Assessing the Impact of Socio-economic Development and Climate Change on Faecal Indicator Bacteria in the Betna River, Bangladesh

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Thesis

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Table of Contents

Chapter 1.

General Introduction

1.1. Background

Access to clean and safe water is a global concern. In many countries, poor water quality is a major threat to human health and limited access to clean water and inadequate sanitation continues to act as a barrier for development (Rochelle-Newall et al., 2015). Most poor developing countries lack an effective water management infrastructure 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. Wastewater treatment facilities are lacking and wastewater thus enters directly into the rivers. This contaminated river water is often used for irrigation, domestic purposes and bathing. This increases the people's vulnerability to waterborne diseases. In Bangladesh, for example, diarrheal disease is very common and every year it causes around hundred thousand deaths (Faruque, 2014).

Outbreaks of waterborne diseases are related to the concentrations of waterborne pathogens in surface water (Freeman et al., 2009). The risks of diseases are determined by the concentrations, together with dose-response relationships and exposure. Waterborne pathogen concentrations are influenced by weather and climate. Changes in climate, such as increased water temperature and changes in precipitation patterns likely affect the concentration of pathogens in the surface water sources (Rose et al., 2001, Hofstra, 2011). Bangladesh is among the most vulnerable countries to climate change in the world. Due to climate change, extreme weather events, such as floods and cyclonic storm surges, are becoming more frequent and intense (Ahmed et al., 2011). Increased flooding is already a major problem in Bangladesh. For example, over nine million people were affected by the 2008 flood (NIDOS, 2009). Increased concentration of pathogens have been observed in the surface water after such flooding events (Ahmed et al., 2010, CCC, 2009). Outbreaks of waterborne diseases usually occur after floods due to contaminated surface water and disrupted water purification and sewage-disposal systems (Kunii et al., 2002, Siddique et al., 1991, Qadri et al., 2005). An increase in polluted surface water that contain high concentrations of pathogens, under future climate change therefore probably increases waterborne disease risks (Freeman et al., 2009).

Several mechanisms determine the net impact of climate change on waterborne pathogen concentrations. The concentration of pathogens in surface water probably increases after extreme precipitation events, because water becomes contaminated by increased surface runoff, sewer overflow and resuspension from sediments (Hofstra, 2011, Funari et al., 2012a). Simultaneously, increased precipitation can dilute and therefore decrease the concentration in surface water. Increased temperatures can also accelerate the inactivation rate of pathogens (An et al., 2002). However, the relative contribution of climate variables (temperature and precipitation) to changes in pathogen concentrations and disease outbreak remains poorly understood (CDSC, 2011, Vermeulen and Hofstra, 2013). Therefore, to better understand this contribution, knowing the balance between climate change and pathogen concentrations in surface water is essential. Although many studies have called for such research (Rose et al., 2001, Coffey et al., 2010a), well designed quantitative studies have not been performed yet (Hofstra, 2011). The changes during floods are particularly interesting.

Future waterborne pathogen concentrations and consequent health risk are also related to future possible socio-economic developments. Several studies have focused on climate change impacts on waterborne diseases (Moors et al., 2014, Rose et al., 2001, Freeman et al., 2009). However, very few studies have quantified the relationship between climate, socio-economic development and pathogen concentrations (Vermeulen and Hofstra, 2013). The present study assesses the impact of climatic variables (e.g. floods, precipitation and temperature) and socio-economic changes (e.g. population growth, urbanization, land use and sanitation) on the spread of pathogens in the surface water of the Betna River through simultaneous measurement, statistical and process-based modelling, and scenario analysis. This introductory chapter introduces the study area, sources and pathways of pathogens, process-based models and scenario analysis, followed by the research questions and thesis outline.

1.2. Study area

The study area comprises an area of approximately 107 km^2 within the Betna River basin. The area is located in the southwest coastal part of Bangladesh (Fig. 1.2). The river has tidal influence and is interconnected with a number of canals. The canals are used for irrigation and carry raw sewage and pollutants to the river. The river and canals are influence by the incoming tide from the Bay of Bengal. Dam construction in upstream countries causes significant reduction of fresh water inflow during the dry season. Consequently, due to heavy rainfall and increased discharge from upstream rivers during the monsoon the excess water cannot be drained completely and results in water logging and drainage congestion (IWM, 2014). Moreover, sea-level rise reduces discharges from the drainage system in low-lying areas and result in prolonged flooding (ADB, 2011).

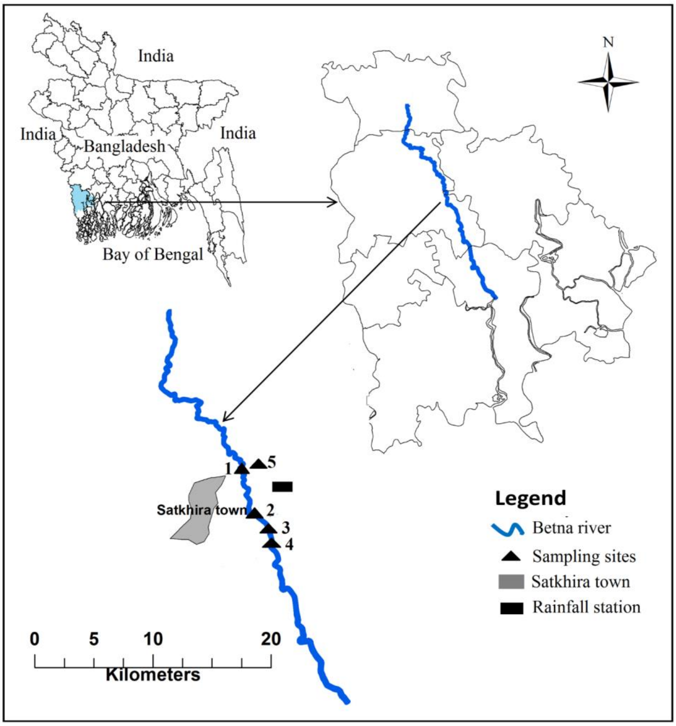

Fig. 1.1. Study area along the Betna River basin in the southwest of Bangladesh.

The Betna River basin experiences flooding due to monsoon precipitation events from June to October and storm surges from the Bay of Bengal during the cyclone season (i.e. April to May). The region was affected by flooding almost every year during the last decade (Hossain, 2003). In this area, April through October is the wettest period with highest rainfall intensity and November through February are the driest months with no or little rainfall. Annual rainfall ranges from 1300 to 1900mm with a 20-years (1992–2011) average of 1642mm. An analysis of rainfall data for this area shows an upward trend. The duration of rainfall has decreased but rainfall intensity has increased. In the last 50 years (1951–2010), the increase in cumulative rainfall is found to be 4.7mm every decade (CEGIS, 2013). The mean annual temperature is 26°C with peaks of over 30°C in May. Winter temperature may fall to 8°C in January (IWM, 2014).

The study area has a high population density of 1050 people per km^2 (BBS, 2011). The soil type of the area is mostly clay (99%) and some loam (1%). Its land use is dominated by paddy cultivation and aquaculture. In winter, due to a lack of an upstream flow, salinity increases and consequently agriculture is hindered. Water salinity is highest from March through April (up to 15ppt) and lowest (near 0ppt) in the rainy season from August to September (IWM, 2014).

Like in many other places, sewage and manure are the main bacteria sources in this catchment. In the Betna River basin, sewage is not treated and goes directly into the river and canals. The contaminated river water is used for irrigation, domestic purposes and shellfish cultivation; people also bathe in the river and consume contaminated shellfish. This increases the population’s vulnerability to outbreaks of waterborne diseases. However, microbial contamination is not monitored and very little knowledge exists on the distribution of microbes in this basin. To mitigate microbial contamination of surface waters, knowledge on microbial fate and transport, and factors that influence their dynamic distribution, is essential (Rochelle-Newall et al., 2015).

1.3. Choice of pathogens and bacteria

Understanding the influence of climatic and environmental factors on waterborne pathogen concentrations is thus needed for assessment of health risks. However, a variety of pathogens, such as viruses, bacteria and parasites, occur in surface waters. In the (sub)tropical climate the major waterborne pathogens reported are salmonella, *V. cholerae*, C. perfringens,, Shigella, cyanobacteria, rotavirus etc. Cyanobacteria and *V. cholerae* are abundant in the aquatic environments of Bangladesh. *V. cholerae* maintains symbiotic relationships with mucilaginous cyanobacteria. Rapid multiplication of *V. cholerae* occurs after cyanobacteria blooms. Seasonal multiplication of *V. cholera* following such blooms play an important role in the cholera epidemics in Bangladesh (Ahmed et al, 2007). Rotavirus is a leading cause of severe diarrhoeal disease in infants and young children in Bangladesh (Tanaka et al., 2007). Although *E. coli* is in particular not a good indicator for these pathogens, the detection and enumeration of pathogens are very difficult due to the great variety of pathogens, the low numbers of each species and the absence of standardized methods to detect some of them (Ouattara et al., 2013, Bruhn and Wolfson, 2007). Therefore, microbial contamination of water sources is often detected by measuring the concentrations of faecal indicator bacteria (FIB) instead of individual pathogen species (Ouattara et al., 2013, WHO, 2008). Measuring FIB is easier and relatively cheap. In addition, although FIB are generally not pathogenic, their presence in the water body indicates the possible presence of other pathogenic microorganisms (Burres 2009) and pathogens are expected to respond to climate change in a similar way as FIB. It is therefore the most common method in use (Rochelle-Newall et al. 2015). *E. coli* and enterococci have been used most widely as indicators of faecal contamination in water sources (Ouattara et al., 2013, Lata et al., 2009). Enterococci are a subgroup within the faecal streptococcus group and are distinguished by their ability to survive in salt water.

US EPA recommends enterococci as the best indicator of health risks in salt water and as a useful indicator in fresh water as well (Burres, 2009). Considering the high salinity level (up to 15ppt) in the study area, I have used enterococci along with *E. coli* as an indicator of faecal contamination.

1.4. Sources and pathways of water contamination

In developing countries, like Bangladesh, sanitation and sewage treatment systems are underdeveloped or poorly managed (Kamal et al., 2008). People are at risk when they are exposed to contaminated water. Surface water can be contaminated with FIB from various sources including untreated waste water discharges, septic leakage, agricultural or urban runoff, wildlife populations or nonpoint sources of human and animal waste (An et al., 2002). The main origin of these FIB is the direct and indirect release of human and animal faeces into the surface water (Fig. 1.2).

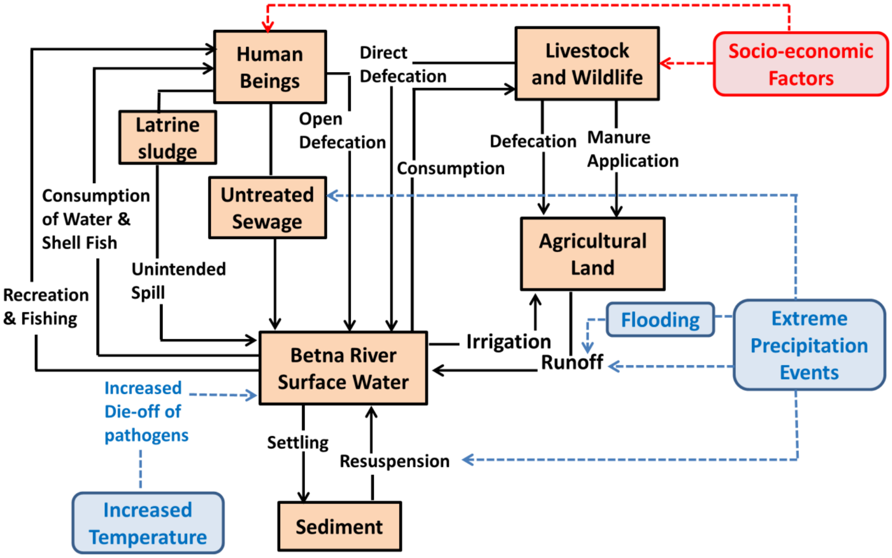

Fig. 1.2. Sources, pathways and influences of climatic and socio-economic changes on the Betna River contamination. Orange boxes show bodies and sources of pathogens/FIB, arrows show pathways. Blue boxes with arrows indicate the impact climate change (increase in temperature, precipitation and flood), and red boxes with arrows indicate the impact of socio-economic change on waterborne pathogens/FIB.

Manure is applied to agricultural fields as organic fertilizer and can become suspended into surface water after heavy rainfall events or via interception with flowing water (Bradford and Schijven, 2002). Surface water may subsequently become contaminated by runoff from agricultural lands and manure storage areas. Additionally, manure can be deposited directly to a stream water from open defecation by livestock, wildlife or other agricultural activities (Parajuli et al., 2009, Coffey et al., 2010b, Coffey et al., 2013). In the study area, sewage are not treated and raw sewage are discharged directly into the Betna River. Occasional leakage of septic tanks and open defecation from humans also contaminate the river water.

1.5. Association between different factors and pathogens

1.5.1. Socio-economic factors and pathogens

Socio-economic changes (in, for example, human and animal population growth, urbanization, land use and sanitation) influence the spread of pathogens and FIB in surface waters. Population growth, urbanisation and expansion of sanitary connections resulted in increased sewage (wastewater) generation and subsequently increase contaminant loads to surface waters. In developing countries, like Bangladesh, manure use is unregulated by legislation. With the increase in livestock densities more manure is produced and manure application to agricultural lands increase. This results in a considerable increase in the surface water FIB concentration through the runoff generated from these lands. More intensive agriculture without environmental legislation can thus increase contaminant load to surface waters (Rankinen et al., 2016). Fig. 1.2 presents the influence of socio-economic and climatic factors on FIB sources and concentrations in the river water. Socio-economic factors are a useful tool to explore the long-term consequences of anthropogenic change (Kriegler et al., 2012). Scenarios should account for future changes in both climate and socio-economic factors (Berkhout et al., 2002). However, surface water microbial water quality scenario analysis studies based on socio-economic changes are lacking. To my knowledge, only(Hofstra and Vermeulen, 2016) have adequately incorporated the socio-economic scenarios on global cryptosporidium emissions to surface waters. Besides, Rankinen et al. (2016) only considered land-use change and Jalliffier-Verne et al. (2016) incorporated population growth with climate change to assess faecal coliform and *E. coli* emissions to surface waters respectively.

1.5.2. Climatic factors and pathogens

A brief literature review is conducted to know the existing studies that explore the association between environmental variables and waterborne pathogens/FIB concentrations (Table 1.1a) or diseases (Table 1.1b). Table 1.1a also distinguishes between temperate and (sub)tropical studies. Studies conducted before 2001 were not considered. Although some studies that focused on the impact of climatic factors on waterborne diseases (e.g. diarrhoea, cholera) are conducted in the developing countries (Table 1.1; b), most of the studies on the climatic impacts on pathogens and FIB have been conducted in developed countries (Rose et al., 2001, Levy et al., 2016, Philipsborn et al., 2016, Howard et al., 2016). Studies based on impact of climatic factors on pathogens and FIB are thus lacking in developing countries (Table 1.1a). This thesis fills this important knowledge gap.

A statistical analysis is a common method to relate surface water pathogen and FIB concentrations and climate change or socio-economic variables. In most studies one environmental variable and one statistical method at a time (either correlation or regression analysis) were used (Table 1.1). All identified studies positively correlated precipitation and pathogen concentrations (Funari et al., 2012b, An et al., 2002, Abia et al., 2015, Vermeulen and Hofstra, 2013, Martinez et al., 2014, Isobe et al., 2004) and waterborne diseases (Seidu et al., 2013, Thomas et al., 2006, Chou et al., 2010). Most of these studies that are conducted in the temperate regions, reported a negative correlation with water temperature (Shibata et al., 2004, Walters et al., 2011, Olyphant and Whitman, 2004, Vermeulen and Hofstra, 2013), while most tropical studies reported a positive correlation (Koirala et al., 2008, Kelly-Hope et al., 2007, Huang et al., 2008). These latter authors relate the positive correlation to the coincidence of high temperature and precipitation during summer period. In a few studies FIB growth was suspected to be a possible reason for the positive relationship between temperature and FIB (Byappanahalli et al., 2003, Tiefenthaler et al., 2009, Hong et al., 2010, Abia et al., 2015). Salinity was negatively correlated with pathogen concentrations (Hoppe et al., 2013, Dastager, 2015, Aragonés et al., 2016, Adingra et al., 2012).

