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Computer-based mathematical model offers an essential tool to understand current catchment dynamics and to investigate the potential effectiveness of mitigation actions aimed at improving water quality conditions. In this study we present a process-based dynamic model to evaluate the impacts on river flow and phosphorus flux from climate change and socio-economic changes (e.g. population change, land use change, upgraded sewage treatment works, and water transfer) in the Ganga River system. The outcome of this study can be used to support policy-making on water resources management plans.

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ARTICLE

Assessing the Impacts of Climate Change and Socio-economic Changes on Flow and Phosphorus Flux in the Ganga River System

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Anthropogenic climate change has impacted and will continue to impact the natural environment and people around the world. Increasing temperatures and altered rainfall patterns combined with socio-economic factors such as population changes, land use changes and water transfers will affect flows and nutrient fluxes in river systems. The Ganga River, one of the largest river systems in the world, supports approximately 10% global population and more than 700 cities. Changes in the Ganga River system are likely to have a significant impact on water availability, water quality, aquatic habitats and people. In order to investigate these potential changes on the flow and water quality of the Ganga River, a multi-branch version of INCA Phosphorus (INCA-P) model has been applied to the entire rive system. The model is used to quantify the impacts from a changing climate, population growth, additional agricultural land, pollution control and water transfers for 2041-2060 and 2080-2099. The results provide valuable information about potential effects of different management strategies on catchment water quality.

Introduction

The Ganga River is the largest and the most important river in India. It drains an area of over one million square kilometer spreading across India, Nepal, Bangladesh and China. More than 400 million people are directly or indirectly dependent on the river.[1] Approximately 40% of the population of India lives in the Ganga River basin. The waters of the Ganga River are extensively used for domestic, industrial and agricultural purposes. All the major cities of the Ganga basin are located on the banks of rivers. Over the past few decades, with rapid population growth, fast urbanization, agricultural development and industrialization, the Ganga River has received massive inputs of nutrients and other pollutants and the water quality has been deteriorating significantly.[2-4] Municipal sewage constitutes 80% by volume of the total waste dumped into the Ganga River, and industries contribute about 15%.[5] It is estimated that approximately 3000 million liters per day (MLD) of wastewater from towns were discharged into the river, however only 1200 MLD were treated at sewage treatment plants (STPs) (CPCB, 2009).[6] The total amount of wastewater is far more than the STP capacity. Discharge of untreated wastewater from towns along the Ganga River constitutes the major source of pollution load of the river. For example, phosphorus (P) in the Ganga River comes mainly from sewage, household effluents and detergents. Total phosphorus (TP) in untreated domestic wastewater typically ranges between 4 and 8 mg/L but can be higher depending on sources.[7] Phosphorus and nitrogen are essential nutrients for plant and animal growth in the aquatic system. Phosphorus is usually the limiting nutrient in most fresh waters and excessive amounts can cause eutrophication, which can have diverse and cascading impacts. Eutrophication accelerates plant growth, depletes oxygen content in the water and causes toxic algae blooms, which not only affects the environment, the fish population and human health, but also increases the need for additional treatment of drinking water and/or health care for illnesses.[7-11]

Furthermore, with a warming climate and changing rainfall patterns, small to large scale changes have been observed in evaporation, surface temperature, intensity and frequency of floods and drought in India.[12-14] A large percentage of agricultural land in India is irrigated and will be severely affected by changing climatic conditions. Therefore all these hydroclimatic changes will have a significant impact on the agricultural sector and millions of people living on the Ganga Plain. Increasing water scarcity and water quality problems may decrease food production, put pressure on food prices and increase the country's dependence on food imports. Water and food security in India may become one of their major concerns associated with a changing climate in the future.

Computer-based mathematical modelling is often used to understand catchment dynamics and assess the potential effectiveness of future actions on flow and water quality.[15] In this study, we present an application of a process-based dynamic model, the integrated catchment model for P (INCA-P) to the entire Ganga River basin to simulate the flow and water quality with the focus on river P concentration and flux. A parallel study looking at the nitrogen dynamics in the Ganga River can be found in this issue by Whitehead et al. (2015).[16] The aim of this study is to evaluate the impact of different hydrological and water quality changes of the Ganga River due to changing climatic conditions and socio-economic changes. This and the companion Whitehead et al. (2015) paper [16] present the first applications the INCA family of models to such a big and complex river system so as to assess a set of shared social-economic pathways (SSPs) as a means of evaluating potential future socio-economic impacts on environmental and resource systems undergoing climate change.

Study Area and Methods

The Ganga River system (Fig. 1) is one of the largest rivers in the world. The Ganga basin, as part of the composite Ganga-Brahmputra-Meghna basin, lies in China, Nepal, India and Bangladesh and drains an area of approximately 1,087,300 km^2. Out of this basin, ~835,744 km^2 (approximately 80%) is located in the Indian states of Uttarakhand, Uttar Pradesh, Madhya Pradesh (in parts), Bihar, Jharkhand and West Bengal. The basin is bounded on the north by the Himalayas, on the west by the Aravallis, on the south by the Vindhyas and Chhotanagpur Plateau and on the east by the Brahmaputra ridge.

The 2,525 km Ganga River rises from the Gangotri glacier (>7000 m) in the Himalaya in the Uttarkashi district of Uttarakhand State in India. It flows south and east through the Gangetic Plain of North India into Bangladesh, where it empties into the Bay of Bengal.

There are a large number of tributaries joining the Ganga River. The Yamuna, Chambal, Betwa, Sind, Ken and Son rivers are the main tributaries that join the Ganga River from the South. The Ramganga, Gomati, Ghaghra, Gandak, Kosi and Mahananda rivers join from the North.

The main sources of water in the rivers are rainfall, snowmelt water from the Himalayas and groundwater recharge. Average annual rainfall varies between 300 mm to 2000 mm with the western side of the region getting less rainfall in comparison with the eastern side. Due to the rainfall being restricted to only 3-4 months (monsoon months June to October) during a year in the basin, the flow is largely controlled by the concentrated rainfall and the dry season flow in the Ganga and its tributaries is only a small fraction of the total annual flow. The river flow is also affected by over-abstraction of groundwater in the basin and hydroelectric dams.

The INCA-P Model

Integrated Catchment Model (INCA) has been subject to continuous development since its first application in 1998.[17-18] INCA is a dynamic, process-based model that predicts water quantity and quality in rivers and catchments. The model simulates factors controlling flow and water quality dynamics in both land and in-stream components of river catchments, while minimizing data requirements and model structural complexity.[17-18] The most recent INCA model development was transforming a single stem of the main river model to a fully branched river network, which simulates

