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EIA statement

The potential impacts of climate change and socioeconomic change on flow and water quality in rivers worldwide is a key area of interest. The Ganges is one of the largest rivers in the world serving a population of over 600 million, and is of vital concern to Indian and Bangladesh as it provides fresh water for people, agriculture, industry, conservation and to the delta system downstream. The Indian Government has placed the Ganges clean up as a key policy for future management and Bangladesh has concerns about water diversions upstream. This paper seeks to assess future changes in flow and water quality utilising a modelling approach as a means of assessment in a massively complex system.

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Dynamic modeling of the Ganga River System: Impacts of future climate and socio-economic change on flows and nitrogen fluxes in India and Bangladesh

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This study investigates the potential impacts of future climate and socio-economic change on the flow and nitrogen fluxes of the Ganga River System. This is the first basin scale water quality study for the Ganga considering climate change at 25km resolution together with socio-economic scenarios. The revised dynamic, process-based INCA model was used to simulate hydrology and water quality within the complex multi-branched river basins. All climate realizations utilized in the study predict increases in temperature and rainfall by the 2050s with significant increase by the 2090s. These changes generate associated increases in monsoon flows and increased availability of water for groundwater recharge and irrigation, but also more frequent flooding. Decreased concentrations of nitrate and ammonia are expected due to increased dilution. Different future socio-economic scenarios were found to have a significant impact on water quality at the downstream end of the Ganga. A less sustainable future resulted in a deterioration of water quality due to the pressures from higher population growth, land use change, increased sewage treatment discharges, enhanced atmospheric nitrogen deposition, and water abstraction. However, water quality was found to improve under a more sustainable strategy as envisaged in the Ganga clean-up plan.

Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) Summary to Policy Makers[1] addresses the global significance of climate change driven by anthropogenic sources of carbon dioxide, and considers the likely positive and negative impacts on the natural environment and people across the globe. Potential changes in precipitation, temperature and sea level rise over the next century are evaluated utilizing an extensive evidence base. In addition, the IPCC report proposes a strategy for assessing future Shared Socio-economic Pathways (SSPs), and how these might interact with climate change to generate a combined effect on people and livelihoods. This then provides a framework for addressing issues of mitigation and adaptation for national, regional and local governments and organizations to consider.

The IPCC report provides a backdrop to a major new research project entitled Ecosystem Services for Poverty Alleviation in Deltas (ESPA-Deltas see www.espadeltas.net), which is aimed at assessing health, livelihoods, ecosystem services and poverty alleviation in populous deltas, with the focus on the delta systems in Bangladesh and India[2 3]. The large river systems of the Ganga, Brahmaputra and Meghna (GBM) combine to create the GBM delta. Over 670 million people depend on the river basins and the associated delta for their livelihood and wellbeing. Thus, knowing how such river systems might be impacted by future changes in climate and socio-economics is important for the wide range of stakeholders in the Delta region. This paper investigates the potential impacts of future climate and socio-economic change on the Ganga River System, whilst a second paper[46] in this special issue considers the combined GBM River system and the impacts of environmental change on Bangladesh and the delta region.

The Ganga River System (Fig. 1) (also known as the Ganges) is the largest river in India and drains an area of approximately 1,087,300 km^2 in India and Nepal. Over the past few years, rapid population growth in the Ganga basin has resulted in agricultural development, urbanization and early stage industrialization, with extensive use of water for irrigation, industry and public supply. Stretches of the Ganga River are polluted with sewage, untreated industrial discharges and chemical runoff from agricultural fields. Furthermore, the future climate change scenarios encompass melting headwater glaciers and changes in rainfall patterns, which pose serious

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threats to the availability of river water throughout the year, as well as altered drought and flooding regimes. There is growing concern about water scarcity and river management under these changing environmental conditions, especially given the increased demand for domestic, agricultural and industrial water. Such concerns have stimulated the Indian Government to develop management plans for the Ganga River system aimed at a long term strategy to improve the environmental flow and address water scarcity issues[4].

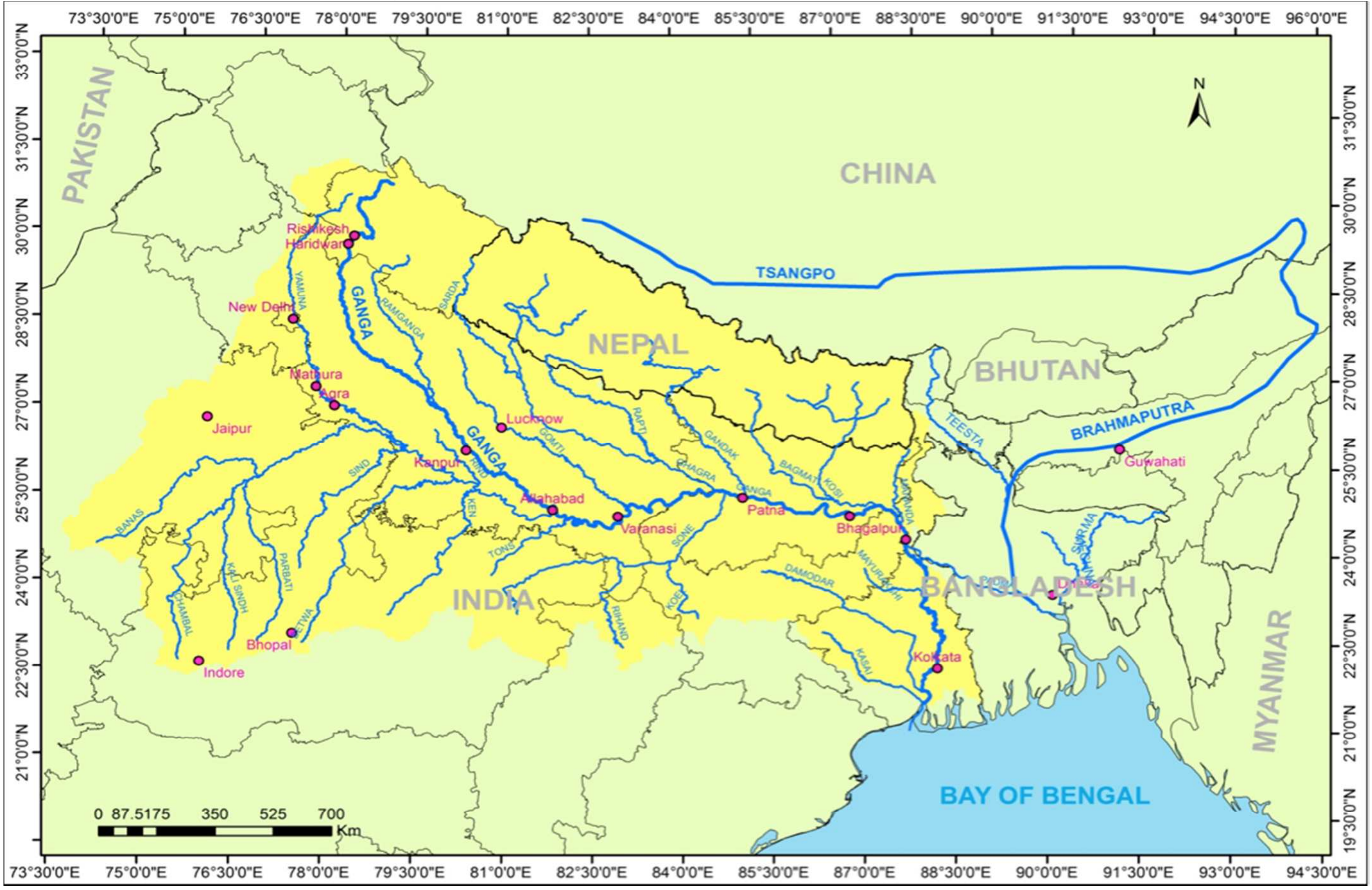

Fig. 1 Map of the Ganga Basins Draining into the Bay of Bengal.

The main objectives of this study are to assess the magnitude and variability in the flow of the Ganga River as a function of future changes in the climate, land use and socio-economic conditions, and to determine the flux of nitrogen moving down the river. The flow and nutrient fluxes then become input data for other modeling teams in the ESPA Deltas project who are assessing the impacts of environmental change on the GBM delta estuary system and the Bay of Bengal. Flow and nutrient fluxes can provide critical information that can assist the Indian and Bangladesh governments to mitigate future impacts. This work also provides data that enables the investigation of impacts on the downstream delta.