Table 1.1. An overview of the relationship between environmental variables and waterborne pathogen/FIB concentrations or diseases

a) Relationship between environmental variables and waterborne pathogen/FIB concentrations

Studies conducted in the temperate region					
Pathogens/FIB	**Environmental parameter**	**Study area**	**Main findings**	**Statistical methods**	**Reference**
C. perfringens Cryptosporidium *E. Coli* Enterococci Enteroviruses	Air temperature, Discharge, Rainfall,	Yarra River, Melbourne, Australia	Rainfall and discharge were positively, and temperature was mostly negatively associated	Correlation Analysis	Henry et al. (2016)
E. coli	Discharge, Precipitation, Water temperature	Rhine, Meuse, and Drentse Aa, Belgium and Netherlands	Precipitation and discharge had positive, and temperature, had negative correlation	Correlation & Regression Analysis	Vermeulen and Hofstra (2013)
Cryptosporidium *E. coli* S. Typhi S. Paratyphi	Rainfall	England and Wales (country-wide)	Significant positive correlation between cumulative rainfall sum over7 days, and diarrhea and *E. coli* concentrations	Correlation Analysis	Nichols et al. (2009)
Salmonella	Air temperature	New Zealand (country-wide)	Positive association was found between air temperature and salmonellosis notifications	Correlation Analysis	Britton et al. (2010)
E. coli Enterococcus	Rainfall, Salinity, Water temperature	Iberian Peninsula, Spain	Temperature, rainfall and salinity showed positive correlation	Correlation Analysis	Aragonés et al. (2016)
E. coli	Rainfall, Air and water temperature, DO, pH, and Turbidity	Chicago beach, USA	Rainfall was positively and temperature was negatively correlated, 71% of the observed variability in the log *E. coli* concentrations	Correlation & Multiple Regression Analysis	Olyphant and Whitman (2004)
E. coli	Air temperature, DO, pH, turbidity, wind	Michigan, USA	DO, pH were negatively and others were positively correlated, *E. coli* count predicted 47% of the explained variance (R^2=0.47)	Correlation & Regression Analysis	Nevers and Whitman (2005)
E. coli	Rainfall, River discharge	Raccoon River, Iowa, USA	*E. coli* concentrations were highest in the May to July period that corresponds with periods of greater rainfall intensity and river discharge	Correlation & Regression Analysis	Schilling et al. (2009)

Studies conducted in the (sub)tropical region					
E. coli	Water temperature	Shenyang, China	Positive association between temperature and diarrheal incidences, *E. coli* concentration was increased initially and then decreased	Correlation Analysis	Huang et al. (2008)
E. coli Enterococci Staphylococci Salmonella	Salinity, Turbidity, Water temperature	Grand-Lahou lagoon, Côte d'Ivoire	Temperature and salinity were negatively, and dissolved oxygen and turbidity were positively correlated with the bacteria	Correlation Analysis	Adingra et al. (2012)
E. coli Salmonella Shigella Proteus *V. cholerae*	DO, Nitrite, Nitrate, pH, Salinity, Water temperature	Veraval Coast, Gujrat, India	All parameters showed negative correlation with the bacteria	Correlation Analysis	Borade et al. (2015)
E. coli	DO, pH, Water temperature	Apies River, South Africa	A strong positive correlation was observed between temperature and the *E. coli* concentrations	Correlation Analysis	Abia et al. (2015)
C. perfringens Enterococci Fecal coliform	Rainfall, Salinity, Stream flow, Water temperature	Florida, USA	Observed variability were between 79 to 82%	Binary logistic regression	Rose et al. (2001)
C. perfringens *E. coli* Enterococci Total coliform	Rainfall, Salinity, pH, Turbidity, Water temperature	Miami, Florida, USA	Rainfall and turbidity had positive, and temperature, salinity and pH had negative correlation	Correlation Analysis	Shibata et al. (2004)
E. coli Enterococci, Total coliform	Conductivity, DO, Flow, pH, Turbidity, Water temperature	California, USA	Flow was negatively associated and other parameters had shown positive association with the bacteria levels	Correlation Analysis	Tiefenthaler et al. (2009)
E. coli Enterococci Salmonella	Rainfall, Salinity, Water temperature	California, USA	*Bacteria* concentrations were negatively correlated to salinity and temperature, and positively correlated to rainfall	Correlation & Regression Analysis	Walters et al. (2011)
E. coli Enterococci Total coliform	Rainfall, Stream flow	Hawaiian Rivers, USA	Observed variability of enterococci, total coliform and *E. coli* were 53%, 63% and 62% respectively	Linear Regression Analysis	Strauch et al. (2014)

b) Relationship between environmental variables and waterborne diseases

Name of disease	**Environmental parameter**	**Study area**	**Main findings**	**Statistical methods**	**Reference**
Cholera	Rainfall, Water temperature	Dhaka, Bangladesh	Positive association between temperature and cholera cases along with increased *V. cholerae* concentration	Regression Analysis	Hashizume et al. (2010)
Cholera	Air Temperature, Rainfall	Matlab, Bangladesh	Temperature is positively associated and rainfall had no	Correlation Analysis	Ali et al. (2013)

			influence on the variation in cholera incidence		
Diarrheal disease	Extreme rainfall events	Canada (country-wide)	Increased risk of diarrheal outbreaks following precipitation events	Step-wise regression analysis	Thomas et al. (2006)
Diarrheal disease	Maximum air temperature	Jinan, China	*E. coli* concentrations are higher in summer than winter, 1°C increase in temperature causes 11% higher diarrheal cases	Time Series Analysis	Zheng et al. (2008)
Diarrheal disease	Heavy rainfall, Stream flow	Cornwall, England	High cases of diarrhoea reported after heavy rainfall events	Correlation Analysis	Ihekweazu et al. (2005)
Diarrheal disease	Heavy Rainfall events	Delhi, India	During heavy precipitation events higher diarrheal causes were reported	Correlation Analysis	Patil et al. (2011)
Diarrheal disease	Heavy Precipitation events	Northern Ghana	Maximum rainfall events have positive association with diarrheal cases	Auto Correlation	Seidu et al. (2013)
Diarrheal disease	Air temperature, Rainfall, Relative humidity	Taiwan (country-wide)	Relative humidity and extreme rainfall events significantly contributed to the diarrhoea-associated morbidity in adult	Regression Analysis	Chou et al. (2010)
Cholera Shigellosis typhoid	Air temperature, Rainfall	Vietnam (country-wide)	Significant positive correlation between temperature, rainfall and cholera cases	Multivariate Analysis	Kelly-Hope et al. (2007)

1.6. Application of process-based modelling and scenario analysis

Climate change combined with socio-economic and land-use changes alter hydrological systems and are affecting water quality in various ways (Funari et al., 2012b, IPCC, 2014). These changes will also accelerate the transport of waterborne pathogens to aquatic systems (Rose et al., 2001, Hofstra, 2011) and thereby deteriorate future contamination. One way to address this increasing contamination is to apply models with scenario analysis to investigate the effects of climate and socio-economic changes on the hydrology and transport of FIB (Miller et al., 2013, Hofstra, 2011).

Different model types can predict the distribution of FIB in streams and rivers. In general, three main model types have been used. The first are statistical models, which are based on empirical statistical relationships, such as linear regression models. These models use input variables (e.g. environmental parameters and land use) to generate outputs using straightforward relationships (e.g. FIB concentrations) (Strauch et al., 2014). Their main advantage is the speed of implementation but their main disadvantages are that they are very site specific and none of the underlying processes are explicitly considered

(Rochelle-Newall et al., 2015). The second are mass-balance models. Such models use the inputs (e.g. nutrients or bacteria) into watersheds and produce systemic results (e.g. trends in concentrations) considering only losses or decay process. In other words, mass-balance models used the potential loads and determine the actual concentrations. Examples of mass balance models are the BLEST (Petersen et al., 2009) and BSLC (Zeckoski et al., 2005) models. The third type is the process-based mechanistic/physical models. Such process-based model is a mathematical representation of one or several processes that describe the functioning of (natural) systems (Buck-Sorlin, 2013). Examples of process-based models are MIKE (DHI, 2011), the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993), ECOMSED (Blumberg and Mellor, 1987) and SENEQUE (Billen et al., 1994). This model type considers watershed morphology, hydrology, rainfall-runoff, soil properties, land use and pollution. Observational data are used to validate them. They analyse and explore, for example, the mechanisms responsible for the mobilization, transfer and density of FIB in the aquatic systems (Rochelle-Newall et al., 2015) and often implicitly include feedbacks and time lags.

All models need to be parameterized and require input data that generally are hardly available, particularly in the data poor tropical or developing countries. Nevertheless, since regular monitoring of microbial river-water quality is very expensive and time consuming, process-based modelling can save time and resources. Previous studies (Harwood et al., 2005) have suggested that microbial concentrations of water sources can be projected using coupled hydrodynamic-microbial models. This approach can generate useful data for microbial risk assessment and plan mitigation measures to reduce microbial contamination of water sources. Modelling is useful to generate continuous spatially and temporally concentrations, can also be used in scenario analysis and informs water managers in their planning. Models can be used to develop early warning systems for low lying areas in the river basins that are affected by flooding, and that face widespread microbial contamination.

Process-based models for pathogens describe the hydrodynamic situation in the water body and take into account the decay of pathogens in the water environment (Sokolova et al., 2013, Liu et al., 2015b). However, process-based modelling of microbial water quality is very sparse, particularly in the developing countries where diarrheal diseases are endemic (Hofstra, 2011). To know the current status of water quality modelling, a brief literature review on the existing process-based water quality models is summarized in Table 1.2. This table shows that, although recently few studies have been conducted in the catchments in developing countries (Vijay et al., 2016, Nguyen et al., 2016, Menendez et al., 2013), most studies exist only for catchments in developed countries (mainly United States and Europe). This thesis reduces this apparent knowledge gap by focusing on a developing country.

The microbial modelling studies generally incorporate hydrological models coupled with water quality models. Examples are the SWAT model that includes a pathogen transport model (Coffey et al., 2010a, Parajuli et al., 2009, Chin et al., 2009), the MIKE model that is coupled with a water quality module ECOLab (Bedri et al., 2014, Sokolova et al., 2013, Vijay et al., 2016), the model developed by Dorner et al. (2006) that uses the WATFLOOD hydrological model, and the EG model that uses hydrology from the SimHyd model (Haydon and Deletic, 2006). Generally the microbial models simulate microbial concentrations or loads for a catchment (Coffey et al., 2010a, Ferguson et al., 2007) and water source (Sokolova et al., 2013, Menendez et al., 2013). The available models still have many limitations which include, for example, lack of available observed microbial and input data (Hofstra, 2011). However, more observational data for proper model validation and comparison with base data, and sensitivity studies may improve model performance and increase the model's robustness (Chin et al., 2009, Haydon and Deletic, 2006).

In this study, a two dimensional (2D) hydrodynamic model (MIKE 21 FM) coupled with a water quality module (ECOLab), developed by Danish Hydraulic Institute (DHI, 2011) is used. The model simulates unsteady 2D flows in one vertically homogenous (depth averaged) layer and assumes that no large flow gradient exists in the vertical direction of the water column (Webster et al., 2014). The model is based on the 2D numerical solution of Reynolds averaged Navier-Stokes equations using Boussinesq approximation and hydrostatic pressure assumptions (DHI, 2011). These equations are the heart of fluid dynamics modelling and are based on the laws of continuity and are applications of concept of finite volumes. The model consists of laws of continuity, momentum conservation, and temperature, salinity and density equations in horizontal direction. The density does not depend on pressure, only on temperature and salinity (DHI, 2011). The input and validation data required for the modelling process are river bathymetry, river cross-section, hydrodynamic (water level, river discharge, inflow from tributaries) and meteorological (wind speed, wind direction, rainfall and relative humidity), and water quality data. The MIKE model is selected in this study because it can efficiently generate outputs of high temporal and spatial resolution, and is very effective for a small watershed like the present study area. MIKE is one of the few models that is very useful in a tidal river. Further details about the MIKE hydrodynamic and microbial water quality modelling is given in Chapters 3 and 4 respectively. The model is also applied in future microbial scenario analysis (Chapter 5).

Table 1.2. Various process-based models applied for water quality modeling with sources of pollution.

Pathogens/FIB	**Pollution Source**	**Location**	**Models Applied**	**Reference**
E. coli	Non-point sources	Australia	EG and SIMHYD-ASP model	Haydon and Deletic (2006)
Cryptosporidium, Giardia and *E. coli*	Point sources	Australia	The non-linear loss module of the IHACRES rainfall-runoff model	Ferguson et al. (2007)
E. coli, Cryptosporidium , Enterovirus, Norovirus	Point sources	River Danube, Austria	QMRAcatch	Schijven et al. (2015)
E. coli	Point and non-point sources	Scheldt River, Belgium	SENEQUE-EC model consists of the hydro-ecological SENEQUE/RIVERSTRAHLER	Ouattara et al. (2013)
E. coli	Point and non-point sources	Scheldt River, Belgium	SENEQUE-EC coupled with SLIM-EC2	Brauwere et al. (2014)
E. coli, Campylobacter, Cryptosporidium	Point and non-point sources	Canada	WATFLOOD/SPL	Dorner et al.(2004)
Cryptosporidium, Giardia, Campylobacter, and *E. coli*	Point sources	Ontario, Canada	WATFLOOD	Dorner et al. (2006)
Fecal coliform	Point and non-point sources	France	hydro-ecological SENEQUE/Riverstrahler model	Servais et al. (2007)
E. coli	Point and non-point sources	France	SWAT	Bougeard et al. (2011)
E. coli	Point and non-point sources	Ireland	SWAT	Coffey et al. (2010a)
Cryptosporidium	Point and non-point sources	Ireland	SWAT	Tang et al. (2011)
*E. coli*and Enterococci	Point and non-point sources	Bray, Ireland	MIKE 11, MIKE 3-ECOLab	Bedri et al. (2014)
Cryptosporidium and Giardia	Point sources	The Netherlands	Water-model National (WATNAT) and the emission model PROMISE	Medema and Schijven (2001)
Faecal coliform and *E. coli*	Point and non-point sources	New Zealand	Watershed Assessment Model (WAM View)	Tian et al. (2002)
E. coli	Point and non-point sources	New Zealand	Watershed Assessment Model (WAM View)	Collins and Rutherford (2004)
E. coli	Point sources	Lake Radasjon, Sweden	MIKE 3-ECOLab	Sokolova et al. (2013)
Fecal coliform	Point and non-point	Danshuei River, Taiwan	Eulerian–Lagrangian finite-element model (SELFE)	Liu et al. (2015b)

	sources			
Faecal coliform	Point and non-point sources	Ribble River basin, UK	DIVAST (Depth Integrated Velocities & Solute Transport), FASTER (Flow & Solute Transport in Estuaries & Rivers)	Gao et al. (2015)
Faecal coliform	Non-point sources	USA	Spatially Explicit Delivery Model (SEDMOD)	Fraser et al. (1998)
E. coli	Point and non-point sources	Charles River, USA	ECOMSED and RCA model	Hellweger and Masopust (2008)
Faecal coliform	Point and non-point sources	Georgia, USA	HSPF and SWAT	Chin et al. (2009)
Faecal coliform	Point and non-point sources	Kansas, USA	SWAT	Parajuli et al. (2009)
Cryptosporidium, Giardia, and *E. coli*	Point and non-point sources	Massachusetts, USA	WATFLOOD/SLP9 Model	Wu et al. (2009)
Fecal coliform	Point and non-point sources	St. Louis Bay, Mississippi, USA	Environmental Fluid Dynamic Code (EFDC) and Hydrological Simulation Program Fortran (HSPF)	Liu et al. (2010)
Faecal coliform	Point and non-point sources	USA	SWAT	Cho et al.(2012)
E. coli	Point sources	Plata River, Argentina	MIKE 21-ECOLab	Menendez et al. (2013)
Faecal coliform	Point sources	Mumbai, India	MIKE 21-ECOLab	Vijay et al. (2016)
E. coli	Point and non-point sources	Mexico	tRIBS Model	Robles Morua et al. (2012)
Total coliform	Point and non-point sources	Vietnam	SENEQUE/RIVERSTRAHLER	Nguyen et al. (2016)
Cryptosporidium	Point and non-point sources	Global	Based on the model of Bouwman et al. (2009)	Hofstra et al. (2013)
Fecal coliform	Point and non-point sources	Europe	World Qual, Part of WaterGAP3	Reder et al. (2015)

Concentrations of the FIB in surface waters will thus likely change with changing socio-economic and climatic conditions. To understand the impact of these changes on FIB concentrations, modelling can be used to develop future scenarios. Such scenarios should account for future changes in both climatic and socio-economic factors, because to evaluate the impact of climate change on future societies, combining climatic and socio-economic factors is important (Berkhout et al., 2002). Climate change combined with socio-economic factors is also a key concern of the fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Developing a new scenario framework by combining the Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) has been proposed by the climate community (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 and change in land use and sanitation) that describe challenges to mitigation and adaptation (O'Neill et al., 2015). 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, which provides a useful look into future consequences of climate and socio-economic changes for human societies and their environments. Few recent studies on microbial water-quality scenario analysis have been done that use either climate change (Jalliffier-Verne et al., 2016, Rankinen et al., 2016, Liu and Chan, 2015, Sterk et al., 2016) or socio-economic scenarios (Hofstra and Vermeulen, 2016). However, assessing the combined impacts of climate change and socio-economic scenarios on river microbial water quality has not been performed yet. To my knowledge, my study is the first to apply a process based model that simulates combined impact of climate and socio-economic scenarios on microbial water quality for a river basin.

1.7. Research objectives and questions

To reduce the obvious knowledge gaps, my PhD thesis aims to quantify the impact of climate and socio-economic changes on flooding and FIB (*E. coli* and enterococci) concentrations in the Betna River basin in southwestern Bangladesh. The specific objectives (obj) are:

Obj1 To assess the influence of environmental variables (i.e. rainfall patterns, water temperature and salinity) on fluctuations in FIB concentrations of the Betna River in southwest Bangladesh. This river floods almost every year.

Obj2 To simulate the present and future water levels, discharges and flood potential in the Betna River using the MIKE 21 FM hydrodynamic model.

Obj3 To analyse the fate, transport and the processes that influence the dynamic distribution of faecal contaminants in the Betna River, using the coupled hydrodynamic-microbial model (i.e. MIKE 21 FM-ECOLab).

Obj4 To assess the impact of socio-economic development and climate change scenarios on FIB (*E. coli* and enterococci) concentrations in the Betna River basin.

The subsequent research questions (RQs) are addressed to fulfil the objectives.

RQ1: What are the concentrations, sources and pathways of *E. coli* and enterococci in the Betna River's surface water?

RQ2: What would be the impacts of climate change on floods in the Betna River basin?

RQ3: How do modelled and observed current concentrations of *E. coli* and enterococci in the surface water of the river compare?

RQ4: What are the projected future faecal indicator concentrations in the river's surface water under climate and socio-economic changes?

