Modelling the impact of future socio-economic and climate change scenarios on river microbial water quality

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ABSTRACT

Microbial surface water quality is important, as it is related to health risk when the population is exposed through drinking, recreation or consumption of irrigated vegetables. The microbial surface water quality is expected to change with socio-economic development and climate change. This study explores the combined impacts of future socio-economic and climate change scenarios on microbial water quality using a coupled hydrodynamic and water quality model (MIKE21FM-ECOLab). The model was applied to simulate the baseline (2014–2015) and future (2040s and 2090s) faecal indicator bacteria (FIB: E. coli and enterococci) concentrations in the Betna river in Bangladesh. The scenarios comprise changes in socio-economic variables (e.g. population, urbanization, land use, sanitation and sewage treatment) and climate variables (temperature, precipitation and sea-level rise). Scenarios have been developed building on the most recent Shared Socio-economic Pathways: SSP1 and SSP3 and Representative Concentration Pathways: RCP4.5 and RCP8.5 in a matrix. An uncontrolled future results in a deterioration of the microbial water quality (+ 75% by the 2090s) due to socio-economic changes, such as higher population growth, and changes in rainfall patterns. However, microbial water quality improves under a sustainable scenario with improved sewage treatment (-98% by the 2090s). Contaminant loads were more influenced by changes in socio-economic factors than by climatic change. To our knowledge, this is the first study that combines climate change and socio-economic development scenarios to simulate the future microbial water quality of a river. This approach can also be used to assess future consequences for health risks.

1. Introduction

Concerns are growing over surface-water quality due to widespread microbial contamination of water systems. An effective water management infrastructure is lacking in most developing countries and a large portion of their population relies on untreated and highly contaminated surface water. This increases the outbreaks of waterborne diseases, such as diarrhoea. Globally, 1.8 million people are estimated to die annually from waterborne diseases and most of them are children from developing countries (WHO, 2012). Most of those deaths are caused by unsafe water supply and poor sanitation (Rochelle-Newall et al., 2015). Also in Bangladesh, access to clean water and adequate sanitation remains a major problem despite recent improvements.

The potential future impact of socio-economic development and climate change on river water quality is a key concern worldwide (Whitehead et al., 2015). Increasing temperatures and change in rainfall patterns combined with socio-economic factors, such as human and animal population growth and land use changes will continue to affect flows and water quality in river systems globally (Jin et al., 2015).

Under future climate change scenarios, tropical systems will likely be subject to increased temperature and shifts in the frequency and intensity of extreme rainfall events (Rochelle-Newall et al., 2015). These projected increases in precipitation and floods combined with population growth, urbanization and agricultural intensification are expected to accelerate the transport of waterborne pathogens to aquatic systems (Rose et al., 2001; Hofstra, 2011) and thereby deteriorate future scenarios of contamination and increase risk of waterborne diseases. This contamination is aggravated in the developing countries like Bangladesh, because of their high susceptibility to climate change, high population growth, rapid urbanization, agricultural intensification and poor water treatment facilities.

Over the past few decades, with rapid population growth, urbanization and agricultural intensification, most Bangladeshi rivers have received enormous inputs of microbial contaminants and the microbial water quality has been impaired. Recent measurements in the Betna River in southwestern Bangladesh revealed very poor microbial water quality due to widespread faecal contamination. Bathing water-quality criteria were found to be violated year round (Islam et al., 2017a). The
highly contaminated river water is also used for irrigation, domestic purposes and shellfish production; people bathe in the river and consume contaminated shellfish. This increases the people's vulnerability to waterborne diseases. Deterioration of water quality may also influence safe food production and livelihoods of the people. In the future, the river water will be severely affected by changing climatic and socio-economic conditions. Therefore the hydro climatic and anthropogenic changes will have substantial impacts on the agricultural sector and thousands of people living on the river basin. Therefore, understanding the link between human activities, environmental changes and microbial spreading are prerequisites for reducing the risks of microbial exposure (Rochelle-Newall et al., 2015).

Climate change combined with socio-economic factors is a key concern of the Intergovernmental Panel on Climate Change (IPCC) (IPCC). Socio-economic scenario analysis is found to be a useful tool for exploring the long-term consequences of anthropogenic change and response options (Kriegler et al., 2012). Scenarios should account for future changes in both climatic and socio-economic factors, because to evaluate the impact of climate change on future societies, combination of the two groups of factors is important (Berkhout et al., 2002). The IPCC report has proposed development of a new scenario framework in which Shared Socio-economic pathways (SSPs) and Representative Concentration Pathways (RCPs) are combined (Van Vuuren et al., 2012, Kriegler et al., 2012). The SSPs provide narratives and quantifications of future possible developments of socio-economic conditions (e.g. population growth, urbanization, economic and technological development, change in land use) that describe challenges to mitigation and adaptation (O’Neill et al., 2017). The RCPs describe trajectories for the development of emissions and greenhouse gas concentrations (consistent with radiative forcing) and the consequent changes in climate factors (e.g. temperature and precipitation) (Van Vuuren et al., 2011). The SSPs and RCPs can be combined in a matrix. The scenario matrix is useful to look into future impact of climate and socio-economic changes on human society and the environment and to evaluate specific policies for mitigation and adaptation.

