 $year^{-1}$, respectively (Table 2). The majority of the most significant declines in water discharge were observed in the stations located within the Bhima, upper Krishna, and Lower Krishna sub-basins. The annual stream flow data before and after 2000 is shown in Table 1. The terminal station, Vijayawada, indicated a noteworthy 53% decline in the mean Q_d with 26.01 $\times$ 10^9 m^3 $year^{-1}$ before 2000, reducing to 12.32 $\times$ 10^9 m^3 $year^{-1}$ after 2000.

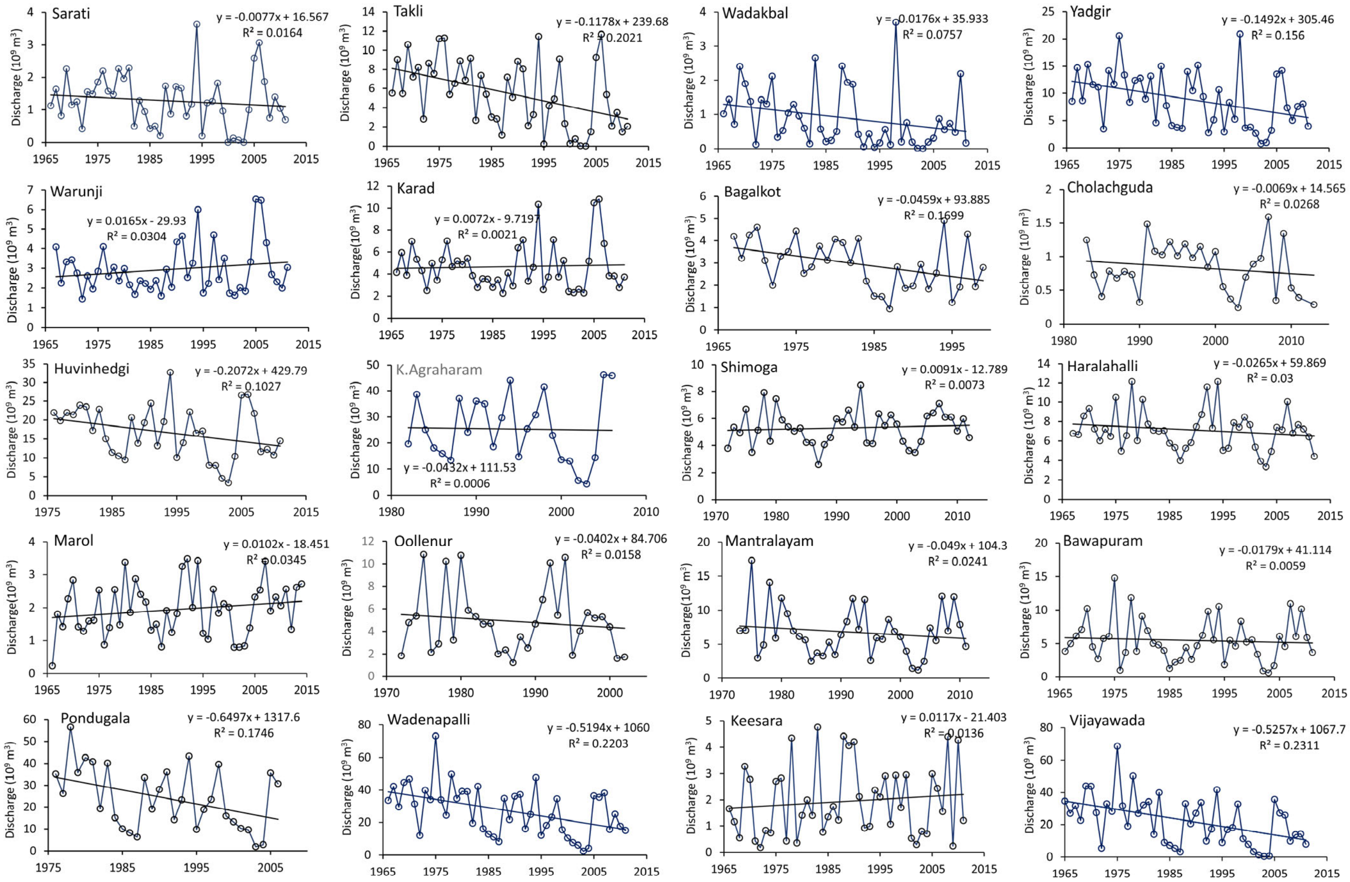

Figure 2. Temporal patterns of water discharge for the gauging stations in the Krishna basin.

Table 2. Mann–Kendall results for discharge and sediment load at various gauging stations in the Krishna basin. Values in **bold** are significant at α = 0.05 level of significance.

St. No	Gauging Station	Discharge					Sediment Load				
		Mann–Kendall Test			Linear Regression		Mann–Kendall Test			Linear Regression	
		Kendall's Tau	Sen's Slope	Trend	Rate of Change (b)	Trend	Kendall's Tau	Sen's Slope	Trend	Rate of Change (b)	Trend
1	Sarati	−0.125	−0.013	(−)	−0.008	(−)	No data	No data	No data	No data	No data
2	Takli	**−0.320**	**−0.133**	**(−)**	**−0.118**	**(−)**	**−0.577**	**−0.150**	**(−)**	**−0.253**	**(−)**
3	Wadakbal	**−0.266**	**−0.018**	**(−)**	−0.018	(−)	**−0.585**	**−0.200**	**(−)**	**−0.235**	**(−)**
4	Yadgir	**−0.285**	**−0.171**	**(−)**	**−0.149**	**(−)**	**−0.552**	**−0.703**	**(−)**	**−0.892**	**(−)**
5	Warunji	0.020	0.003	(+)	0.017	(+)	−0.234	−0.011	**(−)**	−0.006	**(−)**
6	Karad	−0.100	−0.019	(+)	0.007	(+)	**−0.381**	**−0.031**	**(−)**	**−0.036**	**(−)**
7	Bagalkot	**−0.303**	**−0.050**	**(−)**	**−0.046**	**(−)**	No data	No data	No data	No data	No data
8	Cholachguda	−0.140	−0.010	(−)	−0.007	(−)	No data	No data	No data	No data	No data
9	Huvinhedgi	**−0.235**	**−0.237**	**(−)**	−0.207	(−)	**−0.628**	**−0.560**	**(−)**	**−0.782**	**(−)**
10	K.Agraharam	−0.087	−0.260	(−)	−0.043	(−)	No data	No data	No data	No data	No data
11	Shimoga	0.076	0.013	(+)	0.009	(+)	0.113	0.003	(+)	0.006	(+)
12	Haralahalli	−0.109	−0.023	(−)	−0.027	(−)	No data	No data	No data	No data	No data
13	Marol	0.134	0.012	(+)	0.010	(+)	No data	No data	No data	No data	No data
14	Oollenur	−0.084	−0.016	(−)	−0.040	(−)	No data	No data	No data	No data	No data
15	Bawapuram	−0.040	−0.011	(−)	−0.018	(−)	**−0.555**	**−0.156**	**(−)**	**−0.192**	**(−)**
16	Mantralayam	−0.074	−0.032	(−)	−0.049	(−)	No data	No data	No data	No data	No data
17	Pondugala	**−0.308**	**−0.773**	**(−)**	**−0.650**	**(−)**	No data	No data	No data	No data	No data
18	Wadenapalli	**−0.314**	**−0.528**	**(−)**	**−0.519**	**(−)**	**−0.390**	**−0.058**	**(−)**	**−0.068**	**(−)**
19	Keesara	0.080	0.010	(+)	0.012	(+)	No data	No data	No data	No data	No data
20	Vijayawada	**−0.325**	**−0.530**	**(−)**	**−0.526**	**(−)**	**−0.482**	**−0.157**	**(−)**	**−0.206**	**(−)**

Figure 3 displays the annual variation in sediment load for stations available in the Krishna basin. Eight out of ten of the gauging stations exhibited a statistically significant decline in sediment load (Table 2), as determined by Mann–Kendall and Sen's slope analysis. The specific stations displaying this trend included Bawapuram, Huvinhedgi, Karad, Takli, Yadgir, Wadakbal, Wadenapalli, and Vijayawada. Most stations experienced a significant drop in their sediment load, ranging from 0.06×10^6 t year^{-1} at Wadenapalli to 0.70×10^6 t year^{-1} at Yadgir.