There are several existing modeling studies on the Ganga River, most of which were funded by either Government departments or international organizations, such as the World Bank. Many of these studies are available as peer reviewed papers that capture the major findings and large-scale macroeconomic aspects[5 6 7]. There have been several water quality studies on tributaries of the Ganga on nitrogen dynamics in small Himalayan basins[8], on the pollution aspects of the Yamuna River[9], on sediment fluxes and morphology of the river[10].

There have also been several climate change studies on the effects of changing precipitation and temperature on floods and low flows[11 12 13] . There have also been several studies utilizing RCMs [7 26 47 48] and many of these consider the climate impacts on higher altitude Himalayan catchments. Most previous RCM model studies over the region have used a resolution of approximately 50 km [26 35 36] whereas in this study we have made use of a higher resolution 25km RCM[50] developed by the Met Office Hadley Centre. The main advantage of the finer grid RCM is that the approach reduces the spatial and temporal uncertainty in the projections. Also, this is the first time the 25k RCM has been coupled with socioeconomic effects in the Ganga River System.

In order to undertake an assessment of the hydrology and inorganic nitrogen dynamics, the semi-distributed, process-based INtegrated CAtchment model for Nitrogen (INCA-N) [17 18 19 20] has been applied to the whole of the Ganga River System. A set of climate and strategic socio-economic scenarios has then been evaluated to assess the potential impacts on both flows and water quality in the Ganga River System.

The Ganga River System

The Ganga basin extends between the latitude of 22° 30' N to 31° 30'N, and the longitude of 73°0'E to 89° 0' E (Fig. 1). The basin covers an approximate area of 835,744 km^2 in India, encompassing the states of Uttarakhand, Uttar Pradesh, Madhya Pradesh (in parts), Bihar, Jharkhand and West Bengal. The remaining 251,556 km^2 of the basin are in Nepal. The basin is bounded by the Himalaya to the north, the Aravallis on the west, the Vindhyas and Chhotanagpur plateau on the south, and the Brahmaputra ridge on the east.

The Ganga River originates from the Gangotri Glacier in the Himalayas at an elevation of nearly 7010 m and traverses a length of about 2550 km (measured along the Bhagirathi and the Hooghly Rivers) before it flows into the Bay of Bengal. Along its way, the Ganga is joined by a number of tributaries to form the most flat fertile alluvial plain in North India[21]. The main sources of water in the rivers are rainfall, subsurface flow, and snow-melt water from the Himalayas. Average annual rainfall varies between 300 mm to 2000 mm, with the western side of the region receiving less rainfall in comparison with the eastern side. Rainfall is concentrated in the monsoon months of June through to October, causing low flow conditions in the Ganga River and its tributaries during the dry periods of November to May.

Fertile Eutric Cambisols are the main soil type in the lower basin, ideally suited for intensive cultivation. Shallow Luvisols of low fertility dominate the upper basin of the Ganga River[21]. Land use in the India part of the Ganga basin consists of extensive agricultural land with a wide variety of crops, expanding urban areas, and areas of scrub and bare soils. The upper reaches consist of snow and rock, some remaining forest, and urban areas. The major cities located in the river basin are Delhi, Kolkata, Kanpur, Lucknow, Patna, Agra, Meerut, Varanasi and Allahabad. These cities are expanding at a substantial rate as reflected in the rising population levels and extensive industrial growth. According to census data, the average population density in the Ganga basin is of the order of 520 persons per km^2. Electronics, leather, textiles, paper, jute, cement, and fertilizer production are some of the industries situated along the course of the river. Disposal of untreated urban wastes and industrial effluents increase pollution loads into the Ganga river system. According to the Central Pollution Control Board Report[22], the total wastewater generation from 222 towns in the Ganga basin is 8250 ML/d, out of which 2538 ML/d is directly discharged into the Ganga River, 4491 ML/d is disposed of into tributaries of the River Ganga, and 1220 ML/d is disposed onto land or low lying areas. Thus, the Ganga River System is a very large and complex river system to model and becomes even more complex once it enters the Bangladesh Delta region with a complex network of channels and braided river systems. This area is a tidal zone and is considered as part of the estuarine modelling component of ESPA Deltas.

The INCA model

Modeling complex river systems such as the Ganga requires a distributed model that can account for the spatial variability across the basin. INCA is one such model that has been applied extensively to heterogeneous basins and has the advantage that it is dynamic, process-based, and integrates hydrology and water quality. The INCA model has been developed over many years as part of UK Research Council (NERC) and EU funded projects [17 18 19 20].

INCA simulates hydrology flow pathways in the surface and sub-surface systems, and tracks fluxes of solutes/pollutants on a daily time step in both terrestrial and aquatic portions of basins. The model allows the user to specify the spatial nature of a river basin, to alter reach lengths, rate coefficients, land use, velocity-flow relationships, and to vary input pollutant deposition loads from point sources, diffuse land sources, and diffuse atmospheric sources. INCA originally allowed simulation of a single stem of a river in a semi-distributed manner, with tributaries treated as aggregated inputs. The revised version now simulates nutrient dynamics in dendritic stream networks, as in the case of the Ganga River which has many tributaries[19]. The model is based on a series of interconnected differential equations that are solved using a numerical integration method based on the fourth-order Runge-Kutta technique[17 20]. The advantage of this technique is that it allows all equations to be solved simultaneously.

Fig. 2 shows the main flow paths and processes in INCA-Nitrogen (INCA-N). The model performs a mass balance for the basin, accounting for all inputs and outputs, with a daily time step. The key processes of nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) input, transformation and removal in the soil zone are shown in Fig. 3.

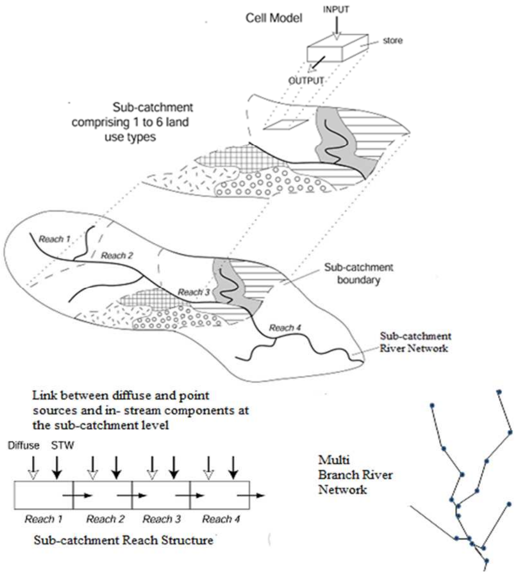

Fig. 2 The INCA model structure.

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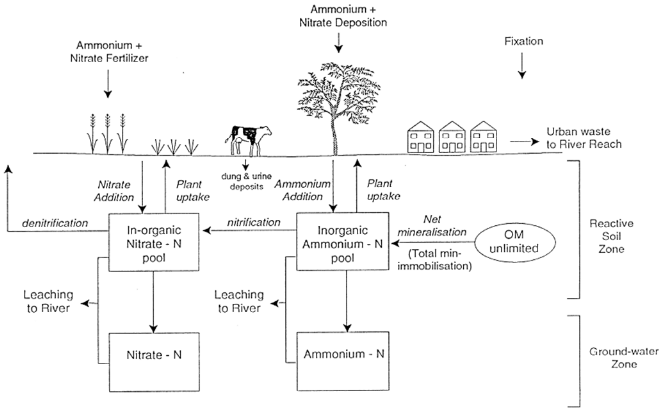

Fig. 3 The soil and groundwater zones in INCA.

In a river reach, as shown in Fig. 4, the source of NO_3-N and NH_4-N input are the previous upstream reach, the soil and groundwater zones, and the direct effluent discharges. The important processes involved for nitrogen mass alteration in a reach are denitrification of NO_3-N and the nitrification of NH_4-N. The instream N alterations are controlled both by temperature and residence time, together with the appropriate rate coefficients[17 18 19 20].

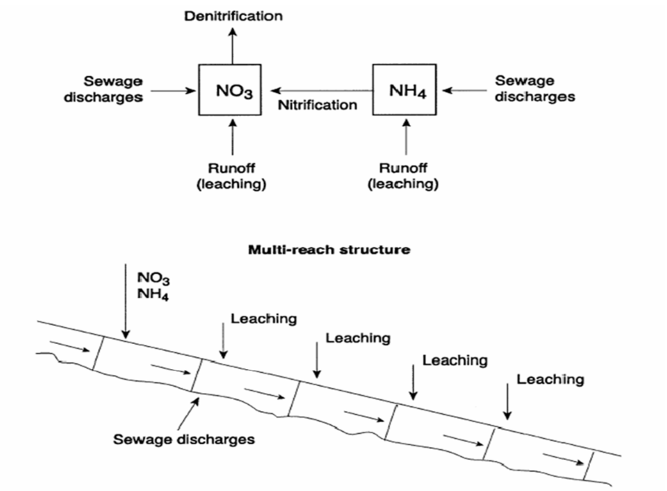

Fig. 4 The instream component of INCA together with the key processes operating.