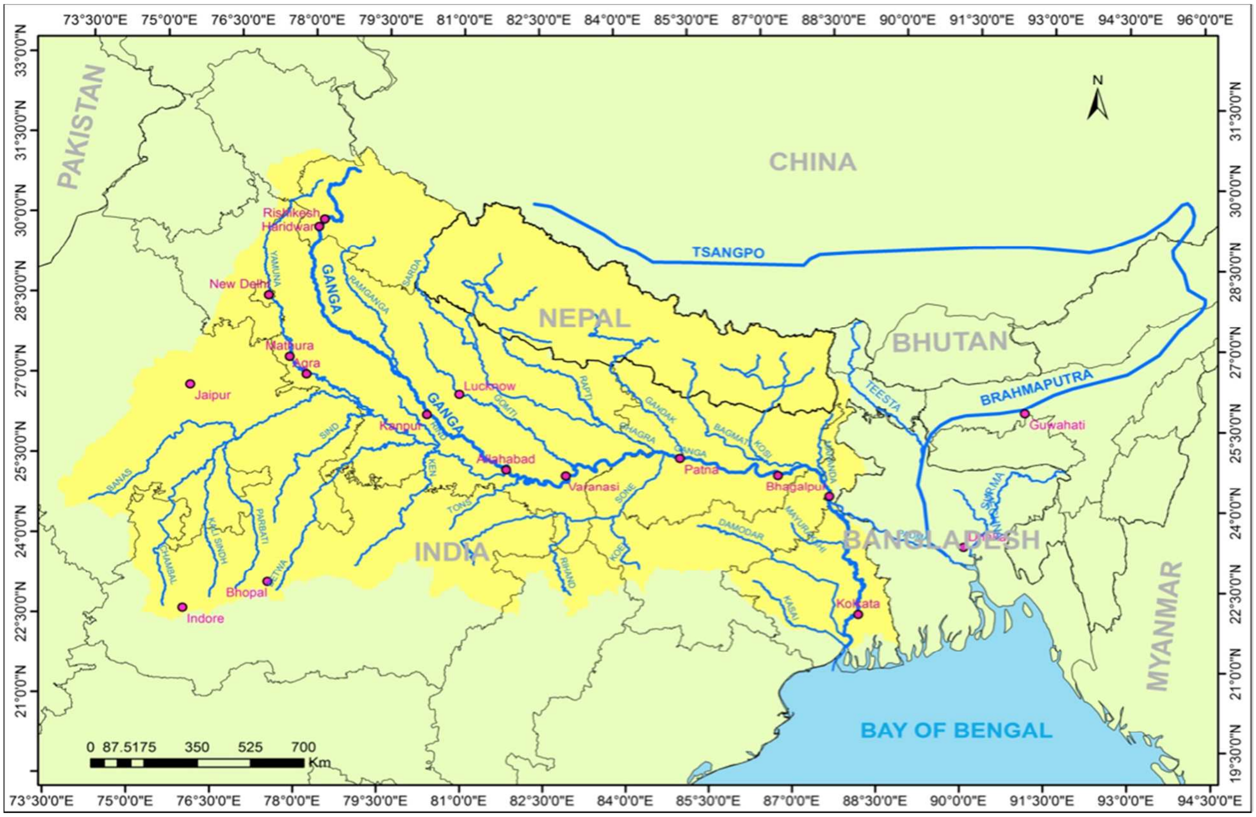

Fig. 1 Map of the Ganga Basins Draining into the Bay of Bengal.

branched tributaries in a fully-distributed manner.[19] Modelling complex river systems such as the Ganga River requires a distributed model that can account for the spatial variability across the catchment. INCA is capable of doing so and has been applied extensively to heterogeneous catchments.[20-22]

The INCA model structure has four levels from a generic cell in which terrestrial processes are simulated, to the land use /land cover scale (with an arbitrary number of types), then to the subcatchment level with multiple land use / land cover types spread across multiple reaches in a single river, and finally to the multi-branch river basin scale in which dendritic river networks can be simulated.[19] The INCA-P model simulates flow through the soil from different land use types to deliver P to the river system, which is then routed downstream after accounting for point sources (e.g., effluent discharges) and in-stream processes.

INCA-P input fluxes include atmospheric deposition, inorganic fertilizer, plant residue, livestock waste and slurry application (Fig. 2). Stream output is calculated by subtracting various output fluxes such as plant uptake and movement to firmly bound P forms from these inputs.[23] The model produces daily estimates of discharge and stream water quality concentrations (e.g. total phosphorus - TP, particulate phosphorus - PP, total dissolved phosphorus – TDP and soluble reactive phosphorus- SRP) and fluxes from both diffuse sources across a catchment and at discrete points along river channels. Both inputs and outputs are affected by different land use type and environmental conditions such as soil moisture and temperature in the air, soil and water. The model utilizes a series of interconnected first-order differential equations that are solved simultaneously using a numerical integration method based on the fourth-order Runge-Kutta technique.[24] Details about the process equations are described in Wade et al. (2002, 2009),[23-24] and the multi-branch version used in this study is described in Whitehead et al. (2011).[19]

Data required for running the INCA-P model include river network topology, reach characteristics, subcatchment areas, land use, fertilizer practice, and hydrological parameters including rainfall, temperature, hydrologically effective rainfall (HER) and soil moisture deficits (SMD). The four key sub-components of the INCA-P model represent land phase process, in-stream process, flow dynamics, and major P inputs. Discharge and stream water P concentrations are used for model calibration.[19,21]

Application of INCA-P to the Ganga River system

INCA-P model setup

The INCA-P model has been set up for the entire Ganga River system. The details of key parameters and data sources used in the model application are shown in Table 1.

The Ganga River has been divided into 70 reaches with 21 reaches covering the main river and 10 reaches for the Yamuna river to reflect its complex river network using the multi-branch structure.

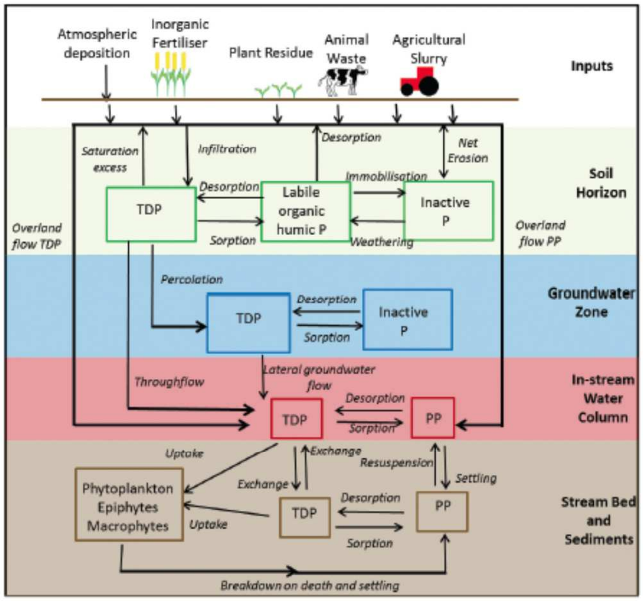

Fig. 2 Diagram showing P processes in the INCA-P model including P inputs to catchments and P dynamics in soil zone, groundwater, in-stream column, and streambed (after Crossman et al. 2013).[25] TDP = total dissolved phosphorus; PP = particulate phosphorus.

The reach boundaries were decided based upon the locations of the tributary confluences, the key flow and water quality monitoring stations, major cities, and the waste water treatment effluent inputs or abstraction points (Fig. 3). A Shuttle Radar Topographic Mission (SRTM) 90m resolution digital elevation model (DEM) data has been used to delineate the subcatchment boundaries for each reach (Fig. 3).

Appendix I (supplementary document) shows each reach characteristics including reach length, subcatchment area and percentage land use of each subcatchment. Land use data was obtained from National Remote Sensing Centre (NRSC). The 56m x 56m resolution grid raster data were used and regrouped into urban, forest, grassland, double / triple crop (e.g. fruits, vegetables, potato), kharif crop (e.g. rice, maize, cotton, soybean) and rabi crop (e.g. wheat, barley, mustard) from 26 original land use classes. Figure 4 shows the land use map developed for the INCA model application.

Both flow and P load from wastewater treatment plants are accounted for in INCA-P as point source inputs. Table 2 shows flow and ortho-phosphate concentration found from the STPs effluent discharging into the Ganga River (data available in Performance Evaluation of Sewage Treatment Plants under NRCD, CPCB 2013).[5] However, the municipal and industrial waste water discharge into the Ganga River is often more than waste water treatment capacity. Percent treatment capacity in each city ranges from 7.4% to 100% of the estimated wastewater discharges.[6] Therefore, flow weighted mean phosphate concentrations were calculated and scaled by treatment capacity for use in the INCA-P model setup to reflect treated and untreated waste water discharging into the river. Water abstraction rates for irrigation and public water supply at numerous locations along the Ganga River have also been estimated and included in the model setup.

The crop growth data and fertilizer input data were obtained from FAO, Ministry of Agriculture and Department of Fertilizers, Ministry of Chemicals and Fertilizers. Kharif crops grow from April to September. Rabi crops grow from October to March. Double/triple crops grow throughout the year. Fertilizer consumption varies by crop types. On average, 24.3 P_2O_5 kg/ha fertilizer has been applied to Karif crops, 30.2 P_2O_5 kg/ha fertilizer has been applied to Rabi crops, and 18.5 P_2O_5 kg/ha fertilizer has been applied to double/triple crops (http://www.fao.org/docrep/009/a0257e/A0257E05.htm#ch4). For urban, forest and grassland land cover types, there is no P addition from fertilizer practice.

