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Simulating climate change and socio-economic change impacts on flows and water quality in the Mahanadi River system, India

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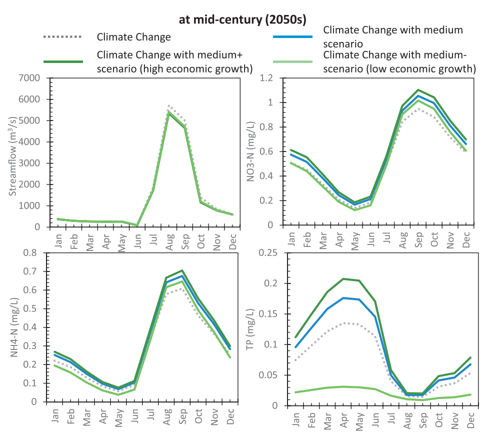
HIGHLIGHTS

- Multi-branched INCA models were used to simulate flow, N and P fluxes.
- Three climate models projected increases in high flow and nutrient reductions by 2090s.
- Some future climate and socioeconomic scenarios lead to increases in nutrient levels.
- Different socio-economic changes greatly alter nutrient fluxes transported into the delta.

GRAPHICAL ABSTRACT



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ABSTRACT

Delta systems formed by the deposition of sediments at the mouths of large catchments are vulnerable to sea level rise and other climate change impacts. Deltas often have some of the highest population densities in the world and the Mahanadi Delta in India is one of these, with a population of 39 million. The Mahanadi River is a major river in East Central India and flows through Chattisgarh and Orissa states before discharging into the Bay of Bengal. This study uses an Integrated Catchment Model (INCA) to simulate flow dynamics and water quality (nitrogen and phosphorus) and to analyze the impacts of climate change and socio-economic drivers in the Mahanadi River system. Future flows affected by large population growth, effluent discharge increases and changes in irrigation water demand from changing land uses are assessed under shared socio-economic pathways (SSPs). Model results indicate a significant increase in monsoon flows under the future climates at 2050s (2041–2060) and 2090s (2079–2098) which greatly enhances flood potential. The water availability under low flow conditions will be worsened because of increased water demand from population growth and increased irrigation in the future. Decreased concentrations of nitrogen and phosphorus are expected due to increased flow hence dilution. Socio-economic scenarios have a significant impact on water quality but less impact on the river flow. For example, higher population growth, increased sewage treatment discharges, land use change and enhanced atmospheric deposition would result in the deterioration of water quality, while the upgrade of the

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sewage treatment works lead to improved water quality. In summary, socio-economic scenarios would change future water quality of the Mahanadi River and alter nutrient fluxes transported into the delta region. This study has serious implications for people's livelihoods in the deltaic area and could impact coastal and Bay of Bengal water ecology.

1. Introduction

River discharge, nutrient load and sediment load of most of the world's largest rivers have experienced great changes in recent decades and are vulnerable to future changes due to the variations of climate and anthropogenic impacts around the globe (Bastia and Equeenuddin, 2016; Hoang et al., 2016; Jin et al., 2015; Walling, 1997; Walling and Fang, 2003; Whitehead et al., 2015; Whitehead et al., 2015). The delta systems forming from deposition of sediments at the mouths of these large river catchments are therefore unavoidably affected by these changes (Eldeberky and Hunicke, 2015; Immerzeel, 2008; Kay et al., 2015; Lazar et al., 2015; Nicholls et al., 2016; Smajgl et al., 2015; Susnik et al., 2015; Whitehead et al., 2015). Deltas have some of the highest population densities and often poor residents in the world. These low-elevation coastal areas are experiencing loss of livelihood from climate change induced risks of flooding, storm surges and seawater intrusion (Hoang et al., 2016; Sherif and Singh, 1999; Van et al., 2012; Vastila et al., 2010; Whitehead et al., 2015). Therefore, it is crucial to analyze the impacts of climate change and other environmental drivers in these large rivers and deltas and to develop strategies and policies that are adaptive to deltas residents.

Climate can significantly affect the hydrological conditions and water resources arising from change in precipitation intensity and frequency, which have resulted in extensive flooding and extended drought (IPCC, 2007, 2013). Additionally, socio-economic changes such as urbanization and population increase have put additional stress on water resources which can worsen the issues of water scarcity and food production (IPCC, 2014). Although climate change is occurring globally, impact is likely to be severe in countries like India due to their agricultural-based rural economy. In India, over two-thirds of the population directly depends on agriculture which is largely controlled by rainfall due to south-west summer monsoon for the period of June to October. Any change in climate such as variability in the monsoon would significantly affect the agriculture and food security. In addition, India has experienced a significant increase in water demand over the years because of increasing population. According to the United Nations Environment Programme (UNEP) (Global Environment Outlook, 2000), if the consumption patterns continue, by the year 2025, India may be under high water stress (more than 40% of total available utilized). Given the circumstances, the country is presently facing water stress which is likely to worsen under climate and socio-economic changes.

