Environmental Science Processes & Impacts

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EIA statement

The GBM River system is one of the largest in the world and so the potential impacts of climate change and social change could be very significant on downstream Bangladesh. In this paper we are investigating potential impacts of climate change and socioeconomic change on flow and water quality in all the GBM rivers and their combined effects. This is very important as the Bangladesh Government is concerned about how future change in flows and water quality will impact the rivers systems, the delta, the estuaries and the bay of Bengal. Moreover the Government is actively engaging with the ESPA Deltas project to evaluate change and assess alternative management and policy strategies.

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Impacts of Climate Change and Socio-economic Scenarios on Flow and Water Quality of the Ganges, Brahmaputra and Meghna (GBM) River Systems: Low Flow and Flood Statistics

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The potential impacts of climate change and socio-economic change on flow and water quality in rivers worldwide is a key area of interest. The Ganges-Brahmaputra-Meghna (GBM) is one of the largest river basins in the world serving a population of over 650 million, and is of vital concern to India and Bangladesh as it provides fresh water for people, agriculture, industry, conservation and for the delta system downstream. This paper seeks to assess future changes in flow and water quality utilising a modelling approach as a means of assessment in a very complex system. The INCA-N model has been applied to the Ganges, Brahmaputra and Meghna River Systems to simulate flow and water quality along the rivers under a range of future climate conditions. Three model realisations of the Met Office Hadley Centre global and regional climate models were selected from 17 perturbed model runs to evaluate a range of potential futures in climate. In addition, the models have also been evaluated using socio-economic scenarios, comprising (1) a business as usual future, (2) a more sustainable future, and (3) a less sustainable future. Model results for the 2050s and the 2090s indicate a significant increase in monsoon flows under the future climates, with enhanced flood potential. Low flows are predicted to fall with extended drought periods, which could have impacts on water and sediment supply, irrigated agriculture and saline intrusion. In contrast, the socio-economic changes had relatively little impact on flows, except under the low flow regimes where increased irrigation could further reduce water availability. However, should large scale water transfers upstream of Bangladesh be constructed, these have the potential to reduce flows and divert water away from the delta region depending on the volume and timing of the transfers. This could have significant implications for the delta in terms of saline intrusion, water supply, agriculture and maintaining crucial ecosystems such as the mangrove forests, with serious implications for people's livelihoods in the area. The socio-economic scenarios have a significant impact on water quality, altering nutrient fluxes being transported into the delta region.

Introduction

The delta regions of Bangladesh and India are particularly vulnerable to future climate change and sea level rise with the potential for extensive flooding due to enhanced cyclone activity and increased river flows or extended droughts with changes in monsoon rainfall[1 4 26 27 28 31]. In addition, socio-economic change such as population increases are placing increasing pressure on resources making issues of water scarcity and food production crucial components of government planning and the focus of international interest[2]. Climate change combined with socio-economic considerations is a key strategic concern of the latest Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[2]. The IPCC report highlights the likely impacts of climate change and 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 catchments, people and livelihoods. This strategy has already been evaluated in a global rivers study with respect to flows[3], but has not been considered in relation to both to both flow and water quality. Other studies such as by Shi et al[33] have examined the impacts of climate change on agricultural aspects and how they affect water quality.

As part of an initiative to better understand the role of ecosystem services in influencing wellbeing and to assist in the alleviation of poverty, the Ecosystem Services and Poverty Alleviation (ESPA) programme has been established[4] by the UK Natural Environment Research Council. The ESPA Deltas project is a component of this programme and seeks to assess health, livelihoods, ecosystem services and poverty alleviation in populous deltas, with the focus on the delta systems in Bangladesh and India[4] (www.espadelta.net). The Ganges, Brahmaputra and Meghna (GBM) Rivers are key drivers of change in this delta system and determine water discharge into the region. The GBM River System (Figure 1) drains an area of 1.612 million km^2 and is one of the largest river systems in the world, providing environmental services for a population of 670 million people. Increasing population levels in the GBM catchment has resulted in agricultural expansion, urbanization and early stage industrialization with extensive use of water for irrigation, industry and public supply. These effects are likely to continue to increase into the future with enhanced development.

Given the complex flow dynamics, diversified land uses, highly variable rainfall and temperature patterns, modelling the GBM River System is a complex task. However, there have been several modelling studies of the rivers, with a greater focus on the Ganges River System. Many of these have been funded by Government departments or international organisations, such as the World Bank, with excellent summary papers that capture the major findings and large scale macroeconomic aspects[5]. Also, there have been several water quality modelling studies of tributaries of the rivers such as nitrogen dynamics in small Himalayan catchments[6], pollution aspects of the Yamuna[7], sediment fluxes and morphology of the river system[8] and phosphorus transport and distribution[26]. Climate change studies have tended to focus on the upper Himalayan catchments, with many projects assessing floods and low flows[9 10 11 12 13 27 28 43 17]. Most previous climate modelling studies over the region have used either the Global Climate Model or a finer resolution Regional Climate Model (RCM) of approximately 50 km [33]. In this study we have made use of a higher resolution 25km RCM 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.

As part of the ESPA Deltas research, the Integrated Catchment model INCA-N has been applied to the rivers and a range of climate realisations and socio-economic pathways evaluated both for flow and water quality[12 13 14 15]. The aim of this study has been to assess the combined effects of climate change and socio-economic change on flows and water quality in the GBM rivers systems. The paper builds on the Ganges flow and nitrogen modelling paper in this special issue[16] which explains the model application in detail. Here a brief description of the INCA-N model applied to the Brahmaputra and Meghna is presented together with the sources of catchment and climate data used in the analysis. The model results for the Brahmaputra and the Meghna catchments are given together with a combined GBM Basin analysis to investigate the integrated response of the whole system to climate and socio-economic change. The effects of flood statistics and low flow duration are evaluated and additional extreme water transfer scenarios are also evaluated.