The RQs are addressed in four steps (Fig. 1.3). Each step answers a specific research question. To answer RQ1, water samples are collected from different locations in the Betna River in different seasons and then microbial analyses are performed to measure *E. coli* and enterococci concentrations. This spatial and seasonal analysis provides an understanding of the current river-basin situation. Moreover, it also helps to understand surface water concentration differences between flooding and non-flooding period. Five sampling sites along the Betna River (Fig. 1.2) are selected on the basis of point and non-point sources of sewage and manure discharge into the river. The sewage inputs from the nearby city Satkhira (point source) and input from agricultural areas (non-point sources) are identified. Monthly water samples over twenty months (April 2014 to November 2015) are collected and analysed in the laboratory of the Environmental Sciences Discipline, Khulna University. Enumeration of *E. coli* and enterococci are performed by the membrane filtration (MF) technique. Correlation and regression analysis is performed to assess the impact of the environmental variables (water temperature, precipitation and salinity) on FIB concentrations in the river water. The detail of sampling and analysis are described in Chapter 2.

The second step addresses RQ2. MIKE 21 FM, a 2D hydrodynamic model, is applied to simulate present and future hydrodynamic conditions in the Betna River basin. A 2D model is used because the river is not very deep (maximum depth 9m) and mixing happens fast. At first, to simulate the present hydrodynamics of the river, the model is set up, calibrated and validated by comparing the modelled results with measured values of river water levels and discharges at different locations. The hydrodynamics (i.e. water levels and discharges) are simulated because increased water levels and discharges are responsible for the periodic floods and knowledge on flooding is important because direct contact with contaminated flood water is a plausible transmission route of waterborne diseases. For future hydrodynamics, the climate projections in this study include predicted increases in air temperature and sea level, and changes in precipitation patterns. In this study, a low (RCP4.5) and a high emission pathway (RCP8.5) combined with sea-level rise are used to capture a range of uncertainties in the climate variables. The daily climate model data are downscaled from two GCMs, MPI-ESM-LR (Max Planck Institute for Meteorology) and IPSL-CM5A-LR (Institute Pierre-Simon Laplace) that uses the 'Delta method' with 'quantile-quantile' correction as described by Liu et al. (2015a). Daily observed air temperatures and precipitation data from 1986 to 2005 are used as a basis for this correction. Two future time periods 2031–2050 (2040s) and 2081–2100 (2090s) are used for the two RCP scenarios.

The third step addresses RQ3. The coupled 2D hydrodynamic and water quality model, MIKE 21 FM-ECOLab, is applied to simulate microbial concentrations in surface water from different contaminant sources. ECOLab utilizes the water flow, currents and other output from the hydrodynamic model to calculate the fate of FIB in the river. The FIB are assumed to be inactivated following first order decay kinetics in the river water, where the inactivation is a function of temperature, salinity and solar radiation as described by Mancini (1978). The model is set up and validated using the measured temperature, salinity and FIB data. Then, the model's sensitivity is tested by removing one process or forcing at a time. These simulations revealed the factors and processes controlling the FIB concentrations and their variability. The model is also applied to investigate the influence of sewage treatment on FIB concentrations.

To answer RQ4 in the final step, the developed model (which is described in Chapters 3 and 4) is used to analyse several scenarios for future climate and socio-economic changes and their impacts on FIB concentrations in the river water. The model takes into account water contamination with FIB through major sources (e.g. human and animal populations), land use, hydro-climatic parameters, meteorology and die-off processes (Fig. 1.1). First of all, the scenarios are developed and implemented in the model with changed input variables and finally the differences between the current and future FIB concentrations are analysed. The scenario development is based on the IPCC's AR5 (IPCC, 2014), which employs the new generation of RCP scenarios (Moss et al., 2010), including the SSPs (O'Neill et al., 2015) and RCPs (Van Vuuren et al., 2011) to integrate future social and climate changes impacts. These scenarios include changes in human and animal population, urbanization, sanitation, land use and climate variables for two future periods

(2040s and 2090s). The final scenarios are based on SSP1 and SSP3 and RCP4.5 and RCP8.5 in a matrix as currently is common practice in the IPCC and my own interpretations for sanitation, wastewater treatment and agricultural-management storylines. Baseline conditions (October 2014–September 2015) and two future scenarios, S1 (sustainability scenario) and S2 (uncontrolled scenario) are developed for this study. These scenarios are implemented in the model. The model simulation results are interpreted to answer RQ4 on future concentrations, fate and transport of faecal indicators in the river basin under changed climate conditions.

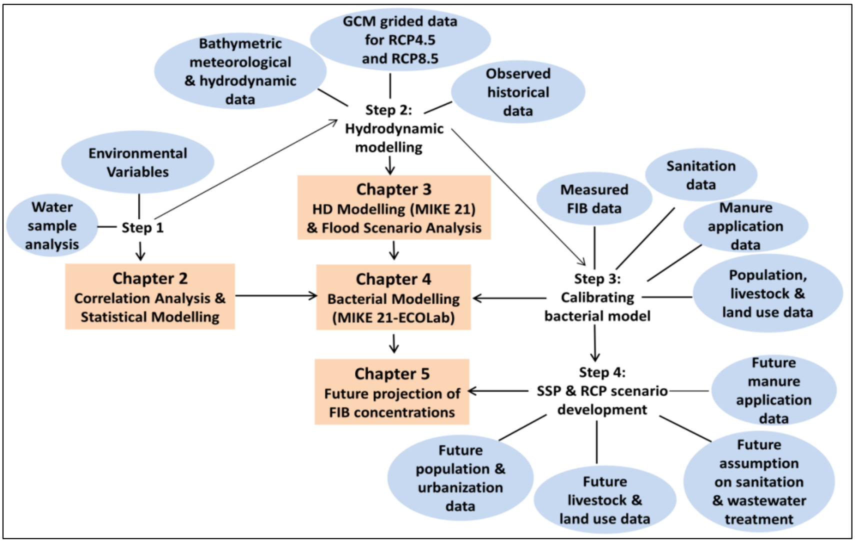

Fig. 1.3. Methodological framework applied in this thesis. Oval boxes are inputs (data/variables) and rectangular boxes are the major analysis and results (Chapters 2 to 5).

My study enhances the understanding of impacts of climate and socio-economic changes on FIB concentrations in river water. Assessing river microbial surface water quality is important as it is related to public health risk when people are exposed through drinking, recreation or consumption of shell fish and irrigated vegetables. Therefore, knowledge on present and future river microbial water quality is important and has a strong public health significance. Findings of my study on the present and future FIB concentrations are could be helpful for water managers and public health professionals in assessing present and future microbial water quality. The model could also be used to estimate pathogen concentrations. These concentrations along with dose-response and exposure data can be used for health risk determination. This study provides useful information for water managers to mitigate flood risks and reduce the widespread faecal contamination and the consequent risks of waterborne disease outbreaks. The findings and model will also be helpful for other basins of the world with similar characteristics.

1.8. Thesis outline

To address the RQs, four independent studies are conducted and presented in the form of four chapters (Chapters 2–5). In Chapter 2 measured concentrations of FIB and other physico-chemical parameters along the Betna River are presented. To analyse the measured data, a statistical linear-regression model was applied to explore the relation between environmental variables and FIB concentrations. This chapter provides information on the spatial and temporal variations of FIB concentrations in the river water and also provides understanding on the relative contribution of the climatic and environmental variables to change in the river's FIB concentrations. However, as regular FIB sampling in the river are expensive and time consuming, in Chapters 3, 4 and 5, the process-based model MIKE 21 FM is coupled to the water quality module, ECOLab to understand the present and future scenarios of hydrodynamics and FIB concentrations in the Betna River basin. In Chapter 3, the river's present and future hydrodynamics are simulated. Its output is used as input into Chapter 4's water quality model. Chapter 3's hydrodynamic modelling determines present and future water levels and discharges in the Betna River and explores the potential of the increased water levels and discharges to cause floods in the basin.

Chapter 4 describes the fate and transport of FIB to the river. This chapter also explores and discusses the processes that influence the variations of FIB concentrations in the river. Moreover, it studies the impacts of wastewater treatment on the river's microbial water quality of the river. Chapter 5 provides the future scenario analysis of FIB dynamics. It assesses the future impact of socio-economic and climate changes on FIB concentrations in the Betna River basin. The chapter provides an understanding on how the FIB concentrations may change in the future, when change in socio-economic conditions (population growth, animal number, land use and sanitation) and climatic factors (temperature, precipitation pattern and rise in sea level) are expected. Finally, in Chapter 6, the main findings are discussed in a broader context, conclusions are made, and an outlook for further research on this topic is presented.

Chapter 2.

The Impact of Environmental Variables on Faecal Indicator Bacteria in the Betna River Basin, Bangladesh

Abstract

Environmental variables influence Faecal Indicator Bacteria (FIB) in surface water. Understanding that influence is important, because presence of FIB, which are an indication of faecal contamination, means that harmful pathogens could be present that could also be influenced by environmental variables. Although some recent studies have focused on this topic, most of this work has been conducted in developed countries. Similar studies in developing countries and in a (sub)tropical climate are lacking. In this study we assess the influence of environmental variables on fluctuations in FIB concentrations of the Betna River in southwest Bangladesh that floods almost every year. Monthly water samples from five locations along Betna River were tested for FIB (*E. coli* and enterococci) in 2014–2015. A linear regression model was developed to assess the effect of the environmental variables on FIB concentrations. The study revealed increased FIB concentrations during wet weather conditions. Precipitation and water temperature were positively correlated with FIB concentrations. Water temperature was positively correlated, because the warm May to September period coincides with frequent precipitation. Precipitation increases manure release from land to surface water. The regression model explains nearly half of the variability in FIB concentrations (R^2 of 0.46 for *E. coli* and 0.48 for enterococci). This study indicates that increased precipitation combined with higher water temperature, as is expected in this region with climate change, likely increases FIB concentrations. Waterborne pathogens are expected to respond similarly to these environmental changes, indicating that disease outbreaks could well become more frequent and severe.

Keywords: Water temperature; Precipitation; Salinity; *E. coli*; Enterococci; Regression

This chapter is based on:

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2.1. Introduction

Due to climate change, the frequency and intensity of extreme weather events, such as floods and cyclonic storm surges are increasing in Bangladesh (Ahmed et al., 2011). The effect of increased flooding is one of the major problems of Bangladesh. For example, over nine million people were affected by the 2008 flood events (NIDOS, 2009). The southwest coastal area of Bangladesh is particularly vulnerable to the above extreme events. Vulnerability of coastal areas to flooding is aggravated by this area's exposure to intense storm surges from the Bay of Bengal (CEGIS, 2013). The recent devastating cyclones in 1988, 2002, 2007 and 2009 caused catastrophic flood in this region (ADB, 2011).

Climate change induced heavy rainfall and flooding indeed has caused epidemics of waterborne diseases like diarrhoea (Zhang et al., 2012, Delpla et al., 2009, Funari et al., 2012b). In Bangladesh, diarrheal disease remains very common, and every year it causes around 0.1 million deaths (Faruque, 2014). These outbreaks of waterborne diseases are related to the concentration of waterborne pathogens in surface water (Freeman et al., 2009). The spread of waterborne pathogens and its relation to environmental variables is poorly studied (Patz et al., 2008, Rose et al., 2001, Hofstra, 2011, Vermeulen and Hofstra, 2013). In Bangladesh, increased concentrations of waterborne pathogens have been observed in the surface water after flooding events (Ahmed et al., 2010). An increase in polluted surface water containing high concentrations of pathogens with future climate change may increase the risk of waterborne diseases.

The water quality of surface waters has been deteriorating in developing countries due to rapid industrialization and population growth (Lata et al., 2016). The Betna River in southwest Bangladesh is a surface water source for about 0.1 million people living along the river. The river is contaminated by several sources of pollutants, such as untreated wastewater discharges, septic tank leakage, surface runoff from urban areas and agricultural lands, and manure storage areas. The untreated surface water is used for irrigation, domestic purposes and shellfish growing and this makes the population vulnerable to outbreaks of waterborne diseases.

The concentration of microorganisms in surface water may increase after extreme precipitation, because water may become contaminated by increased runoff, and resuspension from sediments (Funari et al., 2012b, Hofstra, 2011). Higher bacterial concentrations were reported during periods of intense precipitation and high river discharge (Schilling et al., 2009, Aragonés et al., 2016, Ibekwe et al., 2011). Conversely, increased precipitation may decrease the pathogen concentration of surface water due to dilution (Lucas et al., 2014). An increased temperature may cause die-off of pathogens and thereby reduce their concentrations (An et al., 2002, Vermeulen and Hofstra, 2013, Walters et al., 2011). However, few studies reported positive correlation between water temperature and bacterial concentrations due to coincidence of summer temperature and periods of intense precipitation and high discharge (Schilling et al., 2009, Koirala et al., 2008). Some studies also reported the likelihood of some bacterial growth in tropical temperatures (Winfield and Groisman, 2003, Tiefenthaler et al., 2009). However, the net contribution of environmental variables (temperature, precipitation and salinity) to changes in pathogen concentrations is not clear (Vermeulen and Hofstra, 2013).

Surface water can be contaminated by a variety of pathogens, such as viruses, bacteria and parasites. The presence of faecal indicator bacteria (FIB) does not necessarily indicate the presence of pathogens (WHO, 2008). The correlation between FIB and many waterborne pathogens is often weak. Nevertheless, microbial contamination of water bodies is usually detected by measuring the concentrations of FIB instead of pathogens (WHO, 2008), because detecting varieties of pathogens is very difficult, time consuming and expensive (Bruhn and Wolfson, 2007). Whereas, measuring faecal indicators is easier, requires no complex equipment and is relatively cheap. It is therefore the most common method in use (Rochelle-Newall et al., 2015). Although FIB are generally not harmful themselves, their presence in water body indicates the possible presence of other pathogenic microorganisms (Burres, 2009). Indicators are useful in assessing health risk, regardless of whether the specific pathogens are pathogenic or not (Wu et al., 2011, Teklehaimanot et al., 2014). *E. coli,* faecal coliforms and faecal streptococci have been most commonly used as microbial indicators of faecal contamination in water bodies. Enterococci are a subgroup within the faecal streptococcus group which have the ability to survive in salt water (Burres, 2009). Considering the high salinity level (i.e. up to 15 parts per thousand (ppt)) in the study area, we have used enterococci along with *E. coli* as an indicator of faecal contamination.

This paper assesses the influence of environmental variables (i.e. rainfall patterns, water temperature and salinity) on fluctuations in FIB concentrations of the Betna River in southwest Bangladesh that floods almost every year. First we explore the spatial and temporal patterns of FIB variability and establish the correlation between observed environmental variables and concentration of FIB. Then we estimate the relative contribution of these variables to the observed variation in FIB concentrations by fitting the data to a linear regression model. Finally we discuss how environmental change influences FIB concentrations in a subtropical river system where this type of study is lacking (Rochelle-Newall et al., 2015). Therefore, the findings of this study will also be helpful for other developing countries with similar geographic setting.

2.2. Materials and methods

2.2.1. Study area

The study area covers an area of 107 km^2 in the Betna watershed, located in the Satkhira district of southwest Bangladesh (Fig. 2.1). The total length of the river is about 192km and its average width is 125m. The Betna River is hydrologically linked with Bhairab River in the north and Kholpetua River near Assasuni in the south. The river flows from north to south and has tidal influence. The river has a number of small irrigation canals.

April to October is the wettest period with the highest rainfall intensity and November to February is the driest period with no or very little rainfall. Annual rainfall ranges from 1300mm to 1900mm with a 12 years average of 1640mm (CEGIS, 2013). More frequent and intense rainfall, with shorter rainfall periods have been observed over the last decades. Over the last five decades (i.e. 1948 to 2008), cumulative rainfall has increased 4.7mm every 10 years (CEGIS, 2013).

Two types of weather conditions cause floods. Firstly, during heavy rainfall in the monsoon, the excess water cannot be drained properly due to high siltation in the rivers and the canals. This results in water logging, which is also known as drainage congestion. Secondly, flooding occurs during cyclonic storm surges that emerge from the Bay of Bengal during the cyclone season in April–May (i.e. pre-monsoon). Flood hits the area almost every year (Hossain, 2003, CEGIS, 2013).

Non-calcareous grey floodplain soils are abundant in this area. The topsoil of the entire study area is clay (99%) and loam (1%). Agriculture is the dominant land use. About 61% of the study area is covered by farms for agriculture; 8% are settlements, 0.5% is forest, 10% are waterbodies and the remaining 20.5% is wetland (also used for aquaculture). In winter, due to the lack of upstream flow, salinity starts increasing and reaches up to 15ppt in March–April. As a result agriculture is hindered in this season. During the rainy season from August–September the salinity reduces to nearly zero (IWM, 2014).

The population density is 1050 people per km^2 (BBS, 2011). Many people reside and work on the river banks and their activities contaminate the Betna River. Sewage and manure are the main bacteria sources in this catchment. Wastewater is not treated and it is directly released into the river and canals (Kamal et al., 2008). During heavy rainfall overflow of sewerage systems and septic tanks are common. The manure sources include manure applied to the agricultural farms as organic fertilizer, manure excreted from livestock grazing and direct deposition of animal faeces into the river and canals.

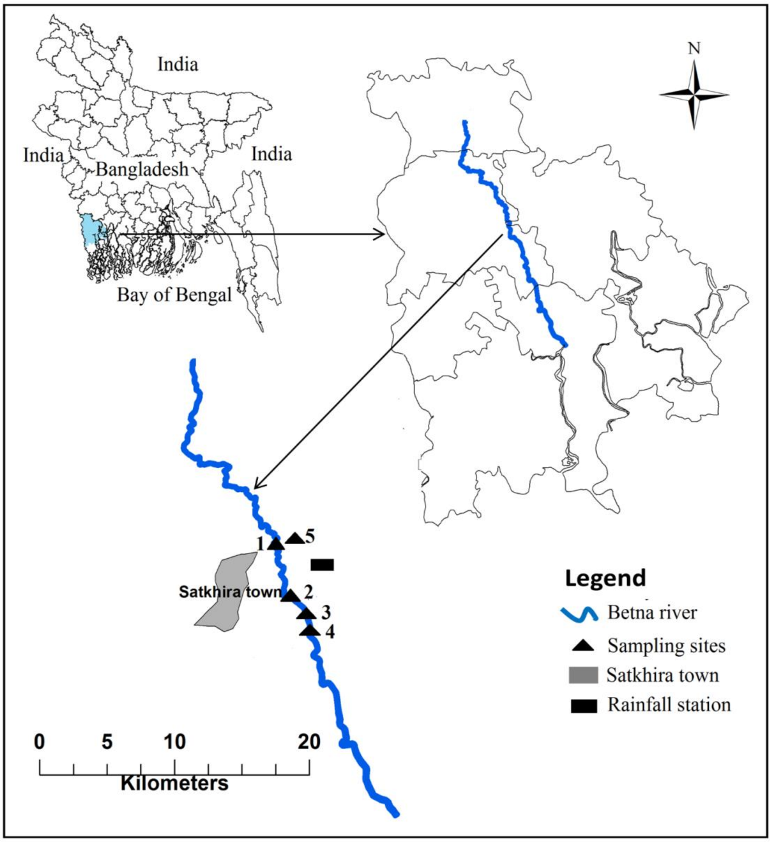

Fig. 2.1. Study area, Betna River basin in the southwest of Bangladesh.

