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Spatio-temporal variation of water flow and sediment discharge in the Mahanadi River, India

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ABSTRACT

The transport of sediments by rivers to the oceans represents an important link between the terrestrial and marine ecosystem. Therefore, this work aims to study spatio-temporal variation of the sediment discharge and erosion rate in the Mahanadi river, one of the biggest rivers in India, over past three decades vis-à-vis their controlling factors. To understand the sediment load variation, the trend analysis in the time series data of rainfall, water and sediment discharge of the Mahanadi river were also attempted. The non-parametric Mann-Kendall and Sen's methods were used to determine whether there was a positive or negative trend in the time series data with their statistical significance. The occurrence of abrupt changes was detected using Pettitt test. The trend test result represents that sediment load delivered from the Mahanadi river to the global ocean has decreased sharply at the rate of 0.515×10^6 tons/year between 1980 and 2010. Water discharge and rainfall in the basin showed no significant decreasing trend except at only one tributary. The decline in sediment discharge from the basin to the Bay of Bengal is mainly due to the increase in the number of dams, which has recorded the increase from 70 to 253 during the period of 1980 to 2010. Over the past 30 years the Mahanadi river has discharged about 49.0 ± 20.5 km^3 of water and $17.4 \pm 12.7 \times 10^6$ tons of sediment annually to the Bay of Bengal whereas the mean erosional rate is 265 ± 125 tons/km^2/year over the period of 30 years in the basin. Based on the current data (2000–2001 to 2009–2010), sediment flux and water discharge to the ocean are $12 \pm 5 \times 10^6$ tons/year and 49 ± 16 km^3/year respectively; and ranking Mahanadi river second in terms of water discharge and sediment flux to the ocean among the peninsular rivers in India.

1. Introduction

Weathering and erosion in drainage basin are the major natural processes which supply dissolve and particulate material to the river water. Rivers are the major dynamic geological transporting media of the dissolved and particulate materials to the oceans and act as a major link between the terrestrial and marine systems. Transportation of materials from continents to the oceans has played an important role on cycling of many chemical elements at the Earth's surface. Fluvial transport of materials to the oceans has been received wide attention during last five decades (Gibbs, 1967; Garrels and Mackenzie, 1972; Ming-Hui et al., 1982; Vaithiyanathan et al., 1992; Dai and Liu, 2013). Quantitative estimation of sediment transport by fluvial system has been made on a global scale by several researchers (Holeman, 1968; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Syvitski et al., 2003; Walling and Fang, 2003). The erosion and sediment transport in a number of Indian rivers have been reported by Abbas and Subramanian (1984); Biksham and Subramanian (1988); Ramesh and Subramanian (1988); Vaithiyanathan et al. (1992); Jain and Sinha (2004); Gupta and Chakrapani (2005); Roy and Sinha (2014). More than 90% of continental weathering products are transported by rivers to the ocean (Syvitski et al., 2003). The current best estimate of global riverine sediment flux to the ocean is 18×10^9 tons/year (Milliman and Syvitski, 1992). About 15–20% of the global sediment flux has been transported by the rivers flowing through Indian subcontinent (Gupta et al., 2012).

Continental erosion has a strong influence on landscape evolution. Erosion and sediments flux are a function of river runoff, basin morphology, tectonics, bedrock lithology, soil type, vegetation cover, climate, basin area and human activity (Milliman and Syvitski, 1992; Chakrapani and Subramanian, 1993; Harrison, 2000). Evidences from long-term sediment load record indicate that river sediment fluxes are sensitive to many anthropogenic influences, including construction of reservoir, land clearance and land use change, other forms of land disturbances, including mining activity, soil and water conservation measures and sediment control programmes (Walling and Fang, 2003). The river-borne sediment flux to the near-shore and oceans is important for understanding coastal and deltaic processes, river behaviour and global biogeochemistry including burial of carbon.

Water discharge and sediment load of most of the world's rivers have experienced great changes due to variation of climate and anthropogenic impacts in the drainage basin. Detecting trends of long time

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series data on water discharge and sediment load is important for understanding impact of natural climate change and anthropogenic disturbances as well as their complex interactions on fluvial system (Walling, 1995, 1997). It can also helpful for the future water resource management. The best estimation of sediment load by the world's rivers on a global scale by Milliman and Syvitski (1992) is dates back. However, even this estimation of sediment load is open to some uncertainty due to the lack of data for some small and middle rivers, which have a substantially large sediment yield. Recent studies on a global scale have shown marked decrease in water discharge and sediment load delivery to ocean. Major rivers of the world such as the Colorado (Meade and Parker, 1985), the Mississippi (Walling and Fang, 2003), the Indus (Stanley and Warne, 1998), the Nile (Walling and Fang, 2003), the Yangte (Yang et al., 2006), and the Yellow (Wang et al., 2006), exhibited substantial reduction in sediment supply. Most of the Indian rivers like the Narmada (Gupta and Chakrapani, 2005), the Krishna (Gamage and Smakhtin, 2009), the Godavari, the Cauvery and the Mahanadi (Panda et al., 2011) have also shown a decreasing trend in sediment load delivery to the ocean. Several studies have been shown that coastal ecosystem faces serious problems due to drastically reduction in sediment discharge. Winterwerp et al. (2005) reported serious coastal erosion in the Chao Phraya delta of Thailand as a result of decrease in sediment load delivery due to dam construction. The major Indian river basins like the Krishna river basin (Biggs et al., 2007; Gamage and Smakhtin, 2009), the Narmada river basin (Gupta and Chakrapani, 2005), the Godavari, the Mahadnadi-Brahmani basins (Panda et al., 2011) were at greater risk to coastal erosion. Hence, it is essential to focus on recent estimation of sediment loads by the individual world's rivers including small and middle rivers.