Figure 1 Map of the GBM Catchments Draining into the Bay of Bengal

THE GBM RIVER SYSTEM

The GBM river system extends between the latitude of 22° 30’ N to 31° 30’N and longitude of 78°0’E to 92° 0’ E in the countries of India, Nepal, China, Bhutan, and Bangladesh (Figure 1), with a total catchment area of 1,612,000 km^2. The GBM river system is considered to be one large trans-boundary river basin, even though the three rivers of this system have distinct characteristics and flow through very different geographical regions for most of their lengths. They join upstream of the GBM delta before flowing into the Bay of Bengal. The GBM river system is the third largest freshwater outlet to the world’s oceans, being exceeded only by the Amazon and the Congo River systems[3]. The headwaters of both the Ganges and the Brahmaputra Rivers originate in the Himalayan mountain range. The Ganges 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) before it flows southeast into the Bay of Bengal. Along its way, the Ganges is joined by a number of tributaries to form the large fertile alluvial plain in North India. At Farakka Barrage, a major diversion delivers water from the Ganges into the Hooghly River. Approximately 50% of flows are diverted except during high flows (> 70,000 m^3/s), with the exact diversions varying depending on inflows and season. The Farakka treaty signed between India and Bangladesh in 1996 was a significant agreement between the two countries and provides an agreed mechanism for sharing the available water (see http://www.thewaterpage.com/farakka_water_treaty.htm). After the Farakka Barrage, the Ganga, Brahmaputra and Meghna Rivers join and flow into the Bay of Bengal.

The Brahmaputra River originates on the northern slope of the Himalayas in China, where it is called Yalung Zangbo. It flows eastwards for about 1130 km, then turns southwards and enters Arunachal Pradesh (India) at its northern-most point and flows for about 480 km. Then it turns westwards and flows through Arunachal Pradesh, Assam and Meghalaya for another 650 km and then enters Bangladesh, where it is also called Jamuna, before merging with the Ganges and Meghna rivers. The tributaries of the Meghna River originate in the mountains of eastern India and flow southwest to join the Ganges and Brahmaputra rivers before flowing into the Bay of Bengal. Bangladesh (and part of West Bengal, India) has been formed as the greatest deltaic plain in the world at the confluence of the Ganges, Brahmaputra and Meghna rivers and their tributaries. About 80 % of Bangladesh is made up of fertile alluvial lowland that becomes part of the Greater Bengal Plain. The country is flat with some hills in the northeast and southeast. About 7 % of the total area of Bangladesh is covered with rivers and inland water bodies and the surrounding areas are routinely flooded during the monsoon.

The GBM river basin is unique in the world in terms of diversified climate. For example, the Ganges river basin is characterized by significant snowfall and precipitation in the northwest of its upper region and very high precipitation in the areas downstream in Bangladesh near the delta. High precipitation zones and dry rain shadow areas are located in the Brahmaputra river basin, whereas the world's highest precipitation area is situated in the Meghna river basin. Monsoon precipitation in the Ganges river basin lasts from July to October with only a small amount of rainfall occurring in December and January. The delta region experiences strong cyclonic storms, both before the commencement of the monsoon season, from March to May, and at the end of the monsson from September to October. Some of these storms result in significant life and the destruction of homes, crops and livestock, most recently in Cyclone Sidr in 2007.

THE INCA-N MODEL

Modelling complex river systems such as the Ganges, Brahmaputra and the Meghna requires a semi-distributed model that can account for the spatial variability across the catchment. INCA-N is one such model that has been applied extensively to heterogeneous catchments and has the advantage that it is dynamic, process-based and integrates hydrology and water quality. The INCA-N model has been developed over many years as part of UK Research Council (NERC) and EU funded projects [12 13 14 15]. INCA-N simulates hydrology flow pathways in the surface and groundwater systems and tracks fluxes of solutes/pollutants on a daily time step in both terrestrial and aquatic portions of catchments. The model allows the user to specify the spatial nature of a river basin or catchment, 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-N 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 GBM system with many tributaries[14]. The model is based on a series of interconnected differential equations that are solved using numerical integration method based on the fourth-order Runge-Kutta technique[12 13]. The advantage of this technique is that it allows all equations to be solved simultaneously. The INCA-N model is described in detail elsewhere[12 13 14] and the detailed application to the Ganges River is given in this volume[16].

INCA-N SET UP FOR THE GBM RIVERS

The INCA-N model has been set up for the Ganges as a multi-reach model with all the Ganges sub-catchments, as shown in Figure 2, with reach boundaries being selected based on a number of factors such as a confluence point with a tributary[16], a sampling or monitoring point or an effluent input or an abstraction point associated with a major irrigation scheme or a large city[19]. For the Brahmaputra and the Meghna, a similar multi-reach model set up has been established, as illustrated in Figure 3, which shows all the reach boundaries and sub catchments, with the reach information given in Tables 1 and 2. The land use data have been derived using a 1 km grid resolution DTM with land cover data generated from the MODIS satellite. There are two major cities within the Brahmaputra catchment, Dibrugarh and Guwahati, with populations of 151,000 and 971,000 respectively. Direct discharges of effluents are incorporated into the INCA-N set up.

Table 1 Summary Reach Information including Length, Area and Land Use for the Brahmaputra

			% Land use					
Reach	length (km)	area (km^2)	snow and ice	forest	grassland	cropland	urban	barren
1	250	22272	0.9	3.5	87.6	0.0	0.0	8.0
2	335	31296	1.2	6.5	88.3	0.0	0.0	4.0
3	350	54912	0.8	0.6	98.6	0.0	0.0	0.0
4	509	61120	4.6	6.0	89.4	0.0	0.0	0.0
5	407	77120	23.8	49.8	23.5	2.8	0.0	1.0
6	224	60160	1.4	59.3	20.1	19.2	0.0	0.0
7	221	40768	1.6	43.5	21.5	33.2	0.2	0.0
8	183	59904	3.4	43.5	34.5	18.5	0.0	0.1
9	77	35840	2.0	19.8	27.1	50.4	0.2	0.5
10	144	9792	1.3	0.0	2.6	96.1	0.0	0.0

Table 2 Summary Reach Information including Length, Area and Land Use for the Meghna

			% Land use				
Reach	length (km)	area (km^2)	Wetland	forest	grassland	cropland	urban
1	114	7424	4.3	69.0	8.6	17.2	0.9
2	76	4544	0.0	100.0	0.0	0.0	0.0
3	63	10112	0.0	94.3	0.6	5.1	0.0
4	45	5568	0.0	55.2	20.7	24.1	0.0
5	63	4288	0.0	43.3	11.9	44.8	0.0
6	95	4864	6.5	38.2	6.6	48.7	0.0
7	44	11648	16.5	23.6	35.2	24.7	0.0
8	39	11136	5.8	5.2	33.9	55.1	0.0
9	45	3200	2.0	0.0	0.0	98.0	0.0
10	44	9536	0.0	4.0	27.5	66.5	2.0