2.2.2. Sampling and data collection

To monitor faecal contamination of river water, water samples were collected from four locations along Betna River and one location from a nearby pond (Fig. 2.1). The sampling sites were selected to properly represent the various sewage sources (most importantly from the nearby town of Satkhira) and manure discharges into the river. Sampling sites 1 to 4 all receive microbial pollution from animal grazing and agricultural activities. The first sampling site (S1) was located in the upstream part of the study area. The river here occasionally receives overflow from a pond (i.e. Sampling site five) during heavy rainfall and/or flooding events. The second sampling site (S2) was located adjacent to some rural households. At the third sampling site (S3) the river receives sewage discharge from urban and industrial areas. Sampling site four (S4) was a connecting point of a creek that receives pollutants from Satkhira town. The fifth sampling site (S5; additionally incorporated after four months of sampling) represents a pond that directly receives human and household waste.

Water samples were collected once a month. These samples were generally taken between the 20th and 25th of every month and the sampling time was around 9.00AM. Samples were collected for a period of 20 months from April 2014 to November 2015. A total of 96 samples were collected throughout the 20 months (except for S5, where sampling was only done for the last 16 months). Water temperature (instrument name: TLX, Dth-73), salinity (Hanna HI 8033), Electrical Conductivity (EC) (Hanna HI 8633), pH (Hanna HI 2211) and turbidity (Hach 2100Q) were recorded on each site at the time of sampling, while bacterial measurements were done later in the Environmental Microbiology Laboratory of Environmental Science Discipline, Khulna University, approximately 45km from the sampling sites. Rainfall (total mm/day) data were collected from Bangladesh Water Development Board's nearest station at Benarpota (see Fig. 2.1).

2.2.3. FIB analysis

Water samples from the selected sites were collected at a depth of 50cm from one river bank into sterile nalgene plastic bottles facing the mouths of the bottles upstream. All samples were collected with the care required for FIB analysis. Sampling bottles were sterilized using procedures described in standard methods (APHA, 1992). All samples were placed in an insulated box filled with ice packs, transported to the laboratory and the analyses were started within six hours of collecting the first sample.

Enumeration of *E. coli* and enterococci were performed by the membrane filtration (MF) technique as described by USEPA (2002), Method 1103.1 and USEPA (2009), Method 1106.1 respectively. Several dilutions of samples were considered. We considered triplicate plates for each dilution to determine the number of bacteria. Samples were diluted with deionized water to an end volume of 100ml. Each of the diluted samples was filtered through 0.45μm membrane filter (Millipore Corp., Bedford, MA, USA). Filtration devices were treated by using a burner to ensure proper sterilization and to prevent cross contamination among samples. For enumeration of *E. coli,* the mTEC agar plates were incubated at 35±0.5°C for two hours followed by further incubation at 44.5±0.2°C for 22–24 hours. Then filters were transferred to a pad saturated with urea substrate for 15 to 20 minutes. After incubation on the urea substrate at room temperature, yellow, yellow-green, or yellow-brown colonies were counted as *E. coli.* For enumeration of enterococci, mE agar plates were incubated at 41±0.5°C for 48 hours followed by incubation on Esculin Iron Agar (EIA) plate for 20 to 30 min at 41±0.5°C. After incubation on the EIA black or reddish-brown colonies were counted as enterococci. The bacteria colonies were expressed as colony forming units (cfu) per 100 ml.

2.2.4. Statistical analysis

All the data were analysed using statistical package software SPSS 22.0**.** First, FIB (*E. coli* and enterococci) observational data were $\log_{10}$ transformed to achieve a normal distribution. Normality of datasets was confirmed using Q-Q plots. The $\log_{10}$ transformed FIB data were always used in all statistical analyses. Water temperature and salinity data were normally distributed. However, precipitation data were gamma distributed, because the precipitation data contained many zero values. Precipitation often requires some time to flush manure into the river throughout the catchment. We analysed FIB data of three heavy rainfall events and found that FIB concentrations remain high in the river water until three days after the rainfall event (data not presented). We, therefore, summed the precipitation data over three days. Such precipitation summation is commonly used (Crowther et al., 2001, Vermeulen and Hofstra, 2013, Walters et al., 2011).

A standard Pearson product–moment correlation analysis was performed for correlations between $\log_{10}$ transformed FIB concentrations and water physico-chemical parameters (temperature, salinity, pH, EC and turbidity). Correlation analysis between $\log_{10}$ FIB concentrations and precipitation was performed using the Spearman's rank correlation, which does not require normally distributed data.

To assess the relative contributions of environmental variables to the observed difference in FIB levels in river water, the data were fitted to a linear regression model. The best model was selected by evaluating different (linear) models with all possible variable combinations. Bacterial concentrations were used as dependent variables and as independent variables initially we had included water temperature, precipitation, and salinity. Other observed parameters (pH, EC and turbidity) did not show any significant correlation with FIB concentrations and were not included in the model.

The models of the following form were applied for each FIB:

$$\log(Y) = \beta_0 + \beta_1 t + \beta_2 p + \beta_3 s + \varepsilon$$

Where, Y is the FIB concentration in cfu per 100 ml, averaged over the four river locations, β_i are constants, t is the water temperature in ^{o}C, p is the precipitation summed over 3 days, s is salinity in ppt, and ε is residual error. At the outset of modelling, collinearity among variables was examined and none was found that can violate the multicollinearity assumption. After running the model with the included variables, we studied the influence of these variables on concentrations of *E. coli* and enterococci. We eliminated the variable from the final model that had no significant influences on bacterial variability. We checked for interaction effects among variables, and no interaction effect was found significant. To test the sensitivity of the model and to assess the contribution of individual variable to the model outcome, we also ran the model leaving each of the independent variables out of the model. One-way analyses of variance (ANOVA) was performed to compare data sets and to assess the relative contribution of different variables to the observed variations in FIB concentration. The coefficient of determination (R^2), adjusted for degrees of freedom, was used to measure the proportion of the variability in FIB concentrations that is explained by the independent variables. All statistical tests were considered significant at a confidence level of 95 % ($p< 0.05$).

The sampling sites S2, S3 and S4 that are situated closest to each other were found to have similar FIB concentrations (see Table 2.1), i.e. they are highly correlated. Spatial autocorrelation or spatial dependency occurs when the values of variables measured at nearby sites are not independent from each other (Tobler, 1970). This implies that the independence assumption of the data is not fulfilled, and p-values can be highly underestimated. Because of the spatial correlation among sampling sites, the regression model was run for mean FIB concentrations over the four river sampling points. We do not expect to find time-dependent correlation in our measurements, as they were usually taken once a month. However, to conform that indeed no temporal autocorrelation exists, a Durbin-Watson test (Montgomery et al., 2001) was performed and no such correlation was found. Therefore, this method is appropriate for this analysis.

2.3. Results

2.3.1. Spatiotemporal variations

The measured water temperatures were between 22 and 32°C. Precipitation occurred on three days preceding the sampling day in half of all FIB measurement days. Maximum 3-day precipitation was 116mm, occurring on the 7th to 9th of July 2015. The lowest salinity was 0.1ppt observed during the rainy season in the month of August, and highest was 12.7ppt in May, 2015 (Fig. 2.2).

Concentrations of FIB vary substantially in time and space (Table 2.1, Fig. 2.2). Comparatively higher concentrations of FIB were found at S1, located upstream. This site receives pollutants from both municipal and agricultural sources. However, there was no statistically significant difference of FIB concentrations among the river sampling sites. S5 (the pond) had the highest concentration in all months and seasons.

FIB concentrations showed a clear seasonality with higher mean concentrations occurring during wet weather in the monsoon (July to October) of 2014–2015 and during storm surges (May and June) of 2014 (Fig. 2.2). Mean FIB concentrations in the wet weather were one to two orders of magnitude higher compared to those of dry weather (October to March). This difference was statistically significant. Wet weather was defined as rainfall larger than 5mm/day within a week preceding the sampling day. Consequently, dry weather is defined as <5mm in a week previous to the sampling day. The result also revealed that high FIB levels do not necessarily depend on the amount of rainfall. Even with little rainfall (<10mm), FIB concentrations are high and can rapidly increase (Fig. 2.2). High *E. coli* concentration of 2.9×10^4 colony-forming units (cfu)/100ml were found in S1 during June after a 7.4mm rainfall event. However, highest concentrations of *E. coli* (3.6×10^4cfu/100ml) and enterococci (8.6×10^4cfu/100ml) were found in the pond (S5) during August 2015 after a heavy rainfall event of 88.4mm.

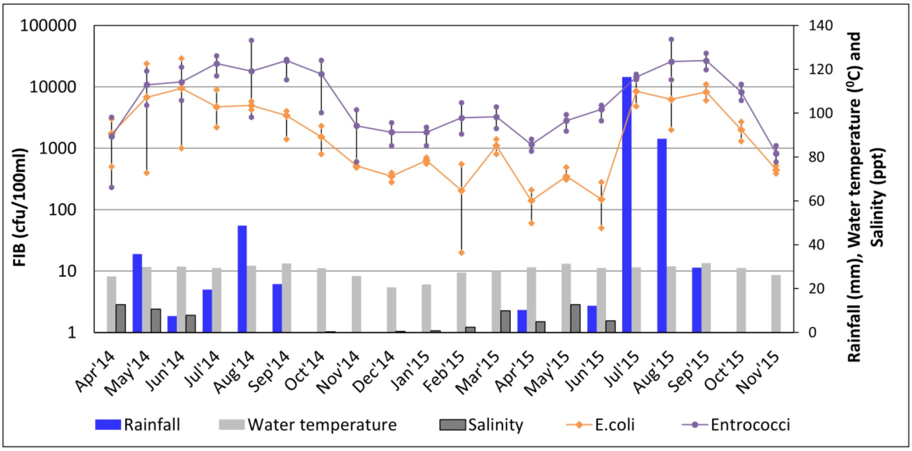

Fig. 2.2. Mean, maximum and minimum FIB concentrations (cfu per 100ml), water temperature (^{0}C) and salinity (ppt) over all four river locations and total recorded rainfall (mm, sum over 3 days preceding the sampling day).

The enterococci concentrations were not always consistent with the *E. coli* concentrations. Comparatively higher enterococci than *E. coli* concentrations were observed in most cases. The variation of concentrations between the two bacteria was found statistically significant across sites. The measured mean concentrations were between 2.9 and 3.4 log cfu/100ml for *E. coli* and 3.5 and 4.0 log cfu/100ml for enterococci (Table 2.1). Approximately 88% of the *E. coli* samples exceeded USEPA daily (single sample) bathing water quality standards of 235 cfu/100ml. For enterococci, all samples exceeded the daily threshold of 104 cfu/100ml. *E. coli* samples that did not exceed the standards were measured during dry winter months (November to April).

Table 2.1. Summary of the measured FIB data by sampling sites

	E. coli concentration (log cfu/100ml)				Enterococci concentration (log cfu/100ml)			
Site (number of samples)	Mean	Median	Range	% samples failing Standard*	Mean	Median	Range	% samples failing Standard**
S1 (20)	3.2	3.1	1.8–4.5	80%	3.8	3.8	2.8–4.8	100%
S2 (20)	3.0	2.9	1.3–4.2	80%	3.6	3.7	2.7–4.5	100%
S3 (20)	2.9	3.0	1.3–4.1	85%	3.5	3.6	2.9–4.5	100%
S4 (20)	2.9	2.9	1.4–4.1	95%	3.6	3.7	2.4–4.4	100%
S5 (16)	3.4	3.3	2.8–4.6	100%	4.0	4.0	3.2–4.7	100%

* Single sample bathing standard for E. coli 235 cfu/100ml and ** bathing standard for enterococci 104 cfu/100 ml.

2.3.2. Correlations

Table 2.2 presents the correlations of different environmental variables with FIB measured at all sampling sites. Correlation analysis showed that the FIB levels were significantly linked with environmental variables: water temperature, precipitation, and salinity. Fig. 2.3 graphically shows the correlation between water temperature, precipitation, and salinity with FIB concentrations of all individual river sites. Log_{10} FIB was significantly correlated with precipitation in all individual measurement sites. *R* values range from 0.57 to 0.62 for *E. coli* and 0.50 to 0.71 for enterococci. Non-significant positive correlation was found between *E. coli* and water temperature in all the river sites, while in S5 (the pond), the correlation was significantly positive. In case of enterococci, two (S1 and S2) out of the five sites showed significant positive correlation with water temperature, while in the other three sites the positive correlation was not statistically significant. Correlation between water salinity and FIB were all negative with one site for *E. coli* (S5) and two sites (S4 and S5) for enterococci having significantly negative correlations. FIB concentrations did not significantly correlate with other parameters studied (pH, EC and turbidity). Heavy rainfall and warmer water temperatures were found to have the strongest correlation with FIB concentrations in the surface waters.

Table 2.2. Overview of correlations between FIB and environmental variables by sampling sites. In each of the sites, twenty samples, except S5 (16 samples). Standard Pearson's product–moment correlation was applied to correlate FIB with water temperature and salinity. For precipitation, the Spearman's rank correlation was used. FIB data were $\log_{10}$ transformed. Precipitation data were summed over 3 days preceding the dates of sampling. Values with ** are significant at P<0.01 and * are significant at P<0.05.

Correlation between	Stations				
	S1	S2	S3	S4	S5
Log *E. coli* & temperature	0.36	0.40	0.38	0.37	0.63**
Log *E. coli* & precipitation	0.58**	0.62**	0.57**	0.62**	0.60*
Log *E. coli* & salinity	- 0.01	- 0.15	-0.33	- 0.26	- 0.51*
Log enterococci & temperature	0.60*	0.51*	0.37	0.26	0.45
Log enterococci & precipitation	0.71**	0.67**	0.61**	0.50*	0.54*
Log enterococci & salinity	-0.13	-0.19	-0.37	-0.54*	-0.55*

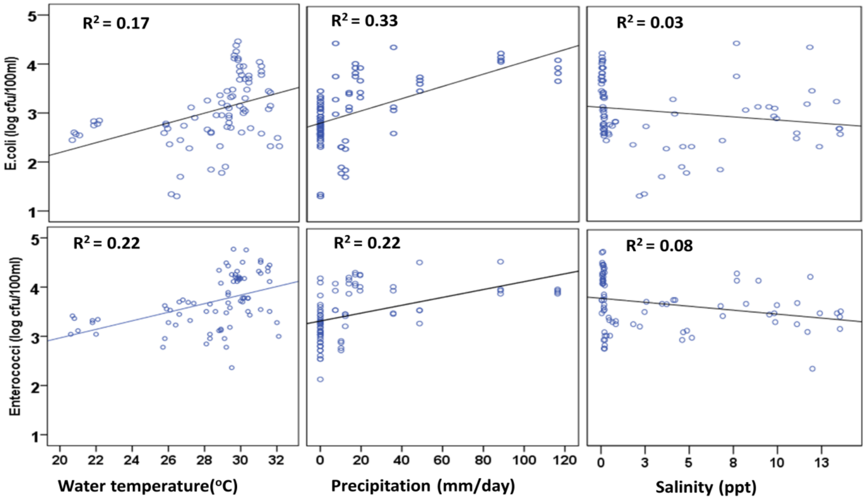

Fig. 2.3. Correlations of log *E. coli* (upper row) and log enterococci (bottom row) of all river sites with water temperature, precipitation, and salinity.

2.3.3. Statistical modelling

A linear regression model was developed to assess the combined effect of the environmental variables on FIB concentration in river water. The model, which is described in Section 2.2.4 gave an adjusted R^2 value of 0.46 for *E. coli* and 0.48 for enterococci (Table 2.3). Table 2.3 presents the β coefficients that indicate how much the dependent variable (mean FIB concentrations) varies with an independent variable while other independent variables remain constant. The regression analysis showed that two independent variables, water temperature and precipitation contributed significantly to the variations in mean FIB concentrations.

Table 2.3. β_i estimates of the model, $log(Y) = \beta_0 + \beta_1 t + \beta_2 p + \varepsilon$. Values indicated with ** are significant at P<0.01 and * are significant at P<0.05.

	β_i **estimates (*E. coli*)**	***β_i*** **estimates (enterococci)**
$\boldsymbol{\beta_o}$	0.937	1.354
$\boldsymbol{\beta_1}$ **(Water temperature)**	0.067*	0.078**
$\boldsymbol{\beta_2}$ **(Precipitation)**	0.011**	0.006*
Adjusted $\boldsymbol{R^2}$	0.463	0.475

The correlation analysis revealed that salinity has a strong negative correlation for some sampling sites, but including salinity did not improve the model. That means that salinity contributed little to the model. We also ran the model with precipitation and salinity excluding temperature. This time the resulted adjusted R^2 values were 0.36 for *E. coli* and 0.23 for enterococci. This is low compared to the result of the previous model, meaning that water temperature contributes more to the variability in surface water FIB concentrations than salinity. This is also consistent with the correlation analysis' results, where we found significant correlations between FIB and water temperature. The model was also applied to all sites separately and similar relations were found. These runs gave adjusted R^2 values between 0.19 and 0.55 for *E. coli* and 0.27 and 0.52 for enterococci. For most sampling sites the variables precipitation and/or water temperature did not significantly contribute to the model.

