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Streamflow trends in the Mahanadi River basin (India): Linkages to tropical climate variability

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SUMMARY

Mahanadi River basin is one of the recognized climatic vulnerable regions of India. Recent occurrences of the extreme climatic events in this basin underscore the importance of evaluating the trend and variability of hydroclimatic variables in order to understand the potential impact of future change. In this study, the monthly streamflow data for the period 1972–2007 and the daily rainfall data for the period 1972–2005 have been analyzed using the Mann–Kendall nonparametric test after removing serial correlation. The results reveal a substantial spatial and subseasonal difference in the monsoon season streamflow and rainfall patterns, with a predominance of the increasing trends in June and decreasing trends in August. However, a marked increase is observed in the streamflow and rainfall of the pre- and post-monsoon season. The correlation coefficients show a direct correspondence of the rainfall and streamflow series with the El Niño–Southern Oscillation (ENSO), which is contrary to the established inverse relationship over India. The noteworthy feature of this study is the observed climate uncertainty in terms of large variability in the extreme indices since the 1990s, consistent with the warming induced intensification of the hydrological cycle. Strong evidences have emerged regarding the basin-wide increases in extreme rainfall indices. In particular, the coastal sector of the basin is more vulnerable to the heavy rainfall, whereas the southern Eastern Ghats region is susceptible to the moisture stress. The discharge at the basin outlet has declined at a rate of 3388×10^6 m^3 decade^{-1}, suggesting the need of environmental flow assessment. The results of this study would help the reservoir managers and policy makers in planning and management of water resources of the Mahanadi River basin.

1. Introduction

Climate change and variability would adversely affect the water and food security of the densely populated Asian river basins (Immerzeel et al., 2010). Among the Himalayan river basins of India, however, the Brahmaputra basin would be more sensitive compared to the moderate response of the Ganges. In general, the water scenario of India, a subcontinent with population over one billion, is becoming critical as the per capita availability of water has decreased from 2309 m^3 in 1990 to 1820 m^3 in 2001, and will be dropped to 1140 m^3 by 2050 (Gupta and Deshpande, 2004). The growing conflict among the river basins of the country, in particular due to the inter-states water transfer and water sharing between industry and agriculture, is directly affecting the social and economic developments (Joy et al., 2008). Under the greenhouse gas scenario, a general reduction in streamflow is also predicted for the non-Gangetic river basins of the country (Gosain et al., 2006). It is, therefore, important to assess the trends and variability of streamflow for judicious planning and management of water resources.

Most of the trend studies have focused on assessing the rainfall and temperatures patterns for different states of the country or for the study area based on the political boundary. The Indian subcontinent is climatologically heterogeneous, ranging from the hot and humid tropical climate to the dry and desert ecosystem. The summer monsoon rainfall during June to September, which is the lifeline of the agriculture-based economy and also modulates the hydrology of the country, exhibits trends of substantial regional and seasonal difference (Guhathakurta and Rajeevan, 2008). The national trend studies suffer from the masking effects of the contrasting climatology. The long-term changes in streamflow and climatic variables on a basin scale can, however, provide evidence of climate change and variability as river basins are climatologically homogeneous and streamflow reflects the integrated response of climatic inputs. But, there are only a few streamflow studies available in literature. Bhutiyani et al. (2008) reported a post-1990 period decreasing discharge trend at four gauging stations for the snow-fed rivers of northwestern Himalaya during the winter and monsoon seasons. Analyzing the annual maximum streamflow of 18 gauging stations of the river basins of south Asia, mostly

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concentrated over the Himalayan region, Kale (2012) observed no clear pattern during the second half of the 20th century. It should be noted that the numbers of gauging stations used in these studies are not sufficient enough to capture the local behavior within the basin.

The Mahanadi River basin is of particular importance to study the hydroclimatic changes because of its location adjacent to the northwest Bay of Bengal, which makes the basin vulnerable to recurrent floods, droughts and cyclones (Swiss, 2002; Dilley et al., 2005). In order to protect the downstream coastal plains from flash floods, the multipurpose Hirakud earthen dam was constructed in 1957 with a water storage capacity of 5.82 km^3. Moreover, the reservoir irrigates an area of 1554 km^2, and has an installed capacity of power generation of 347 MW. Owing to the hydroclimatic sensitivity of the Mahanadi River basin, several studies have investigated the impacts of climate change and variability on the hydrologyusing the General Circulation Models (GCMs). These simulation results suggested that the operation of the Hirakud reservoir would pose a major challenge under climate change scenario in terms of electricity generation and irrigation water availability because of the predicted inflow decreases (Mujumdar and Ghosh, 2008; Raje and Mujumdar, 2009). However, a comparatively higher level of rainfall and water yield for the basin was also predicted (Gosain et al., 2006). Moreover, the basin has also experienced a significant warming trend due to the increases in the greenhouse gases such as CO_2 and CH_4 (Rao, 1993). The monsoon rainfall of central India, that includes some parts of the Mahanadi basin, has experienced changes in the extreme rainfall characteristics (Goswami et al., 2006). Climate simulation models have also predicted increases in extreme rainfall along with decreases in moderate rainfall in the Mahanadi River basin (Raje and Mujumdar, 2009; Kannan and Ghosh, 2010).