This study, as part of DECCMA (DEltas, vulnerability and Climate Change: Migration and Adaptation) project (Hill et al., 2018), will focus on the Mahanadi River, one of the largest peninsular rivers in India. There have been a number of studies in the past which evaluated streamflow (including floods) change under changing climate in the Mahanadi River. For example, a study by P.G. Rao (1995) showed climate warming occurred in the Mahanadi River basin and a steady decrease in the river flows during the 55-year period of the study (1926–1980) (Rao, 1995). Later, General Circulation Models (GCMs) output with 150 km resolution were used and downscaled by a statistical method to assess the flow changes in the Mahanadi river basin (Ghosh et al., 2010). In this study, we have downscaled three GCMs from the most recent (CMIP5) generation of GCMs. These GCMs have been carefully selected by Janes et al. (2018) to sample a broad range of plausible future climate change scenarios for northern India. In addition to using more up to date GCMs than Ghosh et al. (2010), we use data dynamically downscaled to a resolution of 25 km from the GCMs. The dynamical downscaling was done using a Regional Climate Model (RCM), which better represents fine scale processes that are important for determining regional climate conditions than a GCM.

We seek to address flow and water quality issues related to nitrogen (N) and phosphorus (P) in the Mahanadi River and nutrient transport along the river and discharge into the delta system. We evaluate the impact on flow and water quality from climate and socio-economic change utilizing a modelling approach as a means of assessment in this complex river system. The INCA-N and INCA-P models have been applied to the Mahanadi River system to simulate flow and water quality along the rivers under a range of future conditions. This is the first study which uses applications of the INCA models in the Mahanadi River basin to assess both climate change and socio-economic change on water resource systems. Considering both flow and water quality can assist catchment management in a more holistic way. This study emphasizes the need for groundbreaking water management policies to mitigate flooding and drought conditions and impacts on the deltaic environment.

2. Study area and methods

2.1. Study area

The Mahanadi is a major east-flowing peninsular river in east-central India (Fig. 1a). Extending between the longitudes of 80°28′E to 86°43′E and latitudes of 19°8′N to 23°32′N, the Mahanadi River system has a coverage area of 141,589 km^2. It is approximately 4.3% of the total geographical area of India, with the major part of the basin covering the state of Orissa and Chhattisgarh and the rest in the states of Jharkhand, Maharashtra and Madhya Pradesh. The basin is bounded by the Central India Hills on the north, the Eastern Ghats on the south and east and the Maikala range on the west. Geologically the basin comprises of pre-Cambrian hard rock in the upstream reaches and alluvium formation of recent origin in the downstream reaches.

The Mahanadi River is 851 km in length and originates in Pharsiya village in the Dhamtari district of Chhattisgarh. The river drains into the Mahanadi Delta on the east coast of the Bay of Bengal (Fig. 1b). The left bank tributaries of the Mahanadi River are the Seonath, the Mand, the Ib and the Hasdeo, whereas the right bank tributaries include the Rivers Ong, the Jonk and the Tel.

The river course is considered to be divided into 3 sections. Upper Mahanadi originates from a combination of many mountain streams and then flows toward north as a small stream in the plain of Chhattisgarh until it is joined by the River Seonath near Seorinarayan. From its confluence with the Seonath, the river takes an easterly course to enter into the state of Odisha forming Middle Mahanadi. Near the city of Sambalpur, the river flows into a large artificial Hirakud reservoir of capacity 743 km^2 under full conditions created by a 25.8 km long earthen dam (including dykes) of the same name. Below the dam the Mahanadi follows a meandering course through deep, forested ridges and forces its way through the Eastern Ghats via the 64 km long Satkosia Gorge. The Lower Mahanadi enters the Orissa plains leaving the hilly region at Naraj. A barrage has been constructed here to control flooding in the lower sections. At Cuttack, the Mahanadi splits into several branches (or distributaries) that finally discharges into the Bay of Bengal. The delta formed at the mouth of the river is a very fertile agricultural plain and densely populated.

The climate of the basin is sub-tropical in nature with maximum temperatures ranging from 39 °C to 45 °C occurring in the month of