Table 1 Details of key parameters and data sources used in INCA-P setup.

Parameter	Data description		Data Source
Catchment characteristics	Catchment area	1,087,300 km^2	Shuttle Radar Topgraphic Mission (SRTM) raster dataset (90m x 90m resolution)
	Nunmber of subcatchments	70 sub-catchments	
	Land use types	6 types	National Remote Sensing Centre (NRSC) raster dataset (56m x 56m resolution)
Hydrological characteristics	Daily Precipitation		Met Office Hadley Center HadRM3P RCM for the period 1971-2099
	Daily Air Temperature		
	Daily SMD		Derived from Persist Model, Futter et al., 2014 and 2015
	Daily HER		
P inputs	STW P inputs to river reaches	21 facilities	Performance Evaluation of Sewage Treatment Plants under NRCD, CPCB 2013
	Fertilizer inputs		Ministry of Agriculture and Department of Fertilizers, Ministry of Chemicals and Fertilizers
	Atmospheric deposition		Central Pollution Control Board, Ministry of Environment and Forests, Govt. Of India. Annual Water Quality Reports and Data, 2014.
Observed data	Flow	5 sites	Daily flow available from 1979 to 1999
	Ortho-phosphate concentrations	5 sites	Montly ortho-phosphate concentrations available from 2005 to 2013

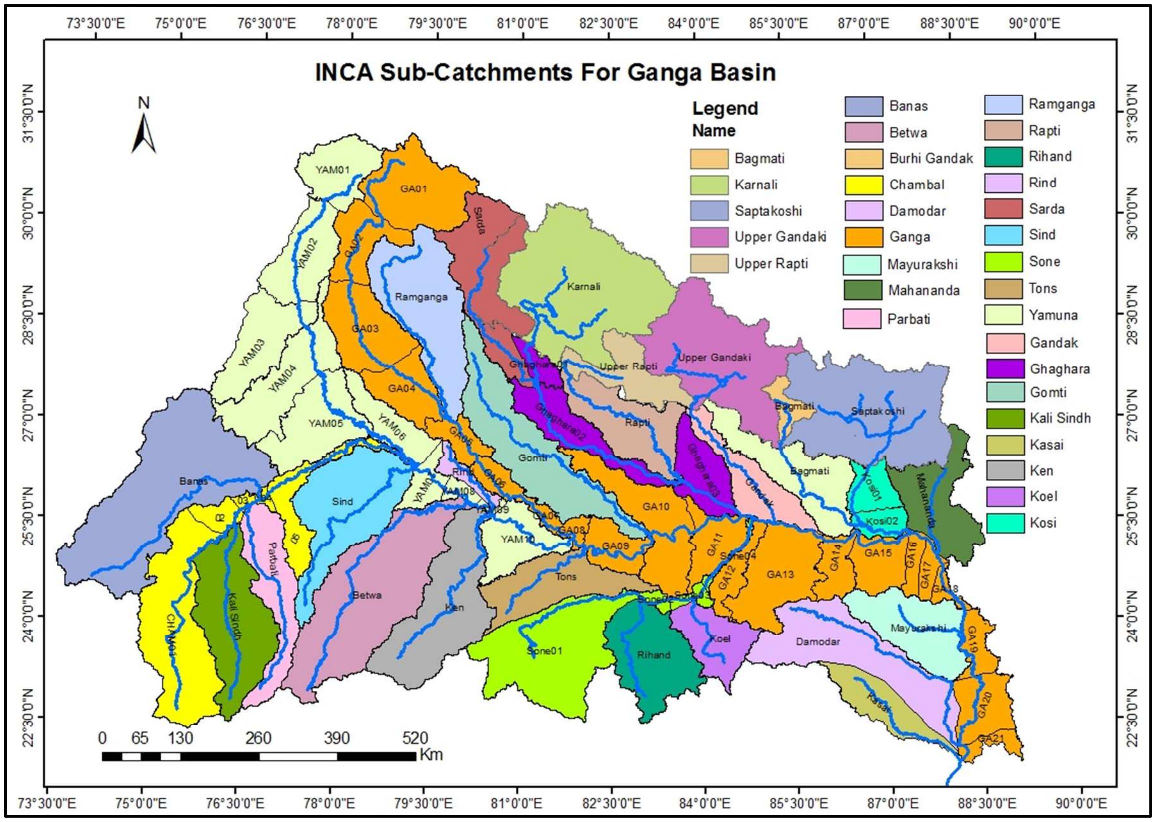

Fig. 3 Site map showing the Ganga River system and the subcatchments.

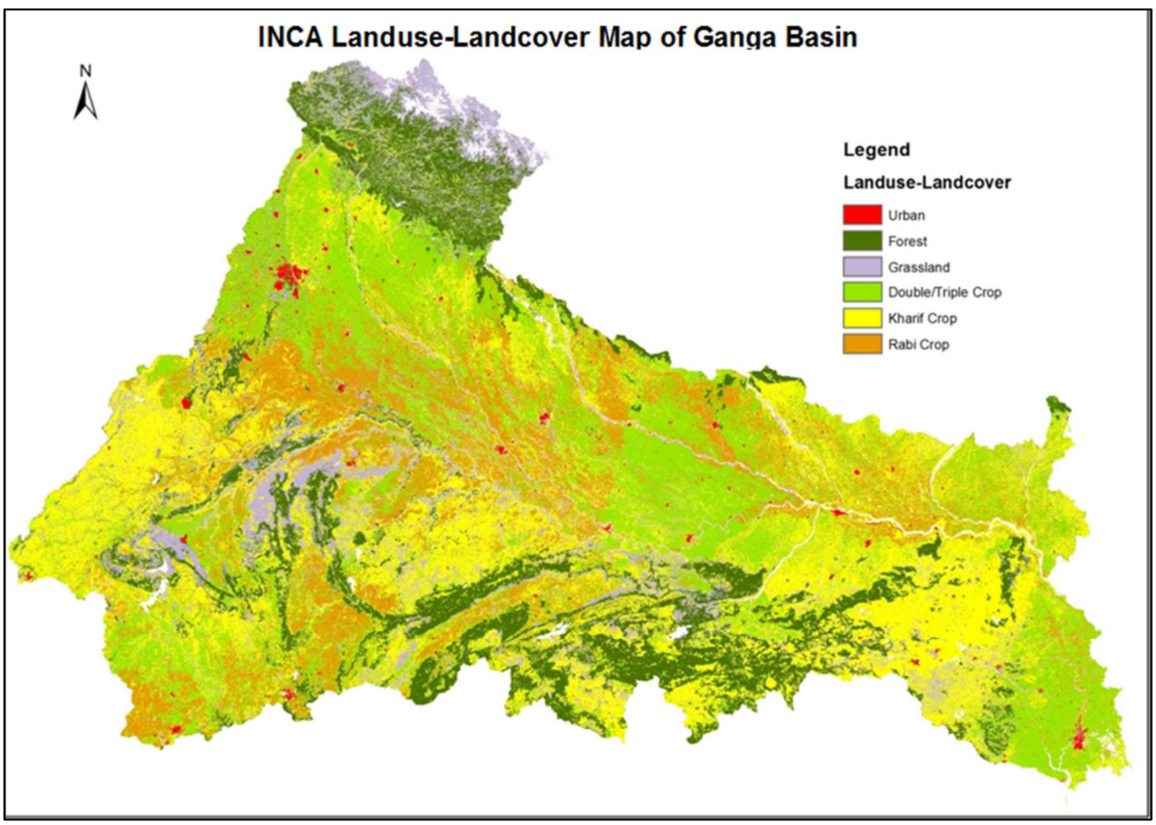

Fig. 4 Land use map with six INCA land classes.