2.4. Discussion

We measured and statistically analysed FIB concentrations in the Betna River of Bangladesh. The measured mean concentrations (log cfu/100ml) of *E. coli* (2.9–3.4) and enterococci (3.5–4.0) are comparable to other studies conducted in developing countries, for instance, in China (*E. coli* 1.8–3.4) (Liu et al., 2009), India (enterococci 2.18–5.84) (Lata et al., 2016), Southeast Asia (*E. coli* 2.8–4.3) (Widmer et al., 2013), and Côte d'Ivoire (*E. coli* 2.55–3.47) (Adingra et al., 2012). In the present study, 88% of *E. coli* and all enterococci samples exceeded bathing water quality standards (specified by USEPA). It indicates potential health risks associated with the use of the river water for domestic, bathing and irrigation purposes. These frequent standard failures are not surprizing for the study area, as the sewers drain directly to the river without treatment. The frequent violation of water quality standards has also been reported in other studies (Myers and Ambrose, 2015, Noble et al., 2003, Schilling et al., 2009). Enterococci concentrations were higher than *E. coli* concentrations in most of our samples, and this is also in agreement with previous studies (Shergill and Pitt, 2004, Tiefenthaler et al., 2009). The observed higher levels of enterococci are explained by enterococci's longer survival than *E. coli* in surface water (Liu et al., 2006). Noble et al. (2003) in their study in southern California also reported that enterococci exceeded the single sample standards most often due to enterococci's longer survival in the marine environment compared to faecal coliform.

Significantly higher FIB concentrations were found during wet weather compared to dry weather, which is in agreement with other studies (Abia et al., 2015, Walters et al., 2011, Aragonés et al., 2016). Precipitation was positively correlated with FIB, because surface water is likely contaminated with manure through increased runoff from agricultural lands and urban areas (e.g. Satkhira town), leakage from manure storage areas and septic tanks leakage, and resuspension from sediments. Other studies (Funari et al., 2012b, An et al., 2002, Abia et al., 2015, Vermeulen and Hofstra, 2013, Martinez et al., 2014, Isobe et al., 2004) report similar reasons for the positive correlations between FIB concentrations and precipitation. Significantly positive correlations between FIB and precipitation indicate that diffuse sources contributed more during wet weather than during dry weather. Similarly, Ibekwe et al. (2011) also found in the Santa Ana River in southern California that storm water runoff from surrounding urban and agricultural areas is a dominant source of faecal contamination. The observed higher FIB concentrations during wet weather and intense precipitation are also consistent with other's findings (Schilling et al., 2009, Dastager, 2015, Walters et al., 2011, Abia et al., 2015, Aragonés et al., 2016).

Water temperature was also positively correlated to FIB, likely because the study area is situated in a subtropical climate where June to September frequent rainfall and high summer temperatures coincide. The same positive correlation was reported in other studies (Schilling et al., 2009, Koirala et al., 2008). These authors also relate it to the coincidence of high temperature and precipitation during the summer period. Therefore, the observed positive correlation with water temperature does not mean that temperature stimulated the increased FIB level in the study area. In some other studies FIB growth was suspected to be a possible reason for the positive relation between temperature and FIB (Byappanahalli et al., 2003, Tiefenthaler et al., 2009, Hong et al., 2010, Abia et al., 2015), for instance because of decreased dissolved oxygen content, algal blooms and nutrient richness (Rouf et al., 2012). However, we have not found proof of FIB growth in the literature. In the studied river, due to the tidal in and outflowing water, the residence time of the bacteria is low. Therefore, long survival, growth and proliferation of bacteria are unlikely.

We found negative correlations between water salinity and bacterial concentrations. This is consistent with results from previous studies (Hoppe et al., 2013, Dastager, 2015, Aragonés et al., 2016, Adingra et al., 2012). Water salinity depends on the amount of precipitation and associated fresh water inflow from the upstream watersheds (Hoppe et al., 2013). In our study area, during the rainy season (July to September) precipitation increases and as a result water salinity decreases. The observed negative correlation with salinity is more likely due to the typical weather pattern during the rainy season when low salinity coincides with increased precipitation and high temperature, rather than salinity dependent die-off of bacteria.

Our linear regression model explains nearly half of the variation in FIB concentration (R^2 = 0.46 for *E. coli* and 0.48 for enterococci) by taking climatic and environmental variables into account. The variation of R^2 depends on the climatic variables added, the number of data used, and the microbes considered (Vermeulen and Hofstra, 2013). The model results compare well with other studies, for instance, Whitman and Nevers (2008) conducted a regression analysis for 23 beaches in Chicago. After adjustments for spatial and temporal autocorrelations they found an adjusted R^2 that ranged from 0.20 to 0.41. Kay et al. (2005) reported *E. coli* with R^2 values of 0.49-0.68 for the river Ribble drainage basin in the UK by including similar climatic and environmental variables. Vermeulen and Hofstra (2013) reported a similar R^2 of 0.49 for *E. coli* in the Rhine, Meuse, and Drentse Aa and Walters et al. (2011) found a lower R^2 value of 0.15 for *E. coli* and 0.11 for enterococci in their regression study in central California coastal water, including similar variables compared to our study.

The presence of indicator bacteria in waterbodies does not pose a direct risk of waterborne diseases, but their presence indicates faecal contamination and the possible presence of waterborne pathogens (Teklehaimanot et al., 2014, Burres, 2009). Risk of waterborne disease outbreaks also depends on water uses, such as consumption and recreational activities. The Betna River water is used for both domestic purposes (e.g. washing of clothes and utensils, and cooking) and agricultural and aquacultural production. People also come in direct contact with polluted river water during fishing and bathing. Therefore, the persistently high FIB concentrations and the intense human exposure to the contaminated river water indeed is a serious public health risk in the study area. The actual risk could be assessed by a quantitative microbial risk assessment. This requires pathogen concentration data in river water, but detection of pathogens is expensive and may cause potential health hazards (Bruhn and Wolfson, 2007). Therefore, to quantify and model waterborne pathogen distribution and dynamics and to assess associated health risk by incorporating pathogens instead of relying on indicator bacteria is challenging. FIB standards for bathing and drinking water are designed to guarantee limited disease risks. In most samples these standards are violated. This also indicates a public health concern in the study area.

We have found that FIB concentrations increase with increased temperature and precipitation. Therefore, we expect that projected increased precipitation and associated runoff under climate change, will increase FIB concentrations in surface waters. We anticipate that pathogens behave similarly to FIB and as a result, health risk will increase with increase in temperature and precipitation.

2.5. Conclusions

Based on the analysis of a total of 96 FIB samples of water temperature, salinity and precipitation of Betna River in southwest Bangladesh, we conclude as follows:

- Eighty-eight percent of the *E. coli* samples and all enterococci samples exceeded USEPA daily (single sample) bathing water quality standards. Therefore, the river Betna is unsuitable for swimming or bathing.
- Water temperature and precipitation summed over three days correlated positively with FIB concentrations.
- Our regression model can explain 46% of *E. coli* and 48% of enterococci variability in river water taking into account the variables water temperature and precipitation.
- From our results we expect that projected increased precipitation, associated with frequent tropical cyclones, and ambient water temperature may further increase the FIB concentrations. Waterborne pathogens likely respond similarly to

environmental variables. This means that disease outbreaks could also increase and even become a larger threat to public health.

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Chapter 3.

Modelling the Present and Future Water Levels and Discharges of the Tidal Betna River

Abstract

The Betna River basin in southwest Bangladesh experiences flooding due to combined effects of extreme precipitation events and storm surges from the Bay of Bengal. Under climate change, the projected changes in precipitation patterns, higher temperature and sea-level rise, increase the likelihood of future flooding. The present and future water level and discharge of the Betna River was assessed using the hydrodynamic model MIKE 21 FM. The model was set up and calibrated using bathymetric, hydrodynamic and meteorological data. The coefficient of determination and Nash-Sutcliffe efficiency between observed and modelled water level and discharge were found to be 0.92 and 0.83 (water level), and 0.81 and 0.66 (discharge), respectively, showing that the model performs well. The model was then applied to simulate baseline and future water level and discharge for RCP4.5 and RCP8.5 scenarios using bias-corrected downscaled data from two GCMs (IPSL-CM5A and MPI-ESM). The modelling results for the 2040s and 2090s indicated a significant increase in water level and monsoon discharges. The water level is expected to increase up to 16% by the 2040s and 23% by the 2090s. The monsoon daily maximum discharge is expected to increase up to 13% by the 2040s and 21% by the 2090s. The duration of water level above the established danger threshold and extreme discharge event can increase by up to half a month by the 2040s and above one month by the 2090s. The combined influence of the increased water levels and discharges has the potential to cause major floods in the Betna River basin. The results of our study increase the knowledge base on climate change influence on water level and discharge at a local scale. This is valuable for water managers in flood-risk mitigation and water management.

Key words: Flood, Precipitation, Water level, Discharge, GCM, MIKE 21 FM model

This chapter is based on:

M.M.M. Islam, N. Hofstra and E. Sokolova, 2017. Modelling the Present and Future Water Levels and Discharges of the Tidal Betna River, *Journal of Water and Climate Change* (Under review).

3.1. Introduction

Floods often cause devastating effects on human life and properties worldwide. Climate change increases floods because of change in precipitation patterns and sea-level rise (SLR) (Webster et al., 2014). Bangladesh is extremely vulnerable to the impacts of climate change. The Betna River basin in the southwest of Bangladesh has been experiencing both fluvial flooding due to extreme precipitation during the monsoon and storm-surge flooding due to cyclones originating from the Bay of Bengal. Floods hit this area almost every year of the last decade, causing losses of lives and economic damage (CEGIS, 2013). Increased precipitation and flooding cause increased runoff that brings polluted water from the land into the river. Outbreaks of waterborne diseases, such as diarrhoea, are very common after flooding events (CEGIS, 2013), and cause serious public health risks in this area (ADB, 2011). More frequent and intense flooding is likely to occur in this area in the future due to climate change and SLR (Karim and Mimura, 2008). Therefore, the impact of flooding could well become more severe, particularly due to the low lying areas, high population density, inadequate flood protection infrastructure, low level of social development and high dependence on agriculture (ADB, 2011).

The fifth assessment report (AR5) by the Intergovernmental Panel on Climate Change (IPCC, 2014) concluded that the projected adverse impacts of climate change on deltas are mainly due to floods associated to extreme precipitation, increases in temperature and rises in sea level. The future precipitation in Bangladesh is expected to increase between 5% and 20% and average temperature is expected to increase between 2°C and 4°C. Trend analysis of SLR along the southwest coast of Bangladesh shows already an annual increase of 5.5mm (BANDUDELTAS, 2015). The consequences of extreme precipitation and SLR on water management and flood risks are substantial. However, current water management practices are not robust enough to cope with climate change consequences. It demands improved incorporation of information about present climate variability and future climate scenarios into planning and management of water bodies (BANDUDELTAS, 2015).

Process based modelling is often performed to understand hydrodynamics of a basin and to assess the effectiveness of future flood protection infrastructure (Jin et al., 2015, Kuchar and Iwański, 2014).Few modelling and climate change studies occurred in South-Asian river basins (Whitehead et al., 2015, Ghosh and Dutta, 2012, Apurv et al., 2015, Alam et al., 2014). These studies were based on mainly two climate-change parameters (temperature and precipitation) and reported that climate change (increased temperature and monsoon precipitation) will likely impact river flows and therefore increases in future floods are very likely in this region. However, in-depth studies on assessing combined impact of climate change and SLR on river hydrodynamics are lacking. Moreover, most of the climate change studies have been conducted in the large or regional river basins like the Ganges, Brahmaputra and Meghna River systems of India and Bangladesh (Ghosh and Dutta, 2012, Apurv et al., 2015, Whitehead et al., 2015, Jin et al., 2015). No such studies have been performed for a relatively small basin like the Betna River to explore present and future flooding in a changing climate. Therefore, what climate change means for water levels and discharges at the local scale remains unclear. Our study on the Betna River basin reduces this knowledge gap. This river basin is an ideal site for this study because it floods almost every year, faces combined effects of extreme precipitation, storm surges and SLR, and its diversified water uses (e.g. domestic, irrigation, shellfish growing and bathing) require adequate water management. Assessing the future water level and discharge in the Betna River is important, because higher water levels combined with higher peak discharges can cause disastrous floods in this river basin. Floods also strongly impact the spread of infectious diseases (Kunii et al., 2002, Qadri et al., 2005). This study could be the basis for water quality studies. It can assist water managers in designing flood protection structures and managing water resources.

Our study aims to assess the present and future water levels and discharges in the Betna River. This will be achieved by testing a process based hydrodynamic model (MIKE 21 FM) to simulate water level and discharge under different future climate conditions. The MIKE 21 FM model for the Betna River was set up, calibrated and validated using the observed water level and discharge data. The model was then used to project the future (2040s and 2090s) water levels and discharges. The output of this study is likely helpful in addressing climate-change induced frequent and intense flooding in the study area. The findings and model can be transformed to other basins of the world with similar characteristics.

3.2. Materials and methods

3.2.1. Study area

The study area covers an area of 10,706 hectares in the Betna River basin, located in the Satkhira district of southwest Bangladesh. The river has a total length of about 192km with an average width of 125m. The modelled stretch of the Betna River is approximately 30km of its downstream part (Fig. 3.1). The river is hydrologically connected with Bhairab River near Jessore district in the north and Kholpetua River near Assasuni of Satkhira district in the south. The Betna River has tidal influence that is the predominant factor for its sustainability, because during the dry season the fresh water inflow from upstream areas becomes very limited. The tide generates from the Bay of Bengal and propagates to the north until the upstream boundary of the study area. Like most coastal areas in

Bangladesh, the study area is governed by the semidiurnal tide. The usual range of fluctuation of the water level is 0.7m during neap tide and 3.0m in spring tide (IWM, 2014).

The study area has a rainy season (monsoon) from June–October, followed by a cool and dry period November–February and a hot season with frequent cyclones (pre-monsoon) during March–May. Mean annual rainfall in the area is about 1800mm of which approximately 70% occurs during the monsoon season. This area is affected by inland flooding due to heavy incessant rainfall during the monsoon in August-September and by storm surge flooding during cyclone season in April-May (Hossain, 2003, CEGIS, 2013). Relative humidity of the area varies from about 70% in March to 90% in July. 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. Wind in the region shows two dominant patterns i.e., south-westerly monsoon wind during June to September and north-easterly wind during November to February. Other months show no distinct wind direction pattern.

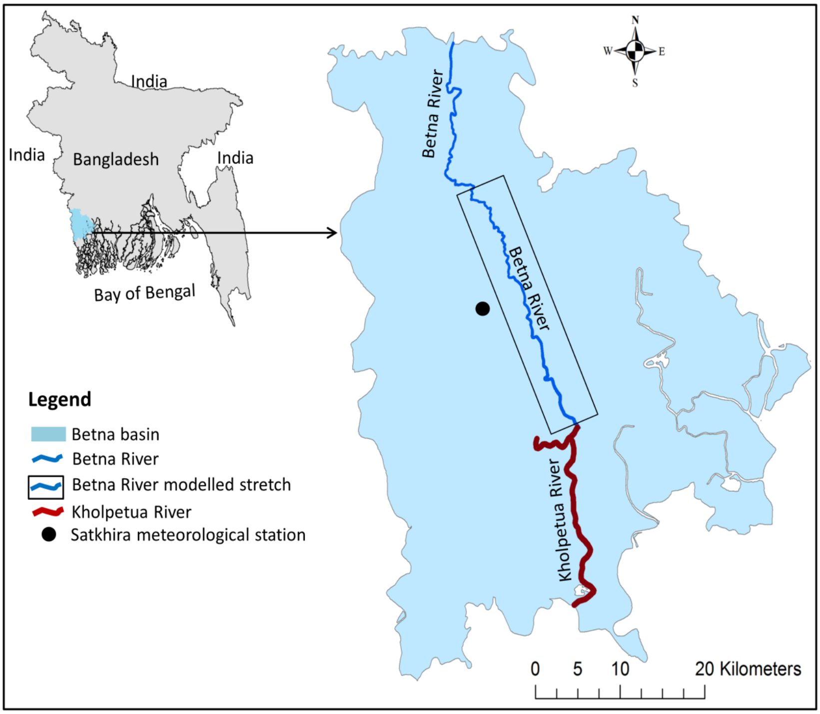

Fig. 3.1. Study area, the Betna River basin in the southwest of Bangladesh

The study area is mainly a flat terrain with some low-lying depressions and many tidal channels and creeks that criss-cross the area. The soils are mostly clay and loam. Land use is dominated by paddy cultivation and shrimp culture. About 8% of the total area are homesteads and settlements and about 10% are water bodies, 61% is agriculture and the remainder is wetlands used for aquaculture or integrated paddy shrimp culture.

3.2.2. Hydrodynamic model set up

The two dimensional (2D) hydrodynamic model, MIKE 21 (DHI, 2011) was applied to simulate water levels and flows and to predict future water level and flood flows in the Betna River. This 2D model was used because the river is not very deep (maximum depth 9m) and mixing happens fast. The model simulates unsteady 2D flows in one vertically homogenous (depth averaged) layer and assumes that large flow gradients are absent in the vertical direction of water column (Webster et al., 2014).

The hydrodynamic (HD) module of MIKE 21 FM simulates variations of water level and flows in response to several forcing functions on a rectangular or triangular grid of the study area when provided with the bathymetry, bed resistance coefficients, forcing parameters and boundary conditions (Uddin et al., 2014). The model is based on a 2D numerical solution of Reynolds averaged Navier-Stokes equations. In the model, the Boussinesq simplifying approximation is used and hydrostatic pressure is assumed. The model consists of vertically integrated laws of continuity and momentum conservation in two horizontal dimensions (DHI, 2011).