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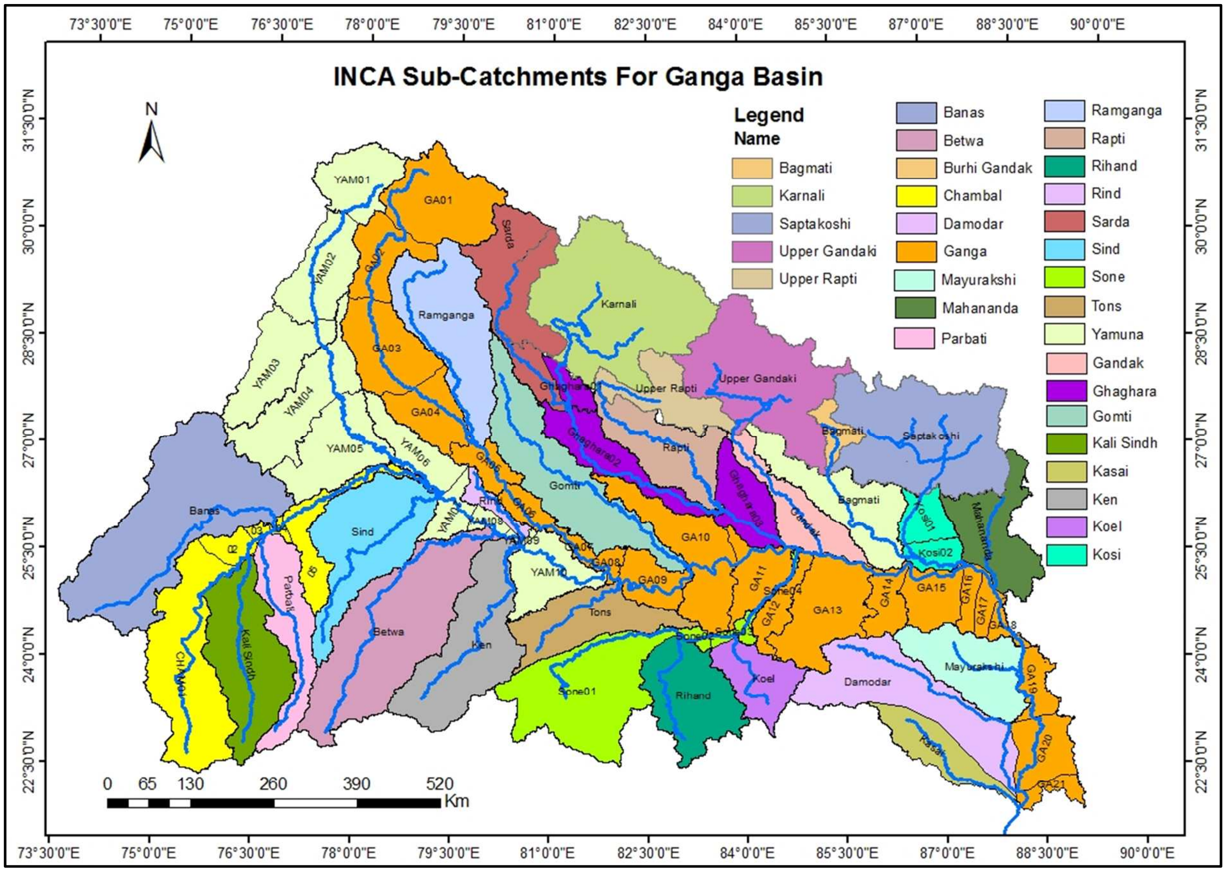

Figure 2 Map showing the multi-branch Ganges river system and sub-catchments

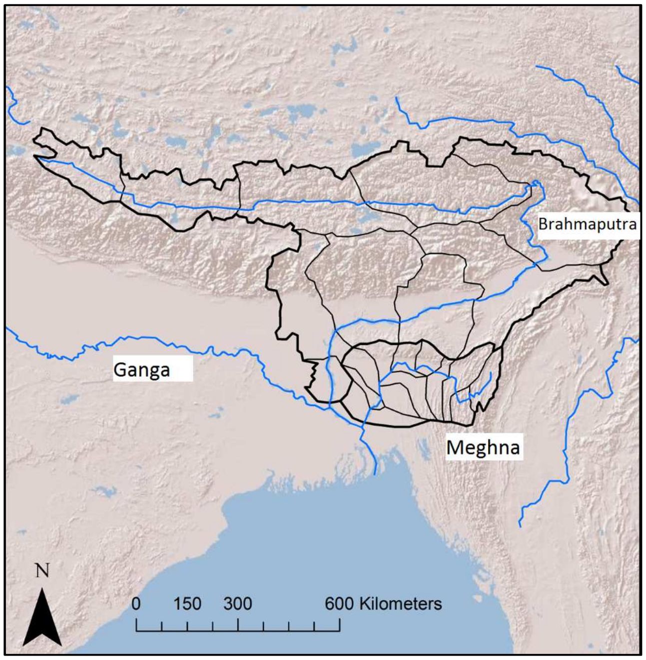

Figure 3 Map showing the multi-branch Brahmaputra and Meghna River systems with the sub-catchment areas

CLIMATE DRIVERS FOR THE GBM RIVERS

In order to run a set of hydrological simulations and climate scenarios, INCA-N requires a daily time series of climate data, namely precipitation, hydrologically effective rainfall (HER), temperature and soil moisture deficit (SMD). The model uses these data to drive the hydrological components of the model which generate the sub-catchment river flows. However, obtaining met data over such a large catchment scale is difficult, especially given the wide spatial differences in topography, altitude and land use in India, China, Bangladesh, Bhutan and Nepal. Observational data are available from in-situ weather stations and also from satellite measurements and these have been integrated into observational datasets which cover the region as part of the Aphrodite online data system[19]. These data have been used to calibrate the climate models both in space and time[19].

The large-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 kilometres in size, and cannot provide the high-resolution climate information that is required for climate impact and adaptation studies. The use of regional climate models (RCMs), which dynamically downscale the GCM simulations through being driven 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, in particular precipitation. There have been relatively few studies focused upon the Ganges River linked to the Bangladesh region which have used RCM output[9 20 42 44 45]. In the current study, we have used an existing set of GCM simulations to provide boundary conditions for a RCM for the period 1971-2099 over a south Asia domain[19]. The GCM is the third climate configuration of the Met Office Unified Model (HadCM3)[21] and is run as a 17 member perturbed physics ensemble driven by the Special Report on Emissions Scenarios (SRES) A1B scenario. SRES A1B was developed for the IPCC 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 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[2], 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. Further details of the Met Office RCM model and how it has been used to generate data for the study are given elsewhere in this special issue[19].