Application of INCA to the Ganga River System

The INCA model was set up as a multi-reach model, with 70 reaches representing the key locations and sub-basin boundaries as shown in Fig. 5 and Fig. 6. Shuttle Radar Topographic Mission (SRTM) 90m resolution digital elevation model (DEM) data was used to delineate the watershed boundaries for each reach, with 21 reaches covering the main Ganga, and 10 reaches its main tributary, the Yamuna River. All the other main tributaries are shown in Fig. 5 and Fig. 6. The reach boundaries were selected based on a number of factors, such as a confluence point with a tributary, a sampling or monitoring point, or an effluent input/abstraction point associated with a major irrigation scheme or a large city. The type of land use is important as it affects the hydrology, evaporation rates, flow paths, and nutrient fluxes through fertilizer application rates[23]. Land use data for the Ganga basin was obtained from the Indian National Remote Sensing Centre (NRSC), and consisted originally as 26 land use classes. In order to limit the parameter input for INCA, these 26 land use classes were aggregated into six similar types of land use classes for the Ganga basin, these being Urban, Forest, Grassland, Double / Triple Crop, Kharif Crop, and Rabi Crop, as illustrated in Fig. 7. The Kharif crops are cultivated and harvested during the rainy monsoon period, with main Kharif crops being millet and rice. Rabi crops are sown after the rains have gone in April and May, with the main crops being wheat, barley, mustard, sesame and peas.

The data required, and their sources, for INCA are listed in Table 1. Table 2 lists the Sewage Treatment Works (STWs) flows and their corresponding NO_3 and NH_3 concentrations on the main Ganga River and the Yamuna River system. This data was incorporated into INCA at the relevant reaches so that the correct discharge and N loads were accounted for. Within the model, estimated abstractions for public and irrigation supply were also accounted for at the relevant reaches.

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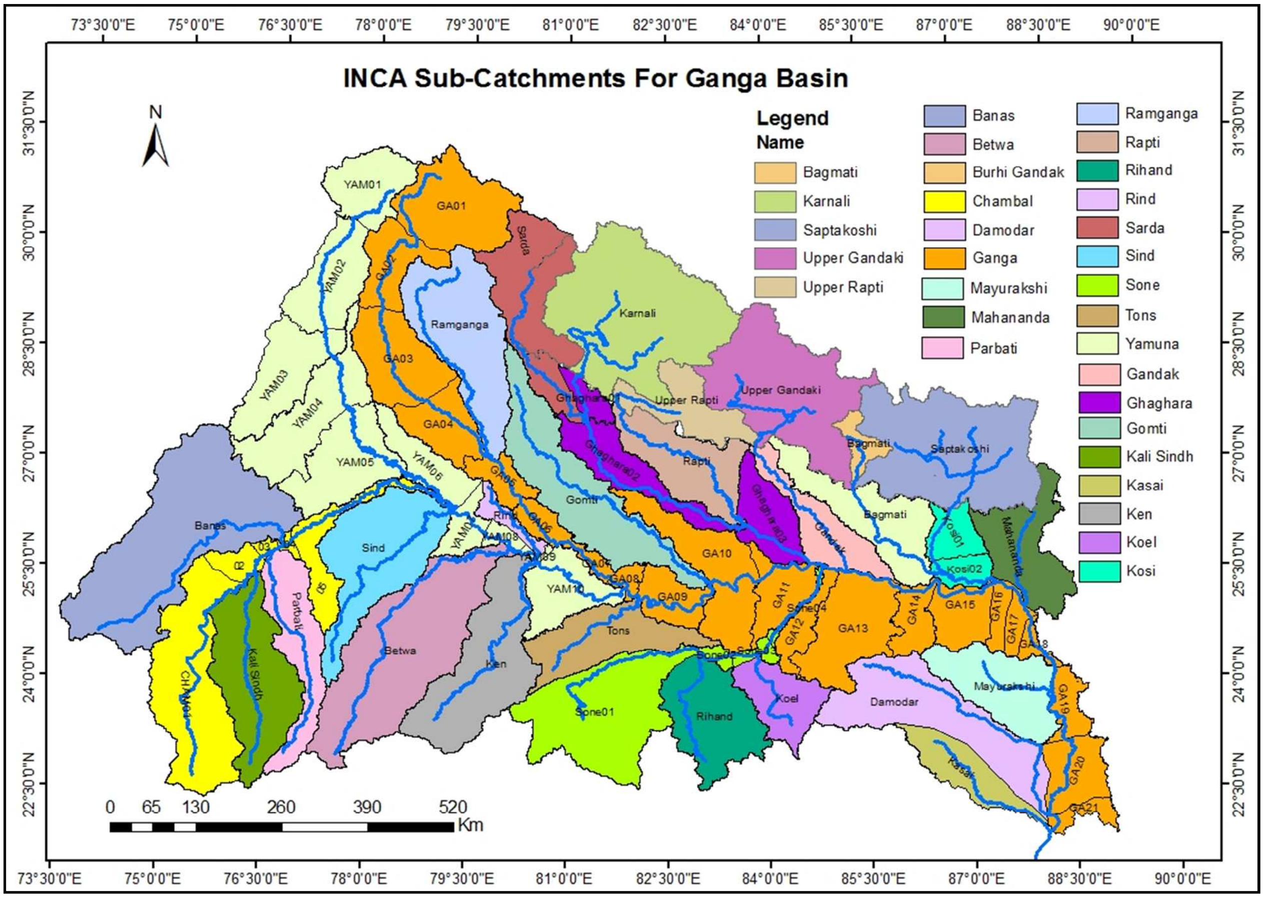

Fig. 5 Map showing the multi-branch Ganga River System and the sub-basin and reach division.

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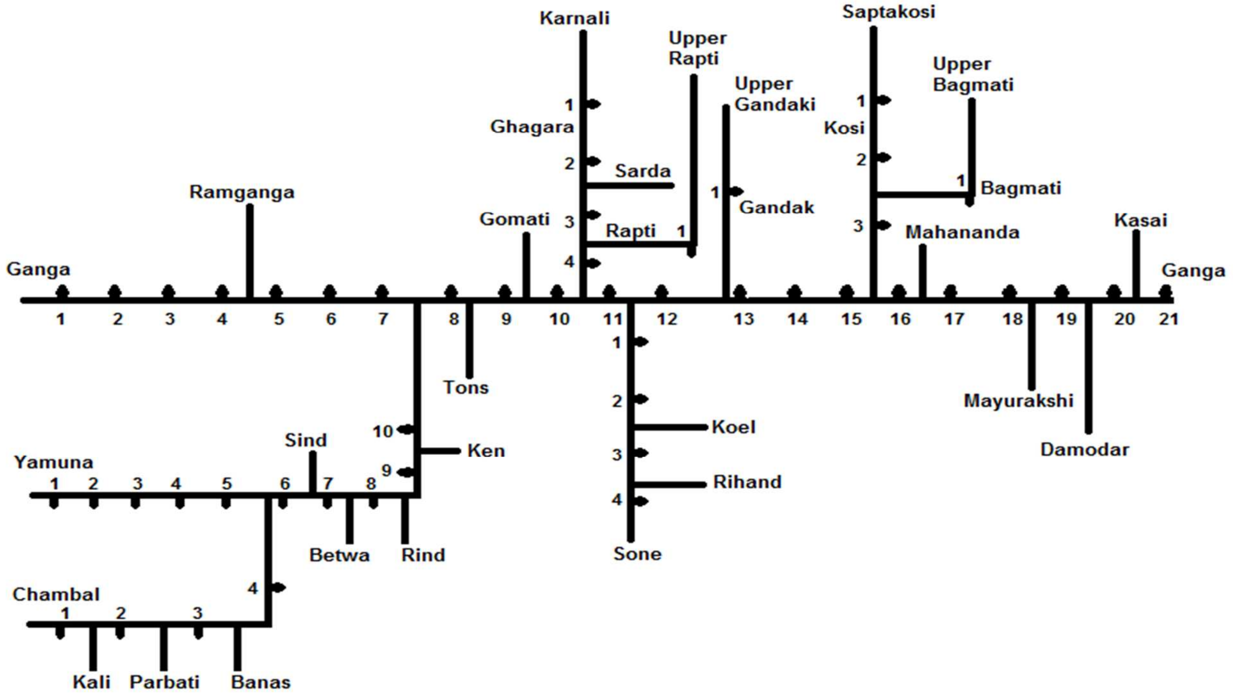

Fig. 6 Schematic network diagram showing reach divisions used in multi-branch INCA model for the Ganga River System.