3.2.3. Bathymetric survey and mesh generation

Modelling in a relatively smaller river watershed like the Betna River in Bangladesh is difficult due to scarcity of data. However, a comprehensive data collection survey was carried out in the Betna River system by the Institute of Water Modelling (IWM), Bangladesh in 2012 to collect primary data, such as river bathymetry, water level and discharge. The distance between the surveyed river cross-sections varied from 400m to 500m. To survey the river cross-sections, a digital Echo-sounder supported by a Differential Global Positioning System (DGPS) and a laptop computer with HydroPRO survey software were used. The Echo-sounder provided the depth while DGPS provided the position of the vessel in co-ordination to the computer. The data were recorded automatically at an interval of one second in the computer in a tabular format MS Access database during the survey. The Nav Edit module of the software compiled depth of water and position of sounding along with date and time. The depth data are referred to meter Public Works Datum (mPWD) of Bangladesh (which is 0.46m below mean sea level) using water level observed at the gauges within the survey area (IWM, 2014).

Mesh generation was done using the MIKE Zero mesh generator (Fig. 3.2). A flexible mesh size with triangular elements was used and the triangulation was performed with Delaunay triangulation (DHI, 2011).The grid or mesh size decreases or resolution increases where the river is more narrow. The mesh consists of 4,089 nodes and 6,628 elements. The smallest element area is 42.5m^2 and the largest area is approximately 498m^2. In the modelling domain, intertidal zones are flooded and dried during every tidal phase to mimic natural conditions. The river is connected with some small drains. These drains have no water flow during dry weather and thus were considered to be the land boundary in the model. However, during wet weather, storm water runoff through the drains was included as source in the model: four main drains were considered in the model. The runoff volume was estimated applying the runoff curve number method developed by the US Department of Agriculture (USDA, 1986).

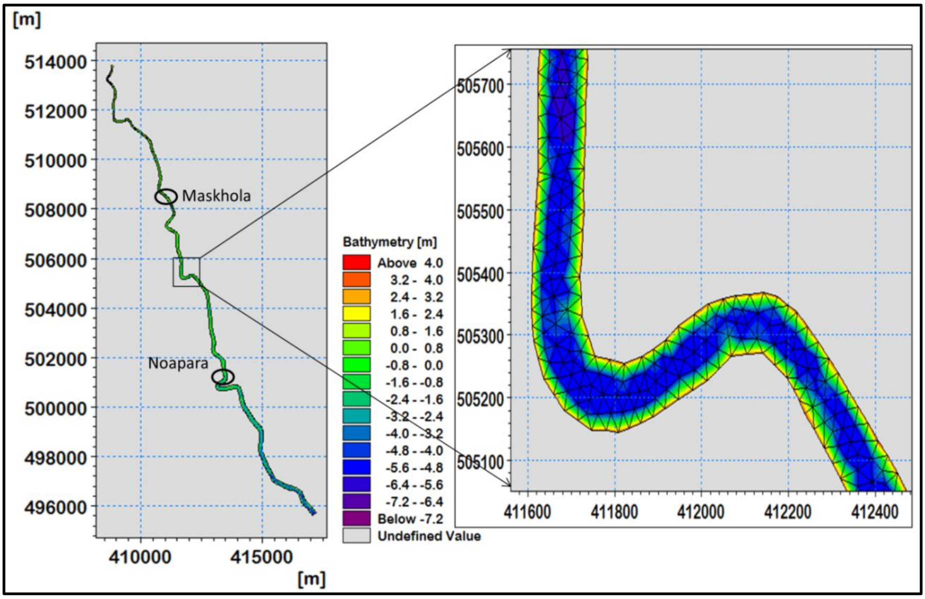

Fig. 3.2. Bathymetry (left) and mesh (right) for the hydrodynamic model of the Betna River

3.2.4. Meteorological and hydrodynamic data

Precipitation, wind speed and direction, air temperature (max and min) and relative humidity data were collected from the Satkhira meterological station (Fig. 3.1, Table 3.1). To calibrate the hydrodynamic model, water level and river discharge data were collected from IWM (Table 3.1). Water level data were collected with half an hour interval at three locations (Maskhola, Noapara and the downstream boundary, Fig. 3.2) along the Betna River for over two months from 1 August to 10 October 2012. The observed minimum and maximum water levels at Mashkhola and Noapara in the Betna River were 1.55 and 3.48 mPWD, and -2.10 and 3.50 mPWD, respectively. Discharge measurements were carried out near Noapara (Fig. 3.2) and upper boundary by IWM in September 2012 for 13 hours with 0.5 hour interval both in spring and neap tide. The observed maximum discharge at Noapara was 277 m^3/s and 392 m^3/s during spring tide at the time of ebbing and flooding respectively. For validation and baseline simulation, water level and discharge (used as upstream boundary) data were gathered from the Bangladesh Water Development Board (BWDB) during the period 2014–2015 (Table 3.1).

The boundary conditions were described using time-series for discharge and water level at the upstream and downstream boundaries, respectively. The initial conditions were specified using the measured data for water surface elevation, and initial water velocity was set to zero. The flooding depth 0.05m, drying depth 0.005m and wetting depth 0.1m were set in the model. 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.

Table 3.1. Input data used for the hydrodynamic model

Data type	**Resolution**	**Period**	**Location**	**Source**
River bathymetry	Cross-section 400–500 m	2012	Modelled stretch	IWM[a]
Water level for calibration period	0.5 h	2012	Maskhola, Noapara and lower boundary	IWM[a]
Water level for validation period	3h	2014-2015	Near Noapara and lower boundary	BWDB[b]
Discharge for calibration period	0.5 h	2012	Near Noapara and upper boundary	IWM[a]
Discharge for validation period	1 week	2014-2015	Near upper boundary	BWDB[b]
Precipitation	1 day	2012-2015	BMD Satkhira	BMD[c]
Air temperature	1 day	2012-2015	BMD Satkhira	BMD[c]
Wind speed and direction	3h	2012-2015	BMD Satkhira	BMD[c]
Relative humidity	1 day	2012-2015	BMD Satkhira	BMD[c]

[a]Institute of Water Modelling, Bangladesh; [b]Bangladesh Water Development Board; [c]Bangladesh Meteorological Department.

3.2.5. Calibration validation and sensitivity analysis

Calibration and validation were performed by comparing the modelling results with measured values of water level and discharge at Maskhola and Noapara. The calibration period from 26 August to 15 September 2012 was selected because the bathimetric survey and measurement of hydrodynamics were conducted in that period. A sensitivity analysis was also performed to estimate the rate of change in model output with respect to change in model inputs. The analysis was done in changing extent of different inputs and parameters, such as water level, discharge, water velocity, river bed roughness, wind speed, flooding/drying depth, eddy viscosity, clearness coefficient and heat exchange rate. From this sensitivity analysis the most sensitive parameters were identified and optimum values were used as default model inputs after calibration. The calibrated model was then applied to simulate water level and discharge for a typical year October 2014 to September 2015 as the baseline condition. The period was selected to coincide with the available meteorological and hydrodynamic data. The model output was validated using the measured water level. The model performance was assessed using two statistical parameters: coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NSE). Generally, model performances are called satisfactory, if $R^2 > 0.60$ and NSE> 0.50; the closer the model efficiency is to 1, the more accurate the model is (Moriasi et al., 2007). After validation, the model was applied to predict future water level and discharge under climate change situation.

3.2.6. Future scenario development

General Climate Models (GCMs) have been used to simulate climate globally. Many GCMs were developed to describe past, present and future changes in climate. Outputs from GCMs used in the fifth phase of the Climate Model Intercomparison Project (CMIP5) were used in this study. CMIP5 was utilised by the IPCC in AR5 (Taylor et al., 2012). Variations in surface air temperature, precipitation and sea level were computed with the help of GCMs. Output from individual GCMs and averages of future climate conditions could be applied in climate change impact analysis (Christensen and Lettenmaier, 2007).

IPCC's AR5 has used four Representative Concentration Pathways (RCPs) for climate change projections (IPCC, 2014). In the current study, we have used a relatively low emission pathway (RCP4.5) and a high emission pathway (RCP8.5). Two GCMs, MPI-ESM-LR (Max Planck Institute for Meteorology) and IPSL-CM5A-LR (Institute Pierre-Simon Laplace) were used. The models were selected because they have been used widely in this region (BANDUDELTAS, 2015). At first, the CMIP5 daily climatic data for both scenarios were downloaded from the Earth System Grid Federation Portal (http://cmip-pcmdi.llnl.gov/cmip5/; https://esgf-data.dkrz.de/search/cmip5/). Then the daily GCM data were downscaled and bias corrected using the 'Delta method' with 'quantile-quantile' correction, as described by Liu et al. (2015a). Daily observed air temperature and precipitation data from 1986 to 2005 were used as a basis for this downscaling. In the current study, two future time periods 2031–2050 (2040s) and 2081–2100 (2090s) were considered for the two RCPs.

To project future precipitation, 20 years average total monthly precipitation was computed for the observed and future downscaled data. Then the percentage change between future and observed data was calculated for each month. The daily observed precipitation data for the baseline year 2014–2015 were modified by this percentage change and subsequently used as model input for the simulation of future hydrodynamic conditions. Inflows into the rivers of this area were on average projected to increase during the monsoon period (driven primarily by increased basin precipitation) by 9% (Billah et al., 2015) and decrease during dry periods by 6% (ADB, 2011) by the 2050s. Greater changes are expected by the end of the century. These values along with the precipitation percentage changes were used to modify the observed current discharge data. The resulting discharge data were used as upstream boundary conditions in performing simulations for future prediction. The future storm water runoff was estimated applying the runoff curve method (USDA, 1986) based on future precipitation data. For air temperature, daily average values were used. Fig. 3.5 presents air temperature, precipitation and discharges for the projected scenarios.

SLR combined with the RCP scenarios was used to investigate the impact of climate change on the hydrodynamic characteristics of the Betna River. The estimated global mean SLR of RCP4.5 is 0.24m and 0.4m for the time horizons 2040s and 2090s respectively, relative to the average sea level for 1986–2005. For RCP8.5, global mean SLR was estimated to be 0.3m and 0.63m for the time horizons 2040s and 2090s respectively (Elshemy and Khadr, 2015). Recent projections from the IPCC AR5 suggest that sea level in the northern Bay of Bengal (close to the study area) may rise between 0.1 and 0.3m by 2050 and 0.3 and 0.6m by 2100 without including local effects, such as land subsidence (Kay et al., 2015). The annual land subsidence rate of the study area is likely to be around 2.5mm (Kay et al., 2015, Dasgupta et al., 2014). In this study, based on the above data and including annual land subsidence of 2.5mm, the relative mean SLR of 0.26m and 0.42m (for RCP4.5); and 0.44m and 0.76m (for RCP8.5) were used for the 2040s and 2090s, respectively. These SLR data were added to the observed water level boundary data to set the future water level boundary of the model. Finally, the model was applied to simulate future (for the 2040s and 2090s) water level and discharge, and the results were compared with simulated baseline year (2014–2015) water level and discharge data (Table 3.2 and Fig. 3.6).

3.3. Results and discussion

3.3.1. Model sensitivity analysis

Wind force and bed roughness (Manning's number) were identified as the two most sensitive parameters. Six scenarios were set up to see the influence of wind speed and bed roughness on water level under a constant wind force and Manning's number. The sensitivity was tested with wind and without wind. With wind scenarios include an average wind speed of 3 m/s and a maximum wind speed of 15 m/s of the respective month (September 2012). In both cases the wind direction was 20^{o}. The influence of bed roughness was tested under a default 32 $m^{1/3}/s$, an average 45 $m^{1/3}/s$ and a high value of 60 $m^{1/3}/s$. In all cases, the boundary conditions (water level and discharge) were the same. The simulations were run for eight days from September 03–10, 2012.

The results indicated that bed roughness has an influence on water level, especially in the upstream shallow locations Maskhola (Fig. 3.3). An higher Manning's number resulted in higher water level and vice versa. During high tide with high water flow, the difference was comparatively larger than during low tide. From this analysis the manning 60 $m^{1/3}/s$ was used in the model. The wind speed of 3 m/s had no strong influence, while the wind speed of 15 m/s caused decreased water level in the upstream (Fig. 3.3) and increased water level in the downstream part of the river compared to the no wind scenario. Under conditions of the wind speed of 15 m/s, the influence was several centimetres in the upstream part of the river (Fig. 3.3), but in the downstream part of the river, the influence was only several millimetres.

3.3.2 Model calibration

The hydrodynamic model was calibrated against measured water level and discharge at Noapara and Maskhola in the Betna River. The calibration period 26 August–15 September 2012 was selected to coincide with the available measured water level and discharge data. Bed roughness (i.e. Manning's number) is one of the controlling calibration parameters of the hydrodynamic model. Based on calibration, a constant Manning's number of $60m^{1/3}/s$ was assigned in the hydrodynamic model. The modelling results were in a very good agreement with the measured data for both water level and discharge (Fig. 3.4), with R^2 0.92 and 0.83, and NSE 0.81 and 0.66, respectively. However, the model slightly overestimated water levels at low tides and underestimated discharges at high tides (although the peaks were well captured).

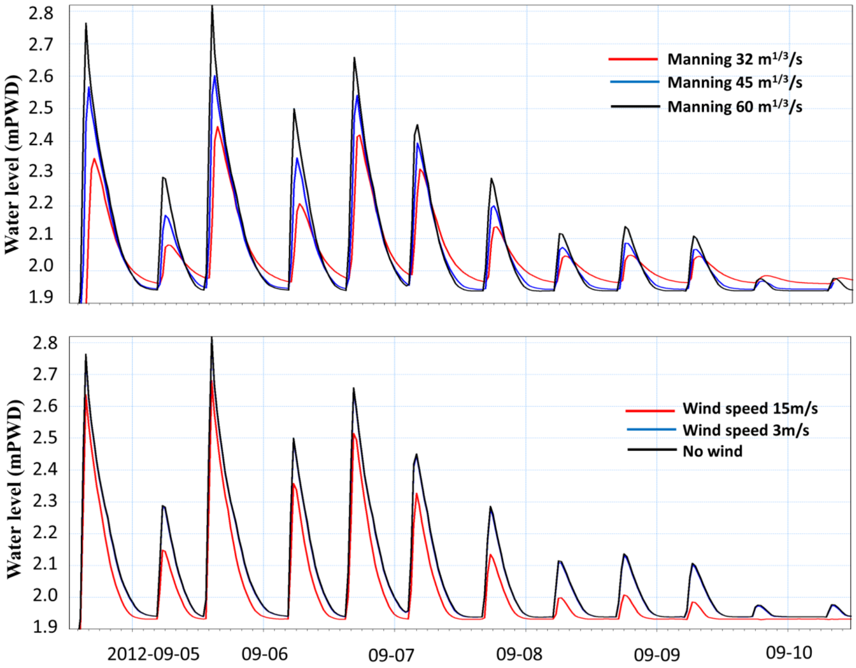

Fig. 3.3. Comparison of modelled water level under three different Manning's numbers (upper panel) and wind speed (lower panel) conditions at Maskhola in the Betna River.

3.3.3 Model validation and present hydrodynamic condition

Water level and discharge of the Betna River were simulated during October 2014 to September 2015 as validation and the baseline year condition. The agreement between the modelled and measured water level was very good (R^2=0.89, NSE=0.76). The comparison for the discharge was not possible due to the lack of measured data. The model calibration and validation show that the model slightly overestimated the water level at low tides (Fig. 3.4 and 3.5). A possible reason can be simplification of river cross-section during mesh generation. The river cross-section survey was made at 400m to 500m interval. Mesh generation was done by interpolation of the survey data. More regular cross-sectional and bottom topography data would be beneficial for further improvement of the model.

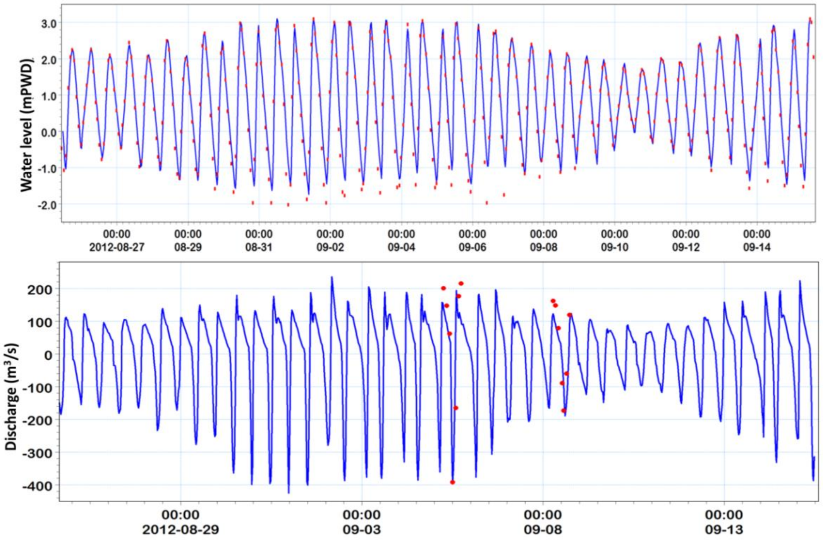

Fig. 3.4. Model calibration: simulated and measured tidal water level (upper panel) and discharge (lower panel) at Noapara, Betna River. The lines and dots represent the modelled values and measured values, respectively. The negative discharge values mean that during flood tide the flow is from the opposite direction.