Table 2 Flow and ortho-phosphate concentration from the STP's outlet for the Ganga River (GA) and tributaries including Yamuna river (YAM), Gomati river and Ramganga river. (Data source: Performance Evaluation of Sewage Treatment Plants under NRCD, CPCB 2013)[5]

Reach	Flow m^3/sec	Ortho-phosphate mg P/L
GA02	0.58	4.4
GA04	0.35	6.0
GA05	0.08	8.0
GA06	4.28	5.1
GA08	2.41	4.9
GA09	2.67	3.0
GA10	0.12	8.0
GA11	0.30	7.4
GA13	3.36	5.0
GA14	0.49	5.6
GA15	0.71	6.7
GA19	0.65	3.6
GA20	14.66	5.1
GA21	0.28	0.6
YAM02	1.96	1.7
YAM03	37.13	2.6
YAM04	3.06	4.6
YAM05	3.59	4.5
YAM06	0.33	5.2
Gomati	3.43	6.9
Ramganga	2.73	8.0

The daily precipitation and temperature data are obtained from output of the Met Office Hadley Centre Regional Climate Model (RCM) HadRM3P for the period from 1971 to 2099.[26] HER and SMD are generated by PERSiST model.[27] PERSiST is a watershed-scale hydrological model suitable for simulating terrestrial runoff and streamflow across a range of spatial scales from headwater catchments to large river basins. It is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA models. PERSiST simulates water fluxes from precipitation through the terrestrial part of a catchment and uses an evaporation mass balance to determine the evapotranspiration, and from this the HER and SMD are calculated. A detailed description of this analysis for the Ganga River system is giver by Futter et al (2015).[28]

The observed flow and water quality data are limited in the study region. Daily flow data were available from 1979 to 1999 at five stations (reaches GA03, G04, GA05, GA06, GA17 in Fig. 3) along the Ganga River.[29-30] Most P data (ortho-phosphate) were available from 2005 to 2013 at five stations (reaches GA04, GA05, GA06, GA21, Ramganga01 in Fig. 3).[31] Based on the availability of the observation data, the INCA-P model was set up for 20 years from 1994 to 2013, which best covers the period when the water quality data are available. In the paper, only modelled SRP (SRP is often considered a measure of ortho-phosphate) results were discussed and compared with the observed ortho-phosphate data. The observed flow data was only used from 1994 to 1999 for calibration. The calibrated model was then applied to simulate daily flow and P concentrations from 1981 to 2000 as the baseline condition, which will be compared with future scenarios.

Climate scenarios

Three climate scenarios (Q0, Q8 and Q16) were selected from the 17-member set of RCM (Q0-Q16) from the HadRM3P RCM which was run over a South Asia domain.[26] Q0 uses the same parameter set as the standard HadCM3 coupled GCM.[32] From Q1 to Q16, global climate sensitivity increases. Two future time periods were considered, 2041-2060 (2050s) and 2080-2099 (2090s). Further details about the description and validation of the RCM can be found in Caesar et al. (2015).[26] It is projected that average temperatures will increase on the order of 2 ºC and 4 ºC by 2050s and 2090s, respectively (Fig. 5). Future precipitation projections show a wide range of changes from three scenarios (Fig. 5). Precipitation increases significantly between 5% to 18% and between 15% to 33% by 2050s and 2090s, respectively. Figure 6 shows the monthly mean temperature and precipitation under the Q0 scenario. The monthly temperature shows consistent increases throughout the year with greater increases by the 2090s compared to the 2050s. During the monsoon season (July to October), monthly mean precipitation and HER are projected to increase compared to the baseline condition, suggesting a wetter monsoon season in the future. However, during the non-monsoon season, precipitation and HER are mostly expected to decrease in the future, which means that less water will be available during the dry season.

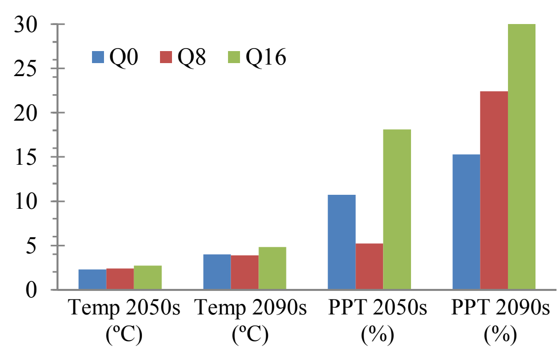

Fig. 5 Future temperature and precipitation changes by 2050s and 2090s under three climate scenarios (Q0, Q8 and Q16).

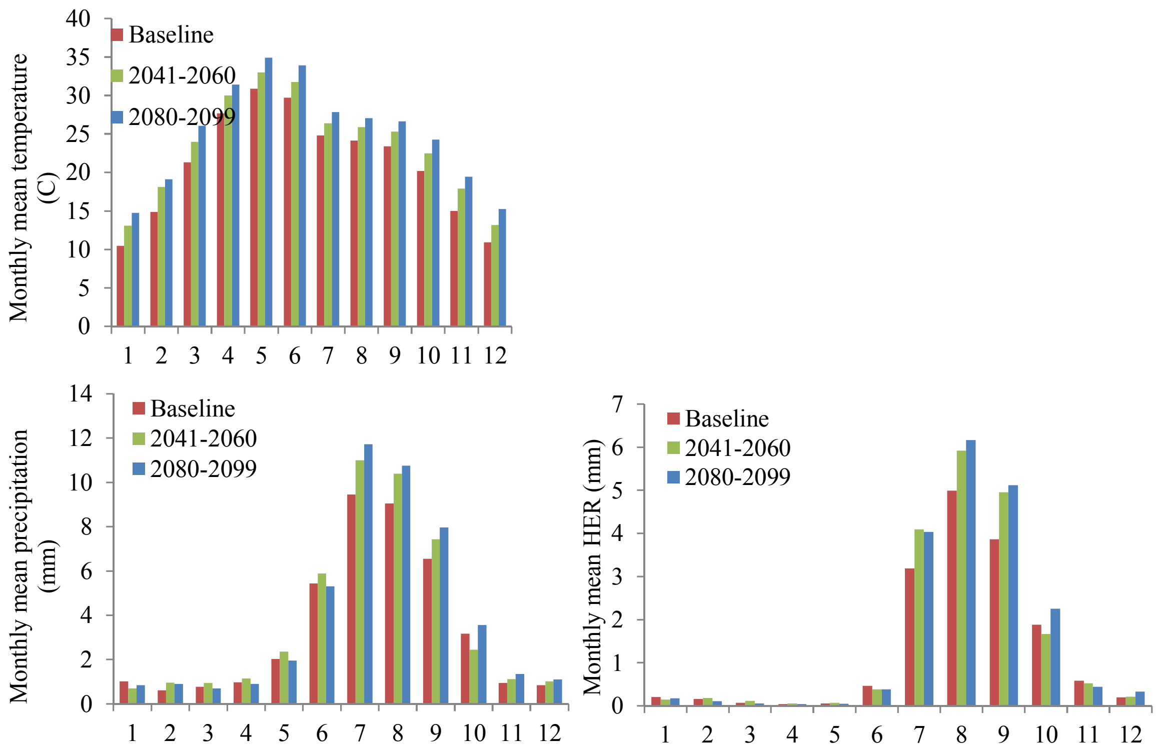

Fig. 6 Monthly mean temperature, precipitation and HER changes under climate scenario Q0.

Table 3 A summary of SSPs changes for three scenarios, a business as usual (BaU), a more sustainable future (SSP-MS), and a less sustainable future (SSP-LS) at 2050s and 2090s.