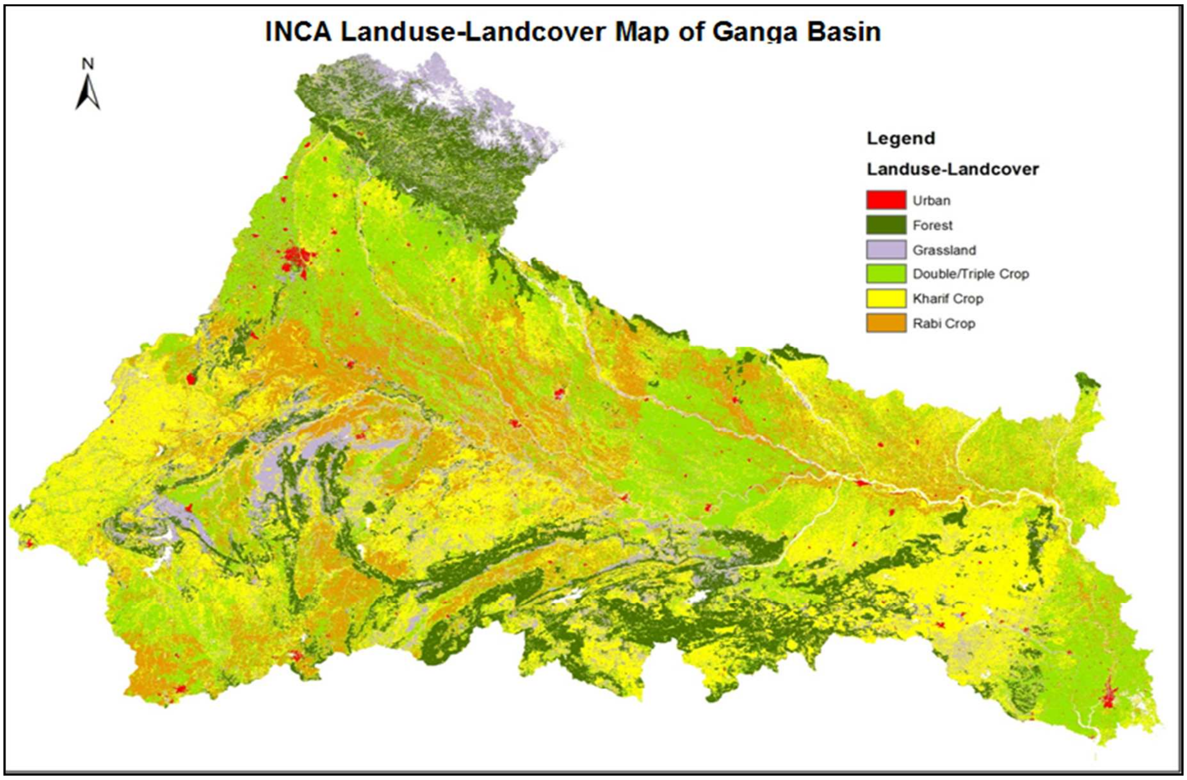

Fig. 7 INCA land use map with six land classes

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Table 1 Data Sources for the Ganga Modelling Study.

Data Required	Data Source
Digital Elevation Model (DEM) of the Study Area	SRTM 90 x 90 m resolution raster data.
Landuse-Land cover for Ganga basin	National Remote Sensing Centre (NRSC) 56 x 56 Resolution Grid raster data.
Sewage Treatment Plant	Design capacity, nitrate and ammonium concentration of outlet of STPs from the reports of Central Pollution Control Board.
Crop growth data	FAO and Ministry of Agriculture Reports- Kharif crops - April–September, Rabi Crops- October to March, Double/Triple Crops & Plantation throughout the year.
Fertilizer input data	Fertilizer used for the different crops available from FAO and Department of Fertilizers, Ministry of Chemicals and Fertilizers, Govt. of India.
Discharge	1. Observed discharge value (1979-2000) at the Hardinge Bridge in Bangladesh is available from CEGIS in Bangladesh. 2. Observed Data of Mean Annual Discharge (1968-2000) is available at 5 Ganga river stations.
Water quality Data	Data available from the Indian Central Pollution Control Board 1. Annual maximum, minimum and mean NO_3-N (2003-2011) at various monitoring stations along Ganga river. 2. Annual maximum, minimum and mean NH_3-N (2003-2007) at various monitoring stations along Ganga river. 3.Monthly NO_3-N and NH_3-N data (2010-2013) for few stations in West Bengal.
Meteorological	Daily Soil Moisture Deficit (SMD, mm), Hydrologically Effective Rainfall (HER, mm), 1.5m Mean Air Temperature (°C) and Actual Precipitation (mm) data were obtained or derived from the output of the Met Office Hadley Center HadRM3P RCM for the period 1971-2099.[24]

Table 2 STWs flow data for the Ganga and Yamuna Rivers.

Reach	Flow m^3/sec	Nitrate mg N/L	Ammonia mg N/L
GA02	0.58	9.0	22.6
GA04	0.35	11.6	23.6
GA05	0.08	15.0	25.0
GA06	4.28	10.1	24.6
GA08	2.41	2.0	15.2
GA09	2.67	5.3	21.6
GA10	0.12	15.0	25.0
GA11	0.30	14.0	24.6
GA13	3.36	10.6	23.0
GA14	0.49	11.0	23.4
GA15	0.71	12.8	24.1
GA19	0.65	7.2	17.3
GA20	14.66	10.5	23.1
GA21	0.28	2.5	20.0
YAM02	1.96	5.4	19.9
YAM03	37.13	6.3	20.5
YAM04	3.06	9.7	22.1
YAM05	3.59	8.8	22.2
YAM06	0.33	9.7	22.8

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Climate drivers for the INCA Ganga model

In order to run a set of hydrological simulations and climate scenarios, INCA requires a daily time series of climate data, namely precipitation, hydrologically effective rainfall, temperature, and soil moisture deficit. INCA then uses these data to simulate the hydrological components of the model that generates the sub-basin and river flows, which also in turn drive the chemical mass balances. However, obtaining such data at a large basin scale is difficult, especially given the wide spatial differences in topography, altitude, and land use in India and Nepal. Therefore, available observational data from in-situ weather stations, combined with satellite-derived measurements, were integrated into observational datasets that cover the region[25].

Global-scale general circulation models (GCMs) have been used to simulate climate across the region and to assess the impacts of increasing greenhouse gas concentrations on the global climate system. However, GCMs typically have coarse spatial resolutions, with horizontal grid boxes of a few hundred kilometers in size, and cannot provide the high-resolution climate information that is often required for climate impact and adaptation studies. The use of regional climate models (RCMs), which dynamically downscale the GCM simulations using boundary conditions from GCMs, can provide higher resolution grids (typically 50km or finer), and are better able to represent features such as local topography and coast lines and their effects on the regional climate. There have been several studies utilizing RCM output [7 26 47 48] and these illustrate the benefits of the RCM approach. In the current study, we used an existing set of GCM simulations to provide boundary conditions for a 25km RCM for the period 1971-2099 over the South Asia domain[24]. The GCM is the third climate configuration of the Met Office Unified Model (HadCM3) [27 28 29] and was run as a 17 member perturbed physics ensemble[29] driven by the Special Report on Emissions Scenarios (SRES) A1B scenario[30]. SRES A1B was developed for the IPCC Third Assessment Report and still underpins much recent research into climate impacts. It is a medium-high emissions scenario, and is based upon a future assumption of strong economic growth and an associated increase in the rate of greenhouse gas emissions. To put this into context with the newer Representative Concentration Pathways (RCPs) used in the IPCC Fifth Assessment Report[1 31], SRES A1B lies between the RCP6.0 and RCP8.5 in terms of the end of 21st century projected temperature increases and atmospheric CO_2 concentrations[32]. The purpose of a perturbed physics ensemble is to explore the uncertainty in a single climate model associated with a variety of model parameters using a range of plausible values [33]. Whilst many model parameters are well constrained by observations, there are others that are subject to uncertainty. Different combinations of model parameters may give equally realistic simulations of present day climate, but could result in different projections for the end of the 21st century.