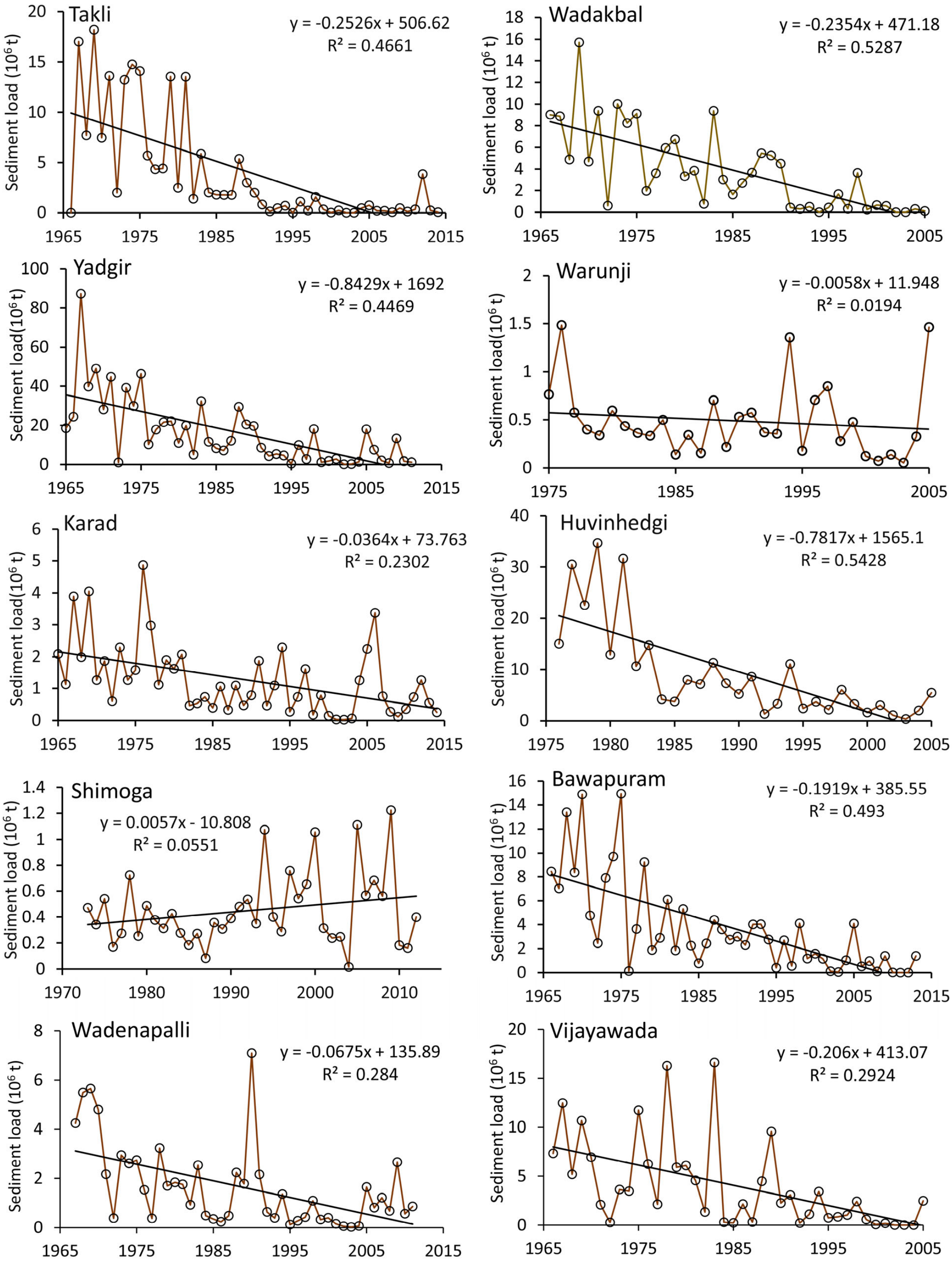

Figure 3. Temporal patterns of the sediment load for the gauging stations in the Krishna basin.

4.2. Spatial Variation in Discharge and Sediment Load

Out of the ten monitoring stations along the upper Krishna and Bhima rivers, nine exhibited a decrease in long-term discharge, with four stations showing statistically significant declines. In the lower Krishna region near the delta, all three monitoring stations recorded notable reductions in discharge. Conversely, the stations that displayed insignificant increases in discharge were mainly found in the Tungabhadra sub-basin (Marol and Shimoga), the upper Krishna basin (Karad and Warunji), and the lower Krishna sub-catchment (Keesara).

About 80% of the analysed stations showed a significant downward trend in sediment, with most observed in the Bhima, upper Krishna, and lower Krishna (Figure 4). An unexpected trend emerged at Karad and Warunji, located in the upper Krishna basin. Though the discharge at Karad increased slightly but not significantly, the sediment load decreased significantly. Warunji station also experienced a similar pattern. Notably, both Karad and Warunji, located in the upper reaches of the Krishna basin, experience comparatively higher average rainfall compared to other monitoring stations within the basin. The lower reaches of the Krishna basin mainly include Wadenapalli and Vijayawada, which showed maximum sediment anomalies in the catchment. The Shimoga station, showing an insignificant increase, was located in the Tungabhadra sub-basin.

4.3. Changepoints in Discharge and Sediment Load

The Pettitt test, employed to analyse discharge data, identifies substantial changes in discharge patterns across the Krishna basin (Figure 5). Twenty stations, out of which seven (i.e., Bagalkot, Pondugala, Takli, Yadgir, Wadenapalli, Wadakbal, Vijayawada) show a statistically significant downward shift in the discharge. The significant identified change points were primarily concentrated in the Bhima sub-basin and lower Krishna. Takli and Wadakbal stations located on Bhima, the principal tributary of Krishna, experienced a downward change in the discharge around 1981 and 1990, respectively, while the rest of the stations showed their changepoints in 1983 (Table 3). At Vijayawada, 52% of the discharge experienced a swift decrease after its change point in 1983. Wadenapalli station saw a significant drop in discharge and marked a decline of 34%, going from 34.88×10^9 m^3 during 1966–1985 to 20.34×10^9 m^3 during 1986–2005.

Table 3. Results of Pettitt test for change points of discharge and sediment load at gauging stations in Krishna basin. Values in **bold** are significant at $\alpha = 0.05$ level of confidence.

St. No.	Gauging Station	Discharge				Sediment Load			
		K-Value	*p*-Value	Changepoint	Year	K-Value	*p*-Value	Changepoint	Year
1	Sarati	204	0.107	-	1981	No data	No data	No data	No data
2	Takli	**284**	**0.007**	**Downward**	**1981**	**538**	**<0.0001**	**Downward**	**1990**
3	Wadakbal	**285**	**0.007**	**Downward**	**1990**	**351**	**<0.0001**	**Downward**	**1990**
4	Yadgir	**276**	**0.008**	**Downward**	**1983**	**427**	**<0.0001**	**Downward**	**1990**
5	Warunji	120	0.620	-	1989	100	0.1797	-	1997
6	Karad	163	0.289	-	1980	**425**	**0.0001**	**Downward**	**1981**
7	Bagalkot	**186**	**0.002**	**Downward**	**1983**	No data	No data	No data	No data
8	Cholachguda	94	0.195	-	2000	No data	No data	No data	No data
9	Huvinhedgi	136	0.124	-	1983	**196**	**<0.0001**	**Downward**	**1991**
10	K.Agraharam	52	0.518	-	1998	No data	No data	No data	No data
11	Shimoga	118	0.462	-	2004	139	0.2364	-	1989
12	Haralahalli	132	0.539	-	2000	No data	No data	No data	No data
13	Marol	180	0.291	-	2004	No data	No data	No data	No data
14	Oollenur	62	0.699	-	1982	No data	No data	No data	No data
15	Bawapuram	121	0.646	-	1982	**437**	**<0.0001**	**Downward**	**1994**

Table 3. *Cont.*

St. No.	Gauging Station	Discharge				Sediment Load			
		K-Value	*p*-Value	Changepoint	Year	K-Value	*p*-Value	Changepoint	Year
16	Mantralayam	108	0.474	-	1982	No data	No data	No data	No data
17	Pondugala	**132**	**0.031**	**Downward**	**1983**	No data	No data	No data	No data
18	Wadenapalli	**310**	**0.003**	**Downward**	**1983**	**320**	**0.0008**	**Downward**	**1991**
19	Keesara	123	0.628	-	1974	No data	No data	No data	No data
20	Vijayawada	**330**	**0.001**	**Downward**	**1983**	**296**	**<0.0001**	**Downward**	**1983**