MODELLING HYDROLOGY AND WATER QUALITY

The INCA-N model has been set up for the Ganges River as part of a separate study[16] and used to model the hydrology, nitrate and ammonia in all the tributaries and the main river system. This study required setting up the INCA-N model for the Brahmaputra and Meghna in terms of reach structure, land use, topography and other factors that affect flow and water quality can be incorporated. The precipitation and temperature data are available for the whole GBM system from the RCM model, however it is necessary to calculate the HER and the SMD from the basic climate data. In order to do this we have used the PERSiST model[22] and this is the same approach used in the Ganges study[16]. PERSiST is a watershed-scale hydrological model suitable for simulating terrestrial runoff and stream flow 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 type 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 the SMD are calculated. A detailed description of this analysis for the rivers is given elsewhere[23]. As an example, Figure 4 shows the daily estimated precipitation, HER, temperature and SMD for the Brahmaputra river system over the baseline period 1981-2000. This data is then used to drive the INCA-N model.

The model uses the HER, SMD and temperature daily time series together with all the reach, land use and catchment data to simulate flow and water quality at every reach along the whole system for the whole period of 1981-2000. The model outputs are then compared to the observed flow data for the river to calibrate and validate the model. The observed flow quality data is sparse on the Brahmaputra and Meghna River systems, although there is a flow gauge on the Brahmaputra at Bahadurabad. In general, the calibration period of 1981-1990 and the validation period of 1991-2000 are both modelled well with R^2 of 0.439 and 0.437 respectively for the 2 periods. The Nash Sutcliffe statistic for the whole period of the observed flow data for the 1981-2000 is 0.55 which given the massive complexity of the Brahmaputra is reasonable. The model captures the main dynamics of the rise to the peaks in monsoon periods and the recession curves towards the dry season, as illustrated in Figure 5. The fits to the Ganges flow data are of a similar order of magnitude[23,16], and the detailed calibration and validation statistics are given elsewhere in this special issue[16]. In addition to calibrating the flow model it is necessary to calibrate the water quality model. The water quality data is limited to infrequent observations at several monitoring points along the river and Table 3 gives the mean and maximum nitrate concentrations at several locations along the lower reaches of the Brahmaputra River system. The simulated concentrations are fairly low reflecting the less polluted nature of the Brahmaputra compared to the Ganges and Figure 5 shows the simulated daily concentrations of nitrate-N and ammonium-N from the model at the lower reach of the Brahmaputra River system. The observed data for water quality along the rivers is available from the Indian Central Pollution Control Board[18,35]. The mean Nitrate (as N) in the Brahmaputra at Dhburi (Table 3) is 0.12 mg/l and compares with 0.11 from the model simulation. A key target of the modelling is to estimate the nutrient load flowing down the river into the Bay of Bengal, as the nutrients are crucial for ecology, fisheries and agriculture and these are of primary concern for the ESPA Deltas Project, as they relate directly to human well-being and resource availability for people in the delta region[1,4]. Figure 6 shows the simulated and observed nitrogen load in the Ganges which suggested that the model is simulating the nutrient fluxes well.

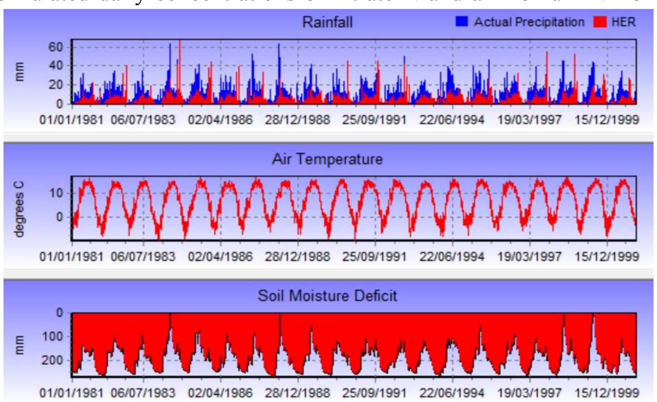

Figure 4 Daily Precipitation, HER, Temperature and SMD for the Brahmaputra Catchment over the period 1981-2000

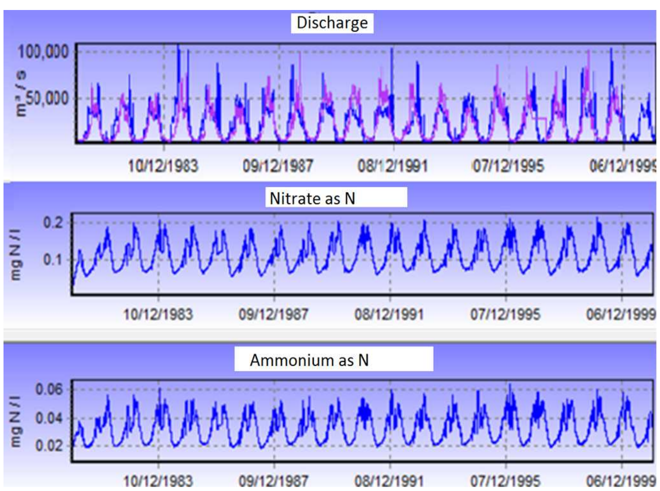

Figure 5 Simulated (blue line) and Observed (purple line) daily flows at the Flow Gauge on the Brahmaputra River System at Bahadurabad for 1981-2000 together with simulated Nitrate and Ammonium

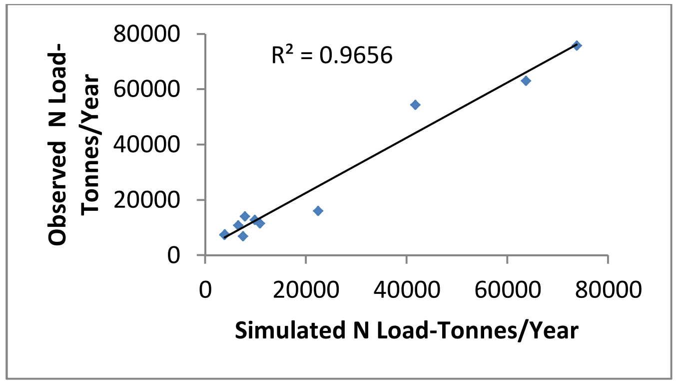

Figure 6 Simulated and Observed Loads in the Ganges River at Kanpur

Table 3 Nitrate-N mg/l mean and maximum concentrations at sampling sites along the Brahmaputra