	BaU		SSP-MS		SSP-LS	
	2050s	*2090s*	*2050s*	*2090s*	*2050s*	*2090s*
Population change[I]	34%	32%	15%	-15%	55%	94%
STP capacity and design for water quality control[II]	flow increase by 34%	flow increase by 32%	flow increase by 15% and P at1 mg/L	flow decrease by 15% and P at1 mg/L	flow increase by 55%	flow increase by 94%
Water demand for irrigation and public supply[III]	abstraction increase by 23%	abstraction increase by 23%	abstraction increase by 11%	abstraction increase by 11%	abstraction increase by 23%	abstraction increase by 23%
Atmospheric deposition[IV]	0.35 kg P/ha/year	0.35 kg P/ha/year	0.175 kg P/ha/year	0.175 kg P/ha/year	0.50 kg P/ha/year	0.50 kg P/ha/year
Land use change[V]	Urban 1.3%, forest 13.4%, barren land 7%, double/triple crops 31.5%, Kharif crop 30.7%, rabi crop 16.1%					
Water transfer plans[IV]	20% from upper Yamuna to Rajasthan from July to October		10% from upper Yamuna to Rajasthan from July to October		30% from upper Yamuna to Rajasthan from July to October	

Data sources: [I] UNDP estimates and the Population Bureau of India estimates. [II] Flow from STPs increases due to the population increase. Target P of 1 mg/L for SSP-MS is from personal communication. [III] FAO, 2013.[33] [IV] CPCB, 2014.[31] [V] Kathpalia and Kapoor, 2010 and FAO, 2013.[34, 33] [VI] Amarasinghe, 2012.[35]

Socio-economic scenarios

The most recent IPCC report (2014) uses shared socio-economic pathways (SSPs) to integrate social impacts from future climate changes.[14] The report categorizes future conditions into sustainability (SSP1), business as usual (SSP2), fragmented world (SSP3), inequality rules (SSP4) and conventional development (SSP5) pathways. Three SSPs were adapted and used in this study. They are a business as usual (BaU), a more sustainable future (SSP-MS), and a less sustainable future (SSP-LS). Six main factors including population change, infrastructure of STPs, water demand for irrigation and public supply, atmospheric deposition change, land use change and water transfer plans were used to quantify the pathways. Table 3 shows the percentage changes for the six factors allowed to vary under different SSPs at 2050s and 2090s.

Results and Discussion

INCA P calibration

INCA-P model was set up to simulate daily flow and SRP from year of 1994 to 2013. The INCA model uses daily precipitation, SMD, HER and air temperature with the reach characteristics to simulate daily flow at 70 reaches for the entire Ganga River system. There are five flow gauges on the main river at or near reaches GA03, GA04, GA05, GA06 and GA17. Flow in the Ganga River is mostly controlled by the monsoons. The annual flow varies by several orders of magnitude from 10s m^3/s up to 150,000 m^3/s. The distinctive seasonal pattern was captured well by the model during the rise, peak and recession of the monsoon season. A summary of model performance statistics is provided in Table 4 and examples of daily model output at the upstream and downstream reaches are given in Figure 7. Both simulated low flow and high flow fit the observation well with r^2 between 0.44 to 0.73 (Table 4). At the lowest flow gauge, GA17, the model generally overestimates the flow (Fig. 7). This is because the gauge at Hardinge Bridge (GA17) in Bangladesh measured part of the flow of the Ganga flowing towards the Bay of Bengal. There is a small percentage of water flowing directly down south, which is not accounted for. The model was also applied to the period from 1981 to 2000 for validation of flow. The model results of 1981 to 2000 were used as the baseline to compare to the future scenarios. The simulated flow during the validation period matches the observation well at all five stations with r^2 between 0.46 to 0.70 (Table 4 and Fig. 8). Previous studies indicate r^2 values greater than 0.5 is considered acceptable for model evaluation.[36, 37] Based on these statistics guidelines, the INCA P model calibration and verification are adequate to represent the flow dynamics of the Ganga River.

The available ortho-phosphate concentrations in the Ganga River basin are sparse. Monthly water samples were collected for ortho-phosphate measurement from 2005 to 2009 at three stations on the main Ganga River (GA04, GA05 and GA06) and one tributary (Ramganga01). Additional monthly water quality data were collected at the bottom of the Ganga River (GA21) from 2011 to 2013. Figure 9 shows the comparison between monthly simulated and observed SRP concentrations at upper Ganga and lower Ganga. SRP concentrations peak in summer (May-June) and remain at the low values during the monsoon period primarily due to high flow dilution. Overall monthly SRP concentrations are well represented with r^2 ranging between 0.46 to 0.90 (Table 4). The fair r^2 value at GA21 needs not be interpreted as the poor model performance. The relatively large discrepancy between modeled and measured SRP concentrations may attribute to higher modeled flow and greater dilution downstream of the Hardinge bridge. Due to the water diversion into Bangladesh, only percentage of water actually flows towards the Bay of Bengal. In addition, some disagreement between modeled and measured SRP concentrations might be resulted from inaccurate measured data. When ortho-phosphate concentrations are low near the detection limit, the accuracy of analytical results is expected to decline. There is also an issue of sample times as the concentrations may vary significantly subdaily.[38] Given such a large and complex river system, numerous P inputs and uncertainties from sampling and measurement, the Ganga river system dynamics and its water quality are adequately represented using the INCA-P model.

INCA P Sensitivity Analysis

Parameter uncertainty is always an issue in environmental modelling study because processes are often poorly understood, or the basic experimental and field data is subject to both sampling errors and laboratory analysis errors. The question of equifinality also arises whereby different combinations of parameter values yield similar model performance as emphasized by Refsgaard and Storm, 1996.[39] Wade et al. (2001) undertook a very thorough analysis of model uncertainty in the INCA-P model and determined the key parameters controlling process behavior.[40] In the Ganga River, there is a paucity of data and so an additional sensitivity analysis has been undertaken to evaluate how the model fit and P concentrations vary with changes in parameters values. The model was run over a wide range of parameter values, and the associated changes assessed at reach GA05 near Kanpur. Table 5 show the parameters ranked from most to least sensitive.

The three most sensitive parameters are hydrological, with groundwater residence time being the most important, followed by river water velocity and base flow index. The Ganga River system is a high energy dynamic system so it is interesting that this feeds through to the sensitivity analysis it is the hydrology that controls the P dynamics. The reach P parameters also seem more important than the land processes and this may be due to dynamics again and the relatively lower sources on P from the land. In order to accurately represent catchment behaviors to external forcing on the model, these parameters were therefore carefully calibrated to observed data (Table 4).

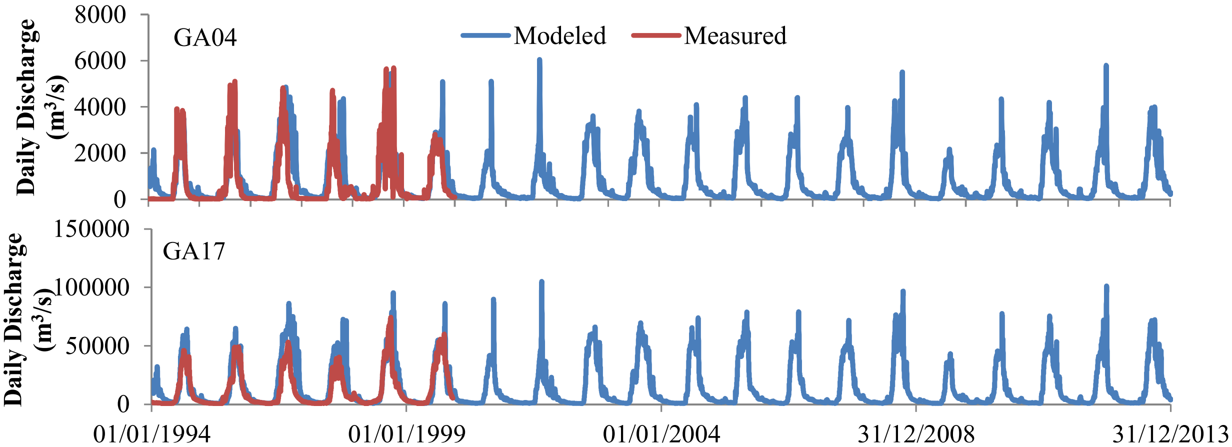

Fig. 7 Comparison of INCA simulated and observed daily flow during the calibration period (1994-2013) at upstream (GA04) and downstream (GA17) flow gauges along the Ganga River.