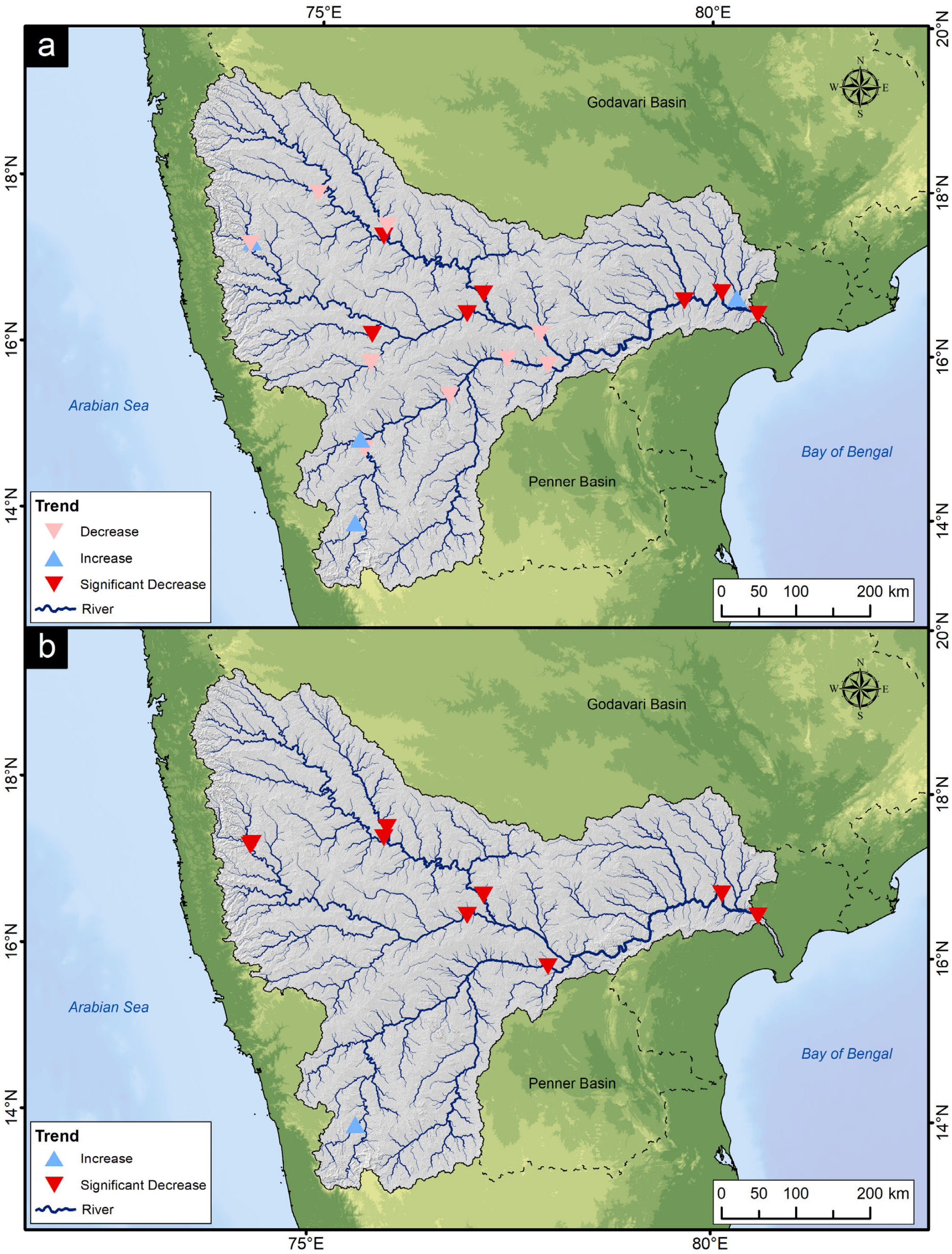

Figure 4. Spatial variability in (**a**) discharge and (**b**) sediment load at different gauging stations within the Krishna basin.

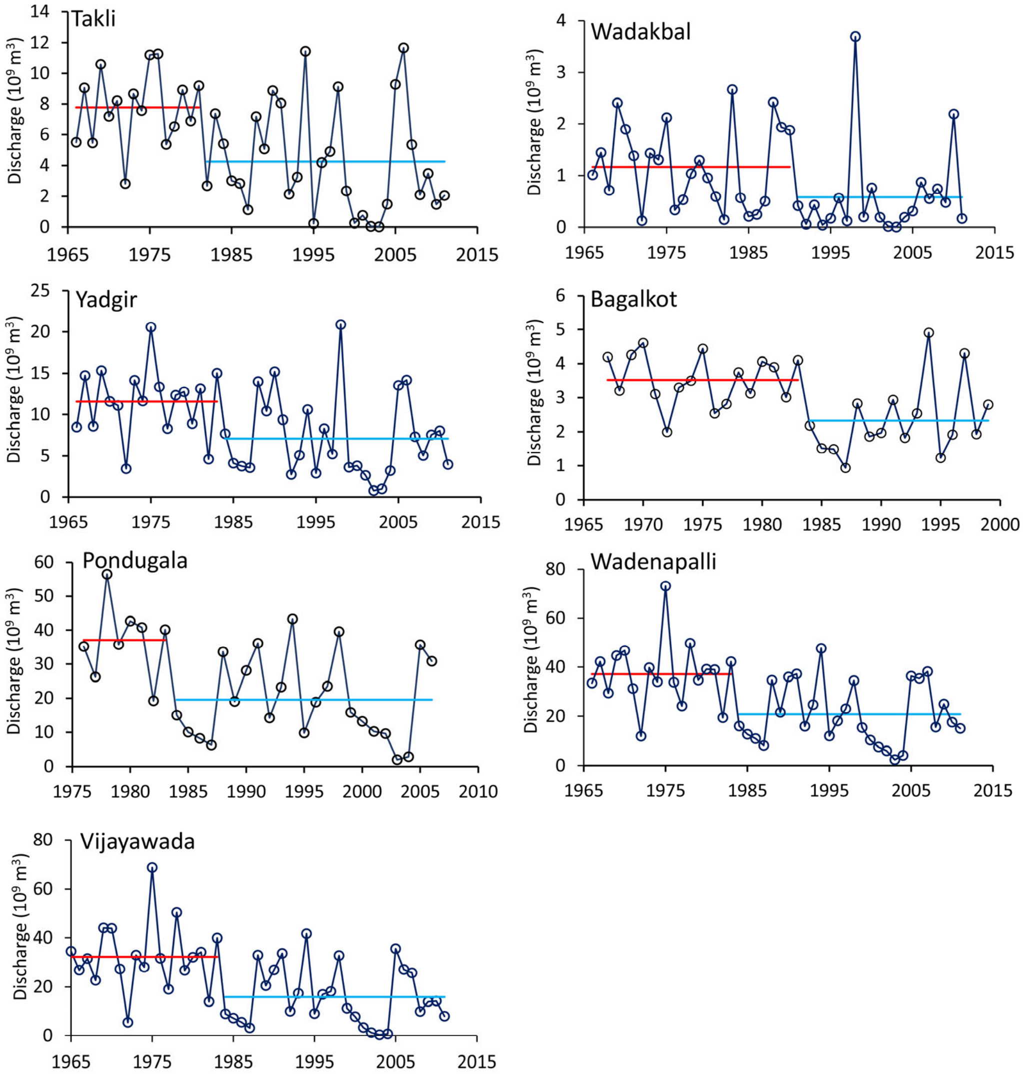

Figure 5. Abrupt shifts in annual water discharge identified at a 95% confidence level. The red and blue lines denote the average discharge before and after changepoint, respectively.

Results of the Pettitt test, which displays the upward and downward shifts in sediment load, are illustrated in Figure 6. Eight stations show an abrupt downward change in the Krishna basin at a 0.05 significance level except for two stations, i.e., Shimoga and Warunji. The early 1990s have been marked by a significant downturn for most of the stations in Krishna. Wadakbal, Takli, and Yadgir, located in the Bhima basin, revealed a sharp downward shift in the sediment load trends in 1990. Karad, located in the upper reaches of the upper Krishna basin, exhibited a change point in 1981. However, the terminal station of upper Krishna, Huvinhedgi, experienced a significant shift in 1991. Bawapuram station exhibited a significant decrease in sediment load in 1994, despite showing insignificant trends in discharge. Wadenapalli, located in the lower reach, experienced a change in discharge patterns in 1983, but the shift in sediment trends occurred later, in 1991. The terminal station Vijayawada indicated a distinct change point for sediment load in 1983.

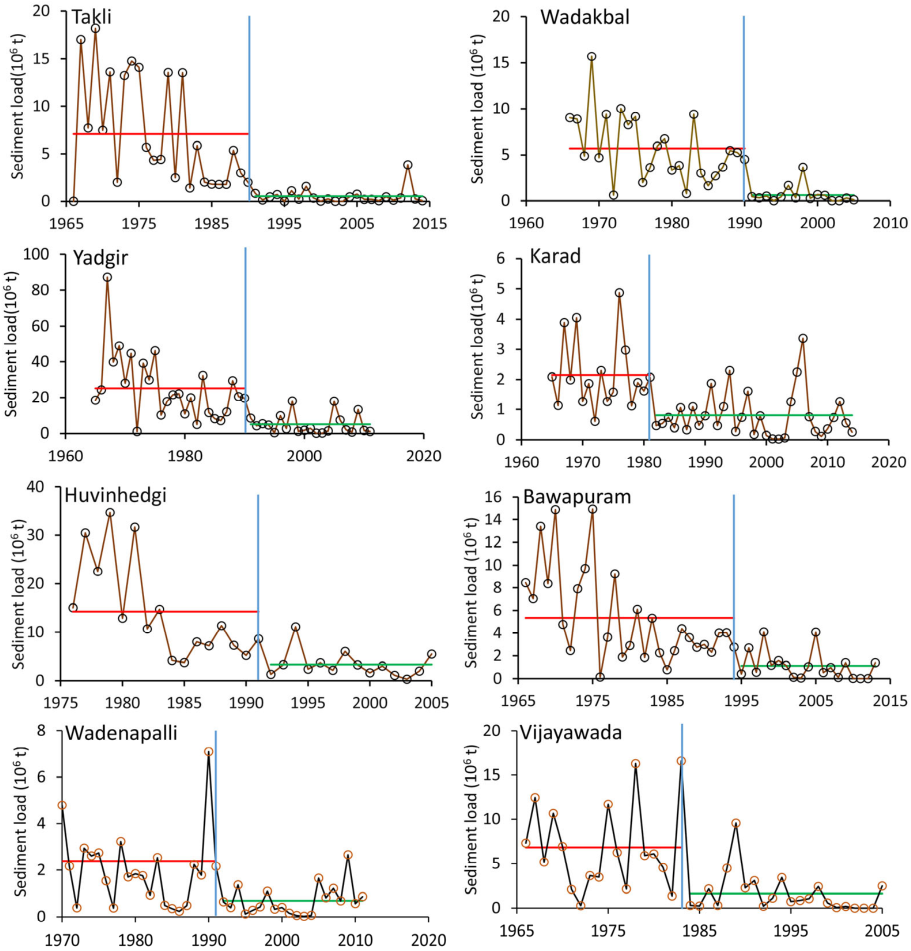

Figure 6. Abrupt shifts in annual sediment load identified at a 95% confidence level. The red and green lines represent average sediment load before and after changepoint, respectively.