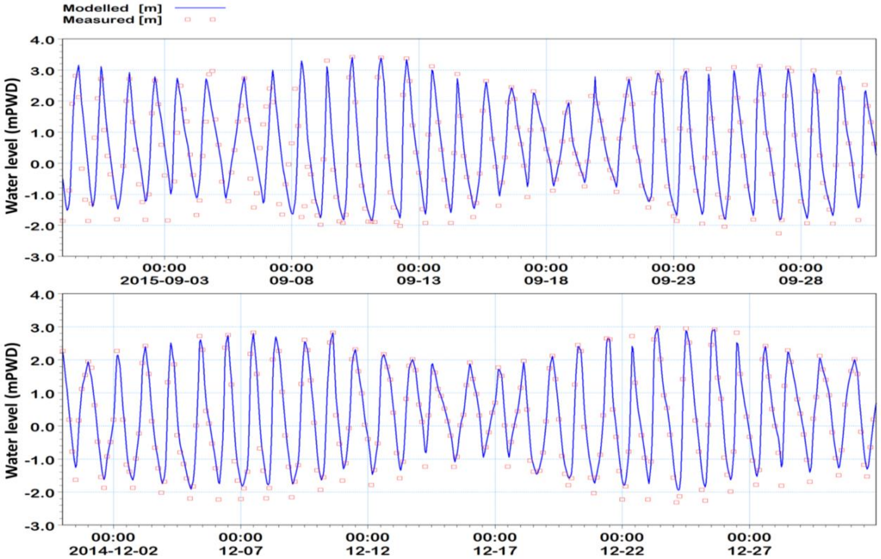

Fig. 3.5. An example of comparison of modelled and measured tidal water level at Noapara in the Betna River. Upper panel represents a wet month (September 2015), and lower panel represents a dry month (December 2014).

3.3.4. Future projections

3.3.4.1. Mean air temperature, precipitation and discharge

Future air temperature, precipitation and discharge projections show substantial variation between the two scenarios (RCP4.5 and RCP8.5) and two GCMs (Fig. 3.6). Average air temperatures are expected to increase by 2^{o}C to 4^{o}C by the 2040s and 2090s, respectively, compared to the observed baseline condition. The temperatures were consistently increased throughout the year, with greater increases by the 2090s compared to the 2040s. During the monsoon season (June–October), precipitation is projected to increase between 3% and 28%, and between 5% and 32% by the 2040s and 2090s, respectively. Monthly average discharges show increases in the near and far future compared to the observed discharges for both GCMs and both scenarios (Fig. 3.6). The discharge is expected to increase in the monsoon periods and slightly decrease in dry periods (November–February). The increase in air temperature, and increased monsoon precipitation and discharge are in good agreement with other studies in this region (Ghosh and Dutta, 2012, Jin et al., 2015, Apurv et al., 2015, Zaman et al., 2016). The increased monsoon precipitation and discharge indicate a wetter monsoon season in the future. However, during the dry season, precipitation and discharge are mostly expected to decrease in the future. This means that less water will be available during the dry season. The decreased precipitation and discharge during the dry season are unlikely to lead to droughts in the study area, because of the continuous tidal water inflow from the Bay. This could exacerbate the existing salinity intrusion problem (Dasgupta et al., 2014). However, the decreased dry weather precipitation and associated salinization were not the focus of this study.

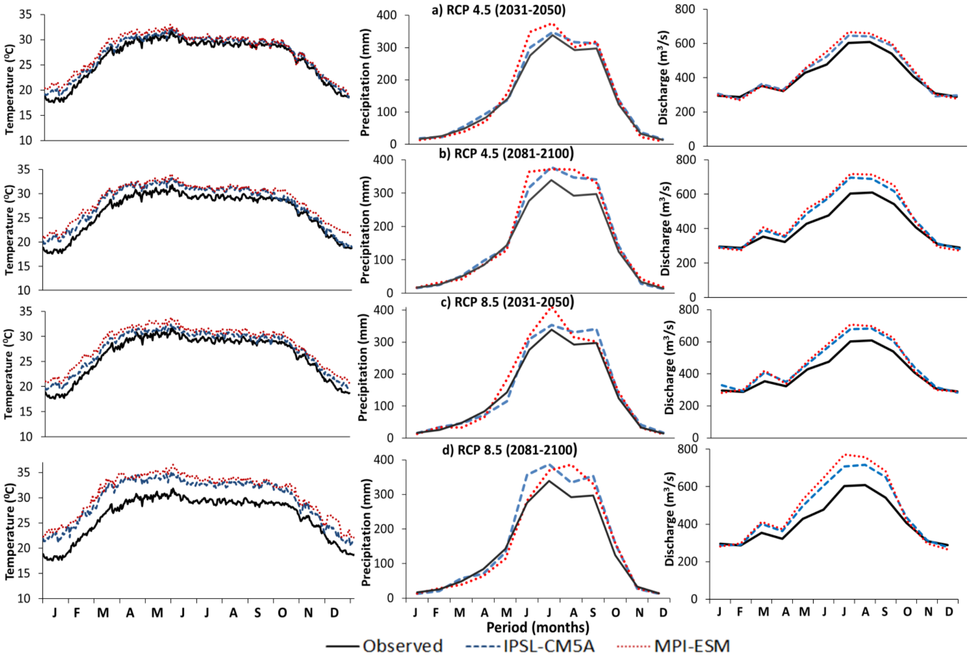

Fig. 3.6. Daily average air temperature (left), monthly average precipitation (middle), and monthly average discharge (right) projections for the Betna River basin for two RCPs, RCP4.5 (a and b) and RCP8.5 (c and d) and two future periods, near future (2031–2050; a and c) and far future (2081–2100; b and d).

3.3.4.2. Extreme water level and discharge

In this study, a combination of climate and SLR scenarios based on RCP4.5 and RCP8.5 have been used to predict changes in water level and discharge in the Betna River for the near future (2031-2050) and far future (2081-2100). The seasonal changes (percentage) in the mean water level and daily maximum discharge under the two GCMs and different scenarios are presented in Table 3.2. The hourly mean water level and daily mean maximum discharge during flood tide and ebb tide conditions will undergo substantial changes, particularly in the far future (2090s). For the RCP4.5 scenario, the results for the near future (2040s) showed that the mean change in water level relative to the baseline year would be about 11% at Noapara. For the RCP8.5scenario, the results for the far future (2090s) showed that the mean change in water level relative to the baseline year would be 23%. Increases are slightly larger in the monsoon than in the dry season.

The projected change in climate in both near and far futures has the most discernible influence on the seasonal discharge in the monsoon period (June–September), compared to other months. For RCP4.5 and in the near future, the increase in the daily maximum discharge compared to the baseline year would be at most 8% during the monsoon. In the far future with RCP4.5, the discharge would increase up to 16%. The discharge is projected to increase by up to 21% for RCP8.5 by the end of century. These increased discharge combined with the high water level would likely worsen the flooding situation in southwest Bangladesh and cause major flooding problems in the Betna River basin. Whitehead et al. (2015) also indicated in their study that a 15% increase of discharge in the Ganges, Brahmaputra and Meghna River systems by the 2050s would have the potential to increase flood risk within Bangladesh. The increased river discharge in the monsoon season in the future is consistent with the projected increased precipitation in the future (up to 28% and 32% by the 2040s and 2090s respectively) that was obtained in our study (Fig. 3.6). The increase in monsoon discharges can also be attributed to the increased monsoon discharges in the upstream rivers of the Betna River. The increasing trend of monsoon precipitation and river discharge in South Asia is also evident from other studies (Apurv et al., 2015, Ghosh and Dutta, 2012, Kirby et al., 2016, Mirza et al., 2003, Billah et al., 2015, Jin et al., 2015).

The dry season data shows no noticeable change in the future discharges (Table 3.2) due to lack of connectivity with upstream rivers during the dry months. This is in agreement with Zaman et al. (2016) in their study in the GBM River systems of Bangladesh. Zaman et al. (2016) also found increased monsoon discharge and little change in the dry season discharge due to siltation at the upstream river mouth. The dry season discharge is expected to reduce by maximum 2% in the far future and this is unlikely to substantially change the present situation of the Betna River and cause local droughts, because of continuous tidal water inflow from the Bay. However, it could deteriorate existing salinity intrusion problems. A decrease in freshwater inflow may decrease the dry season discharge and that could be crucial for agriculture, aquaculture, salinization and public water supply in the river catchment. The magnitude fresh water inflow in the dry season is uncertain and depends on the potential construction of dams and water transfer schemes in the upstream of Bangladesh, as described by Whitehead et al. (2015). The mean seasonal water level and discharge values for the two GCMs were not very different during the flood and ebb tide periods. The GCM MPI-ESM showed slightly higher water level and more extreme discharge in the Betna River compared to the IPSL-CM5A GCM.

The impact of climate change and SLR was also assessed by comparing probability density functions (PDFs) developed for the baseline year and for the future conditions. Fitting the water level and discharge values to PDFs allowed identification of the trends and tendencies in changes of river water level and discharge caused by climate change. Modelling results regarding hourly water level and daily maximum discharge were fitted to a non-parametric probability distribution. The resulting graphs (Fig. 3.7) indicate tendencies of water level and daily maximum discharge values over the analysed periods for the two RCPs and two GCM projections. The results revealed substantial variations of water levels and discharges between the simulated baseline (2014–2015) and the future scenarios. In the future, the frequencies of higher water level and daily maximum discharge events will increase. The comparison of the RCP4.5 scenarios with the baseline year showed a little increase in water level and daily maximum discharge in the near future (2040s), while in the far future (2090s), comparatively higher water level and daily maximum discharge can be expected. The comparison of the RCP8.5 scenarios with the baseline year showed that a comparatively higher (than the RCP4.5) water level and more extreme discharge would be expected for both the near and far future. Larger change was projected for the results from the MPI-ESM model compared to the IPSL-CM5A model.

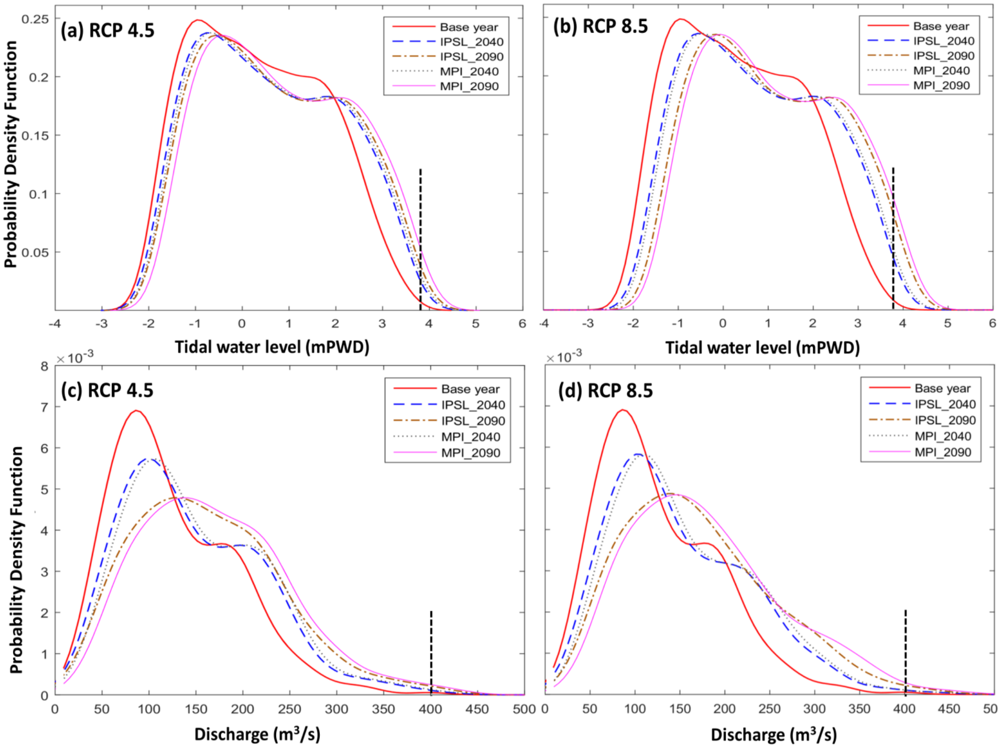

Fig. 3.7. PDFs of hourly water levels (a, b) and daily maximum discharges (c, d) in the Betna River at Noapara for the baseline year (2014–2015) and in the near (2040s) and far (2090s) future under RCP4.5 (a and c) and RCP8.5 (b and d) for the two GCMs. The vertical dotted lines represent flood danger water levels (a, b) and extreme discharge levels (c, d).

Table 3.2. Projected change (%) in seasonal mean water level and discharge at Noapara in the Betna River: Comparison of the two RCP scenarios for the near (2040s) and far (2090s) future with the baseline year. The monsoon season occurs during June–October and the dry season during November–February.

	Near Future (2040s)								**Far Future (2090s)**							
	RCP 4.5				**RCP 8.5**				**RCP 4.5**				**RCP 8.5**			
	Monsoon		**Dry**		**Monsoon**		**Dry**		**Monsoon**		**Dry**		**Monsoon**		**Dry**	
	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide	Flood tide	Ebb tide
Water level (% change)																
IPSL-CM5A	11.1	11.3	10.6	10.7	15.5	15.1	14.2	13.9	15.6	15.4	14.5	14.4	21.4	21.7	19.7	19.9
MPI-ESM	11.4	11.7	11.1	11.3	15.8	15.4	14.5	14.1	16.1	15.9	14.8	14.9	22.1	22.7	20.3	20.5
Discharge (% change)																
IPSL-CM5A	7.6	7.2	1.2	1.3	11.6	11.4	0.8	0.6	14.7	14.9	0.4	0.5	20.2	20.5	-1.8	-1.6
MPI-ESM	8.2	8.1	0.8	0.9	12.4	12.7	0.7	0.7	16.1	16.2	-1.3	-1.2	21.3	21.1	-2.2	-2.3

The highest water level of the last 25 years in the Betna River at Benarpota (near Noapara) was 4.05 mPWD, and the flood danger level for 2014 was 3.84 mPWD (IWM, 2014). The modelling results revealed that duration above the current flood danger level will increase up to 15 days by the 2040s and 34 days by the 2090s (Table 3.3). This is also evident from the study of Zaman et al. (2016) in the Bangladeshi Gorai River. They reported that the duration above the flood danger level will increase by 25 days. The duration of extreme discharges (>400 m^3/s) will increase up to 14 days by the 2040s and 33 days by the 2090s. This increased duration of the water danger level combined with increased frequency of extreme discharges (Table 3.3 and Fig. 3.6) would have negative consequences on the study area. This can severely affect the surrounding agricultural land by prolonged inundation during the monsoon and cause losses in terms of lives and livelihoods. When the water danger level coincides with the extreme discharge event, it would cause disastrous floods in the Betna River basin.

Table 3.3. Change in duration above the current (2014–2015) flood danger level and extreme discharge at Noapara in the Betna River for two RCPs, two GCMs and two future periods.

	Scenarios	**Duration above flood danger level**	**Duration above discharge of 400 m^3/s**
Baseline (2014–2015)		13 days	11 days
IPSL- CM5A	RCP 4.5 (2040s)	25 days	21 days
	RCP 8.5 (2040s)	27 days	24 days
	RCP 4.5 (2090s)	41 days	35 days
	RCP 8.5 (2090s)	45 days	46 days
MPI-ESM	RCP 4.5 (2040s)	25 days	22 days
	RCP 8.5 (2040s)	28 days	25 days
	RCP 4.5 (2090s)	43 days	36 days
	RCP 8.5 (2090s)	47 days	46 days

The modelling study has provided a set of outputs on the likely future conditions for the Betna River in terms of water level, discharge and flood potential under climate change scenarios. There are some uncertainties within the MIKE 21 FM model and input data. The limited availability of the bathymetric and discharge data limits full evaluation of the model performance. However, the comparison with the available data demonstrated a very good agreement between the observed and modelled water level and discharge. In this study, bias-corrected downscaled data were used from only two GCMs. The use of more climate models would enable better comparison of the uncertainties of climate impacts. To use more data and GCMs is recommended to further improve the model performance and increase the robustness of its results.

3.4. Conclusions

In this study a hydrodynamic model MIKE 21 FM was applied to assess the present situation and the future climate change impacts on the water level and discharge in the Betna River. The model was calibrated using the measured water level and discharge data and validated using the measured water level data at Noapara and Maskhola. The validated model was then used to simulate a baseline year (2014–2015). Data from two GCMs were statistically downscaled to point scale and subsequently used in the model to simulate the future (2040s and 2090s) water levels and discharges of the river for RCP4.5 and RCP8.5. The modelling results for the future were compared with the results for the baseline year in order to assess changes. Based on the obtained results, we conclude that:

- Increased precipitation and SLR are expected in the Betna River basin in the near and far future under both RCP4.5 and RCP8.5.
- In RCP8.5, water levels and discharges in the Betna River are expected to increase up to 16% and 13% for the 2040s, and 23% and 21% for the 2090s, respectively.
- In RCP4.5, although the expected increase in river discharge is relatively low (i.e. between 7% and 16%), the increased discharge combined with an increased water level is likely to cause major floods in the Betna River basin.
- The modelling results suggest that during the dry season, a small decrease in discharge (up to 2%) is expected for the 2090s.
- In the future, the frequencies of higher water levels and daily maximum discharge events are expected to increase. The duration above the flood danger level and extreme discharge events will likely increase by half a month in the 2040s and by more than one month in the 2090s. This would cause prolonged inundation in the river basin, particularly during the monsoon.

Identifying trends and future scenarios for hydrodynamic characteristics triggered by climate change are required for the effective management of water bodies. This information on present and future hydrodynamic conditions can assist policy makers and water managers to prepare for flood-risk mitigation planning and design adequate flood protection structures. Our approach and results can potentially be useful for other river basins in the world with similar geographic settings.

Acknowledgements

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Chapter 4.