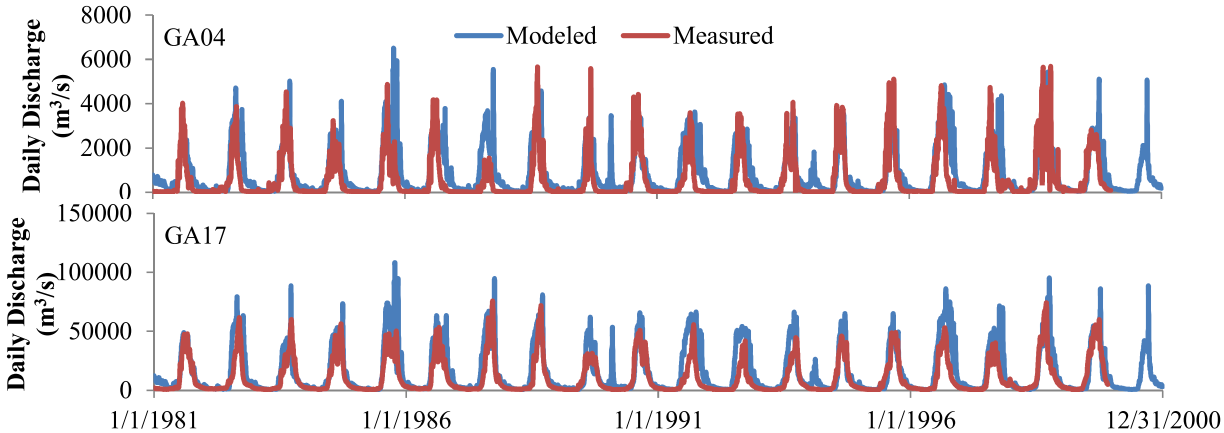

Fig. 8 Simulated and observed daily flow during the validation period (1981-2000) at upstream (GA04) and downstream (GA17) flow gauges along the Ganga River.

Table 4 INCA-P model performance statistics (r^2) showing the comparison between observed and simulated results. Flow statistics represent daily values and SRP statistics represent monthly averages.

		Flow		Water Quality
Location	Reach number	Flow calibration	Flow validation	Monthly mean SRP concentrations
Garhmukteshwar	GA03	0.44	0.46	
Kachlabridge	GA04	0.60	0.54	0.88
Ankinghat	GA05	0.56	0.51	0.90
Kanpur	GA06	0.49	0.49	0.77
Hardinge bridge, Bangladesh	GA17	0.73	0.70	
Diamond harbour	GA21			0.46
Moradabad	Ramganga01			0.87

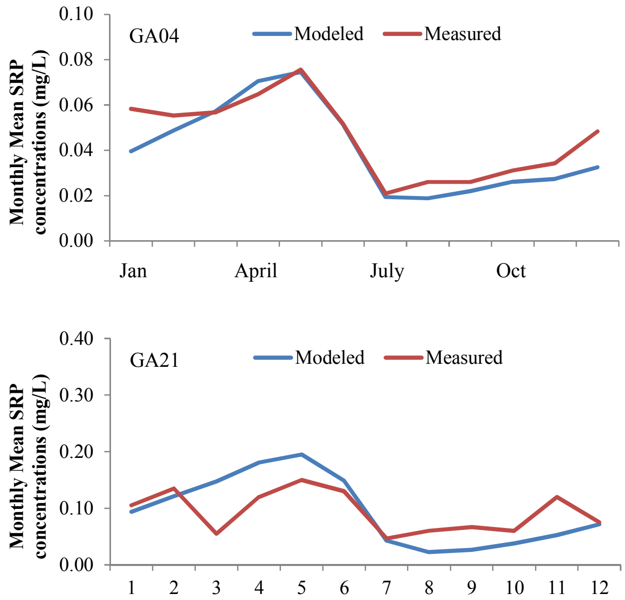

Fig. 9 Comparison of the simulated and observed monthly SRP concentrations at upper Ganga (GA04) and lower Ganga (GA21).

Table 5. Sensitivity analysis (sensitivity expressed as the percentage change in SRP or r^2 per model parameter).

Model Parameter	Percentage change in SRP and r^2 per percentage change in model parameter	
	SRP GA05	r^2 GA05
Ground Water Residence Time	0.3887	0.2801
‘a’ flow parameter	0.2883	0.1523
Base Flow Index (BFI)	0.1776	0.0983
Water Column-Sediment P Exchange	0.1931	0.0737
Reach Equilibrium P Concentration	0.0051	0.0049
Reach Freundlich isotherm constant	0.0026	0.0025
Land: Equilibrium Phosphorous Concentration	0.0021	0.0010

Climate change effects on flow and water quality

The projected climate changes have the most profound impact on the monsoon flows (Fig. 10; results are shown at the Farakka Barrage location – GA17, as this is the crucial site where the major water diversion occurs near the border between India and Bangladesh). Flow increases up to 70% by 2090s (Q16 scenario) reflecting the greater rainfall (Table 6). The increased flow would provide additional water for irrigation or water abstraction when needed. But the likelihood of floods also increases with the greatest impact occurring between 40,000 to 80,000 m^3/s (Fig. 11). Although the low flows are predicted not to change as dramatically as high monsoon flows, both Q0 and Q8 suggest flows in February and November will decrease, which might lead to more severe drought condition during these months with the greatest impact taking place between 4,000 to 2,000 m^3/s (Fig. 11). The future rainfall patterns increase the frequency of drought and floods. The drought condition together with the warming climate will increase soil salinization and desertification, while flooding will increase soil erosion and land degradation.

SRP concentrations in water show decreasing trends at 2050s and 2090s, which is largely due to the increase in the flow and its dilution effect (Fig. 10). Greater decreases in P concentrations are seen during the monsoon time. Comparing to the flow change, SRP concentrations’ change is less. The highest SRP reduction is 35% in the summer under Q16 scenario, which corresponds with the predicted highest flow happening at the same time (Table 6).

Contrary to SRP concentration change, the general trends of SRP fluxes are largely driven by the flow change and increases at both 2050s and 2090s from future higher runoff (Fig. 10). The increase of SRP fluxes is relatively small during the non-monsoon season (Table 6). Greater changes are usually seen during the monsoon season (Table 6). Under Q0, the flow is predicted to decrease during the non-moon period at 2090s, which results in lower SRP fluxes.

SSPs effects on flow and water quality

Impacts from the three SSPs on the flow regime are similar. All show flow increases by 2050s and 2090s (Fig. 12). This suggests that flow is primarily controlled by future rainfall pattern. Figure 13 shows the impact from each main factor such as population change or STPs capacity change. For example, UNDP estimates 15% decreases in population by 2090s under SSP-MS, which will lead to decreases in the STP effluent into the rivers and abstraction for irrigation and public drinking water supply. However, due to the size of the river, the decreases in effluent discharge and abstraction would not have any significant impact to the Ganga River flow (Fig. 13). In addition, water transfer also has little impact on flows in the lower Ganga because the transfer was considered to take place only in the upper Yamuna reaches. Other factors like atmospheric deposition and land use change have minimum impact on flows (Fig. 13).

Unlike flow, river P concentrations are predicted to change significantly. For the most sustainable future (SSP-MS), SRP reduction would reach 70% by 2090s. SRP concentrations decrease throughout the year and will be below 0.05 mg/L (Fig. 12). This is the combination effects from reduced STPs effluent into the rivers, less water abstraction, lower P in atmospheric deposition and better land uses as well as changing climate. Among the six SSPs factors, the STPs capacity and effluent water quality control have the greatest impact on the water quality of the Ganga River. Reduced effluent quantity and lower P concentration in effluent (1 mg/L) will decrease the SRP concentration by 10-70% by 2090s (Fig. 13).