4.4. Precipitation Trends

The long-term trend for annual rainfall in the Krishna basin reveals an insignificant increase (Table S1). Tungabhadra is the only sub-basin that indicates a significant increase in rainfall at a rate of 3.14 mm year^{-1} (Figure 7).

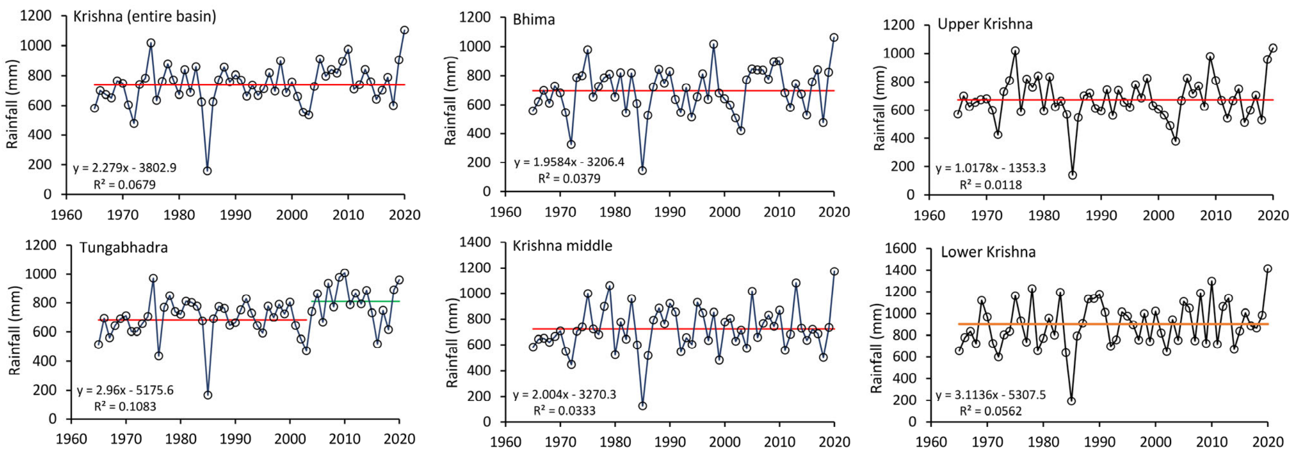

Figure 7. Precipitation patterns and abrupt shifts in rainfall identified at a 95% confidence level in the Krishna basin. The red and green lines represent the average rainfall before and after the changepoint, respectively. For some stations, the green line is absent because no changepoint was detected using the Pettitt test.

4.5. Double Mass Plots

The double mass curves of the cumulative discharge and cumulative rainfall reveal the linear relationship between the variables in most of the stations (Figure 8). However, distinct breaks in the curves have been identified in the cumulative sediment and cumulative rainfall (Figure 9). The breaks identified in the double mass curves corroborate very closely with the change points in the Pettitt test. The observed break at Bawapuram station in 1992 closely aligns with the change point in 1994, as detected by the Pettitt test. Likewise, the year 1990, identified through the double mass curve at Wadenapalli station, closely corresponds to the year 1991, detected by the Pettitt test. Given the sensitivity of double mass curves to any changes, multiple minor discontinuities have been observed in certain stations. Vijayawada was identified with a minor break in 1972, followed by a more pronounced decline after 1983. The notable breaks in the double mass curves for stations have been predominantly centred around the mid-1980s to mid-1990s.

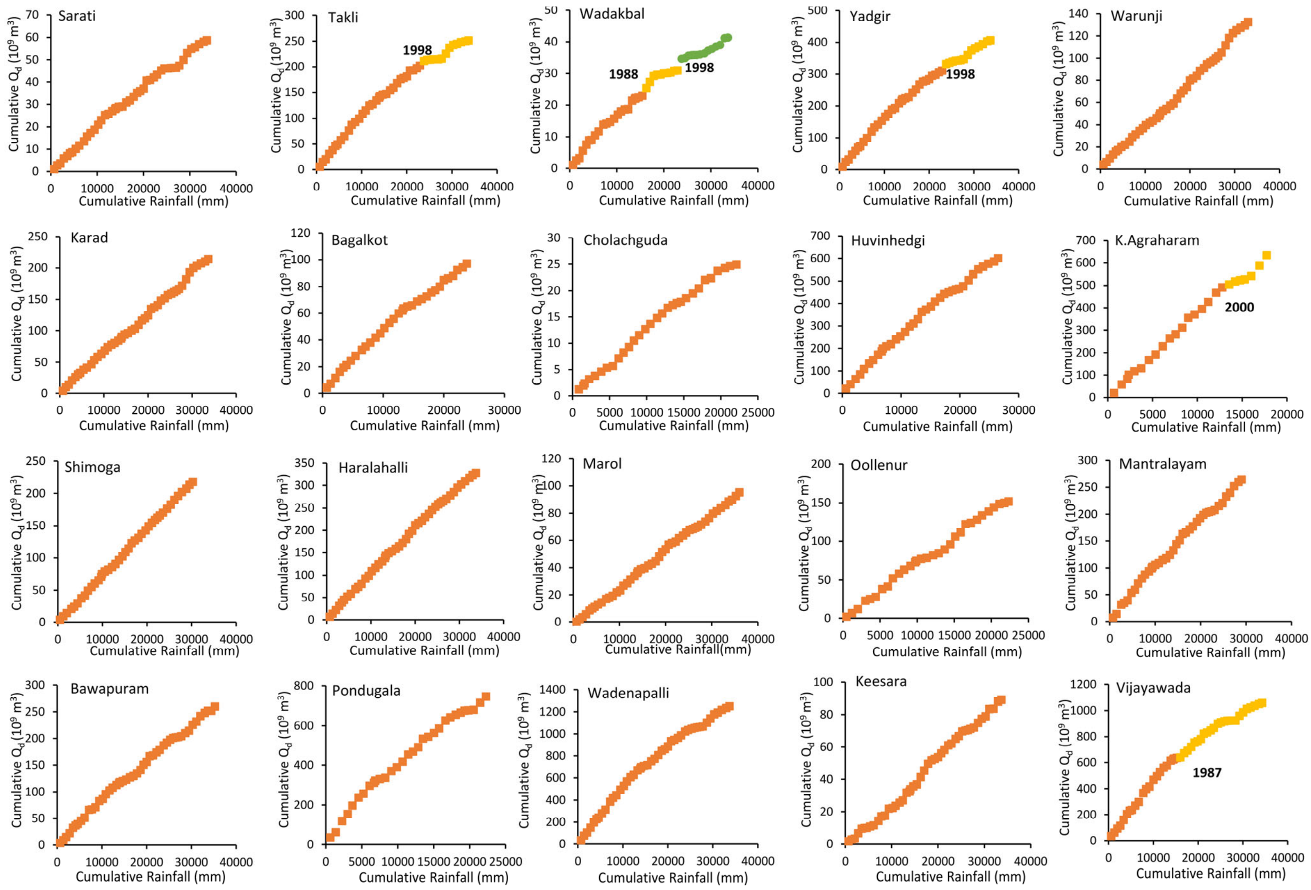

Figure 8. Double mass curve analysis of annual discharge and rainfall across Krishna basin stations. Different colours are provided to indicate sudden change in the curve pattern.

The significant slope changes in the cumulative Q_s and Q_d were pronounced in eight stations, indicating disturbances in the natural sediment load regime (Figure 10). There was a high degree of correspondence between the breaks observed in the discharge–sediment load relationship for each gauging station and the results of the Pettitt test analyses. A significant decrease in regression slope was observed at the terminal station, Vijayawada, following the 1983 transition point, with a decline from 0.25×10^9 t year^{-1} to 0.099×10^9 t year^{-1} (Figure 11). Shimoga and Warunji are the only stations displaying an unbroken linear relationship between sediment and discharge.