Changes in socio-economic conditions are often not adequately incorporated in climate change impact assessment and scenario analysis (Berkhout et al., 2002). Some studies focused on assessing the impacts of climate change only on river hydrodynamic characteristics (Elshemy and Khadr, 2015; Kuchar and Iwaśni, 2014) or waterborne pathogens/ FIB (Jaliliffer-Verne et al., 2016; Rankinen et al., 2016; Liu and Chan, 2015; Sterk et al., 2016) without considering socio-economic changes (i.e. the SSPs). Few studies have applied the new SSPs without including the climatic factors. For instance, Van Puijenbroek et al. (2015) studied nutrients and Hofstra and Vermeulen (2016) Cryptosporidium emissions to surface water globally. Some studies assessed future impact of climate and socio-economic changes on water flow and water quality separately, without combining both groups (Whitehead et al., 2015; Jin et al., 2015). Moreover, these limited approaches have been evaluated with respect to flows and nutrient flux, but have not been used to study changes in microbial water quality. Applying combined scenarios is rare. Only a couple of recent studies have applied this approach. For instance, Borris et al. (2016) applied this combined approach in assessing urban storm water quality (with respect to suspended solids and heavy metals) in Sweden and Zhuo et al. (2016) assessed changes in agricultural water availability for China. To our knowledge, our study is the first study that applies a process based model to simulate the combined impacts of climate change and socio-economic development scenarios on microbial water quality in a river basin. Identifying trends and implementing them in future scenarios to assess future microbial water quality is required to address changes in widespread microbial contamination. The Betna River basin is an ideal site for this study because firstly, the river is situated in a subtropical developing country, where microbial water quality is not adequately studied. Secondly, the basin flooded almost every year during the last decade and its diversified water uses (e.g. domestic, irrigation, shellfish growing and bathing) require much better water management. Thirdly, due to climate change, more frequent and intense flooding is expected in this basin (floods have a strong impact on the spread of infectious diseases). Finally, socio-economic developments are happening fast. All this signifies the importance of our socio-economic and climate change impact assessment on the Betna River’s microbial water quality.

Mathematical model-based scenario analysis can be a useful tool to investigate the impacts of socio-economic development and climate change on the hydrology and transport of waterborne pathogens. Despite their inherent uncertainties, models can estimate future changes in the concentration of waterborne pathogens due to climate change (Hofstra, 2011). Microbial contamination studies are usually based on Faecal Indicator Bacteria (FIB). E. coli and enterococci are the two most widely used indicators of microbial water quality (Lata et al., 2009). This paper aims to assess the impact of socio-economic development and climate change scenarios on FIB (E. coli and enterococci) concentrations in the Betna River basin using a process based model (MIKE 21 FM) coupled with a water quality module (ECOLab). These coupled models were initially calibrated and validated using observed water level, discharge, water temperature, salinity and FIB data (Islam et al., 2017b). Then, socio-economic development and climate change projections for the near (2040s) and far (2090s) future were made. The model was run for these futures using the projections in different scenarios. Finally, the future scenarios were discussed and guidelines were proposed to address changes in microbial water quality induced by socio-economic development and climate change. This study illustrates the application of future microbial water-quality scenarios in the context of a subtropical river system in a developing country. The findings will help water managers and public health professionals in assessing health risks, and policy makers to formulate policy and reduce the elevated health risks. The results can also be utilized by a broad scientific community involved in water, climate, food security and socio-economic research.

2. Methodology

2.1. Study area and sources of contaminants

The study area covers an area of 107 km² in the Betna River catchment in southwestern Bangladesh (Fig. 1). The total length of Betna River is about 192 km with an average width of 125 m. The maximum water depth is 9 m. Our modelling study focuses on the downstream 30 km of the Betna River. In this part of the river the tide influences the discharge. The study area has a tropical monsoon climate with a hot season March–May, followed by a rainy season June–October and a cool period November–February. Mean annual rainfall in the area is about 1800 mm, of which approximately 70% occurs during the monsoon season. This area is affected by both inland flooding due to heavy incessant rainfall during the monsoon in August–September and during the cyclone season (pre-monsoon) in April–May (CEGIS, 2013). Mean annual air temperature is 26 °C with peaks of around 35 °C in May–June. Temperature in winter may fall to 10 °C in January.

The study area is densely populated, with 2.23 million people. Sewage and manure are the main bacteria sources in this catchment. In the study area, sewage, in particular from the town of Satkhira (0.4 million inhabitants), is discharged into the river without treatment. The manure sources include manure applied to the paddy rice fields as organic fertilizer, and direct deposition of manure to the river and canals. Various waterborne diseases, including gastrointestinal and skin diseases, have been observed in this area throughout the year, but with peaks during and after flooding (CEGIS, 2013).