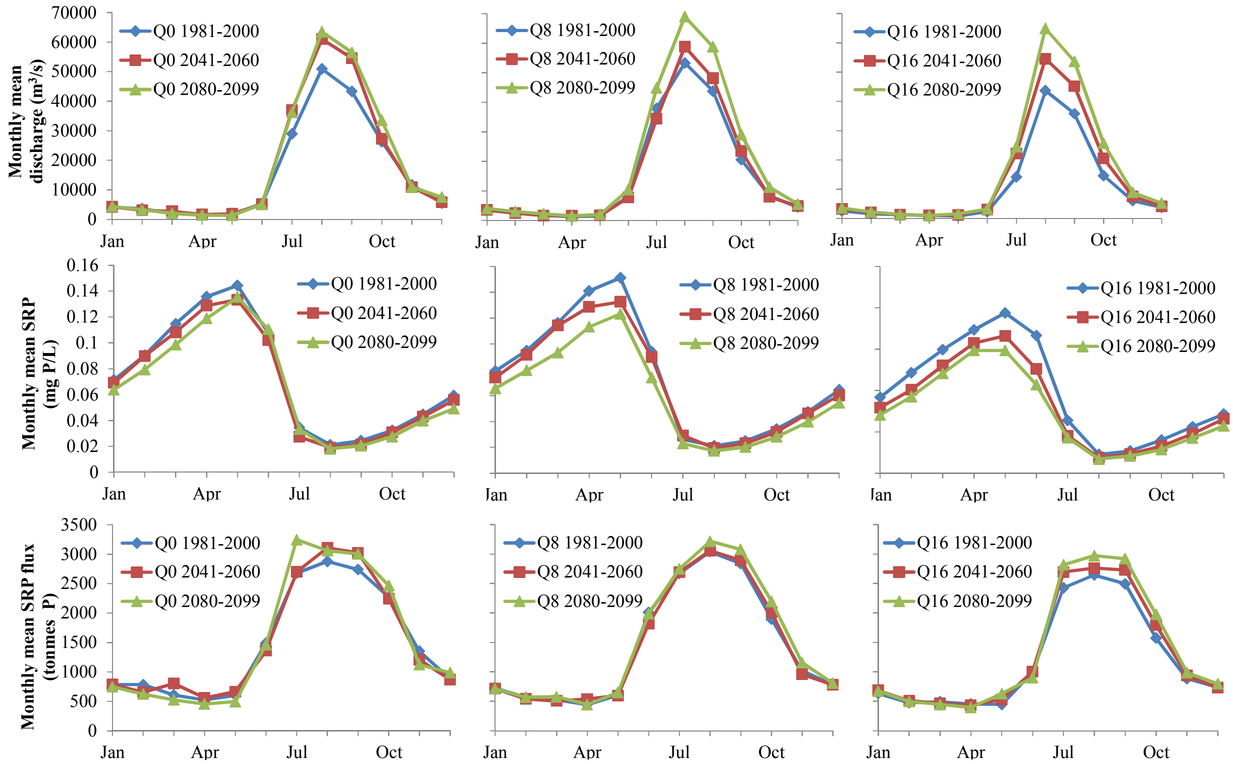

Fig. 10 Effects of climate change (Q0, Q8 and Q16 scenarios) on monthly mean flow, SRP concentrations and SRP fluxes for 1981-2000 (baseline), 2041-2060 (2050s) and 2080-2099 (2090s) at GA17.

Table 6 Percentage changes of monthly mean flow, SRP concentrations and SRP fluxes from baseline to 2050s and 2090s under three climate scenarios.

Flow	Q0		Q8		Q16	
	2050s	2090s	2050s	2090s	2050s	2090s
Jan	3.3	6.9	4.8	18.0	25.5	38.8
Feb	-15.4	-9.2	-1.0	20.2	29.4	37.2
Mar	39.5	0.6	-1.9	36.6	8.0	11.9
Apr	12.1	-0.8	33.0	25.1	4.8	2.2
May	19.1	-12.1	12.8	32.3	39.2	84.7
Jun	-4.2	-4.7	-5.3	25.6	32.9	41.1
Jul	27.4	25.2	-9.3	18.1	56.1	72.2
Aug	19.8	24.6	10.4	29.5	24.8	48.5
Sep	25.9	30.5	9.9	34.3	26.3	49.9
Oct	3.4	27.2	14.3	41.1	40.3	75.4
Nov	-6.7	-6.3	-3.5	35.9	25.2	47.3
Dec	4.8	35.3	6.9	22.7	8.4	36.2

SRP	Q0		Q8		Q16	
	2050s	2090s	2050s	2090s	2050s	2090s
Jan	-3.2	-10.8	-6.5	-17.0	-13.6	-23.2
Feb	-0.8	-12.3	-3.5	-16.1	-17.1	-23.8
Mar	-5.7	-14.1	-1.9	-19.8	-12.9	-19.2
Apr	-5.1	-12.4	-8.7	-19.7	-9.2	-14.4
May	-7.6	-6.2	-12.2	-18.5	-14.3	-23.4
Jun	-4.6	3.1	-4.6	-21.4	-24.3	-35.8
Jul	-20.9	-3.2	11.0	-12.9	-28.8	-32.6
Aug	-10.0	-14.7	-8.9	-18.3	-16.4	-24.3
Sep	-12.3	-16.0	-7.2	-19.2	-13.4	-21.9
Oct	-4.3	-14.6	-7.0	-17.8	-18.5	-28.4
Nov	-4.3	-11.2	-2.5	-16.4	-15.1	-24.2
Dec	-6.1	-17.2	-6.5	-15.7	-8.1	-20.1

SRP flux	Q0		Q8		Q16	
	2050s	2090s	2050s	2090s	2050s	2090s
Jan	-0.1	-4.7	-1.9	-2.0	8.4	6.6
Feb	-16.1	-20.4	-4.4	0.8	7.3	4.5
Mar	31.6	-13.6	-3.8	9.6	-5.9	-9.6
Apr	6.4	-13.1	21.4	0.5	-4.9	-12.5
May	10.1	-17.6	-1.0	7.9	19.3	41.4
Jun	-8.6	-1.8	-9.6	-1.2	0.6	-9.3
Jul	0.8	21.2	0.7	2.8	11.1	16.1
Aug	7.9	6.3	0.6	5.8	4.4	12.4
Sep	10.4	9.6	2.0	8.5	9.4	17.0
Oct	-1.1	8.7	6.3	16.0	14.4	25.6
Nov	-10.6	-16.8	-6.0	13.6	6.3	11.6
Dec	-1.5	12.0	0.0	3.4	-0.4	8.8

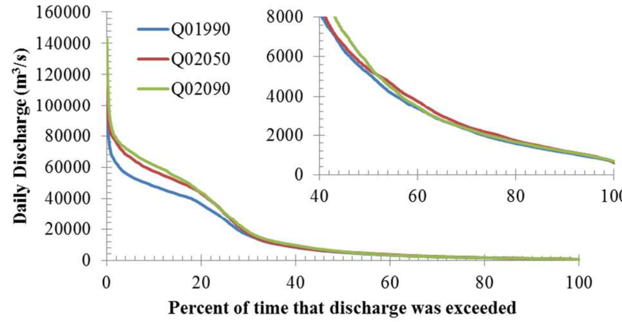

Fig. 11 Flow duration curve at GA17 under the climate scenario Q0. The inset plot shows the low flow range.