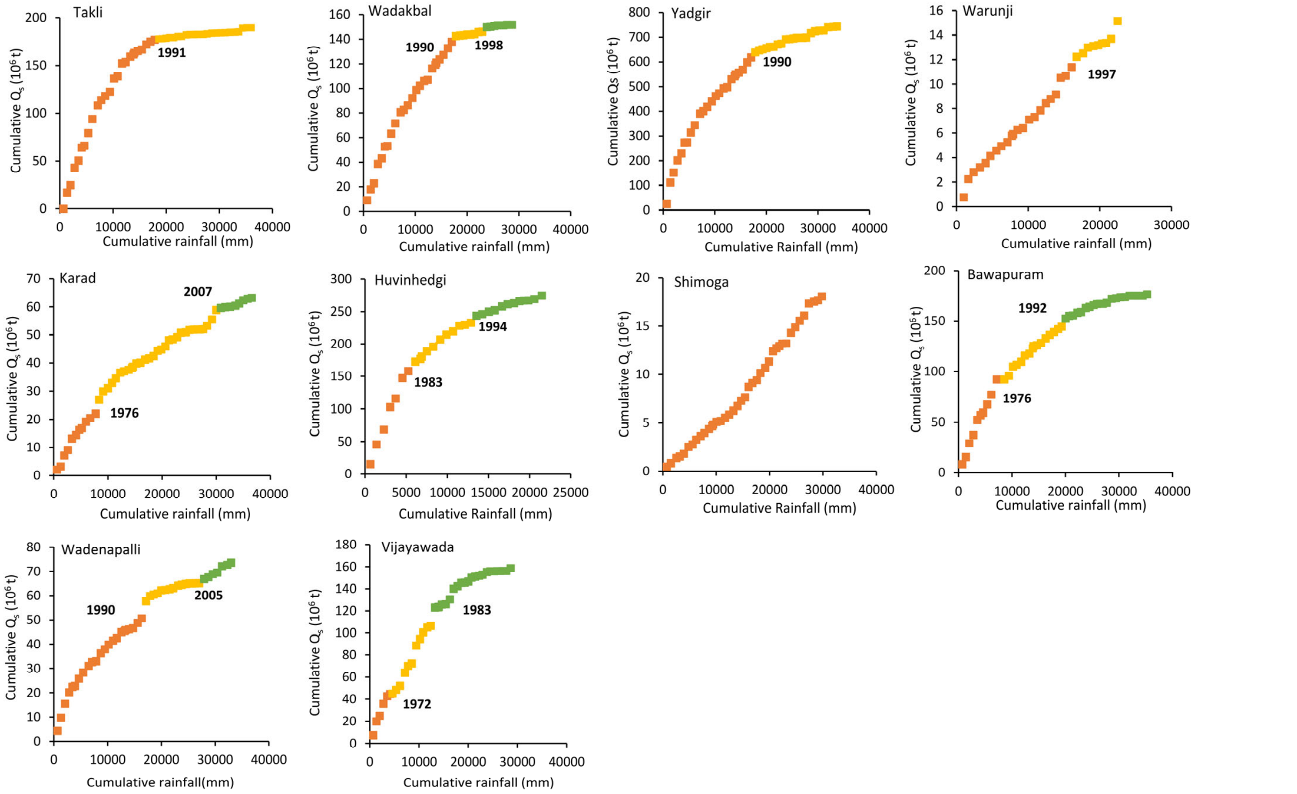

Figure 9. Double mass curve analysis of annual sediment and rainfall across Krishna basin stations. Different colours are provided to indicate sudden change in the curve pattern.

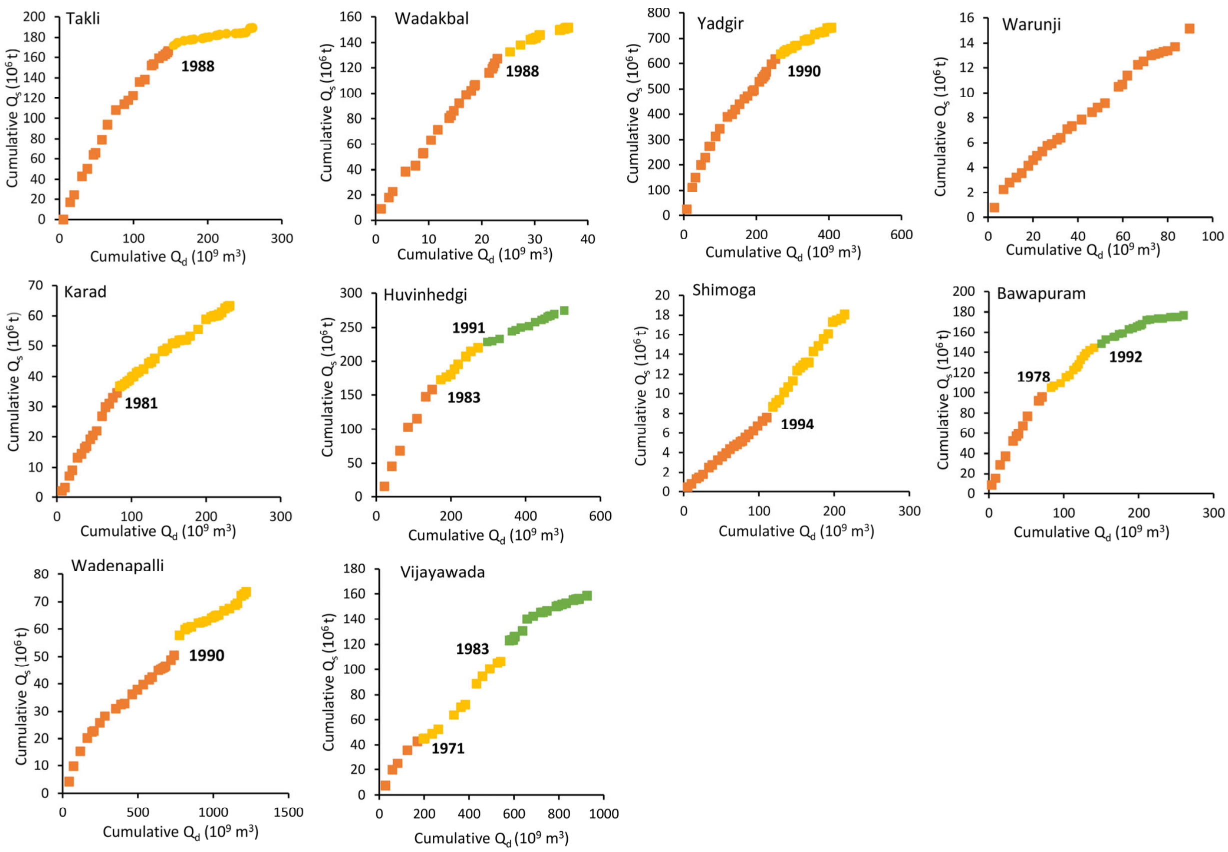

Figure 10. Double mass curve analysis of discharge and sediment load in the Krishna basin. Different colours are provided to indicate sudden change in the curve pattern.

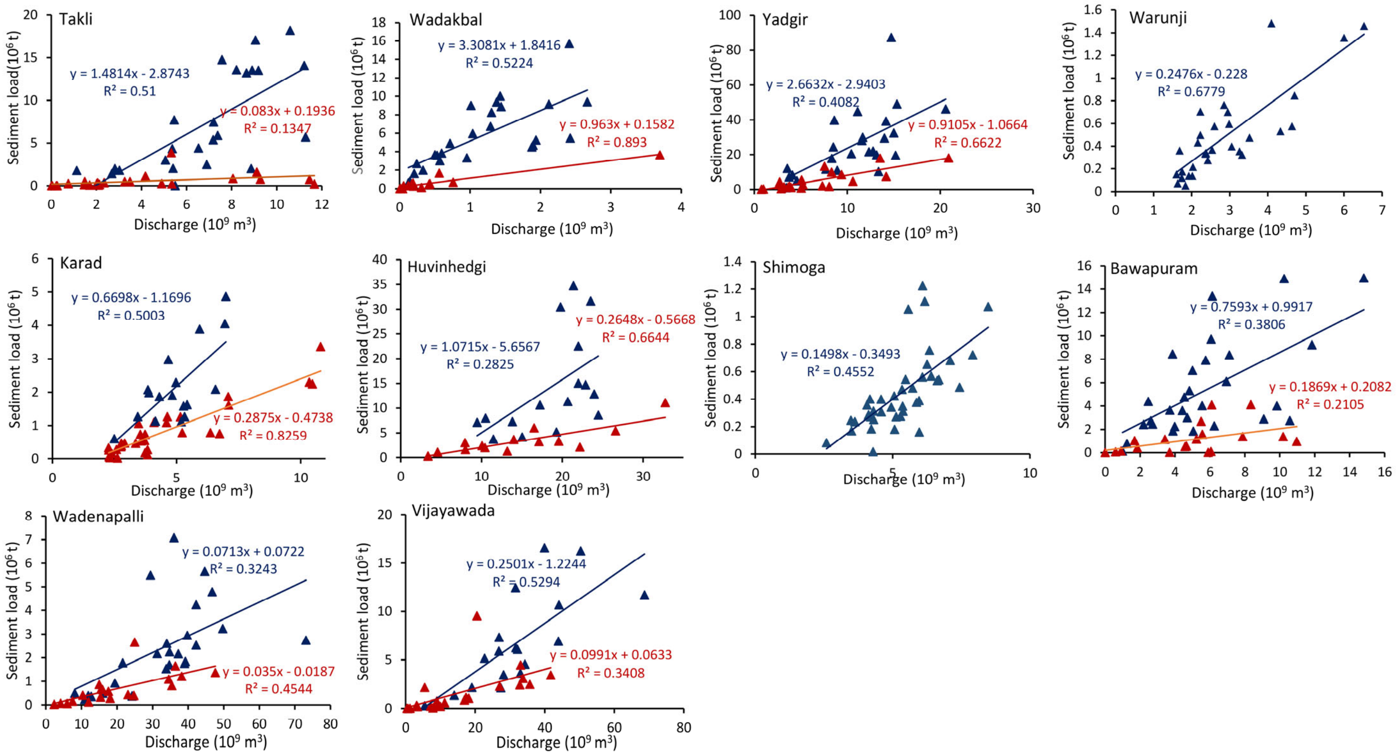

Figure 11. Double mass plot analysis of water and sediment load, differentiating pre- and post-change point periods using blue and red colours, respectively.