2.2. Coupled hydrodynamic and water quality model

A two dimensional hydrodynamic model, MIKE 21 FM (DHI, 2011) coupled with the water quality module (ECOLab) was applied to
simulate FIB concentrations in the Betna River. A flexible mesh size with triangular elements was used, and the triangulation was performed with Delaunay triangulation (DHI, 2011). The mesh size was decreased and resolution increased where the river is narrow. The mesh consists of 4089 nodes and 6628 elements. The smallest element area is 42.5 m$^2$ and the largest area is approximately 498 m$^2$. The model was initially calibrated with observed water level and discharge data for 2012, and validated with water level, water temperature and salinity data for 2015 (Islam et al., 2017b). To calibrate the hydrodynamic model, water level and river discharge data were collected from the Institute of Water Modelling, Bangladesh (IWM). Water level data comprised half an hour interval data at two locations (near the upstream and downstream boundary) along the Betna River for over two months from 1 August to 10 October 2012. Discharge measurements were carried out around the same location of the water level data by IWM in September 2012 for 13 h with 0.5 h interval both in spring and neap tide. Precipitation, wind speed and direction, air temperature and relative humidity data were collected from the Satkhira meteorological station (Fig. 1). For validation and baseline simulation, water level and discharge data were gathered from the Bangladesh Water Development Board during the period 2014–2015. The boundary conditions were described using time-series for discharge and water level at the upstream and downstream boundaries, respectively. In the model, a constant horizontal eddy viscosity (0.28 m$^2$/s), a constant clearness coefficient (70%), and default parameterisation for heat exchange were used. The model performance test for water level (coefficient of determination, $r^2 = 0.92$; Nash-Sutcliffe efficiency, NSE = 0.81) and river discharge ($r^2 = 0.83$; NSE = 0.66) signifies the potential of the model to be used in microbial water quality simulation.

The ECOLab module is used to simulate water temperature, salinity and daily FIB ($E$. coli and enterococci) concentrations. ECOLab utilizes the output (e.g., water level, flow, currents) from the hydrodynamic model to calculate the fate and transport of FIB in the river. The FIB were assumed to be inactivated following first order decay kinetics in the river water; the inactivation was described as a function of temperature, salinity and solar radiation (Mancini, 1978). The model was validated for water temperature, salinity and FIB concentrations for one year (October 2014–September 2015, which is our baseline year). The model performed well for temperature and salinity (Root Mean Square Error, RMSE = 0.51 °C and 0.38ppt; NSE = 0.93 and 0.94 respectively). The model output was compared with measured FIB concentrations (Islam et al., 2017b) from three sampling sites (2, 3 and 4) along the Betna River (Fig. 1). Fig. 2 shows the measured and modelled FIB concentrations at sampling site 3 to get a feel for the model fit. The model output during the base year (2014–2015) corresponded very well with the measured FIB concentrations in the river. The Root Mean Square Error and the NSE for log transformed FIB concentrations were found to be 0.23 and 0.19, and 0.84 and 0.86 for $E$. coli and enterococci respectively (Islam et al., 2017b).

The model was then applied to investigate the impact of future socio-economic and climate changes on FIB concentrations. The model considers inputs from both point (untreated wastewater through sewer drains) and diffuse sources (urban and agricultural runoff). Daily FIB measurement data at the upstream boundary were not available. The upstream boundary data were estimated by interpolating the monthly concentrations measured at Sampling Site 1 (Fig. 1). The detail of the model development, calibration, validation and input data used have been described previously (Islam et al., 2017b).

2.3. Scenario development and analysis

Scenarios are sets of plausible futures about how the future might unfold from current conditions under alternative human choices (Polasky et al., 2011). To develop adaptation and/or mitigation strategies, climate change impact assessment is important. The assessments are generally based on future scenarios, which reflect plausible future developments (Borris et al., 2016). In the present study, two scenarios (sustainability, S1 and uncontrolled, S2) have been developed (details
are in Section 2.3.3) that are based on the new approach developed for the IPCC (2014). This new approach employs a new generation of scenarios (Moss et al., 2010) that include socio-economic scenarios (SSPs) (O’Neill et al., 2017) and radiative forcing scenarios (RCPs) (Van Vuuren et al., 2011) to integrate future socio-economic development and climate change impacts. Two future time periods 2031–2050 (2040s) and 2081–2100 (2090s) were considered for this study.

2.3.1. Socio-economic scenarios

Five future scenarios (SSP1–SSP5) were categorized within a space of socio-economic challenges to mitigation and adaptation outcomes (O’Neill et al., 2017). To cover both the best and worst possible future conditions of Bangladesh, we choose the two extreme scenarios (SSP1 and SSP3) as two plausible but contrasting futures. They describe contrasting developments in population, sanitation, economic growth, environmental policy and technology advancement (O’Neill et al., 2017). Our socio-economic scenarios have been based on the two SSPs and our own assumptions that are in line with the SSP storylines.

Table 1 provides an overview of the changes in model input variables and the sources of information used.