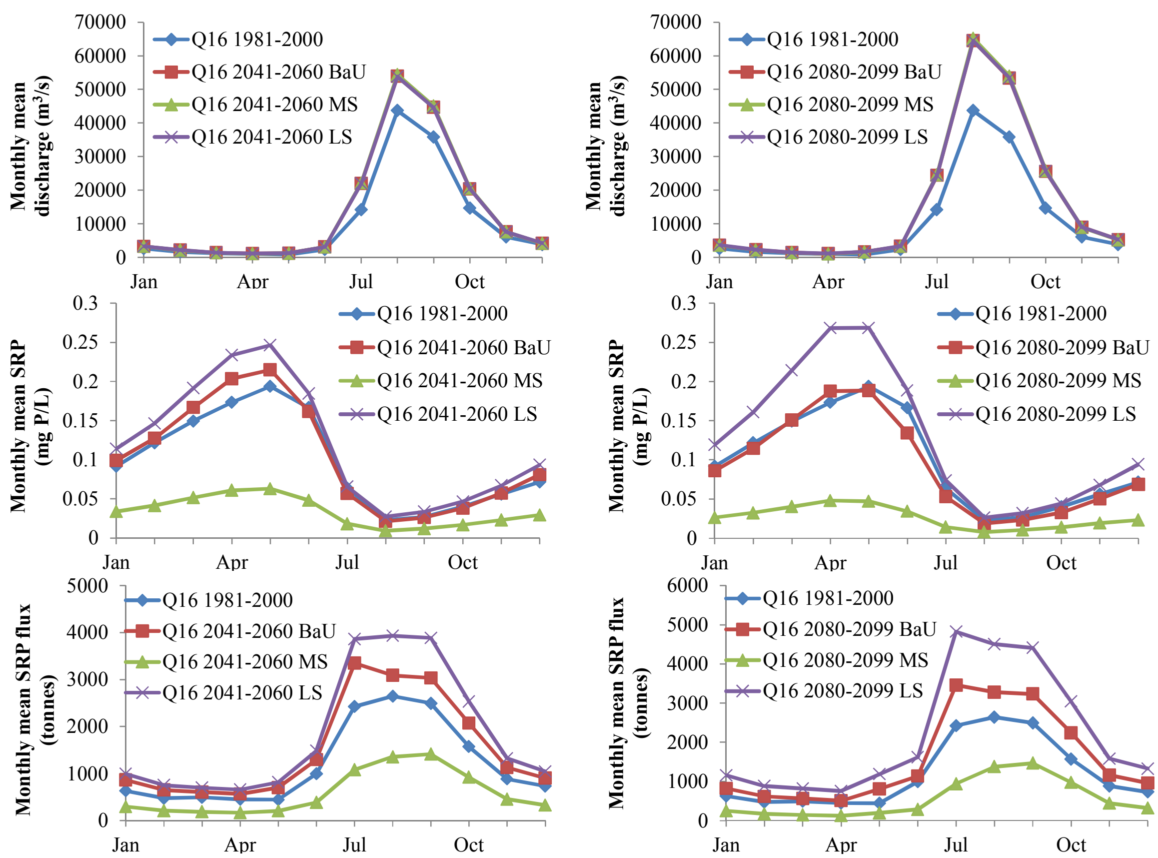

Fig. 12 Comparison of mean monthly flow, SRP concentrations and SRP fluxes for three SSPs (BaU, MS and LS) at 2050s and 2090s with the baseline 1990s under the Q16 climate change scenario at GA17.

The highest reduction (70%) occurs from January to June when the flow is low and STPs effluents constitute larger proportion of the total Ganga flow (Fig 13). During the monsoon season, the high flow mainly comes from the rainfall. The reduced effluent discharge would have less impact (10%) (Fig. 13). Atmospheric deposition is an important source of P to the Ganga River.[41] The reduction in atmospheric deposition for a more sustainable future will likely have a strong impact on the river P concentrations (Fig. 13). In August and September, the reduction of river SRP concentration from the atmospheric deposition would reach 30%. This is consistent with the findings from Pandey et al., (2013) that shows the significant positive correlation with atmospheric phosphate and river dissolved reactive-P.[41] SRP fluxes also have considerable changes due to the SRP concentration change. SRP fluxes decrease dramatically under SSP-MS at 2050s and 2090s. The highest monthly SRP fluxes are less than 1500 tonnes during the monsoon season, which is approximately half of the baseline condition (Fig. 12).

In contrast to SSP-MS, under SSP-LS, population rises resulting in more water usage and more wastewater generation and worse atmospheric deposition, which all lead to worsening water quality in the future with increases in SRP concentrations and fluxes close to 30% and 90% by 2090s, respectively (Fig. 12). For BaU, SRP concentrations decrease during the monsoon season reflecting more water in the river channel and therefore greater dilution. However, during the dry season, SRP increases (Fig. 12). SRP fluxes show consistent increase throughout the year with larger increase during the monsoon season.

a)

b)

c)

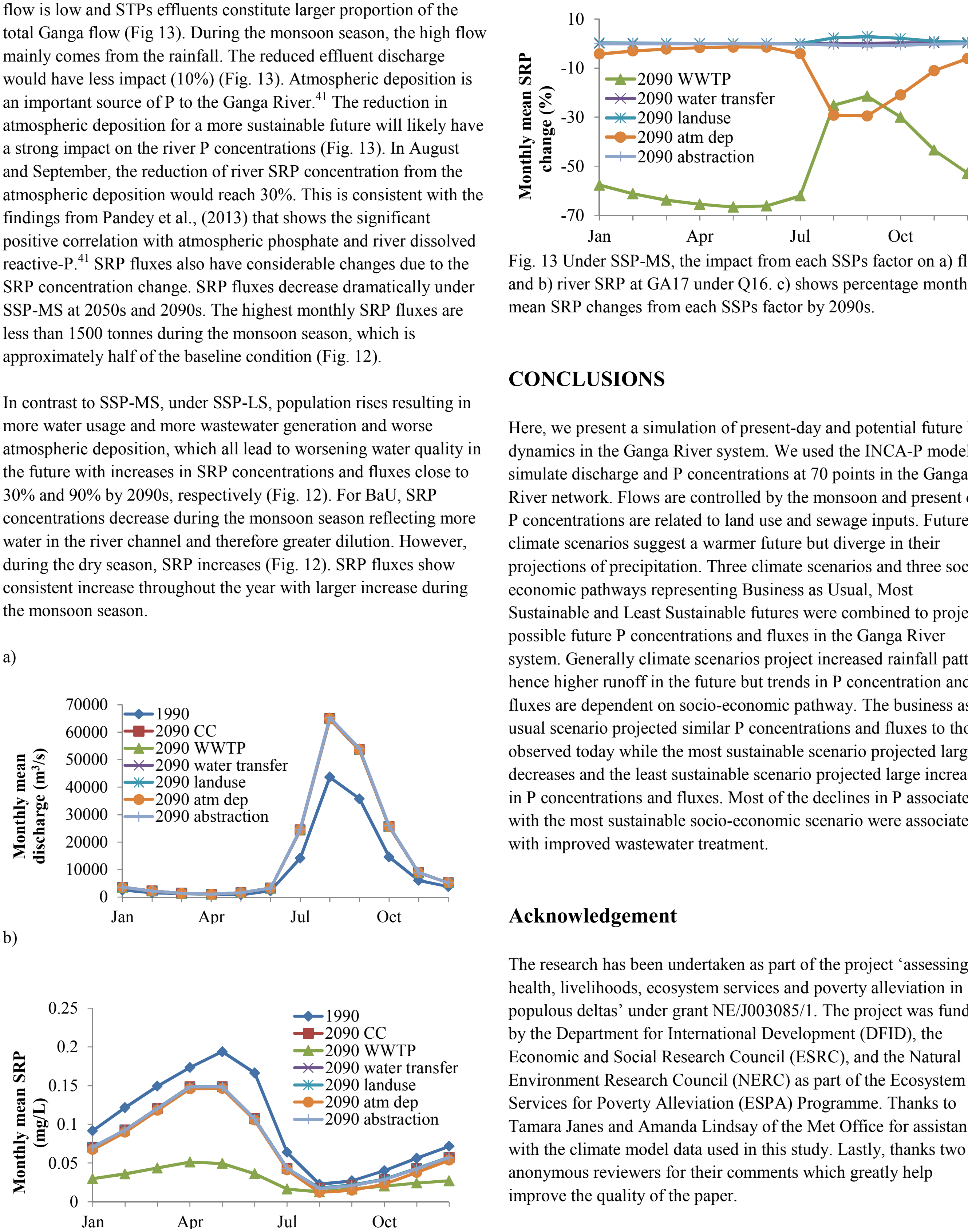

Fig. 13 Under SSP-MS, the impact from each SSPs factor on a) flow and b) river SRP at GA17 under Q16. c) shows percentage monthly mean SRP changes from each SSPs factor by 2090s.

CONCLUSIONS

Here, we present a simulation of present-day and potential future P dynamics in the Ganga River system. We used the INCA-P model to simulate discharge and P concentrations at 70 points in the Ganga River network. Flows are controlled by the monsoon and present day P concentrations are related to land use and sewage inputs. Future climate scenarios suggest a warmer future but diverge in their projections of precipitation. Three climate scenarios and three socio-economic pathways representing Business as Usual, Most Sustainable and Least Sustainable futures were combined to project possible future P concentrations and fluxes in the Ganga River system. Generally climate scenarios project increased rainfall pattern hence higher runoff in the future but trends in P concentration and fluxes are dependent on socio-economic pathway. The business as usual scenario projected similar P concentrations and fluxes to those observed today while the most sustainable scenario projected large decreases and the least sustainable scenario projected large increases in P concentrations and fluxes. Most of the declines in P associated with the most sustainable socio-economic scenario were associated with improved wastewater treatment.

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