Till date, streamflow trends and their linkages with the major climatic variables have not been investigated systematically for any of the river basins of India, except the recent study of Pal et al. (2013) for the western Himalayan Satluj River. Therefore, the current research aims to assess the streamflow and rainfall trends and variability in the Mahanadi River basin. Given the uncertainty associated with the use of different GCMs (Ghosh et al., 2010), the results of this study will corroborate the modeling predictions, and also improve the understanding about the hydroclimatic changes at the annual, seasonal and subseasonal scales. To this end, the monthly streamflow records of 17 gauging stations have been used, which represent the microclimates of the subbasins and reflect the natural flow regimes within the basin. In addition, using a high resolution gridded daily rainfall dataset, this study also attempts to understand the changes in extreme rainfall indices, defined by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMIs).

Although a daily streamflow time series can capture the fine scale phenomena of the extreme flow characteristics, such datasets are not available for most of the basins of India. This could be one of the reasons for a fewer streamflow studies in India. Streamflow record at the basin outlet is important as they are employed for the basin scale water balance calculation, climate change analysis and GCM applications over large regions (Arora, 2001; Dai and Trenberth, 2002). In this study, the daily streamflow data for the gauging station at the outlet of the Mahanadi basin is analyzed to understand the changes in fundamental flow characteristics. Because of the proximity to coast of the Bay of Bengal, the Mahanadi river basin is sensitive to the large-scale coupled atmospheric-oceanic circulation modes such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Maity and Nagesh Kumar, 2009; Ajayamohan and Rao, 2008). With the available dataset, the hydroclimatic teleconnection with the hydroclimatic variables of the basin is also explored. From the Indian prospective, this study is a step forward to the ongoing international efforts towards more regional studies to adapt the climatic impacts given the hydroclimatic importance of the Mahanadi basin in supporting agriculture, hydropower generation and coastal ecosystems.

The paper is organized as follows. The study area and datasets used in this study are described in Section 2. Section 3 outlines the methodology applied in this study. The main results are presented in Section 4. Finally, the results are discussed in Section 5 and the salient conclusions are drawn in Section 6.

2. Study area and dataset

The Mahanadi River is one of the major east flowing river of peninsular India (Fig. 1), which originates at an elevation of about 442 m above MSL (near Pharsiya village in Raipur district of Chattisgarh) and drains an area of 141,589 km^2 between 80°26′ E and 86°50′ E longitude and 19°20′N–23°35′N latitude. The Mahanadi basin lies in the states of Chhattisgarh (75,136 km^2), Orissa (65,580 km^2), Bihar (635 km^2) and Maharashtra (238 km^2). The total length of the river from its origin to confluence to the Bay of Bengal is about 851 km. The main tributaries (a total of 12), such as the Seonth, the Jonk, the Hasdeo, the Mand, the Ib, join the upstream of Hirakud reservoir while the Ong and the Tel join the downstream of it. As there is no major control structure upstream of the Hirakud reservoir, the streamflow at most of the gauging stations can be considered as unregulated. The basin is characterized by a tropical monsoon (June to September) climate, with an average rainfall of 1360 mm. More than 80% of the annual runoff occurs during the monsoon season. The average annual flow is 1895 $m^3 s^{-1}$, with a maximum of 6352 $m^3 s^{-1}$ during the monsoon season and a minimum of 759 $m^3 s^{-1}$ during the dry summer premonsoon season (January to May). Before discharging into the Bay of Bengal, the Mahanadi River segregate into several distributaries and channels, thereby creating a coastal delta. The synoptic disturbances over the Bay of Bengal, which contribute a bulk of the rainfall, generate flash flood in the densely populated and agriculturally-intensive coastal delta. Geology of the upstream region is mostly characterized by the pre-Cambrians hard rock of Eastern Ghats, while the downstream is dominated by the recent deltaic alluvium of the river. Temperatures show a large variation, with the winter (December to January) minimum temperature ranging from 4 °C to 12 °C, and the hottest month of May experiences a maximum temperature ranging from 42 °C to 45 °C. The basin population has registered a decadal growth of about 20% since 1971, with the population density of 202 (people per km^2) and 243 in 2001 and 2011, respectively.

The monthly streamflow discharge time series in 10^6 m^3 (million cubic meters, mcm) for 17 gauging stations of the Mahanadi River basin were obtained from the Central Water Commission, Government of India. Table 1 presents the detailed information regarding the basin characteristics and the gauging stations. As the gauging stations were established at different point of time, the length of the records also differed during the period 1972–2007 (Table 1). For most of the river basins in India, a systematic hydrological monitoring with proper spatial representation started since the middle of 1980s. Moreover, the daily streamflow data for the gauging stations situated at the outlet of the basin (Tikerpara, Id. 19) for the period 1972–2007 was used. The daily rainfall data for 60 grids at the resolution of $0.5° \times 0.5°$ for the period 1972–2005 was obtained from the recently developed high resolution gridded rainfall dataset of the Indian Meteorological Department (IMD) (Rajeevan and Bhate, 2008). Most of the previous trend studies employed the earlier version of gridded daily rainfall dataset at the spatial resolution of $1° \times 1°$. The pre-monsoon (January–May) and post-monsoon (October–December) streamflow and rainfall totals were used as their monthly values contribute a small