In SSP1, entitled ‘Sustainability-Taking the green road’, the world makes relatively good progress towards sustainability; developing countries have relatively low population growth, high but well managed urbanization and rapid economic development. Technological development is fast and focuses on environmentally friendly processes and environmental protection (O’Neill et al., 2017). In this scenario, we assume that the study area’s microbial water quality is improved by developing water treatment and other water-management strategies. We assume that, in line with the storyline in 2040 and 2090 the whole study area population has access to sewer lines and that sewage treatment facilities have developed with 50% primary treatment and 50% secondary treatment in 2040, and with 50% secondary treatment and 50% tertiary treatment in 2090 (see Table 1). We assume, based on Saleem et al. (2000) and George et al. (2002), that primary treatment equals one log unit removal (90%) of FIB concentration from the sewage, secondary equals two log unit removal (99%), and tertiary equals three log unit (99.9%) removal. Future upstream boundary concentrations are assumed to change based on the same assumptions that similar levels of wastewater treatment facilities would be established in the upstream areas of the study area.

SSP3 ‘Regional rivalry-A rocky road’ represents a world that is separated into regions characterized by low investments in education and technology. This results in slow economic growth, widespread poverty, and slow developments in technology, health care, safe water and improved sanitation (O’Neill et al., 2017). In this scenario, the population will grow rapidly and urbanization is slow and poorly managed (Jiang and O’Neill, 2015). Such a world is struggling to maintain the living standards for a strongly growing population, and economic goals are prioritized over environmental goals (Borris et al., 2016). We assume that in this scenario the proportion of population in the study area that has access to water supply and connection to sewers is not improved much. However, the total number of people connected to sewer network will increase, because the population grows rapidly in this area. We also assume that sewage treatment facilities will not be established by the 2040s (as in the present condition) but will be established with limited capacity (30% primary and 20% secondary treatment) by the 2090s.

2.3.2. Climate change scenarios

Climate change projections by two Global Climate Models (GCMs): MPI-ESM-MR (Max Planck Institute for Meteorology) and IPSL-CM5A-LR (Institute Pierre-Simon Laplace) within the Coupled Model
Intercomparison Project (Taylor et al., 2012) were used. The models were selected because they have been widely used in this region (BANDUDELTAS, 2015). Two GCM model outputs were used to represent some of the uncertainty in the climate models. The daily GCM data were downscaled using the ‘Delta change method’ with ‘quantile-quantile’ correction as described by Liu et al. (2015). The climate projections utilized in the study include predicted increases in temperature and precipitation and rises in sea level by the 2040s with significant increase by the 2090s. The discharge projection at the upstream boundary was based on the predicted future changes in upstream discharge and precipitation. All these changes were used to overlay and modify the observed current discharge data and the resulting discharge data were used as upstream boundary conditions in performing the future simulations. The future storm-water runoff was based on future precipitation data and we applied the runoff curve method (USDA, 1986). IPCC distinguishes four RCPs (RCP2.6, 4.5, 6.0 and 8.5) based on different radiative forcing levels (from 2.6 to 8.5 W/m²) by 2100 (Van Vuuren et al., 2011). In our study, we have used two different climate change scenarios: a relatively low emission pathway (RCP4.5) and a high emission pathway (RCP8.5). The changes under different RCPs at 2040s and 2090s are summarised in Table 2.

### Table 1
Socio-economic variables for different scenarios for base year, 2040 and 2090.

| Scenario features | Source | Baseline (2014–2015) | SSP1 2040 | SSP1 2090 | SSP3 2040 | SSP3 2090 |
|-------------------|--------|----------------------|-----------|-----------|-----------|-----------|
| Population (million) | SSP data downscaled with landscan data | 2.23 | 2.67 | 2.07 | 3.11 | 3.78 |
| Urban population (%) | SSP data | 32.4 | 58.3 | 87.3 | 35.7 | 47.4 |
| Sanitation (%) connected | Own assumptions | 58 | 75 | 100 | 60 | 65 |
| Wastewater treatment (%) | Own assumptions | Primary | 0 | 50 | 0 | 0 | 30 |
| Secondary | 0 | 50 | 50 | 0 | 20 |
| Tertiary | 0 | 0 | 50 | 0 | 0 |
| No treatment | 100 | 0 | 0 | 100 | 50 |
| Land use change (%) | RCP data | Agriculture/Crop land | 60.9 | 61.8 | 62.1 | 59.3 | 57.1 |
| Wetlands/Aquaculture | 20.5 | 19.3 | 18.6 | 20.7 | 21.1 |
| Urban, Homestead & Settlement | 7.9 | 8.4 | 8.8 | 10.1 | 12.2 |
| Water bodies | 10.1 | 9.7 | 9.5 | 9.4 | 9.2 |
| Forest (Mixed) | 0.6 | 0.8 | 1.0 | 0.5 | 0.4 |
| Livestock number (thousands) | Census data adjusted with SSP data | Cattle/Cows/ Buffaloes | 8.19 | 8.64 | 6.72 | 10.08 | 12.22 |
| Goats | 7.75 | 8.18 | 6.36 | 9.54 | 11.56 |
| Sheep | 0.39 | 0.41 | 0.32 | 0.48 | 0.58 |