	2006		2007		2008		2009		2010		2011	
Reach Name	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Kherghat	0.2	0.11	0.2	0.11	0.1	0.1	0.1	0.1	0.2	0.1	0.21	0.13
Dibrugarh	1	0.19	1	0.19	0.4	0.16	0.7	0.2	0.2	0.1	0.3	0.14
Nimatighat	1	0.19	1	0.19	0.1	0.1	0.1	0.1	0.12	0.1	0.2	0.12
Dhenukhapahar	0.1	0.1	0.1	0.1	0.2	0.11	0.16	0.11	0.17	0.1	0.3	0.16
Pandu	2.5	0.35	2.5	0.35	0.3	0.13	0.1	0.1	0.16	0.1	0.3	0.15
Jogijhoga	0.3	0.13	0.3	0.13	0.1	0.1	0.13	0.1	0.19	0.1	0.3	0.13
Panbazar	0.3	0.18	0.3	0.18	0.1	0.1	0.1	0.1	0.11	0.1	0.17	0.12
Chandrapur	0.1	0.1	0.1	0.1	0.2	0.15	0.1	0.1	0.1	0.1	0.17	0.12
Sualkuchi	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.11	0.1	0.3	0.16
Dhubri	0.2	0.17	0.2	0.17	0.2	0.13	0.1	0.1	0.11	0.1	0.1	0.1

SCENARIO ANALYSIS FOR CLIMATE AND SOCIO-ECONOMIC CHANGE

Climate Scenarios

The climate realisations used in the study are derived from three of the 17 model variants of the Met Office Hadley Centre HadRM3P RCM for South Asia[19]. The three realisations, Q0, Q8 and Q16 represent uncertainty associated with the climate model and demonstrate a range of possible precipitation and temperature projections as shown in Figures 7 and 8. These three model variants therefore represent three ranges of precipitation increases from moderately wetter to considerably wetter monsoon periods. All realisations project an increase in temperature for the region and the catchment average temperatures and precipitation are shown in Figures 7 and 8. There is a strong upward trend in temperature with the Brahmaputra being at a much lower catchment average temperature compared to the Ganges and the Meghna reflecting the higher altitude of the upper Himalayan reaches of the Brahmaputra. Precipitation trends are more variable with some evidence of decline up until the 2050s and thereafter a rise in precipitation under the Q0 realisation. The precipitation in the Brahmaputra and the Meghna is much higher than the Ganges, reflecting the increased rain and snowfall in the Himalayan Brahmaputra sub-catchments and the coastal and Bay of Bengal effects in the Meghna. Note that there is a lot more variability in the Meghna precipitation in general compared to the Brahmaputra and the Ganges reflecting the coastal proximity of the Meghna River Catchment.

Socio-economic Scenarios

The IPCC Shared Socio-economic Pathways (SSPs) strategy[2 3 24] considers a set of socio-economic pathways as a means on integrating social aspects of future change with climate change. There are five broad classifications for future conditions, namely 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 consider 3 plausible socio-economic scenarios which have been adapted from the 5 IPCC SSPs, namely Business as Usual (BaU), plus two others, a More Sustainable Scenario (MS) and a Less Sustainable Scenario (LS). In order to assess these in terms of their impacts on the GBM flow and water quality, we need to quantify these sceanarios.

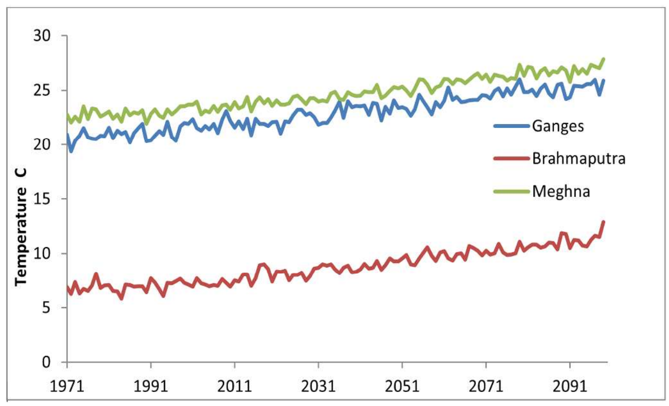

Figure 7 Annual Mean Temperature Change in the GBM Catchments for the Q0 realisation for 1971-2099

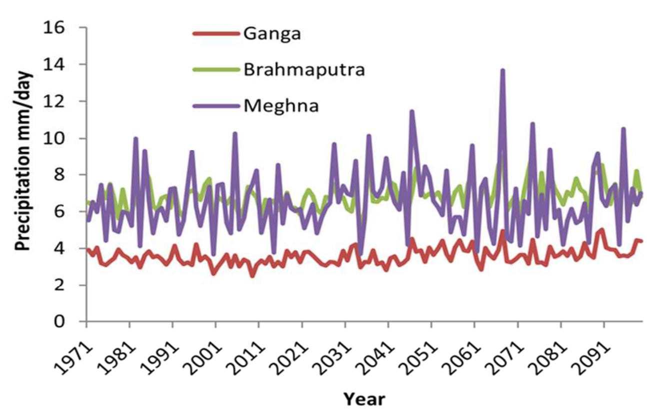

Figure 8 Annual Mean Precipitation Change over 1971-2099 in the Ganges and Brahmaputra Catchments for the Q0 realisation

There are many socio-economic factors that have the potential to affect flows and water quality in the GBM basin. 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
6. Water transfer plans

Whilst dams can also have a significant impact, this was outside the scope of this study. The impact of hydropower dams on flows in the Ganges was considered by Jeuland et al.[11], and found to have minimal impact on peak flows based on the magnitude of these flows.

To model changes in the above six socio-economic factors they need to be quantified for the baseline (1981-2000) and two future time periods of 2041-2060 and 2080-2099, representing mid-century and end of the century respectively. The details of each scenario, covering the above factors, are given in the Ganges paper in this special issue[16] together with a set of assumptions. However some detail is given here to explain the strategy.

Table 4 shows the predicted population forecasts for India and Bangladesh based on UNDP population projections for 2041-2060 and 2080-2099.

Table 4 Percentage Population Change in India and Bangladesh based on UNDP estimates.