The perturbed physics ensemble of 17 members, represents a range of possible future outcomes for the same emissions scenario (i.e. SRES A1B). The individual ensemble members are referred to as Q0–16, where Q0 has the same parameter values used in the standard HadCM3 coupled GCM[8]. Q1 to Q16 are arranged in order of increasing global climate sensitivity, with Q16 representing the ensemble member with the highest climate sensitivity, though note that regional and seasonal temperature responses should not be assumed to follow linearly[34].

Output from the perturbed physics ensemble of the HadCM3 GCM was used as lateral boundary conditions to drive a consistent 17-member set of RCM simulations. The RCM is the Met Office Hadley Centre HadRM3P, a high-resolution limited area model which is used in the Providing Regional Climates for Impacts Studies (PRECIS) regional modeling system[16]. The resolution is 0.22° x 0.22° (approximately 25km) with 19 vertical levels and 4 soil levels. In this case, the model domain covers south Asia (with rotated pole coordinates of 260° longitude, and 70° latitude), which allows for the development of full mesoscale circulations over the region of interest, and captures important regional dynamics.

The monsoon provides a large proportion of the annual rainfall for the region over the month of June to September, and so it was particularly important to assess the ability of the model to simulate the monsoon flows. The RCM was validated by comparing model output temperature and precipitation with observational datasets[24 25 37].

Modeling hydrology and water quality

Hydrologically effective rainfall (HER) and soil moisture deficit (SMD) data were estimated for the Ganga River Basin using the Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport (PERSiST) model [38]. PERSiST is a watershed-scale hydrological model suitable for simulating terrestrial runoff and streamflow across a range of spatial scales from headwaters to large river basins. It is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA model. PERSiST simulates water fluxes from precipitation through the terrestrial part of a basin and uses an evaporation mass balance to determine the evapotranspiration, and from this the HER and the SMD. A detailed description of this analysis for the Ganga is published in a separate paper in this volume[39]. Fig. 8 shows the daily estimated precipitation, HER, temperature and SMD for the river system over the baseline period 1981-2000 used as input into INCA-N.

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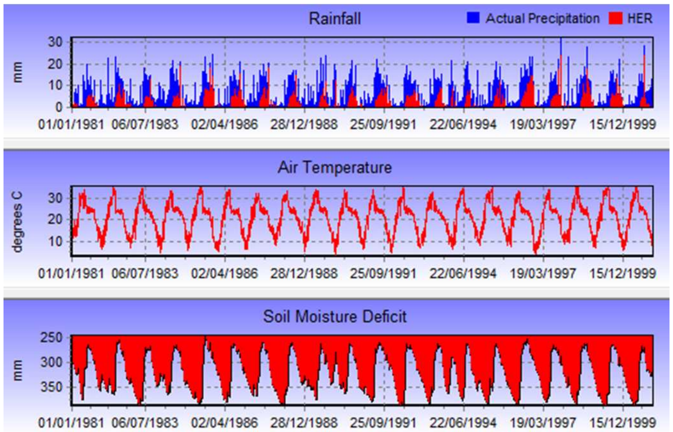

Fig. 8 Daily precipitation, HER, temperature and SMD for the Ganga Basin over the period 1981-2000.

The INCA model used the daily time series meteorological data together with all of the reach, land use and basin data to simulate daily flow and water quality at each reach along the whole Ganga system for the period of 1981-2000. The model outputs were then compared to the observed flow data for the river during calibration and validation of the model (Fig. 9). The observed flow data is sparse on the Ganga River system[6], although there are some flow gauges on the main river upstream at reaches GA03, GA04, GA05, and GA06. Observed flow rates and water quality data are also available further downstream at Hardinge Bridge in Bangladesh and have been included for model calibration and validation (Fig.10).

Table 3 shows the degree of model fit to observed data showing the R^2 in those reaches where measured flow data is available. The results for the model calibration period of 1981-1990 and for the validation period of 1991-2000 are given and illustrate that the model fit is good in both data sets. Simulated daily flow provided an acceptable reproduction of the observed flow, particularly given the multi-reach complex nature of the Ganga River system (Table 3, Fig. 9 and Fig. 10). In general, the simulations capture the main dynamics of the rise in precipitation during the monsoon period and the recession curves at the end of the monsoon period.

Table 3 Statistics of comparison between observed and simulated flows for calibration and validation periods.

Reach	Calibration R^2	Validation R^2
Ganga 3	0.52	0.45
Ganga 4	0.59	0.57
Ganga 5	0.58	0.53
Ganga 6	0.58	0.48
Ganga 17	0.76	0.7

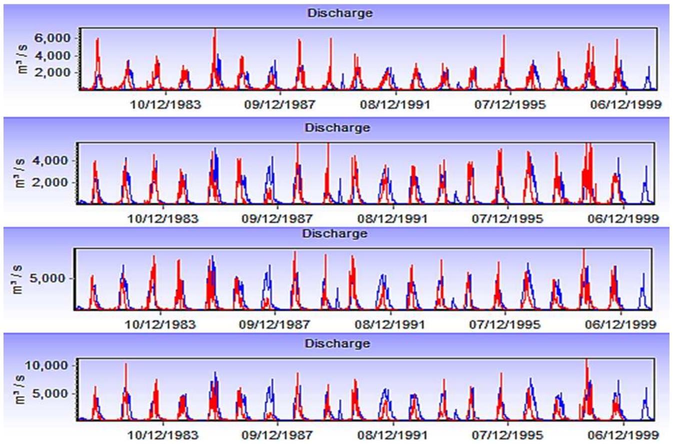

Fig. 9 Simulated (blue line) and Observed (red line) daily flows at 4 flow gauges on the Ganga River System – Top graph -Reach 3 (Garhmukteshwar), 4 (Kachlabridge), 5 (Ankinghat) and bottom graph – Reach 6 (Kanpur).

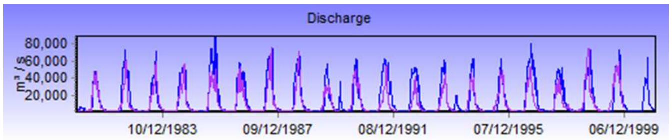

Fig. 10 Simulated (blue line) and observed (purple line) daily flows on the Ganga at Hardinge Bridge, Bangladesh.

In addition to calibrating the flow model, it is necessary to calibrate the water quality model. Nutrients are critical for agriculture, but are also a primary pollutant concern for the ESPA Deltas Project. When used in excess, they can impact on water quality, ecology, and fisheries, which directly affect human well-being and resource availability for people in the delta region. Therefore, a key target of this study was to estimate the nutrient load flowing down the Ganga River into the Bay of Bengal.

The water quality data is limited to monthly observations at 10 monitoring points along the river, plus the observations from Hardinge Bridge in Bangladesh. Fig. 11 illustrates the comparison between observed and simulated monthly nitrate concentrations at Hardinge Bridge. Fig. 12 shows the simulated and observed monthly nitrate concentrations at Farakka, just upstream of Hardinge Bridge, and is representative of several other locations along the river which yielded similar results. The degree of fit in terms of load with an R^2 of 0.96 is good and suggests the model can be used with some confidence in predicting nutrient loads

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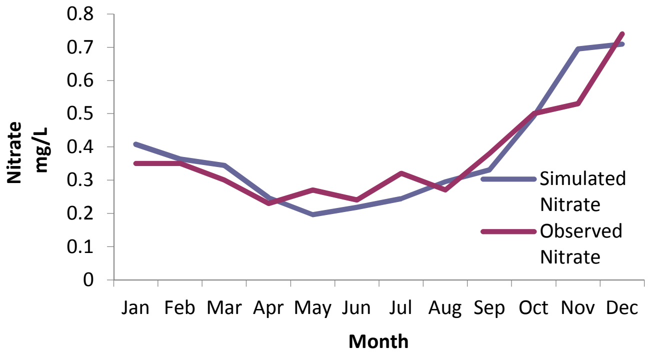

Fig. 11 Simulated (blue line) and observed (purple line) monthly average nitrate concentrations for in the Ganga at Hardinge Bridge, Bangladesh.

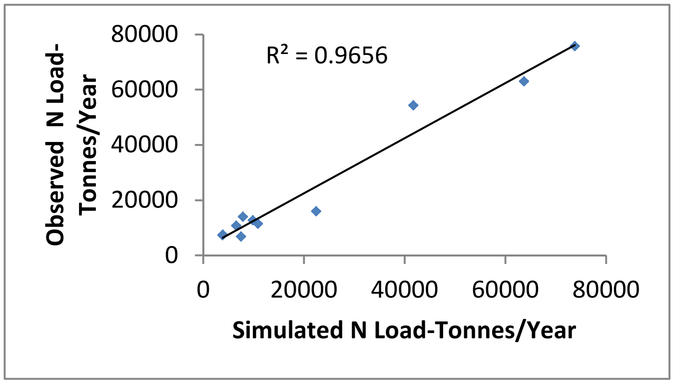

Fig. 12 Simulated and Observed Nitrogen Load in the Ganga River at Kanpur.