### Table 2
Projected changes in climate variables in the study area for the two GCMs for RCP4.5 and RCP9.5 by the years 2040 and 2090 compared to base year 2014–2015.

| Change in climate variables | RCP4.5 | RCP 8.5 |
|-----------------------------|--------|---------|
|                             | IPSL-CM5A-LR | MPI-ESM-MR | IPSL-CM5A-LR | MPI-ESM-MR |
| Year 2040                   |         |         |         |         |
| Annual precipitation increase | 6.4% | 6.8% | 7.3% | 7.7% |
| Mean sea air temperature increase | 2.8% | 4.1% | 4.6% | 5.8% |
| Mean sea level rise (m) Year 2090 | 0.26 | 0.26 | 0.44 | 0.44 |
| Annual precipitation increase | 11.6% | 12.2% | 13.5% | 13.7% |
| Mean sea air temperature increase | 4.9% | 5.7% | 10.5% | 12.3% |
| Mean sea level rise (m) | 0.42 | 0.42 | 0.76 | 0.76 |

### 2.3.3. Scenario matrix framework
To develop future scenarios for climate change research, a new scenario framework was suggested by the climate community (Van Vuuren et al., 2012; Kriegler et al., 2012). Within this framework, a new scenario matrix was developed by combining the SSPs and RCPs. This new scenario matrix is based on various combinations of SSPs and RCPs extending until the end of the 21st century. The application of this framework would be helpful in developing consistent and comparable research within and across different research communities (Van Vuuren et al., 2012). For this study we considered a baseline scenario (October–September 2015) reflecting the current conditions and two future scenarios, S1 (sustainability scenario) and S2 (uncontrolled scenario) mimicking different plausible future developments of socio-economic and climate change factors. By combining climate scenarios forced by RCP4.5 with socio-economic scenarios SSP1 (S1), and RCP8.5 with SSP3 (S2), a new scenario matrix was developed. The scenario matrix and associated assumptions for the scenarios have been summarised in Table 3. Although the chosen combinations may not be appropriate globally, they are logical choices for the study area in Bangladesh. The

### Table 3
Scenario matrix and assumptions of socio-economic changes.

| Scenario matrix | S1 (Sustainable scenario) | S2 (Uncontrolled scenario) |
|-----------------|---------------------------|---------------------------|
| Shared socio-economic pathway | SSP1 | SSP3 |
| Population growth | Low | High |
| Urbanization | Rapid/planned | Slow/unplanned |
| Economic development | Rapid | Slow |
| Sanitation | Improved | Current trend |
| Sewage treatment | Improved | Little improved |
| Environmental policy | Stringent and effective | Weak |
| Environmental technology advancement | Rapid | Slow |
| Representative concentration pathway (RCP) | RCP4.5 | RCP8.5 |
| Dependency on fossil fuels and CO2 emissions | Reduced and declining | Uncontrolled |
| Contributions to climate change | Controlled | Uncontrolled |
| Global climate models (GCMs) | IPSL-CM5A-LR, MPI-ESM-MR | |
| Future periods | 2040s, 2090s | |
3. Results

3.1. FIB concentrations for different scenarios

In Fig. 2, the socio-economic development and climate change scenarios (S1 and S2) are compared with the modelled FIB concentrations for 2014–2015 (baseline condition), the near future (2040s) and far future (2090s) at Sampling Site 3 in the Betna River Basin. The results (Fig. 2) reveal that different future scenarios have substantial impact on FIB concentrations in the river. The selected sustainable scenario (S1), with moderate population growth, planned urbanisation and strong sanitation and wastewater treatment improvements and moderate climate change showed a substantial improvement in the FIB concentrations in the near future. However, still the concentrations do not comply with the USEPA bathing water quality standards (E. coli: 235 and enterococci: 104 cfu/100 ml) most of the time (Fig. 2a). The S1 by the far future was an ideal case with 100% wastewater collection and 100% treatment and resulted in compliance with bathing standards all the time with the only exception after heavy precipitation events (Fig. 2b).

After these events sudden high concentration peaks were found in the wet period due to the high incoming concentrations from the upstream areas and higher FIB release from lands. These high FIB concentrations can lead to severe contamination but only during a short period (Fig. 2).

The uncontrolled scenario (S2), with large population growth, moderate urbanisation and sanitation and partial or no waste water treatment, and the worst case climate change scenario (RCP 8.5) by the 2040s resulted in the highest concentrations of all scenarios. The S2 by the 2090s, which considers 50% treated wastewater, also showed higher FIB concentrations than the baseline conditions (Fig. 2d).

Table 4 presents changes in seasonal mean FIB concentrations along the river. In the S1 scenario, FIB concentrations decreased by 87–91% and 95–98% by the 2040s and 2090s respectively. For the S2 scenario, the concentrations increased by 51–75% by the 2040s (with no wastewater treatment) and 10–19% by the 2090s (with 50% wastewater treatment) compared to the situation by 2014–2015 (Table 4). The percentage changes in FIB concentrations were comparatively higher in the dry season. The variation in the future changes in FIB concentrations among the sampling sites and between the two bacteria and two GCMs was found to be small.