5. Discussion

5.1. Discharge and Sediment Load Dynamics in the Krishna Basin

The Krishna basin provides water resources to millions of populations and has experienced marked variability in discharge and sediment transport over the last forty years (Figures 2 and 3). A closer look at the spatial distribution of stream flow trends in the Krishna illustrates that stations exhibiting decreasing trends are predominantly situated in the middle and downstream reaches. Bhima, the longest tributary of the Krishna basin, contributes a significant amount of water and sediment to the trunk channel. Due to its proximity to the Western Ghats, the Bhima sub-basin experiences higher precipitation. However, the Bhima catchment is characterised by a dense network of hydraulic structures that impounds water, reducing downstream flow. With 341 dams, primarily for irrigation, the Bhima sub-basin has a high dam density [24]. Although these dams have limited individual storage capacity (less than 25 MCM), their cumulative effect on the basin's hydrology is considerable. By trapping water, they can lead to decreased sediment load in the river. The intensive development of irrigation infrastructure in the upper Bhima River basin over the past few decades, especially in the 1980s and 1990s, has resulted in a noticeable decrease in the river's water flow [38]. Wadakbal and Takli, located in the upper Bhima, have experienced a marked decrease in discharge by 43.75% and 42.77%, respectively. The Yadgir station, situated at the mouth of the Bhima sub-basin, has undergone a substantial 37% decline in discharge. Reduction in the discharge in the upper reaches was likely to have resulted in an overall decrease in the discharge by 47.73% in Vijayawada. Additionally, the upper Krishna basin at Huvinhedgi also showed a notable decline in water discharge. The Tungabhadra basin has not experienced any significant increases or decreases in discharge at its monitoring stations. This could be primarily due to the steady increase in rainfall the basin has received over the years.

Krishna is subjected to extensive regulation, with a considerable portion of their annual runoff being allocated for diverse purposes, including hydroelectric power generation, irrigation, and urban water supply [25]. Irrigation accounts for the vast majority of water usage in this basin, consuming 61.9 billion m^3 $year^{-1}$, whereas domestic and industrial water use is relatively modest at 1.6 and 3.2 billion m^3 $year^{-1}$, respectively [39]. Additionally, Biggs et al. [38] reported an increase in evaporation by 20% from 1901 to 1960 and 1990 to 2000 in the Krishna basin. This suggests that climatic variations and anthropogenic activities, including increased water demand for irrigation industrialisation and urbanisation, likely have influenced water discharge in the basin.

Discharge acts as a primary driver for sediment transport. Disruptions to flow patterns directly impact the river's ability to transport and deliver sediment to downstream areas. Terminal stations for Bhima, Tungabhadra, and upper Krishna sub-basins display a sharp downturn ranging from 77 to 80% in sediment load. Mean annual sediment transport at the Vijayawada station exhibits a declining trend, from 4.11×10^6 t $year^{-1}$ during 1971–1981 [20] to 3.96×10^6 t $year^{-1}$ during our study period (1966–2005). Most of the stations in the Krishna basin displayed a notable downward shift in discharge and sediment load during the mid-1980s and early 1990s. The construction of all the major dams and high-capacity reservoirs in the Krishna basin mainly occurred in 1970–1990, which remarkably corroborates the decline in sediment load at most stations. Two major large-scale dams, particularly Nagarjuna Sagar and Srisailam, have significantly reduced downstream flow and trapped sediment, reducing the storage capacity by 23.52 and 29.96%, respectively, leading to sediment starvation near the river mouth (Table 4).

Table 4. Loss of storage capacity and high siltation rates in reservoirs located in the Krishna basin.

Sr. No	Reservoir Name	Year of Completion	Original Capacity (MCM)	Last Surveyed	% Loss of Live Storage upto Last Survey	Siltation Rate (10^3 m^3 km^{-2} $year^{-1}$)
1	Koyna	1964	2980.68	2012	5.83	3.90
2	Jurala	1996	338.1	2012	19.13	0.05
3	Hidkal	1977	1434.14	2000	8.06	3.15
4	Ujjani	1980	3320	2012	12.77	0.82
5	Malaprabha	1972	1239.66	1991	6.34	3.61
6	Narayanpura	1982	1071.55	2007	26.84	0.24
7	Tungabhadra	1953	3751.17	2008	23.87	0.88
8	Srisailam	1984	8724.88	2011	29.96	0.50
9	Nagarjuna Sagar	1974	11,553	2009	23.52	0.28
10	Warna	2000	974.19	2003	5.05	8.59

For 75% of the stations (fifteen out of twenty stations), the cumulative discharge and cumulative rainfall relationship exhibited a strong linear correlation, suggesting a direct proportionality between precipitation and runoff (Figure 8). The findings indicate that climate variation is the predominant factor influencing discharge variability in these stations. On the contrary, multiple breaks identified by double mass plots of cumulative sediment and cumulative rainfall suggest that anthropogenic activities, rather than climate variability, are primarily responsible for the observed decline in the sediment load (Figure 9). The cumulative sediment and cumulative discharge curves exhibit a strikingly similar pattern. The decline in the sediment–discharge curves observed in the Bhima sub-basin after 1990, as evident at the Yadgir station, can be attributed to the construction of numerous small dams upstream and the completion of the Ujjani dam (3320 MCM) in 1980 (Figure 10). These structures have effectively trapped sediment, reducing the amount of sediment reaching downstream areas of Bhima. The significant decline in sediment observed at Vijayawada station coincides with the completion of major dams along the lower Krishna River. The construction of the Srisailam reservoir in 1984 and the Nagarjuna reservoir in 1974, both large-capacity reservoirs, has led to a substantial reduction in sediment transport downstream. This is evidenced by the observed breaks in the sediment–discharge curves at Vijayawada in 1971 and 1983, which align with the duration of completion of these reservoirs. Furthermore, the significant loss of live storage in both reservoirs (29.96% and

23.52%, respectively) highlights their effectiveness in trapping sediment and reducing its downstream transport (Table 4).

Table 5 summarises the percent contribution of climate change and anthropogenic activities in altering the sediment load in the Krishna basin. Bhima River experienced an 80.39% reduction in its sediment load after the abrupt change point. This reduction is mainly attributed to 106.9% of human-induced alteration. The sediment was estimated to increase by 5.57% to 26.92 × 10^6 t $year^{-1}$ by the observed precipitation of the anthropogenic period but instead experienced a pronounced decline. Similarly, 102% of human-influenced sediment decline has been observed in the upper Krishna basin. Tungabhadra, the only basin to witness an increasing trend in rainfall, also experienced a change of 113.3%, attributed to human activities. Despite increased precipitation, the sediment load in the Tungabhadra basin decreased by 79.64%. This suggests that human activities had a significantly stronger negative impact on the sediment transport than the positive influence of increased precipitation. The −13.3% of precipitation contribution indicates that rainfall played a significant opposite role in the sediment load decline of the Tungabhadra basin. Overall, the contribution of anthropogenic activities and climatic variations in the Krishna basin accounts for 82.7% and 17.1%, respectively. These findings indicate that anthropogenic activities have been the predominant force driving change in the basin, overshadowing the impact of climate variations.

Table 5. Percent contribution of anthropogenic activities and climate variation in the sediment load.

Sub-Basins	Period of Human Influence	Average Sediment in the Reference Period (Q_r) 10^6 t/yr	Average Sediment in the Anthropogenic Period (Q_s) 10^6 t/yr	Sediment Estimated by Precipitation in the Period (Q_p) 10^6 t/yr	Change			Percentage of Change (%)	
					Effects of Human-Induced Alteration $Q_{CH} = Q_s - Q_p$	Effects of Precipitation $Q_{CP} = Q_p - Q_r$	Change by Human and Precipitation $Q_C = Q_{CH} + Q_{CP}$	Human Influence (ΔQ_H)	Precipitation Influence (ΔQ_P)
Bhima	1991–2011	25.50	5.00	26.92	−21.92	1.42	−20.50	106.9	−6.9
Upper Krishna	1995–2005	12.83	2.82	13.10	−10.28	0.27	−10.01	102.7	−2.7
Tungabhadra	1993–2013	5.50	1.12	6.05	−4.71	0.55	−4.16	113.3	−13.3
Krishna	1984–2005	6.83	1.62	5.94	−4.32	−0.89	−5.21	82.9	17.1

5.2. Relationship Between Dam Construction and Sediment Load Decline

Ramesh and Subramanian [20] reported that the Krishna River carries significantly less sediment downstream of dams, with concentrations reduced to about 13% of upstream levels. Our findings reveal a marked downturn in sediment discharge at 80% of the gauging stations within the Krishna basin, with a distinct breakpoint occurring around the mid-1980s–1990s. The depreciating sediment load rates in the Krishna basin reveal the impact of intensive water consumption and the construction of water-impounding structures on riverine sedimentation processes. The increasing intensity and extent of anthropogenic activities and intervention align well with the decreasing rates of sediment in the Krishna basin. The construction of hydraulic structures and projects on various tributaries was largely observed after 1970 in the Krishna basin. The construction of the large dams has led to significant sediment trapping, altering natural sediment transport processes and causing downstream sediment deprivation. At present, >855 hydraulic structures (660 dams) have been constructed in the Krishna basin, and 90% of these dams primarily serve irrigation purposes [24]. The highest number of dams observed in the Bhima sub-basin (341) and Krishna upper sub-basin (188) entails the deposition of sediment in the storage units of dams and restriction of sediment flux downstream. The abrupt increase in cumulative storage capacity coincides with the swift decrease in the sediment load, mainly around the 1970s to mid-1980s (Figure 12a). The relationship between the sediment load and cumulative storage capacity of dams (significant at 95% confidence) indicates the direct impacts of dams on the sediment load decline in the Krishna basin (Figure 12b).