Scenario For India	**Fertility Assumptions**	**2041-2060 % Change**	**2080-2099 % Change**
SSP - BaU	Medium fertility	34.1	31.5
SSP - LS	High fertility	54.8	94.4
SSP - MS	Low fertility	15.3	-14.9
Scenario for Bangladesh	**Fertility Assumptions**	**2041-2060 % Change**	**2080-2099 % Change**
SSP - BaU	Medium fertility	33.6	22.9
SSP - LS	High fertility	55.9	98.1
SSP - MS	Low fertility	13.8	-28.2

Future scenarios from changes in STW discharge rates and concentrations of nutrients were developed based upon future changes in population (Table 4) and requirements for upgrading of STWs. This reflects the implementation of the Ganges Management Plan to enhance the capacity of all the STWs on the Ganges river system and treat effluents from a larger population. The demand for public water supply has increased with population growth and changes in irrigation water demand reflect changes in agriculture and land use. The Food and Agriculture Organization of the United Nations (FAO)[38] estimates a 22.7% rise in Kcal/person/day in food production in India by 2050 and we have assumed that abstractions from the Ganges River will increase by 22.7 % in accordance with the predicted increase in food production for both the BAU and the LS scenario. Under the more sustainable scenario we assume that the abstractions increase by 11.3%

Atmospheric nitrogen pollution has become an increasing problem around the world, as industrial development, power generation and ammonia release from intensive agriculture has expanded[35]. In the future, increased industrial development and more intensive farming methods will cause atmospheric N concentrations to increase. It has been assumed that N deposition rates are 8, 10, and 6 kg/ha/year for the BaU, LS, and MS SSP scenarios respectively.

Changes in agriculture crops and technology can be represented as land use change and Table 5 summarize these based on FAO findings[39 38]

Table 5 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

According to IWMI-TATA Water Policy Research[38], India's National River Linking Project (NRLP) has been proposed to join water surplus rivers to water scarce Western and Peninsular river basins via canals to reduce drought conditions in different parts of India and boost economic growth. Should these transfers occur, they have the potential to impact on water availability downstream in Bangladesh and the GBM delta. We therefore considered the impact of different rates of water transfer from the Ganges River to the drought prone areas such as Rajasthan, and from the Brahmaputra upstream of Bangladesh. A range of 5% to 30% diversion during the monsoon season was tested to explore the sensitivity to different volumes of water transfer. This range was based on feedback from a recent stakeholder meeting in Bangladesh[39] .

CLIMATE AND SOCIO-ECONOMIC SCENARIO EFFECTS

The impact of the three climate realisations of the HadRM3P RCM on flows for the separate and combined rivers of the GBM system is shown in Figure 9. The distinct seasonal pattern of monsoon and dry season flows can be seen, with flows increasing during the year and peaking in August/September. The Brahmaputra has a much longer high flow period reflecting the effects of snow and glacial melt in the Himalayas. The Ganges has a relatively short high flow period. However, the resulting combination of the rivers generates an extended high flow period from May through to November. The Meghna has proportionally much lower flows and responds largely to the monsoon precipitation.

Figure 10 shows the effects of climate change on the GBM flows under the Q0 climate realisation, showing significantly higher flows in the 2050s and 2090s. As might be expected under the higher diluting peak flows nitrate concentrations are likely to fall and this is shown in Figure 11 for the combined rivers under a business as usual strategy. However, there are some seasonal variations as the flows in the 2090s are lower in March, April and May and this should mean higher concentrations of nitrate, as there is less dilution. However, because of the increased temperatures and longer residence times in the lower flow conditions, the denitrification processes in stream will generate nitrogen loss, due to the lower velocities and hence longer residence times, generating more denitrification and lower nitrate concentrations.

The effects of changing socio-economic conditions on the GBM flows are fairly limited because of the volume of water flowing down the rivers. Figure 12 shows the effects in the 2090s of the different socio-economic scenarios on the mean GBM flows under 3 climate scenarios. The socio-economic changes have limited effect on the GBM total flows, as indicated in Table 6. However, a significant reduction in the flows could occur if large volumes of water from the Brahmaputra and the Ganges were to be diverted in a major water transfer scheme. Figure 13 shows the effects of different water diversion schemes on the GBM flows and with the assumption that 30% of the Brahmaputra and 20% of the upper Ganges are diverted then a serious reduction in flows. This would generate a 22% reduction in monsoon flow for the 2090s but with a significant 48% reduction in low flows. This is a very large effect and very significant for sustaining ecosystems in the delta. The 5% transfer has a much smaller but still observable impact.

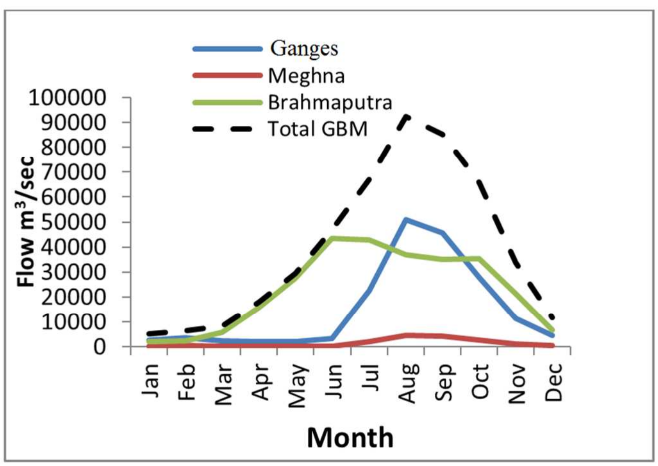

Figure 9 GBM Total Monthly Flows showing contributions from the Ganges, Brahmaputra and the Meghna

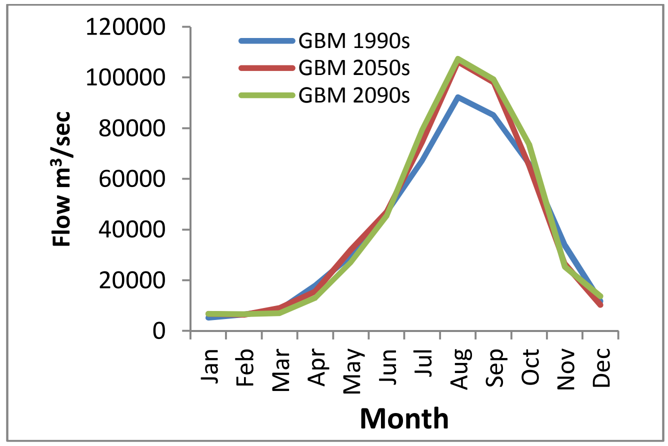

Figure 10 Monthly GBM Flows into the 2050s and the 2090s under the Q0 Climate Realisation