3.2. Relative importance of different scenarios and sources

In order to understand the relative influence of future climatic factors from the RCPs compared to socio-economic factors from the SSPs, and to assess the contribution from each contamination source to the total FIB concentration, a sensitivity analysis was performed (Table 5, Fig. 3). The model was run for 15 days during a wet period (6–20 July) and 15 days during a dry period (16–30 January). To assess the influence of RCPs and SSPs, for a chosen scenario the model was run with one type of variables (climate or socio-economic) constant. For example, to evaluate the influence of RCPs, the model was run without changing climate variables. To determine the contribution from different contamination sources to the total contamination, we ran the model with and without upstream boundary concentrations, wastewater discharges and diffuse contaminant sources.

3.2.1. Relative importance of socio-economic and climate change scenarios

The results (Table 5) revealed that the climatic inputs (RCPs) have lower influence compared to the socio-economic factors (SSPs). Without RCPs the changes in FIB concentrations were found to be 1.8–6.1% in the wet period and 2.2–13% in the dry period; while without SSPs the changes were 10–2230% in the wet period and 12–3420% in the dry period. Without the influence of SSPs (e.g. improved wastewater treatment) for sustainable scenario S1, E. coli and enterococci concentrations could increase by up to 3250% and 3420% respectively compared to the original scenarios for the 2090s. For uncontrolled scenario S2, without the SSP influence (e.g. high population growth) E. coli and enterococci concentrations could decrease by up to 36% and 21% respectively. Without RCP, FIB concentrations can change a little (from −1.8–13%). This is because, although climatic factors (e.g. temperature, precipitation, discharge, pathogen release from surface runoff) can affect river FIB concentrations positively or negatively, the overall influence on the FIB concentrations is limited.

3.2.2. Relative importance of different contaminant sources

Fig. 3 presents the relative contribution from different contaminant sources to the total contamination of the river water during the wet and dry periods for the baseline period and different scenarios. During the wet period the highest contribution was found to be the incoming upstream boundary, with the exception of the uncontrolled scenario S2 by the 2040s. During the dry period contribution from the wastewater drains were found to be higher than the upstream boundary inputs in all the scenarios. For the sustainability scenario S1, contributions from wastewater drains were reduced because wastewater treatment was applied. Contribution from diffuse sources (i.e. agriculture and urban runoff) was found to be lower in all the scenarios. Differences of diffuse source contribution among scenarios were found to be very small.

Table 4

| GMCS     | Scenarios   | Dry season (November-February) | Wet season (June-September) |
|----------|-------------|--------------------------------|------------------------------|
|          | E. coli (%) changes | Enterococci (%) changes | E. coli (%) changes | Enterococci (%) changes |
| Site 2  | Site 3 | Site 4 | Site 2 | Site 3 | Site 4 | Site 2 | Site 3 | Site 4 | Site 2 | Site 3 | Site 4 |
| IPSL-CM5A | S1 (2040s) | −90 | −89 | −91 | −91 | −91 | −90 | −89 | −89 | −89 | −89 | −89 |
|         | S1 (2090s) | −98 | −98 | −98 | −98 | −98 | −97 | −96 | −95 | −97 | −96 | −96 |
|         | S2 (2040s) | +68 | +73 | +70 | +69 | +71 | +72 | +52 | +53 | +54 | +49 | +52 | +53 |
|         | S2 (2090s) | +14 | +17 | +16 | +13 | +18 | +15 | +11 | +11 | +12 | +11 | +14 | +12 |
| MPI-ESM | S1 (2040s) | −90 | −88 | −89 | −90 | −91 | −90 | −87 | −89 | −88 | −89 | −89 |
|         | S1 (2090s) | −98 | −98 | −98 | −97 | −98 | −97 | −96 | −96 | −97 | −96 | −96 |
|         | S2 (2040s) | +71 | +75 | +73 | +71 | +73 | +74 | +51 | +56 | +57 | +48 | +51 | +53 |
|         | S2 (2090s) | +17 | +19 | +18 | +14 | +19 | +17 | +10 | +10 | +11 | +10 | +13 | +11 |
4. Discussion

In this study, the combined socio-economic development and climate change scenarios reflecting a ‘more sustainable S1’ future and an ‘uncontrolled S2’ future have been established. They mimic different future developments of socio-economic and climate change factors that affect Betna River’s water quality. This modelling study provided the likely future behaviour of the river microbial water quality under socio-economic development and climate change scenarios. The results revealed that, in general, for S2 in both the near and far future, FIB concentrations are expected to increase in the river system because of high population growth, moderate urbanization and sanitation usage proportional to the baseline situation. In this scenario, increase in human and livestock population, urbanization and percent connected to the sewer network were increased, but wastewater was not treated by the 2040s or partially treated (30% primary and 20% secondary treatment) by the 2090s. For S2 by the 2090s, although half of the wastewater is treated, the concentrations would not decrease. Instead, they are expected to increase by 19% compared to the baseline year because of the high population growth. In this scenario, population growth, urbanization and increased sewage generation from increased sanitation connection do not balance the wastewater treatment level. This result thus highlights the importance of wastewater treatment. S1 generates lower FIB concentrations in the near future and a further reduction in the far future. If climate and the socio-economic conditions change, and wastewater are treated according to S1, FIB concentrations in the river will be reduced up to 91% by the 2040s and 98% by the 2090s. For S1 by the 2040s, the predicted increases in population number and sanitation connection are compensated by the implementation of wastewater treatment. For instance, although the