The Mahanadi is one of the largest Indian peninsular rivers in terms of water discharge and suspended sediment transport. Chakrapani and Subramanian (1990, 1993) worked on sediment load of the Mahanadi basin using the limited data of water discharge for ten years (1977–1978 to 1986–1987) and sediment discharge data for five years (1980–1981 to 1983–1984 and 1985–1986). The recent work has been done by Panda et al. (2011) on the sediment load of the Mahanadi basin using water discharge and suspended sediment data (1993–1994 to 2002–2003) by using 14 stations but reported only at Tikarapada, which is the farthest downstream location. Panda et al. (2013a) carried a very detailed work on the variation of stream flow and rainfall in the Mahanadi basin by using long term data (1972–2007). However, these recent studies have not focused on the variation of sediment load and erosion characteristics among the sub-basins and their controlling factors. The main objective of this study is to quantifying the annual mean sediment load discharge, erosion rate and water discharge vis-a-vis to detect their gradual and abrupt changes in the Mahanadi river and its major tributaries during the last 30 years. Also the factors influencing both spatial and temporal variations of water discharge, sediment load and erosion rate in the basin are explored.

2. Study area

The Mahanadi is the second largest peninsular river in terms of water potential and flood producing capacity next to the Godavari river in India (India-WRIS, 2015). It flows from west to east with a total length of about 851 km, of which 357 km lies in Chhattisgarh and 494 km lies in Odisha (Sundaray et al., 2009) and draining into the Bay of Bengal. The Mahanadi river basin lies north-east of Deccan between 19°20′ and 23°35′N and 80°30′ and 86°50′E with a drainage area of about 141,600 km^2 (CWC, 2012). The Mahanadi river originates from a pool 6 km from Pharsiya village to the south of Nagri Town in Raipur district of Chhattisgarh state, 457 m above mean sea level. It flows over different geological formations of Eastern Ghats and adjacent areas and joins the Bay of Bengal at Paradip and Nuagarh after dividing into different branches in the deltaic area (Sundaray et al., 2009; Dixit et al., 2013). The major part of the Mahanadi river basin lies over the states of Chhattisgarh (75,136 km^2), Odisha (65,580 km^2) and comparatively smaller parts of Bihar (635 km^2) and Maharashtra (238 km^2) (Asokan and Dutta, 2008). There are 14 major tributaries joins on both the banks out of which 12 are joining upstream of Hirakud reservoir and 2 downstream of it. The major six tributaries which drain into main channel upstream of Hirakud reservoir on the left bank of the Mahanadi river are the Seonath, the Hasdeo, the Borai, the Mond, the Kelo and the Ib. The six major tributaries join upstream of Hirakud reservoir on the right bank of the river namely and the Jonk, the Pairi, Kanji, the Lilar, the Lath and the Sukha and two tributaries namely the Tel and the Ong join downstream of it. The basin is characterized by tropical climate with a mean annual rainfall of 135 cm, whereas the annual rainfall for the entire basin varies from 99.3 cm to 150 cm. A major portion of the precipitation in the basin takes place during monsoon (June to September), which accounts for about 85–90% of the total precipitation. December and January are the coldest months with the minimum temperature of 12 °C whereas April and May are the hottest months in this region where maximum temperature ranges from 39 °C to 40 °C. Western portion of the basin records the lowest and highest temperature as compared to eastern portion and delta area during winter and summer respectively. The highest relative humidity in the basin varies from 68% to 87%, and occurs during July/August and the lowest relative humidity occurs during April/May and varies from 9% to 45%. The average highest relative humidity for the basin is 82% and the average lowest relative humidity is 31.6% (Water Year Book, 1997). Approximately 54% of basin area is under agricultural land cover, 32% under forest cover and remaining 14% area are under wasteland, waterbodies, built up land, etc. (India-WRIS, 2015). Geological map of the Mahanadi river basin with sampling stations is shown in Fig. 1. The basin geology consists of four major components, such as granites, Khondalites, charnockite, and gneiss of the Precambrian; the limestones and shales of Proterozoic; sandstone, shale and conglomerate of Gondwana Supergroup; and the recent laterite and deltaic alluvium of the river with littoral deposits of coastal regions (Panigrahy and Raymahashay, 2005). The different lithologies of the basin area comprises of 34% of granite suite, 7% of Khondalite suite, 15% of charnockite suite, 17% of limestone and shale of Lower Gondwana age, 22% of Sandstone and shale of Upper Gondwana age and 5% of coastal alluvium (Chakrapani and Subramanian, 1993). The basin is a peri-cratonic basin along the eastern continental margin of India (Datta et al., 2012) and was believed to has come to existence as a result of rifting and break up of Gondwanaland during the Jurassic period (Subrahmanyam et al., 2008). The basin is a part of richest mineral belt of the Indian sub-continent consisting of coal, iron, bauxite, manganese, gold, galena, graphite, pyrite, lead, zinc, copper, limestone, mica, dolomite, fireclay, china clay, soap-stone and quartz deposits occurs in the basin (Chakrapani and Subramanian, 1993).

3. Data and methodology

Long term daily water discharge and total suspended sediment data (1980–2010) and rainfall data (1990–2010) were analyzed from 12 hydro-meteorological observation stations in the Mahanadi river basin (Fig. 1). Water discharge and suspended sediment data were obtained from the Water Resources Information System of India (India-WRIS) (http://www.india-wris.nrsc.gov.in). Rainfall data were obtained from Central Water Commission (CWC), Bhubaneswar, an apex organization of the Ministry of Water Resources, Government of India. Sediment load for a particular day at a particular location was calculated using following equation:

$$Q_s = Q_w \times C_s \times 95.2591 \quad (1)$$

where

Q_s = sediment load in tons per day (English short tons)