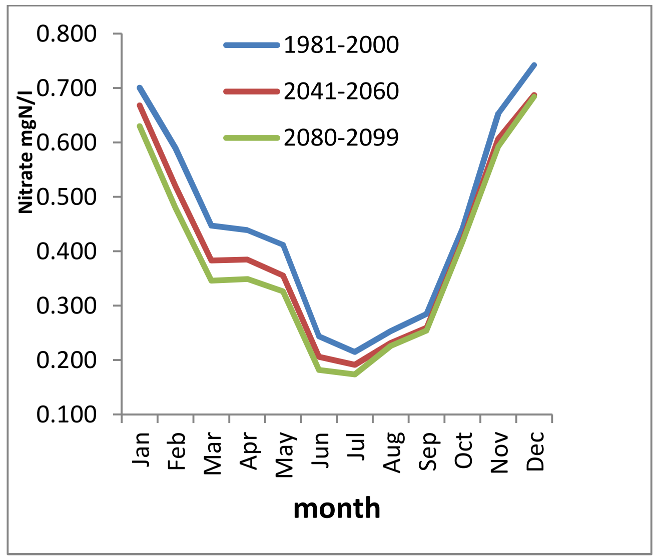

Figure 11 Nitrate-N Monthly Concentrations for the 2050s and 2090s for the Business as Usual Scenario under the Q0 Climate Realisation.

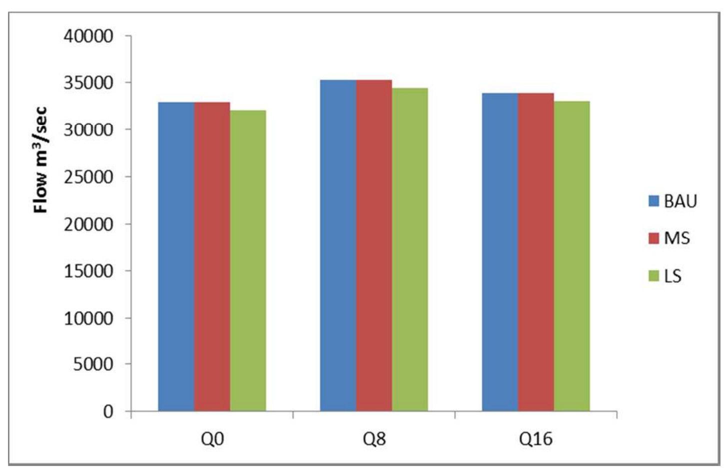

Figure 12 Effects of SSPs and Climate Realisations on mean GBM Flows in the 2090s

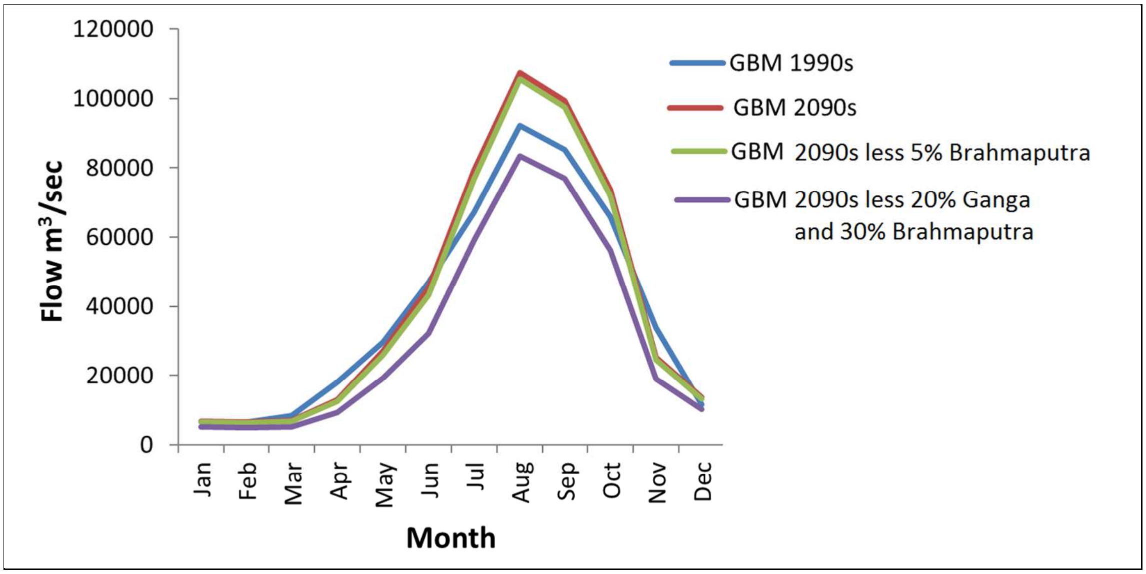

Figure 13 Effects of different future Water Transfer strategies on the monthly GBM Flows

Table 6 Mean GBM Flows m^3/sec under 3 SSPs and 3 Climate Realisations

	Q0			Q8			Q16		
	BaU	MS	LS	Bau	MS	LS	BaU	MS	LS
1990s	31742.1	31742.1	31742.1	32327.0	32327.0	32327.0	29101.6	29101.6	29101.6
2050s	32695.4	32705.5	32187.1	31282.5	31290.1	30777.5	30771.0	30780.8	30263.9
2090s	32921.2	32926.6	32098.4	35317.5	35325.8	34491.7	33916.0	33922.0	33093.9

Floods and Droughts

The projected climate change has the most observable impact during the seasonal monsoon flows, as shown in the flow duration curve in Figure 14. Monsoon flows would increase by the 2050s and these increased high flows would have the potential to increase flood risk within Bangladesh. The extreme high flow exceeded 5% of the time is projected to increase by 15% by mid-century, as indicated in Figure 15. The INCA-N model projects that low flows will also increase, as shown in Figure 16 with the Q95 flow increasing from 2608 m^3/sec in the baseline period to 3243 m^3/sec (+24%) in the mid-century, and decreasing slightly to 3221 m^3/sec by the end of century. Although the low flows statistics suggest there may be an increase in the magnitude of low flows, analysis of the low flow sequence indicates an increase in the duration of low flow periods. Figure 17 shows the duration periods for dry periods when flows fall below Q80 or 5700 m^3/sec and indicates that in the 2090s there will be increased duration of drought periods. This might appear inconsistent with the overall increase in low flows but the drought threshold exceedance depends on the daily patterns of behaviour generates by the climate model and so a change in the patterns of climate and hence drought periods is possible. As shown in Figure 17, the effects of the different socio-economic scenarios have minimal impacts on the drought duration statistics.