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Table 5
Relative importance of RCP and SSP scenarios for the 2040s and 2090s.

|                | Wet period |Dry period |
|----------------|------------|-----------|
|                | Without SSP | S1(2040s) | S1(2090s) | S2(2040s) | S2(2090s) | Without SSP | S1(2040s) | S1(2090s) | S2(2040s) | S2(2090s) |
| E. coli (% changes) | | | | | | | | | | | |
| S1(2040s) | +730 | +1820 | +18 | +10 | +840 | +2230 | −14 | −11 |
| S1(2090s) | −5.2 | +6.1 | +3.2 | −1.8 | +2.3 | +5.3 | +3.6 |
| S2(2040s) | +890 | +3250 | −36 | −15 | +1260 | +3420 | −21 | −12 |
| S2(2090s) | +2.2 | +13 | −7.3 | −9.4 | +2.5 | +12 | −8.2 | −6.6 |

- Analysis based on percentage change in mean FIB concentrations in the Sampling Sites 2–4 (overall) in the Betna River. The simulations cover a wet period 6–20 July and a dry period 16–30 January.
- Percentage change for the new scenario compared to the original, full, scenarios for the 2040s and 2090s.

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Fig. 3. Relative contributions (%) from different sources to the mean E. coli (a, b) and enterococci (c, d) concentrations in the Sampling Sites 2–4 (overall), Betna River for two scenarios (S1 and S2) and two future periods (2040s and 2090s). The simulations cover a wet period 6–20 July (a, c) and a dry period 16–30 January (b, d).
basin’s total population is expected to increase by 20% and sanitation connection by 29%, 100% of the wastewater produced is expected to be treated (50% primary and 50% secondary treatment), compared to the current situation in which no wastewater is treated. For S1 in the 2090s, the concentrations will decrease by 98% due to the combined effect of population control (7% reduction) and wastewater treatment (50% secondary and 50% tertiary treatment).

Table 5 shows that the changes in climatic input (RCPs) produced significantly lower variability compared to the effects of changes in the socio-economic factors (SSPs). Therefore FIB concentrations were generally more sensitive to changes in SSPs (i.e. human and livestock population growth, urbanization, changes in sanitation and land use) than to the RCPs (i.e. precipitation, discharge and temperature). This is in agreement with the findings of Borgis et al. (2016) and Sterk et al. (2016). Changes in climatic factors do not affect microbial water quality negatively as higher precipitation increases discharge and runoff and thus dilute contaminants in the river (Rankinen et al., 2016), higher temperature increase the die-off of pathogens. At the same time increased runoff increases pathogen release from lands. Although due to the influence of climatic factors, processes like die-off, pathogen release, surface runoff fluxes and dilution are affected (positively or negatively), the net influence on the pathogen concentration in surface waters is limited (Sterk et al., 2016). The modelled scenario results show that climate change has little overall impact, and socio-economic changes resulted in the major impact on the FIB concentrations in the river water. This underlines the importance of socio-economic factors in assessing and improving microbial water quality.

The extent of the impacts of socio-economic development and climate change on FIB concentrations in surface waters is also affected by the different input sources and period of the year (Sterk et al., 2016). Climate change differs between seasons. For instance, future precipitation and associated river discharge in the studied basin are projected to increase in the wet period and decrease in the dry period. Therefore, precipitation change will have a different effect in the dry summer than during the wet monsoon. We analysed changes in seasonal mean future FIB concentrations along the river (see Table 4). In the dry season, contributions from diffuse sources were absent, only point sources and upstream areas were contributed. In the wet season diffuse sources were added. For S1, the wastewater treatment had the largest effect. Then concentrations became so low already, that changes in climate did not make much of a difference. However, for S2 in particular the wastewater drains have had a more important contribution (see Fig. 3). The influence of wastewater drains was more important in the dry than in the wet season, because in the wet season also diffuse sources play a role. Therefore, for S2 the change was largest in the dry compared to the wet season.

The relative contribution from diffuse sources (urban and agricultural runoff) in the future remains almost the same as the baseline conditions (Fig. 3). Currently manure application on lands is not regulated in Bangladesh. Therefore, with the predicted increase in livestock numbers (Table 1), manure application in the agricultural lands likely increases. Although this results in a considerable increase in FIB concentration in the runoff generated from these lands, its relative contribution remains very low compared to the increased point source (wastewater drains) and incoming concentrations from upstream river system (Fig. 3). Nguyen et al. (2016) also reported in their modelling study that diffuse sources had substantial contributions to the total coliform concentrations in the Vietnamese Red River, but that was unlikely to increase near future (2050s) concentrations significantly. Comparatively lower diffuse source contributions are also reported in other studies (Quattara et al., 2013; Sokolova et al., 2012; Gao et al., 2015).

