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Water quality assessment and catchment-scale nutrient flux modeling in the Ramganga River Basin in north India: An application of INCA model

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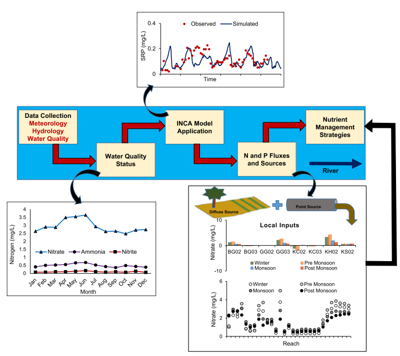
HIGHLIGHTS

- Simulation of flows and nutrient flux for the Ramganga river
- Seasonal variability in N/P fluxes and controls
- High concentration during low flows but larger transport during high flows
- Annual transport of ~548 and ~77,051 tonnes for phosphate and nitrate respectively
- Large contribution from industries and agriculture wastes

GRAPHICAL ABSTRACT



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ABSTRACT

The present study analyzes the water quality characteristics of the Ramganga (a major tributary of the Ganga river) using long-term (1991–2009) monthly data and applies the Integrated Catchment Model of Nitrogen (INCA-N) and Phosphorus (INCA-P) to the catchment. The models were calibrated and validated using discharge (1993–2011), phosphate (1993–2010) and nitrate (2007–2010) concentrations. The model results were assessed based on Pearson's correlation, Nash-Sutcliffe and Percentage bias statistics along with a visual inspection of the outputs. The seasonal variation study shows high nutrient concentrations in the pre-monsoon season compared to the other seasons. High nutrient concentrations in the low flows period pose a serious threat to aquatic life of the river although the concentrations are lowered during high flows because of the dilution effect. The hydrological model is satisfactorily calibrated with R^2 and NS values ranging between 0.6–0.8 and 0.4–0.8, respectively. INCA-N and INCA-P successfully capture the seasonal trend of nutrient concentrations with $R^2 >$ 0.5 and PBIAS within $\pm$17% for the monthly averages. Although, high concentrations are detected in the low flows period, around 50% of the nutrient load is transported by the monsoonal high flows. The downstream catchments are characterized by high nutrient transport through high flows where additional nutrient supply from industries and agricultural practices also prevail. The seasonal nitrate (R^2: 0.88–0.94) and phosphate (R^2: 0.62–0.95) loads in the catchment are calculated using model results and ratio estimator load calculation technique. On average, around 548 tonnes of phosphorus (as phosphate) and 77,051 tonnes of nitrogen (as nitrate) are estimated to be exported annually from the Ramganga River to the Ganga. Overall, the model has been able to successfully reproduce the catchment dynamics in terms of seasonal variation and broad-scale spatial variability of nutrient fluxes in the Ramganga catchment.

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1. Introduction

Freshwater systems are constantly under the influence of multiple stressors that include changing environment, changing demands on water resources and changing nutrient cycles (Heathwaite, 2010). Increasing population and living standards along with rapid urbanization and industrialization have exposed river waters to various forms of degradation (Sharmila and Arockiarani, 2016). Very recently, studies have reported that lack of properly functioning sewage systems can severely damage water quality at national scale (Pacheco and Fernandes, 2016), especially in urbanized catchments, where poor sewage treatment is the most influencing cause for water quality degradation and biodiversity loss (Ferreira et al., 2017). Often, it is observed that high population density, untreated sewage, industrial discharge and excessive use of fertilizers are the prime reasons for nutrient pollution in rivers. The problem is more severe when rivers are under other anthropogenic pressure or interventions. For example, Álvarez et al. (2017) and Santos et al. (2017) reported the degrading effects of damming in rivers on catchment water quality as well as on river biodiversity. Excess concentration of nutrients in rivers can cause problems of eutrophication, acidification and decreased biodiversity (Heathwaite et al., 1993). High levels of nutrients disrupt the ecological balance in rivers and also have implications for water management costs.

The Ganga basin is the largest and the most populated river basin in India. Approximately 43% of the population of India is supported by this large basin as per 2001 census. The water quality of the Ganga, along some stretches, has degraded to an extent that it is unfit even for bathing purposes (CPCB, 2013). There have been significant efforts to improve the water quality in the Ganga catchment on which >400 million people are directly or indirectly dependent (Verghese and Iyer, 1993). The National Ganga Council was formed in October 2016, as an authority for the protection, prevention, control and abatement of environmental pollution in the river Ganga along with the National Mission for Clean Ganga Authority (NMCG) created in August 2011.