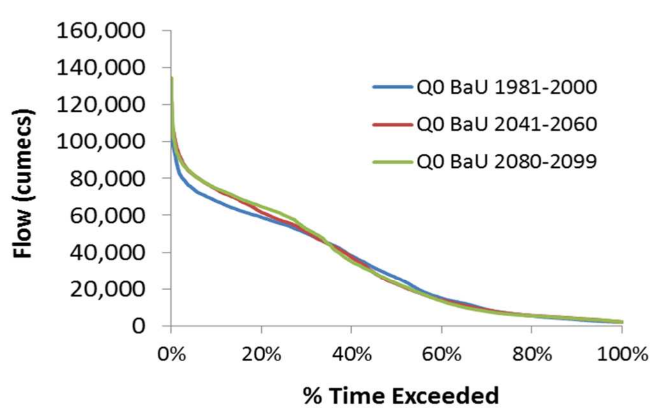

Figure 14 Flow Duration Curves for the QO Climate Realisation over the high flow range for current conditions and for the 2050s and the 2090s

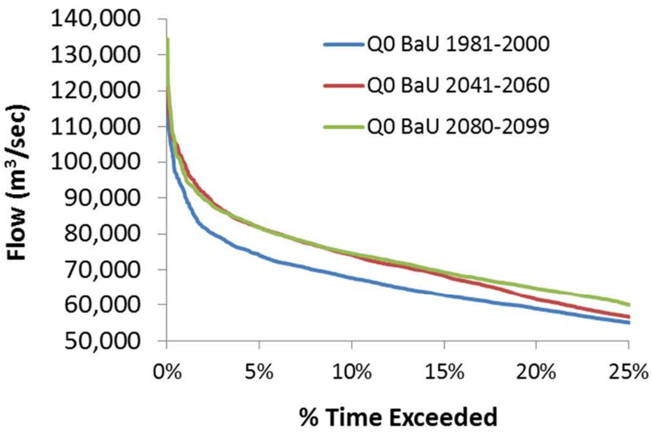

Figure 15 Flow Duration Curves for the QO Climate Realisation over the high flow range for current conditions and for the 2050s and the 2090s

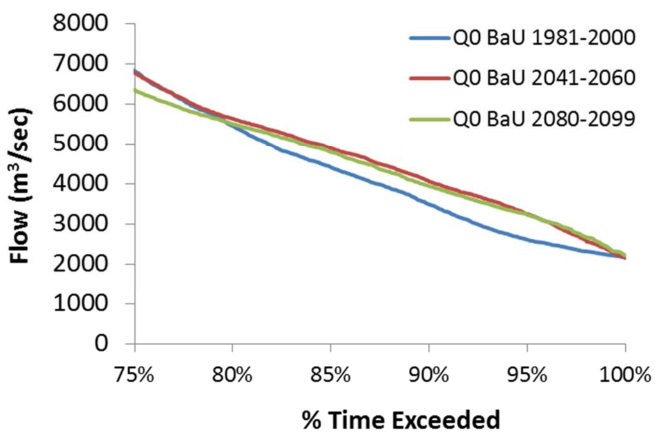

Figure 16 Flow Duration Curves for the QO Climate Realisation at the low flow range for current conditions and for the 2050s and the 2090s

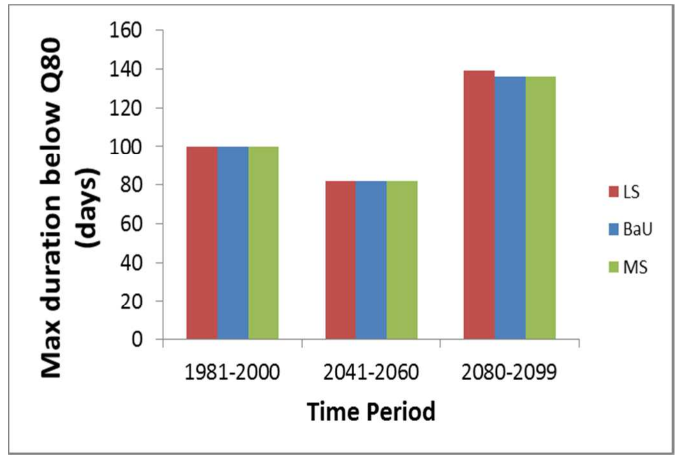

Figure 17 Number of days below Q80 (5700 m^3/sec) showing increased drought periods in the 2090s

DISSCUSSION AND CONCLUSIONS

The GBM Rivers are of crucial importance providing water for public supply, hydropower[40], irrigation water for agriculture, and are also of great cultural significance. The sediment loads delivered by the rivers helps to supply silts and nutrients to support agriculture and maintain ecosystems, as well providing new land as islands form in the delta region[41].

In this study, INCA-N has been applied to the GBM Rivers to assess the likely future impacts of climate change as well as socio-economic changes. It is recognised that there are a number of uncertainties within the model, input data and parameters. The lack of adequate flow and water quality data limits the ability to fully evaluate the model's performance. However, comparison with the data that is available demonstrates reasonable replication of the overall magnitude and pattern of flows, and a close match between modelled and observed data for water quality.

In the case of the application of INCA-N to the GBM Rivers there is a significant increase in flows predicted under a future climate change during the monsoon season. This is consistent with all of the 17 ensemble members of the climate model projections which indicate higher monsoon rainfall. These increased flows in the monsoon suggest there will be increased flooding into the future, which could have significant consequences for Bangladesh. Such changes in flow on a seasonal basis will also affect nutrients with nitrogen being diluted under the higher flows

Changes to low flows are also likely to occur given projected increases in variability. Here, the model results suggest that drought duration may become more frequent, whilst extreme low flows may actually increase in magnitude. However, changes to low flows are likely to be more sensitive to uncertainties in climate projections and assumptions regarding land-surface runoff and river channel transport. The impact of low flows warrants further investigation, given they are crucial for irrigated agriculture, saline intrusion, aquaculture and public water supply..

In general, the socio-economic changes considered had minimal impact on flows. However, the magnitude of these changes is also uncertain. Of most concern is the potential development of large-scale dams and water transfer schemes upstream of Bangladesh. These could seriously threaten the flows in the river system, significantly reducing both peak flows and low flows, with some major consequences for water availability, public policy and poverty alleviation in the delta region. However, through negotiation and cooperation between countries the impact of these developments can be minimised, and the benefits equitably shared.

The development of models for such large and complex systems as the GBM provide an important planning tool for assisting in exploring future scenarios, engaging stakeholders in dialogue on water resources management, and identifying gaps in knowledge and data. Considering both flows and water quality for a range of climate and socio-economic scenarios can assist in a more holistic management approach.

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