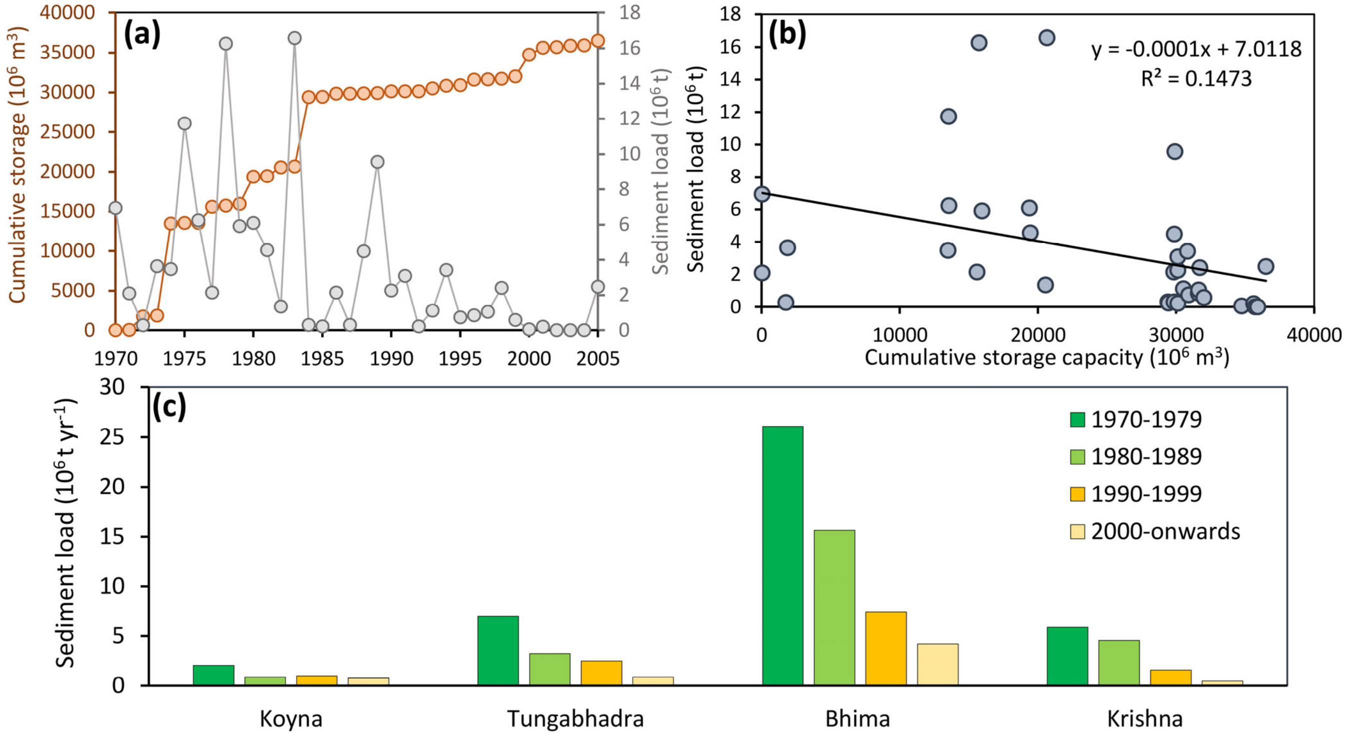

Figure 12. (**a**) Cumulative storage capacity of all reservoirs in the Krishna basin and sediment load variation at Vijayawada from 1970 to 2005. (**b**) Association between cumulative storage capacity and annual sediment load at Vijayawada. (**c**) Decadal sediment load changes in the Krishna and its major tributaries.

Figure 12c shows the decadal decline in the important tributaries of the Krishna River. The terminal station Vijayawada shows a mean annual sediment load of 5.87 Mt between 1970 and 1979, which reduced to 4.56 Mt in 1980 and 1989, 1.57 Mt in 1990 and 1999, and 0.46 Mt in 2000 and onwards, respectively. The Bhima and Tungabhadra rivers, significant contributors of sediment to the Krishna basin, have experienced a notable decline in sediment load over the past few decades, leading to a reduction in the overall sediment reaching the basin's terminal station. It is notable that despite having the second largest catchment in Peninsular India, the sediment contribution of Krishna is relatively less than many other Peninsular rivers [17,20]. Sediment load entering the Krishna delta, as measured at the Prakasam Barrage near Vijayawada, exhibited a dramatic decline from approximately 9.0 Mt year^{-1} during 1965–1969 to nearly zero by 2010–2015 [22]. Sediment flux reduction near downstream rivers can significantly affect coastal ecosystems and eventuate coastal erosion. Fluctuations in sediment load have contributed to shoreline erosion through increased wave energy and sediment deprivation at the coast [40].

5.3. Impact of Reduced Sediment Load

The ever-changing boundary between land and sea through time is of elemental importance to coastal engineers and scientists [41,42]. According to the Intergovernmental Panel on Climate Change (IPCC) 2023 report, a significant rise in global sea levels is projected for the 21st century, with the regional relative sea level rise anticipated to reach within 20% of the global average along two-thirds of the world's coastlines [43]. Upstream modifications constitute a primary anthropogenic driver of change in global deltas and coastlines. Excessive water consumption and water diversions have significantly reduced the water flow of many large rivers around the world, such as the Colorado, Ebro, Huanghe, Indus, Nile, and Po rivers [44]. Syvitski et al. [45] demonstrated that human activities, including dam construction, groundwater extraction, and land-use change, are accelerating the subsidence of deltas globally. This increased vulnerability to flooding and saltwater intrusion poses significant risks to millions of people. Tessler et al. [46] included the Krishna-Godavari, Ganges, and Brahmaputra deltas among the 48 globally significant deltas identified as being at high risk due to human-induced pressures. The planned construction of additional dams within the Krishna River basin could exacerbate coastal erosion and land loss in the Krishna delta, potentially leading to irreversible damage akin to the situation observed in the neighbouring Godavari-Krishna delta [22]. Krishna and Godavari, with their combined hydrocarbon reserves of 1.06 million tons [47], are susceptible to coastal subsidence due to the extraction of natural gas from the underlying sediments [25]. The Krishna delta has undergone a 25-year retreat dominated by erosion due to the significantly reduced water and sediment inflow caused by upstream reservoir and barrage construction [48]. Sediment retention is likely to accelerate erosion, leading to beach loss, dune retreat, and increased vulnerability to storm surges and sea-level rise. The consequences are far-reaching, affecting biodiversity, coastal protection, and the livelihoods of millions of people who depend on deltaic resources.

6. Conclusions

The Krishna basin serves as a crucial water resource for millions of people in India. This study comprehensively examines sediment and water discharge trends within the Krishna basin. This downward trend in sediment transport is most pronounced at approximately 80% of the stations, with change points concentrated around the mid-1980s and early 1990s. The terminal station, Vijayawada, experienced a marked 76% decrease in mean sediment load from 1966 to 2005 after its change point. Double mass curve analysis corroborates these findings, indicating significant changes in the sediment-water relationship. The widespread construction of large-scale reservoirs coincides with these changes, suggesting a strong link between human intervention and the observed decline in discharge and sediment load. The findings of this study reveal that anthropogenic influences have exerted a more dominant influence on the basin's sediment dynamics than climate variability. The effects of human activities are more profoundly observed in the sub-basins. The loss of live storage capacity and accelerated siltation rates in upstream reservoirs significantly disrupt the natural flow regime and sediment transport processes. A primary limitation of this study is the availability of sediment and discharge data, restricted to specific periods. For instance, the absence of data post-2005 for Vijayawada hinders the assessment of recent trends. Overall, this study emphasises the need for a sustainable approach towards water management in the Krishna basin and coastal management strategies to mitigate the adverse effects of sediment starvation, which include coastal erosion, loss of coastal wetlands, altered river morphology, and excessive reservoir sedimentation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16243648/s1, Figure S1: Linear regression equations of the annual sediment load and annual rainfall in pre-anthropogenic period; Table S1: Results of linear regression and Mann-Kendall trend test for the rainfall time-series for sub-basins in the Krishna.

Author Contributions: Conceptualization, S.D.; methodology, H.J. and S.D.; software, H.J. and S.D.; validation, S.D.; formal analysis, H.J.; investigation, H.J. and S.D.; resources, S.D.; data curation, S.D.; writing—original draft preparation, H.J.; writing—review and editing, H.J., A.M.K. and S.D.; visualization, H.J. and S.D.; supervision, S.D.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The APC was waived by the Water (MDPI) editorial office.

Data Availability Statement: Discharge and suspended sediment concentration data were obtained from Central Water Commission (CWC, India). Rainfall data was taken from https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html, (accessed on 12 December 2024). Reservoir and dam data was taken from the Krishna Basin Report published by CWC and NRSC (https://indiawris.gov.in/, (accessed on 12 December 2024)). For visualization, SRTM Digital Elevation Model was obtained from http://srtm.csi.cgiar.org, (accessed on 12 December 2024). All data computed and generated are provided within the manuscript. Any additional background data can be made available upon request to the authors.