In the Ganga basin, approximately 12,000 Million Liters per day (MLD) of sewage is generated out of which only 4000 MLD can be treated (Sharmila and Arockiarani, 2016). CPCB (Central Pollution Control Board) reports that municipal sewage constitutes 80% of the total volume of waste dumped into the Ganga, while industries constitute around 15% (CPCB, 2013). The industrial pockets in the catchments of the Ramganga and Kali Rivers (major tributaries of Ganga) are major contributors to pollution in the Ganga (Sharmila and Arockiarani, 2016). Pulp and paper, sugar, distilleries and other industries are discharging wastewater into these tributaries. The Ramganga River carries maximum industrial wastewater followed by the main stream of the river Ganga and Kali-East (CPCB, 2013) in the Ganga basin. The Ramganga River, comprised of 11 tributaries and 4 drains, receives 235 MLD of industrial and 227 MLD of domestic sewage load (CPCB, 2016). Additionally, >60% of the area of the Ramganga catchment is utilized for agricultural practices with majority of this agricultural land lying in the Uttar Pradesh state. Uttar Pradesh has the highest number of farm holdings (over 20 million) in India and produces about one fifth of the total food grains in the country, which is the highest among all states (Comprehensive - District Agriculture Plan, Sitapur, C-DAP, 2007). Data from a 2012 livestock census show maximum livestock population (~68 million) of India reported in the Uttar Pradesh state (DOAHDF, 2015) with an increase of 7.42% from the data of previous census in 2007 (ENVIS, 2017). The intensive farming practices and a high number of livestock population of Uttar Pradesh covered by the Ramganga catchment may be a major contributor to the pollution in the river. Pollution sources and processes acting at regional scales that are important in terms of pollution contribution need to be examined for better management of large systems like the Ganga. However, such information is typically not known or incompletely compiled for many of the river basins.

There are few studies on the Ramganga River which assess water quality along short stretches (Alam and Pathak, 2010; Chandra et al., 2011; Sharma et al., 2003). Khan et al. (2016) have assessed spatial and temporal variation in the physico-chemical parameters and heavy metal pollution for the entire Ramganga basin. To control nutrient pollution, a comprehensive understanding of the underlying hydrological and chemical processes is essential, in addition to the assessment of water quality status. Hydrological models have been developed and applied to establish a thorough understanding of the river system by capturing the river behavior and reproducing the catchment dynamics through computer simulations (e.g. Futter et al. (2015)). These models are particularly useful in catering useful knowledge about dominant processes and inputs/outputs that influence hydrology and nutrient dynamics in the river. Stanford Watershed Model-SWM (now HSPF) was one of the first models to simulate the entire hydrologic cycle (Singh and Woolhiser, 2002). Other popular hydrological models include Precipitation-Runoff Modelling Systems (PRMS) (Leavesley et al., 1983), Système Hydrologique Europèen (SHE) (Abbott et al., 1986), TOPography based Hydrological MODEL (TOPMODEL) (Beven and Kirkby, 1979), Soil and Water Assessment Tool (SWAT) (Arnold and Allen, 1996), INtegrated CAtchment Model (INCA) (Whitehead et al., 1998), etc. Extensive studies have been done across the globe that use such models to assess various environmental issues and catchment responses to different future scenarios (Jin et al., 2015; Whitehead et al., 2014; Whitehead et al., 2015). Many such studies have also used soft modeling statistical techniques (Fonseca et al., 2017; Pacheco et al., 2015; Rankinen et al., 2006) to support their modeling results.

In this study, we have used INCA model, a semi-distributed physically based model that runs on daily time steps. The semi-distributed nature of the model incorporates the processes occurring at catchment scale resolution. Data requirements for this model are rather simple making it suitable for the Indian catchments like the Ramganga where data availability is a big concern. Whitehead et al. (2015) and Jin et al. (2015) applied INCA-N (the Integrated Catchment Model for Nitrogen) and INCA-P (the Integrated Catchment Model for Phosphorus) respectively in the Ganga basin. They concluded that a more sustainable future scenario leads to decrease in the nutrient levels, whereas a less sustainable scenario leads to further degradation in the water quality. Khan et al. (2018) applied the INCA-Sed model for the Ganga basin to understand the basin-scale sediment dynamics under modern and future climate change scenarios.

Here, we aim to advance upon the previous works by achieving the following goals: (1) to understand the water quality characteristics of the Ramganga River using long-term secondary data; (2) to test the INCA model for the catchment through application of INCA-N and INCA-P; (3) to develop an understanding of the reach scale variation in the flow and nutrient fluxes; (4) to compare the simulated and observed seasonal loads and estimate the nutrient load contribution from the Ramganga to the Ganga river, and (5) to propose nutrient management and monitoring strategies.

2. Methods

2.1. Overview of INCA model

INCA is a semi-distributed process-based dynamic model that uses a mass-balance approach to track the flow and nutrient pathways, in both terrestrial as well as aquatic compartment. The model builds upon a series of first order differential equations that are solved using the fourth-order Runge-Kutta method. The detailed description and governing equations of INCA-N are provided in Whitehead et al. (1998) and Wade et al. (2002a) while documentation of INCA-P is provided in Jackson-Blake et al. (2016).

INCA-N accounts for various inputs/outputs to simulate N fluxes at discrete points along the river. The INCA model was first developed by Whitehead et al. (1998) for modeling nitrogen fluxes and was further modified by Wade et al. (2002a). The main inputs of nitrogen are through atmospheric deposition, sewage/industrial effluent discharge,