Scenario analysis for climate and shared socio-economic Changes

A set of climate change realizations and shared socio-economic scenarios were developed for this study on the Ganga River Basin following the broad protocol established in the IPCC analysis[1] where these are named Socio-economic Scenario Pathways[1].

Climate

Three climate change realizations were selected from a total of 17 model variants from the Met Office HadRM3P regional climate model for south Asia. The three selected scenarios, Q0, Q8 and Q16 are summarized in Table 5, and show that the temperature increases relative to current observations are of the order of 2.3 °C by the 2050s and 4.0 °C by the 2090s. The climate change scenarios also provide three ranges of precipitation changes. Precipitation increases by up to 10.7% by the 2050s under scenario Q0. However, under the Q8 scenario precipitation increases 5.23% by 2050. Toward the end of the century, all three scenarios show increases in precipitation of 15%, 22% and 33% respectively, in relation to current observations, so these are quite significant increases.

Table 5 Three climate scenarios from the Met Office Hadley Centre HadRM3P RCM for the Ganga basin area

Ensemble Member	Mid Century		End of Century	
	Temp increase (°C)	Precipitation increase (%)	Temp increase (°C)	Precipitation increase (%)
Q0	2.29	3.98	10.72	15.28
Q8	2.40	3.87	5.23	22.41
Q16	2.70	4.85	18.11	33.30

Shared Socio-economic Scenarios

The IPCC SSP strategy[1] [40] [14] considers socio-economic pathways as a means on integrating social aspects of future change using the following 5 broad classifications for future conditions: SSP1 for Sustainability, SSP2 for Business as Usual, SSP3 for Fragmented World, SSP4 for Inequality Rules, and SSP5 for Conventional Development in terms of energy sources. Within the ESPA Deltas project we considered 3 plausible SSPs which have been adapted from the 5 proposed SSPs, namely SSP-BaU for Business as Usual, plus two other SSPs; an SSP-MS for a more sustainable future, and an SSP-LS for a less sustainable future. In order to assess the impact of these scenarios on the Ganga River flow and water quality, the SSPs had to be quantified. There are many factors that affect the socio-economic conditions and potential futures in the region from both a flow and a water quality perspective, and these include:

1 Population change;
2 Sewage Treatment Works capacity and design for water quality control;
3 Water Demand for irrigation and public supply;
4 Atmospheric Nitrogen Deposition;
5 Land use change; and
6 Water Transfer Plans.

The construction of additional dams are also likely to occur, but were not considered as part of this study as previous work[5] [7] has indicated that the majority of proposed hydropower dams will not have a significant impact on peak flows. Whilst there is the potential to have greater impact on low flows, this analysis was outside the scope of this study. A summary of the three scenarios based on the above six changes in socio-economic conditions is provided as follows.

Population

Predicted population forecasts for India vary widely depending on fertility rates. Based on fertility assumptions, UNDP population projections for 2041-2060 and 2080-2099, representing the mid-century and end of century respectively, were used as scenarios to evaluate the impact of population growth[15] (Table 6).

Table 6 Percentage Population Change in India based on UNDP estimates.

Scenario	Fertility Assumptions	2041-2060 % Change	2080-2099 % Change	Source of Data
SSP - BaU	Medium fertility	34.1	31.5	UNDP
SSP - LS	High fertility	54.8	94.4	UNDP
SSP - MS	Low fertility	15.3	-14.9	UNDP

Sewage Treatment Works (STWs)

Future scenarios from changes in STW discharge rates and concentrations of nutrients were developed based upon future changes in population (Table 6) and requirements for upgrading of STWs. This reflects the implementation of the Ganga Management Plan to enhance the capacity of all the STWs on the Ganga river system and treat effluents from a larger population. The Ganga Management Plan also aims to considerably upgrade the treatment processes. Assuming the secondary treatment processes are introduced, average ammonia discharge concentrations should fall from 19mg/L to 5mg/L. Nitrate is likely to stay much the same unless tertiary treatment is implemented. However, this represents the more sustainable option, with nitrate concentrations falling to 4mg/L. Under the BaU and MS options the STWs water quality stay at the current observed concentrations[22] indicated in Table 2.

Water demand for irrigation and public supply

The demand for public water supply has increased with population growth, although much of the supply in rural areas is from groundwater. Changes in irrigation water demand reflect changes in agriculture and land use. However, agricultural changes in India are difficult to predict as any changes will depend on factors such as world food prices, which are driven by increasing population, potential food scarcity and how farmers react to changing crop prices. Other key influential factors include technological developments such as the introduction of new crop varieties adapted to changing local environmental conditions. The Food and Agriculture Organization of the United Nations (FAO) estimates a 22.7% rise in Kcal/person/day in food production in India by 2050 with much of this from increased production of dairy and meat, as well as additional crops producing vegetable oils and sugar[41]. Agricultural expansion and intensification will be required to feed a growing population. It is assumed in the BaU scenario that new improved crop yields and more efficient farming will occur, and irrigation abstraction from the rivers and groundwater will increase. For the purposes of this study we have assumed that the abstraction from the Ganga River will increase by 22.7 % for the BAU and the LS scenario in accordance with the predicted increase in food production. Under the more sustainable scenario we assume that the abstractions will increase by only 11.3% reflecting changed crop varieties and improved irrigation.

Atmospheric nitrogen deposition

Atmospheric nitrogen pollution has become an increasing problem around the world, as industrial development, power generation and ammonia release from intensive agriculture has expanded. For example, across Europe, a set of Nitrogen Protocols have been established by the UN/ECE Commission of Transboundary Pollution and these protocol have been agreed and implemented by all EU countries. Deposition can be high with 15kg N per hectare per year being deposited in certain parts of Europe such as the UK. The effect of high atmospheric N is to alter the terrestrial ecology of plants and natural vegetation, and provide a baseline source of N to groundwaters and streams, which can then affect aquatic ecology. Research in the Himalayas, in which INCA N was applied to a range of basins, suggests generally low concentrations of atmospheric N[8], but across northern India, levels are likely to be much higher, with greater urban and industrial sources of atmospheric N[22]. In the future, increased industrial development and more intensive farming methods will cause atmospheric N concentrations to increase. INCA-N can incorporate these effects as deposition loads to the sub-basins, and thus N levels have been altered to reflect the different socio-economic scenarios into the future. It has been assumed that N deposition rates are 8, 10, and 6 kg/ha/year for the BaU, LS, and MS scenarios respectively.

Land use change

Kathpalia and Kapoor (2010) and the FAO (World Agriculture Report 2013) [41] [42] reviewed projected changes in agriculture in India. Their predicted changes in agriculture translate into crop production and land use change across the basins as indicated in Table 7, and these changes have been implemented in the INCA land use characteristics and applied to all three SSPs. They have been applied to all 3 SSPs as there is very limited information on how land use might change in the future.

Table 7 Summary of Land use Change for the model land use categories.

Landuse	Current %	Future %
Urban	0.7	1.3
Forest	14.3	13.4
Barren land	11.4	7
Double/Triple Crop + Plantation	26.8	31.5
Kharif Crop	30.7	30.7
Rabi Crop + Zaid Crop	16.1	16.1

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Water transfers

According to IWMI-TATA Water Policy Research[43], India's National River Linking Project (NRLP) has been proposed to join water surplus Himalayan rivers to water scarce West Indian and Peninsular river basins via canals to reduce drought conditions in different parts of India and boost economic growth. The water surplus basins identified by NRLP are the Brahmaputra in the Himalayan component, and the Mahanadi and the Godavari in the peninsular component. Should the interlinking project proceed in full it has the potential to impact upon water availability in Bangladesh. However, it is likely that some form of reduced water transfer will occur from the Ganga River to the drought prone areas such as Rajasthan. In the INCA model set up for the Ganga River basin, we have simulated two water transfers as part of the less sustainable scenario, these being the water transfer from the Sarda river system to the Yamuna, and then the Yamuna transfer to Rajasthan. The exact amount of water planned to be diverted from the Sarda and Yamuna Rivers is not available from the literature. We have therefore assumed that 20% of water from the upper reaches of these rivers will be abstracted during the wet season (July-October).