The higher contribution from the upstream open boundary during the wet period is attributable to the untreated wastewater discharges from the point sources of upstream areas and surface runoff from surrounding watersheds. Even while the contributions from drains are constant and diffuse source contributions are lower, high concentration peaks were found in the wet period due to the high incoming concentrations from the upstream areas and higher FIB release from lands after (extreme) rainfall events. The climatic factors do not strongly influence the river’s FIB concentrations. This indicates that microbial water quality in the Betna River can be improved substantially by applying adequate wastewater treatment both in the Betna basin and its upstream areas. Major investments to construct wastewater treatment plants are necessary to compensate for population growth and increased volume of wastewater generation. The current contamination level is already too high. If the investment in increasing sewage connections is not supported by adequate improvement in wastewater treatment, FIB emissions will continue to increase and the water quality will deteriorate further. As a result, uses of the river water (e.g. domestic, aquaculture, fishery and recreation/swimming) will increasingly be detrimental for people’s health and well-being.

We have for the first time analysed changes in FIB concentrations in surface water using scenarios based on the new scenario matrix approach that combines RCPs and SSPs. The government of Bangladesh is encouraging socio-economic development at a fast pace and is committed to manage the rivers more effectively and to provide improved wastewater treatment in Bangladesh. Assessing the consequences of these future socio-economic developments and incorporating them into modelling studies is challenging. Each of the factors that could affect water quality, has been considered and is then quantified in terms of potential changes. For the Betna basin population growth, urbanization, livestock numbers and land-use data were obtained from the SSP and RCP databases (details are in Section 2.3.1). Proper data on sanitation and wastewater treatment were absent. We assumed values for sanitation and wastewater treatment, because sanitation and wastewater-treatment scenarios do not exist for Bangladesh. To our knowledge, only few recent studies have applied regional (Bao et al., 2013) and global (Haller et al., 2007) sanitation scenarios. We assumed improvements in sanitation and wastewater treatment in line with the SSPs and the country’s future policy plan and economic and technological developments. We used the RCP future land-use data, because thus far SSP land-use data was not available. Our study is a first step towards the application of a process based model to comprehensively simulate combined impact of climate change and socio-economic scenarios on microbial water quality for a river basin. A bottom-up approach that engages local people and experts in the field to determine crucial factors and their potential changes, would increase the quality of such scenario development (Hofstra and Vermeulen, 2016). However, this study aimed to understand how the FIB concentrations will change in the near and far future with socio-economic development and climate change. We have been able to do that. We found that possible future improvements in sanitation and wastewater treatments in the Betna basin will reduce the river FIB concentrations to a large extent. Concentrations of FIB in surface water expose the population to faecal contamination, increased health risks and threaten people’s dependency on surface water (for domestic, bathing, shell fish growing). Our developed model and scenario analysis approach will be helpful for water managers or public health specialists in assessing future water quality and resulting health risks.

5. Conclusions

The study assesses the combined impact of expected socio-economic development and climate change on FIB concentrations in the Betna River basin by applying a coupled hydrodynamic and water quality model (MIKE 21 FM-ECOLab) for different future scenarios. Based on the obtained modelling results, the following conclusions are drawn:

- By the 2040s, FIB concentrations will decrease by up to 91% or increase by up to 75% for S1 and S2 scenario respectively. In 2090 for S1 scenario with all wastewater collection and treatment, results
in further improvement of the river contaminant (concentrations decrease by up to 98%); 
- For S2 by the 2090s, although half of all wastewater is treated, the concentrations are expected to increase up to 19% compared to current condition because of the high population growth. In this scenario, the population growth is faster than the improvement of wastewater treatment. Therefore 50% wastewater treatment would not be sufficient by the 2090s. Improving sanitation by connecting all the population to sewers should be combined with all wastewater treatment. Investments in sewage systems will increase sewage generation and will cause increased FIB concentrations in the river water, when this is not combined with investments in wastewater treatment;
- Concentrations of FIB are generally more influenced by changes in socio-economic factors (i.e., population growth, urbanization, change in sanitation, land use and increase in animal numbers) than in climate change. Therefore socio-economic development should be considered in assessing microbial water quality and consequent health risks by water managers or public health professionals; and
- During the wet period FIB inputs from the upstream rivers and during the dry period inputs from the wastewater drains were found to be highest in all scenarios. Contribution from diffuse sources (agriculture and urban runoff) was found to be lower both in the baseline condition and future scenarios.

The assessment of future trends in river microbial water quality is very helpful to assess the effectiveness of the existing water management facilities in the future and mitigating the associated impacts on the river. This study confirms the usefulness of the model to assess the impact of land-use changes and wastewater-treatment planning on microbial water quality in rivers. The methodology developed in this study, would be useful for water managers in planning climate change adaptation strategies based on local situations.

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