Acknowledgments: This paper is a part of H.J.'s M.Sc. thesis. H.J. and A.M.K. thank the Department of Geography, Savitribai Phule Pune University, for providing all the necessary facilities to carry out this research. The director of the India Meteorological Department (IMD, Pune) is acknowledged for providing the rainfall data. Constructive comments from two reviewers improved the manuscript significantly. S.D. is grateful to the Water Editorial Office (MDPI) for the invitation to submit this manuscript and for offering a full waiver of the APC.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Walling, D.E.; Fang, D. Recent trends in the suspended sediment loads of the world's rivers. *Glob. Planet. Chang.* **2003**, *39*, 111–126. [CrossRef]
2. Meybeck, M.; Vörösmarty, C. Fluvial filtering of land-to-ocean fluxes: From natural Holocene variations to Anthropocene. *Comptes. Rendus. Geosci.* **2005**, *337*, 107–123. [CrossRef]
3. Walling, D.E. Human impact on land-ocean sediment transfer by the world's river. *Geomorphology* **2006**, *79*, 192–216. [CrossRef]
4. Walling, D.E. Human impact on the sediment loads of Asian rivers. *IAHS Pub.* **2011**, *350*, 37–51.
5. Miao, C.; Ni, J.; Borthwick, A.G.L.; Yang, L. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Glob. Planet. Chang.* **2011**, *76*, 196–205. [CrossRef]
6. Wei, J.; He, X.; Bao, Y. Anthropogenic impacts on suspended sediment load in the Upper Yangtze river. *Reg. Env. Chang.* **2011**, *11*, 857–868. [CrossRef]
7. Wu, Z.; Zhao, D.; Syvitski, J.P.M.; Saito, Y.; Zhou, J.; Wang, M. Anthropogenic impacts on the decreasing sediment loads of nine major rivers in China, 1954–2015. *Sci. Tot. Env.* **2020**, *739*, 139653. [CrossRef] [PubMed]
8. Syvitski, J.; Ángel, J.R.; Saito, Y.; Overeem, I.; Vörösmarty, C.J.; Wang, H.; Olago, D. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* **2022**, *3*, 179–196. [CrossRef]
9. Das, S.; Kandekar, A.M.; Sangode, S.J. Natural and anthropogenic effects on spatio-temporal variation in sediment load and yield in the Godavari basin, India. *Sci. Total Environ.* **2022**, *845*, 157213. [CrossRef] [PubMed]
10. Li, X.; Liu, J.P.; Saito, Y.; Nguyen, V.L. Recent evolution of the Mekong Delta and the impacts of dams. *Earth Sci. Rev.* **2017**, *175*, 1–17. [CrossRef]
11. Best, J. Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **2018**, *12*, 7–21. [CrossRef]
12. Dethier, E.N.; Renshaw, C.E.; Magilligan, F.J. Rapid changes to global river suspended sediment flux by humans. *Science* **2022**, *376*, 1447–1452. [CrossRef] [PubMed]
13. Carriquiry, J.D.; Sánchez, A. Sedimentation in the Colorado River delta and Upper Gulf of California after nearly a century of discharge loss. *Mar. Geol.* **1999**, *158*, 125–145. [CrossRef]
14. Guillén, J.; Palanques, A. A historical perspective of the morphological evolution in the lower Ebro River. *Environ. Geol.* **1997**, *30*, 174–180. [CrossRef]
15. Wiegel, R.L. Nile delta erosion. *Science* **1996**, *272*, 337. [CrossRef]
16. Wang, H.; Saito, Y.; Zhang, Y.; Bi, N.; Sun, X.; Yang, Z. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. *Earth Sci. Rev.* **2011**, *108*, 80–100. [CrossRef]
17. Das, S. Dynamics of discharge and sediment load in Peninsular Indian rivers (1965–2015). *Sci. Total Environ.* **2021**, *799*, 149372. [CrossRef]
18. Syvitski, J.P.; Vörösmarty, C.J.; Kettner, A.J.; Green, P. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* **2005**, *308*, 376–380. [CrossRef]
19. Restrepo, J.D.; Escobar, H.A. Sediment load trends in the Magdalena River basin (1980–2010): Anthropogenic and climate-induced causes. *Geomorphology* **2018**, *302*, 76–91. [CrossRef]
20. Ramesh, R.; Subramanian, V. Temporal, spatial and size variation in the sediment transport in the Krishna River basin, India. *J. Hydrol.* **1988**, *98*, 53–65. [CrossRef]
21. Rao, K.N.; Saito, Y.; Kumar, K.C.V.N.; Kubo, S.; Pandey, S.; Li, Z.; Rajawat, A.S. Holocene evolution and Anthropocene destruction of the Krishna Delta on the east coast of India: Delta lobe shifts, human impacts, and sea-level history. *Mar. Geol.* **2020**, *427*, 106229.
22. Rao, K.N.; Saito, Y.; Nagakumar, K.C.V.; Demudu, G.; Rajawat, A.S.; Kubo, S.; Li, Z. Palaeogeography and evolution of the Godavari delta, east coast of India during the Holocene: An example of wave-dominated and fan-delta settings. *Palaeogeography* **2015**, *440*, 213–233.
23. Nikam, B.R.; Garg, V.; Jeyaprakash, K.; Gupta, P.K.; Srivastav, S.K.; Thakur, P.K.; Aggarwal, S.P. Analyzing future water availability and hydrological extremes in the Krishna basin under changing climatic conditions. *Arab. J. Geosci.* **2018**, *11*, 581. [CrossRef]
24. Central Water Commission. *Krishna Basin*; Ministry of Water Resources Government of India: New Delhi, India, 2014.
25. Panda, D.K.; Kumar, A.; Mohanty, S. Recent trends in sediment load of the tropical (Peninsular) river basins of India. *Glob. Planet. Change* **2011**, *75*, 108–118. [CrossRef]

26. Mann, H.B. Nonparametric tests against trend. *Econom. J. Econom. Soc.* **1945**, *13*, 245–259. [CrossRef]
27. Kendall, M.G. *Rank Correlation Methods*, 4th ed.; Charles Griffin: London, UK, 1975.
28. Sen, P.K. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
29. Das, S.; Sangode, S.J.; Kandekar, A.M. Recent decline in discharge and Sediment load in the Godavari basin, India (1965–2015). *Catena* **2021**, *206*, 105537. [CrossRef]
30. Pettitt, A.N. A non-parametric approach to the change-point problem. *J. R. Stat. Soc. Ser. C (Appl. Stat.)* **1979**, *28*, 126–135. [CrossRef]
31. Cavadias, G.S. *A Survey of Current Approaches to Modeling of Hydrological Time Series with Respect to Climate Variability and Change. Report WCASP-23*; World Meteorological Organization: Geneva, Switzerland, 1992.
32. Moraes, J.M.; Pellegrino, G.Q.; Ballester, M.V.; Martinelli, L.A.; Victoria, R.L.; Krusche, A. Trends in hydrological parameters of a southern Brazilian watershed and its relation to human induced changes. *Water Resour. Manag.* **1998**, *12*, 295–311. [CrossRef]
33. Verstraeten, G.; Poesen, J.; Demarée, G.; Salles, C. Long-term (105 years) variability in rain erosivity as derived from 10-min rainfall depth data for Ukkel (Brussels, Belgium): Implications for assessing soil erosion rates. *J. Geophys. Res.* **2006**, *111*, D22109. [CrossRef]
34. Mu, X.; Zhang, L.; McVicar, T.R.; Chille, B.; Gau, P. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. *Hydrol. Process.* **2007**, *21*, 2124–2134. [CrossRef]
35. Zhang, S.; Lu, X.X. Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijiang, China. *Catena* **2009**, *77*, 130–142. [CrossRef]
36. Mu, X.M.; Zhang, X.Q.; Gao, P.; Wang, F. Theory of double mass curves and its applications in hydrology and meteorology. *J. China Hydrol.* **2010**, *30*, 47–51.
37. Gao, P.; Zhang, X.; Mu, X.; Wang, F.; Li, R.; Zhang, X. Trend and change-point analyses of discharge and Sediment load in the Yellow River during 1950–2005. *Hydrol. Sci. J.* **2010**, *55*, 275–285. [CrossRef]
38. Biggs, T.; Gaur, A.; Scott, C.; Thenkabail, P.; Gangadhara Rao, P.; Gumma, M.K.; Turral, H. *Closing of the Krishna Basin: Irrigation, Streamflow Depletion and Macroscale Hydrology*; IWMI: Colombo, Sri Lanka, 2007; Volume 111.
39. Rooijen, D.J.; Turral, H.; Biggs, T.W. Urban and industrial water use in the Krishna Basin, India. *Irrig. Drain.* **2008**, *58*, 406–428. [CrossRef]
40. Reshma, K.N.; Murali, R.M. Current status and decadal growth analysis of Krishna-Godavari delta regions using remote sensing. *J. Coast. Res.* **2018**, *85*, 1416–1420. [CrossRef]
41. Douglas, B.C.; Crowell, M. Long-term shoreline position prediction and error propagation. *J. Coast. Res.* **2000**, *16*, 145–152.
42. Boak, E.H.; Turner, I.L. Shoreline definition and detection: A review. *J. Coast. Res.* **2005**, *21*, 688–703. [CrossRef]
43. Lee, H.; Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.; Park, Y. *IPCC, 2023: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023.
44. Syvitski, J.P.; Saito, Y. Morphodynamics of deltas under the influence of humans. *Glob. Planet. Chang.* **2007**, *57*, 261–282. [CrossRef]
45. Syvitski, J.P.; Kettner, A.J.; Overeem, I.; Hutton, E.W.; Hannon, M.T.; Brakenridge, G.R.; Nicholls, R.J. Sinking deltas due to human activities. *Nat. Geosci.* **2009**, *2*, 681–686. [CrossRef]
46. Tessler, Z.D.; Vörösmarty, C.J.; Grossberg, M.; Gladkova, I.; Aizenman, H.; Syvitski, J.P.; Foufoula-Georgiou, E. Profiling risk and sustainability in coastal deltas of the world. *Science* **2015**, *349*, 638–643. [CrossRef]
47. Rao, G.N. Sedimentation, stratigraphy, and petroleum potential of Krishna—Godavari basin, east coast of India. *Am. Assoc. Pet. Geol. Bull.* **2001**, *85*, 1623–1643.
48. Gamage, N.; Smakhtin, V. Do river deltas in east India retreat? A case of the Krishna Delta. *Geomorphology* **2009**, *103*, 533–540. [CrossRef]