Scenario results on flows and water quality

With three climate scenarios and three SSPs, nine combinations of scenarios were investigated in this study. Simulations were been run for the period 1971-2099 along the 70 reaches of the Ganga River system. Thus for the whole catchment each set of runs generate over 89 million items of daily data covering flow, nitrate and ammonia concentrations. It is not possible to present all the results here and so key results are presented for the Farakka Barrage location, as this is the crucial site where the major water diversion occurs near the border between India and Bangladesh.

Climate change effects

The effects of climate change on flows and water quality in the Ganga River system are illustrated in Fig. 13, 14, 15 and 16 and in Table 8. Fig. 13 shows that under climate change scenario Q0, flow is predicted to increase by 2050 and 2090; a reflection of increased rainfall during the monsoon period. Figure 13 also shows that, under the Q0 scenario, simulated nitrate and ammonia concentrations decrease by 14% and 21% respectively and this reflects the enhanced dilution due to the increased river flows. Figure 14 shows the flow duration curve for the lower Ganga River at Farakka under climate change scenario Q0, and illustrates that the high flow end of the flow distributions are affected by the climate change scenario by the mid-century, suggesting the potential for increased flooding. The low flow distributions do not appear significantly affected with a small increase in Q95 levels, as indicated in Table 8.

Table 8 Mean, Maximum and Minimum Statistics and % Change for flow, nitrate and ammonium concentration at Farakka for baseline 2090s, 2050s and 2090s under the three climate change realizations.

Climate scenario	Flow	Flow m^3/s (1981-2000) Baseline	Flow m^3/s (2041-2060)	Flow m^3/s (2080-2099)	Flow % change (2041-2060)	Flow % change (2080-2099)
Q0	Mean	14597	16877	17706	15.6	21.3
	Q95	1805	1839	1842	1.9	2.1
	Q05	53384	65732	68684	23.1	28.7
Q8	Mean	14421	15193	18643	5.4	29.3
	Q95	1794	1829	1834	2.0	2.2
	Q05	56018	61504	72974	9.8	30.3
Q16	Mean	9951	12679	15030	27.4	51.0
	Q95	1789	1821	1827	1.8	2.1
	Q05	43028	54958	68258	27.7	58.6

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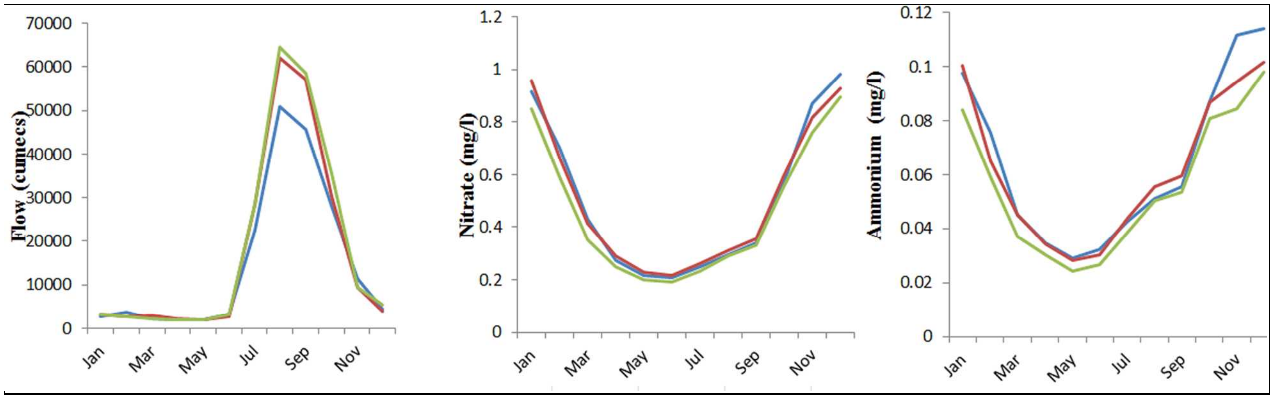

Fig. 13 Effects of climate change on monthly mean Farakka Ganga flow, and nitrate and ammonia concentrations for baseline 1990s (blue), 2050s (red) and 2090s (green) under climate scenario Q0.

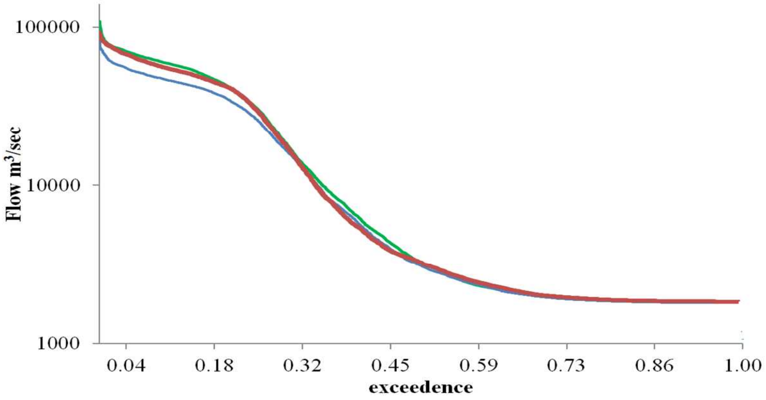

Fig. 14 Flow duration curves for 1990s (blue), 2050s (green) and 2090s (red) for the Lower Ganga River at Farukka under the climate realization Q0.

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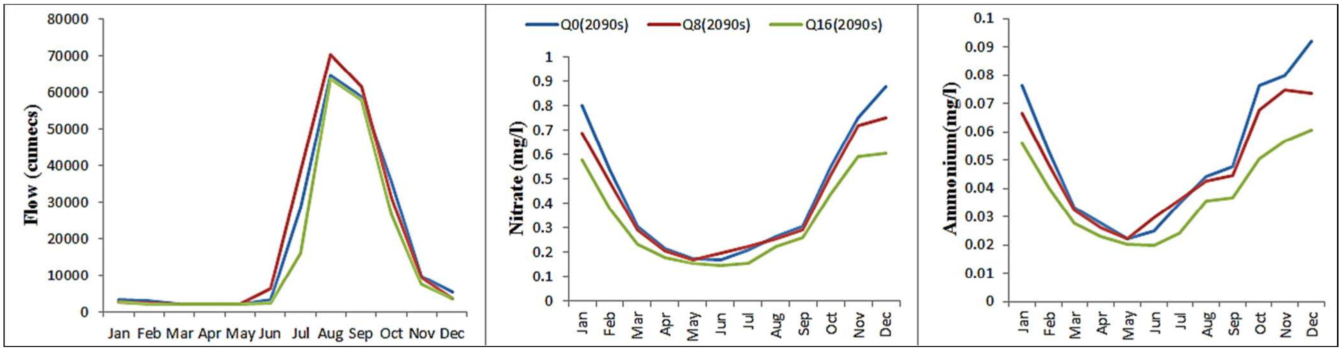

Fig. 15 Monthly mean flow, nitrate and ammonium concentrations for the 2090s under the three climate change realizations Q0, Q8 and Q16.

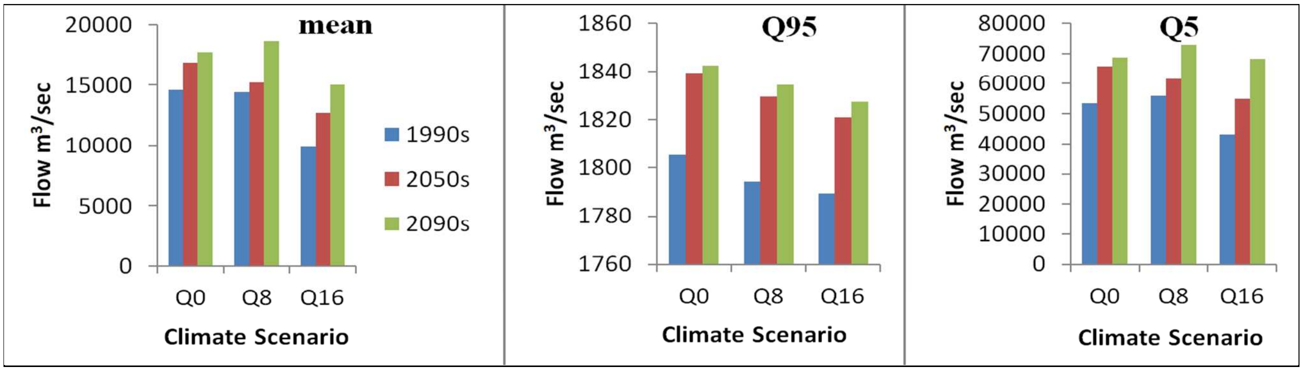

Fig. 16 Annual Mean, Q95 and Q05 flows for baseline 1990s, 2050s and 2090s under the three climate change realizations Q0, Q8 and Q16.

The effects of all three climate realizations, Q0, Q8 and Q16 on mean flow and NO_3 and NH_3 concentrations by the 2090s are illustrated in Fig. 15. The future flows show some differences reflecting the variation in future projected precipitation and temperature patterns, with the Q16 scenario suggesting a shorter monsoon period. Future simulated nitrate and ammonia concentrations also reflect the effects of the variable temperature patterns and flow dilution effects. However, these are relatively small changes in concentration. Fig. 16 shows the effects of the different climate scenarios on flow, with mean flow, high flows (Q5) and low flows (Q95) all increasing into the future under all three scenarios. However, the flows show variability between the Q0, Q8 and Q16 climate realizations, reflecting the variability associated with the different climate realizations, as might be expected with the uncertain GCM/RCM model projections. Table 8 summarizes the results of the climate analysis, and shows that in percentage terms there are expected to be significant increases in flows in the River Ganga during the monsoon periods, although increases in low flows are minimal and given the uncertainties the GCM/RCM models could actually fall.

Shared Socio-economic Pathways (SSPs)

The socio-economic scenarios give different perspective on future change in the Ganga River System. Fig. 17 shows the effects of the socio-economic scenarios on the flow, and nitrate and ammonia concentrations for the Q16 scenario. In terms of flows, there seems to be little difference between the scenarios, which is not surprising given that relatively small changes in flow for irrigation and water transfers have been simulated. The 20% transfers at upper Sarda and Yamuna represent a small flow relative to the main flows in the lower Ganga. In addition, STWs flow will not change significantly in comparison to the large flows of the Ganga. However, the water quality is significantly affected, with large reductions in nitrate and ammonia concentrations in the case of the more sustainable scenario. This reflects the improved effluent treatment at the STWs assumed to be implemented as part of the Ganga management plan and reduced atmospheric deposition on N.

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These reductions in concentrations would enhance the ecology of the river by reducing algal blooms in the river and reducing the loads entering Bangladesh. The effects of the more sustainable scenario on phosphorus concentrations is considered by Li et al (2015)[44].

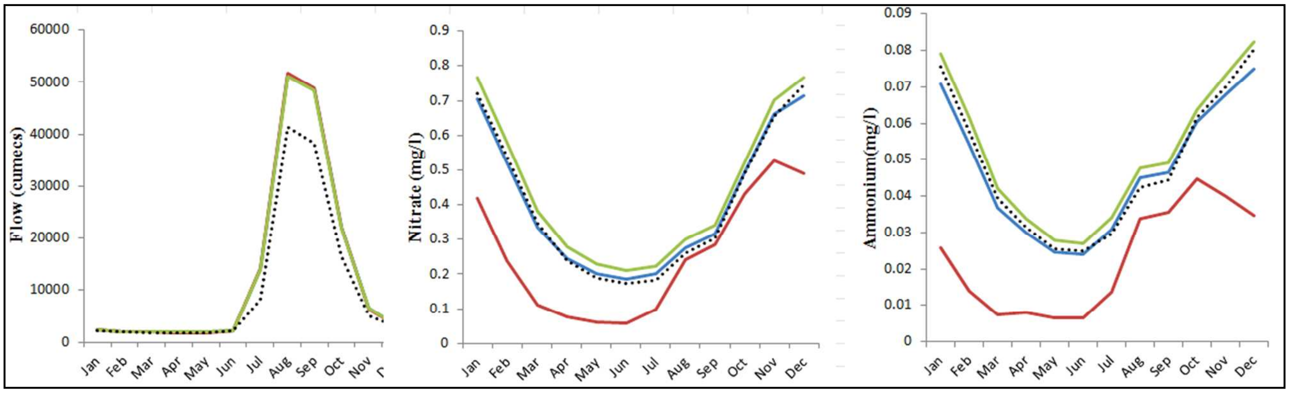

Fig. 17 Mean monthly flow, and Nitrate and Ammonia concentrations 2050s means for the three SSPs (Blue- BaU, Red- MS, Green-LS) compared to the baseline 1990s (dotted line), assuming the Q16 climate change scenario.

Discussion and conclusions

The INCA model has successfully simulated the spatial and temporal complexity of the flow and nitrate and ammonia concentrations in the Ganga basin which is subject to storms, floods and droughts and a large altitudinal range. With such a high variability in precipitation, residence times and flow dynamics are constantly changing which affects dilution patterns and the reaction kinetics of chemical constituents.

The INCA model has been shown to simulate the short-term dynamics from the upper reaches on the Ganga, down to lower reaches at the Farakka Barrage and into Bangladesh at Hardinge Bridge. The available field data on flows and water quality have been used to calibrate and validate the model and provide statistical evidence that in general, the model does adequately represent the river system dynamics. The quality of the observational data is problem in the Ganga with limited high frequency observed available for testing models and assessing model uncertainty[45].

The model accounts for the main sources of N including STWs effluent discharges, agricultural runoff and atmospheric deposition, and this fairly complete N budget allows for a realistic assessment of nutrient fluxes, especially under future conditions of changing climate and changing N input conditions. The processes in the model allow for nutrient fluxes to alter according to biochemical processes in the soil which control mineralization, denitrification and nitrification, as well as instream processes such a nitrification and denitrification. The soil N processes are temperature dependent and also soil moisture dependent, so that the soil denitrification will be at a maximum during the wet monsoon period. Also, the stream processes are both temperature dependent and residence time dependent. This means that in stream denitrification will be higher in the warmer months and this is seen in both the model outputs and in the observed water quality data.

The GCM and RCM climate models developed by the Met Office Hadley Centre have provided downscaled precipitation and temperature data to drive three climate change scenarios in the INCA model both over the baseline period of 1981-2000, and future periods of 2041-2060 and 2080-2099. The three climate scenarios have provided contrasting future hydro-climatic conditions with an increase in precipitation ranging from 5 - 33% and a 2.3 - 4.9 °C increase in temperature by the end of the century.

In general, the increased rainfall patterns generated increased flows in the river system, with large increases in both mean flows and maximum flows by the 2050s. This suggests that additional monsoon flows would be available for groundwater recharge and irrigation, but also suggests that flooding may be more frequent. Further research is required to analyze the data and evaluate the flooding behavior and the low flow conditions at different locations along the Ganga River System.

A set of socio-economic scenarios have been evaluated for a regional analysis of the Ganga coupled with a climatic assessment utilizing a dynamic process based model. The concept of SSPs has been proposed by the IPCC[1] as a means of assessing future socio-economic impacts on environmental and resource systems undergoing climate change. Whilst the India Government is encouraging development at a fast pace in India, the Government is also committed to a Ganga Management Plan. The Plan will enable the river to be managed more effectively and provide improved STWs treatment. Evaluating the impact of these changes is an important but difficult task. One major difficulty is in quantification of the future socio-economic conditions such that they can be evaluated in a hydrochemical modelling study. Adding an economic cost component is the next step is such an analysis[51]. Assessing what changes will occur by the middle of the century and the

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end of the century is subject to multiple uncertainties, and thus all that is really possible is to propose plausible futures. Each of the factors that could affect water flow or quality have been considered in turn, and then quantified in terms of potential changes in flow and quality.

The socio-economic scenarios reflect a 'Business as Usual' future, a 'More Sustainable' future and a 'Less Sustainable' future. Each of these scenarios have been established to reflect changing conditions into the future that affect both water flows and water quality. In general, the high flows conditions are relatively insensitive to the socio-economics due to the large volumes of water flowing down the Ganga. However, the water quality is certainly affected with the Less Sustainable scenario generating deteriorating water quality conditions, with higher N fluxes moving down the river system. The Sustainable Future generates lower N fluxes as the clean-up of the Ganga generates a positive impact by the middle of the century.

This modeling study has provided a set of results on the likely future behavior of the Ganga River system flow and water quality under climate and socio-economic change scenarios. Simulated flow and water quality data has been generated at all reaches and along all tributaries of the Ganga River Basin, and hence a wealth of data is still available for further analysis. For example, other key locations such a Kanpur on the Ganga River, or the large cities such as Delhi on the Yamuna tributary can all be studied using the dynamic model outputs and could be the subject of future analysis. The implications of these changes in Ganga flows and water quality on Bangladesh and the delta system has also been investigated as part of an extended analysis of the Ganga, Brahmaputra and Meghna River System[46].

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