Modelling of River Faecal Indicator Bacteria Dynamics as a Basis for Faecal Contamination Reduction

Abstract

To improve microbial water quality and to prevent the consequent waterborne disease outbreaks, knowledge on the fate and transport of contaminants and on the contributions from different faecal sources to the total contamination is essential. The fate and transport of faecal indicators *E. coli* and enterococci within the Betna River in Bangladesh were simulated using a coupled hydrodynamic and water quality model. The hydrodynamic model for the river was set up and calibrated in our earlier study using water level and discharge data during 2012. In this study, the model was further developed and validated using measured water temperature and salinity during October 2014–September 2015. Bacterial load data from various identified sources were collected and used as input in the water quality model. The model output corresponded very well to the measured *E. coli* and enterococci concentrations in the river; the Root Mean Square Error and the Nash-Sutcliffe efficiency for log-transformed concentrations were found to be 0.23 (log cfu/100 ml) and 0.84 for *E. coli* and 0.19 (log cfu/100ml) and 0.86 for enterococci respectively. Then, the model's sensitivity was tested by removing one process or forcing at a time. These simulations revealed that the decay process, upstream concentrations and untreated wastewater discharge are the primary factors controlling the concentrations in the river. While tide, wind and the contribution from the diffuse sources (i.e. urban and agricultural runoff) were unlikely to have a major influence. Finally, the model was applied to investigate the influence of wastewater treatment on bacteria concentrations. This revealed that wastewater treatment would result in a considerable improvement of the microbial water quality of the Betna River. This study provides insight in bacterial fate and transport, contribution of different sources to the faecal contamination, and the effectiveness of wastewater treatment in a river of a subtropical developing country, where this type of study is lacking.

Key words: Faecal contamination, *E. coli*, Enterococci, Wastewater, Water quality modelling, MIKE 21 FM model

Chapter based on:

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4.1. Introduction

Waterborne diseases caused by faecal contamination of surface waters are a major problem worldwide. Faecal contaminant load in surface water may increase after extreme precipitation, due to increased runoff, flooding and resuspension from sediments (Hofstra, 2011, Funari et al., 2012b), causing outbreaks of waterborne diseases (Zhang et al., 2012, Delpla et al., 2009, Funari et al., 2012b). In Bangladesh, the widespread faecal contamination in surface waters has often led to outbreaks of diarrheal diseases (Wu et al., 2016), and increased concentrations of faecal contaminants in surface waters have been observed after flooding events (Ahmed et al., 2010).

Recent measurements in the Betna River in southwest of Bangladesh (Chapter 2) revealed very poor microbial water quality due to widespread faecal contamination (Islam et al., 2017). The river is highly contaminated by untreated wastewater discharges, and storm-water runoff from urban areas, agricultural lands and manure storage areas. In this region, wastewater is not treated and is discharged directly into the river and canals. The untreated river water is used for irrigation, domestic purposes and shellfish growing; people bathe in the river and consume contaminated shellfish. This makes the population vulnerable to outbreaks of waterborne diseases. However, faecal contamination is not monitored and very little knowledge exists on the distribution of microbes in water bodies of Bangladesh. To mitigate faecal contamination of surface waters, knowledge on microbial fate and transport and the factors that influence their dynamic distribution, is essential (Rochelle-Newall et al., 2015).

While regular monitoring of microbial water quality of a river is very expensive and time consuming, process-based mathematical modelling can save time and resources. Modelling is useful to generate spatially and temporally continuous concentrations. Previous studies have shown that concentrations of faecal contaminants in water sources can be described using coupled hydrodynamic-microbial models (Harwood et al., 2005, Sokolova et al., 2013, Ouattara et al., 2013, Liu et al., 2006). These models describe the hydrodynamic situation in the water body and take into account the decay of microorganisms in the water environment (Sokolova et al., 2013, Liu et al., 2015b). These models can be used for scenario analysis in order to provide a basis for water management, for example to plan mitigation measures in terms of reducing faecal contamination of a water body. However, process-based modelling of microbial water quality is very sparse, particularly in developing countries where diarrheal diseases are endemic (Hofstra, 2011). Therefore, in this study, we implement a microbial water quality model in the highly contaminated Betna River in Bangladesh.

This study aims to analyse the fate, transport and the processes influencing the dynamic distribution of faecal contaminants in the Betna River using a coupled hydrodynamic-microbial model (i.e. MIKE 21 FM-ECOLab).To represent the faecal contamination, we used faecal indicator bacteria (FIB) *E. coli* and enterococci, the two most widely used indicators of microbial water quality (Lata et al., 2009, Ouattara et al., 2013). The hydrodynamic model for Betna River was set up and validated using water temperature and salinity distribution in the river. The model was then applied to simulate the fate, transport and dynamics of *E. coli* and enterococci in the river, taking into account the bacterial decay. The model results were compared with observed FIB concentrations in the river. Next, the processes that influence the FIB concentrations in the river, were discussed and contributions from different contaminant sources were analysed. Finally, the model was applied to predict the effect of different wastewater management scenarios on the river microbial water quality. This paper thus provides an enhanced understanding on the application of fate and transport modelling of faecal contamination in surface water in the context of a subtropical developing country.

4.2. Materials and methods

4.2.1. Study area

The study area covers an area of approximately 107 km^2 in the Betna River catchment in the southwest of Bangladesh (Fig. 4.1). The total length of Betna River is about 192km with an average width of 125m. The maximum water depth is 9m. The present modelling study focuses on the Betna's downstream 30km. This river is hydrologically connected with the Bhairab River near the Jessore district in the north and the Kholpetua River near Assasuni of the Satkhira district in the south. The river has a tidal influence, which contributes to the river's sustainability due to the limited fresh water inflow from upstream during the dry season. The study area has a typical monsoon climate with a hot season March–May, followed by a rainy season June–October and a cool period November–February. The mean annual rainfall in the area is about 1800mm, of which approximately 70% occurs during the monsoon season. This area is affected from 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). Relative humidity of the area varies from about 70% in March to 90% in July. Mean annual air temperature is 26°C with peaks of around 35°C in May–June. The temperature in winter may fall to 10°C in January. Wind in the region shows two dominant patterns, i.e. south westerly monsoon wind during June–September and north easterly wind during November–February.

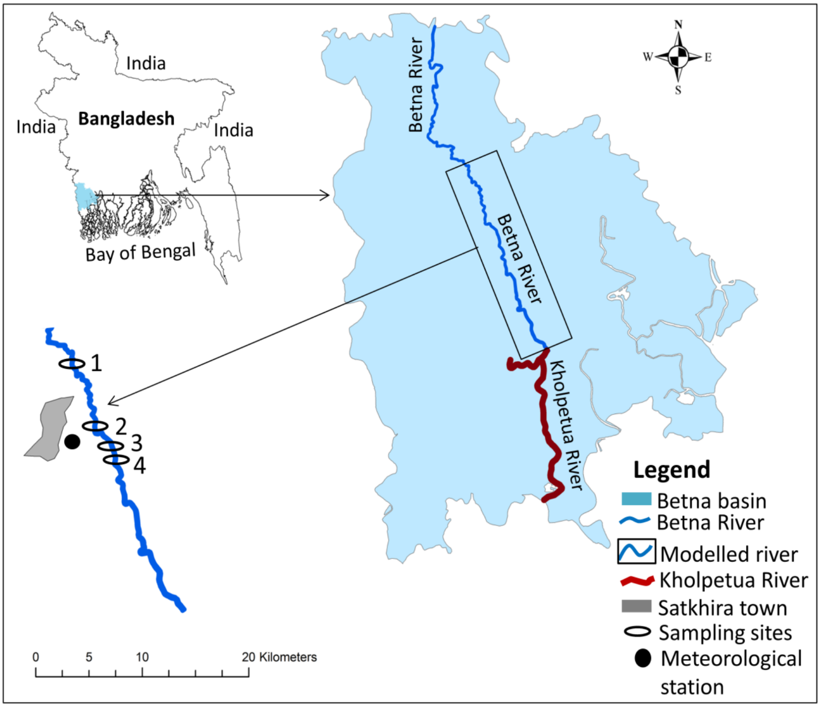

Fig. 4.1. Map of the study area: The Betna River basin in the southwest of Bangladesh

The study area consists of flat terrain with low-lying depressed areas and many tidal channels and creeks criss-crossing the area. The soils are mostly clay and loam. The land use of the study area is dominated by paddy rice cultivation and integrated paddy rice-shrimp culture. About 8% of the total area is used for homestead and settlements, about 10% is water body, 0.5% is forest, 61% is used for agriculture/paddy rice cultivation and the remaining 20.5% is wetland (also used for aquaculture or integrated paddy rice-shrimp culture). In winter, due to a lack of upstream flow, salinity increases, and as a result agriculture is hindered in this season. Water salinity reaches the highest level during March–April (up to 15 parts per thousand (ppt)) and the lowest level (near 0 ppt) in the rainy season during August–September (IWM, 2014).

The study area has a high population density of 1050 people per km^2 (BBS, 2011). Wastewater and manure are the main sources of bacteria in this catchment. Wastewater treatment facilities are very limited in Bangladesh. In the study area, domestic wastewater, municipal and industrial wastewaters are discharged into the river without treatment. The manure sources include manure applied to the agricultural lands as organic fertilizer, and direct deposition of manure in to the river and canals. Various waterborne diseases, including gastrointestinal and skin diseases, are observed in this area during and after flooding (CEGIS, 2013).

4.2.2. Data collection and analysis

To validate the microbial water quality model, water temperature, salinity and FIB (*E. coli* and enterococci) concentrations were measured from samples collected from four sites along the Betna River (Fig. 4.1). The sampling sites were selected to ensure representation of the various wastewater sources (including wastewater input from the nearby city Satkhira) and manure discharge into the river. The stations are: an upstream site that receives pollutants mostly from diffuse sources (Site 1), a site adjacent to households (Site 2), a site that receives untreated wastewater discharge from urban and industrial areas (Site 3), and a site adjacent to a creek that receives storm-water runoff from nearby town Satkhira (Site 4).

Samples were collected monthly between April 2014 and November 2015 and during heavy rainfall events. In total we included 30 sampling days. The sampling methods and FIB analysis were discussed in detail in Chapter 2. In brief: water temperature and salinity were measured on the spot and the water samples for bacterial analysis were collected into sterile nalgene plastic bottles with the care required for FIB analysis. Enumeration of *E. coli* and enterococci was performed by the membrane filtration (MF) technique (USEPA, 2002, USEPA, 2009). Diluted water samples were filtered through 0.45 µm membrane filter. For enumeration of *E. coli,* the mTEC agar plates were incubated at 35±0.5°C for two hours followed by further incubation at 44.5±0.2°C for 22–24 hours. For enterococci, mE agar plates were incubated at 41±0.5°C for 48 hours. After incubation, colonies were counted and expressed as colony forming units (cfu)/100 ml.

Water level and discharge data were gathered from the Bangladesh Water Development Board and precipitation, wind speed, wind direction, air temperature and relative humidity data were collected from the Bangladesh Meterological Department’s Satkhira station (Fig. 4.1).

4.2.3. Modelling

A coupled hydrodynamic-microbial model, MIKE 21(DHI, 2011) was applied to simulate hydrodynamics and FIB concentrations in the Betna River. The MIKE 21 is a two-dimensional hydrodynamic model, which includes a water quality module (ECOLab) for modelling bacterial spread in surface water from different contaminant sources.

4.2.4. Hydrodynamic model

The hydrodynamic model is based on the two-dimensional numerical solution of the Reynolds averaged Navier-Stokes equations, and consists of laws of continuity, momentum conservation, and temperature, salinity and density equations in horizontal direction. The density does not depend on pressure, only on temperature and salinity (DHI, 2011).

The hydrodynamic model for the Betna River was initially set up and calibrated for 2012 based on a bathymetric survey and water level and discharge measurements conducted by the Institute of Water Modelling (IWM) in Bangladesh. The model performance for water level (coefficient of determination: R^2=0.92; Nash-Sutcliffe efficiency: NSE=0.81) and for river discharge (R^2=0.83; NSE=0.66) signifies the potential of the model to simulate microbial water quality. The details regarding the model development, input data, calibration and validation are described in Chapter 3.

In this study, the model was further developed and validated using measured water temperature and salinity to simulate microbial water quality from October 2014 to September 2015. One upstream discharge boundary and one downstream water level boundary have been used in the model. The land boundary was set to zero normal velocity. Measured and interpolated water temperature and salinity data were assigned to the open boundaries. The horizontal eddy viscosity was simulated using the Smagorinsky formulation. A constant clearness coefficient (70%) was assigned in the model. The model also accounts for wind forces and precipitation on the river surface, and calculates the heat exchange between the atmosphere and the river. For heat exchange, default parameterisation was assigned in the model as recommended by MIKE 21 FM (DHI, 2011).

4.2.4.1. Microbial water quality model

In the present study, the transport and fate of FIB in the Betna River were simulated for October 2014 to September 2015. The microbial water quality module ECOLab utilizes the water flow, currents and other output from the hydrodynamic model to calculate the fate of FIB in the river. In our study, the modified ECOLab template contained two state variables: *E. coli* and enterococci was used.

Faecal contaminants can enter the river through wastewater discharges from the nearby urban areas and households through sewer drains. The wastewater discharges from drains were described as sources of faecal contamination in the model. The input flows from the drains were estimated based on the number of people connected to the sewer network and water consumption per person of 90 L/day (WSP, 2009). An average *E. coli* concentration of 1.5×10^6 cfu/100ml in untreated wastewaters was assigned as input based on the concentrations reported by Payment et al. (2001), Carlos et al. (2013) and Sokolova et al. (2013). Enterococci concentration in untreated wastewaters was set to1.0×10^6 cfu/100 ml, which is comparable to the value reported by Ahmed et al. (2008).

In addition, faecal contamination can occur through storm water runoff from the nearby town Satkhira (Fig. 4.1). The runoff volume was estimated applying the curve number method. The runoff curve number developed by the US Department of Agriculture (USDA, 1986) is a hydrological empirical parameter to predict approximate amount of direct runoff from a rainfall event (Balvanshi and Tiwari, 2014). The curve number is based on the soil type, land use and hydrologic condition. Stormwater is not treated and is likely to carry faecal contaminants from cats and dogs that live in the urban area. The FIB concentration in urban stormwater ranges between 10^3 and 10^4 cfu/100ml (Marsalek and Rochfort, 2004). In this study a concentration of 5×10^3 cfu/100ml was used for both bacteria.

Loadings of bacteria from the paddy fields were estimated based on estimated discharge from paddy fields and FIB concentrations in the water of paddy fields. At first, the *E. coli* concentration in paddy fields of the study area was estimated from a manure application rate of 420 kg/ha/yr (Hasanuzzaman et al., 2011), *E. coli* concentration in manure of 4.2×10^5 cfu/g (Coffey et al., 2010a)and water height of the farm. The resulting concentration was 4.1×10^3 cfu/100 ml. A similar average *E. coli* concentration of 4.6×10^3 cfu/100 ml was found in the paddy fields in South Korea by Kim et al. (2006). For confirmation and to get accurate concentrations for both *E. coli* and enterococci, sampling was performed in five paddy fields around the Betna River in August 2016, when most discharges from the paddy fields occur. The measured average *E. coli* and enterococci concentrations in the paddy fields were 3.6×10^3 and 7.4×10^3 cfu/100 ml respectively. This is still in the same order of magnitude. These measured values were applied in the model.

Another source of faecal contamination is the inflowing bacterial load from the upstream part of the river. The daily concentrations at the upstream boundary were estimated by interpolating the concentrations measured at Sampling Site 1 (Fig 4.1). We assumed that the river water beyond the downstream boundary is not influenced by anthropogenic activities, because the sea water replaces the river water there twice a day. Therefore, the concentration at the downstream boundary was set to 0 cfu/100 ml. The model sensitivity analysis also showed that the concentration at the downstream boundary does not have an impact on the location of interest, because it is far away. Bedri et al. (2014) in their modelling study also used zero concentrations for open boundaries and indicated that the far distance from the shoreline is sufficient to negate the effect of boundary conditions on the location of interest.

Occasional leakage of septic tanks and open defecation from humans can also contaminate the river water (An et al., 2002). However, lack of sufficient data (e.g. corresponding amount of faecal matters and bacterial concentration) prevented us to include the leakage and open defecation in the model. Direct defecation from cattle was also ignored in this study due to difficulty in estimation of the coincident amount of manure deposition. We have found no correlation between the measured turbidity and FIB concentrations. This may indicate that the influence of bacterial resuspension from sediments on FIB concentrations is not strong in case of this river. For this reason and the lack of sediment data, resuspension of bacteria from sediments was not taken into account in the model.

FIB are exposed to decay or inactivation after entering into rivers. 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):

$$\frac{dC}{dt} = -k_0 . \theta_S^{Sal} . \theta_I^{Int} . \theta_T^{(Temp-20)} . \mathrm{C} \qquad \text{Equation 4.1}$$

In Equation 4.1, C is the concentration of bacteria; k_0 is the decay rate (1/day) at 20˚C for a salinity of 0‰ and in a dark condition; θ_S is the salinity coefficient; Sal is the salinity (‰); θ_I is the contribution to decay rate due to light intensity; Int is the light intensity (kW/m^2); θ_T is the decay rate due to temperature deviation from 20˚C; $Temp$ (˚C) is the water temperature.

The temperature (θ_T) and the decay rate (k_0) constants for *E. coli* were set to 1.07 and 0.80 respectively. These values are comparable to the values used by Hellweger and Masopust (2008), Mancini (1978) and Liu et al. (2006). As enterococci survive longer than *E. coli* in natural water bodies (Liu et al., 2006), the θ_T and k_0 constants for enterococci were set to 1.04 and 0.50 respectively. This is also consistent with the values used by Liu et al. (2006). The salinity coefficient (θ_S) was set to 1.006 for both the bacteria based on the values reported in the literature (Canteras et al., 1995, McCorquodale et al., 2004, Brauwere et al., 2014). A constant light intensity of 0.14 kW/m^2 was assigned in the model, which was based on the study area's daily average light intensity and daily sunshine hours data, collected from NASA's satellite derived data centre and the Bangladesh Meteorological Department respectively. The light coefficient (θ_I) was set to 7.4, which is the default value and comparable to the value used by Gao et al. (2015).

4.2.4.2. Microbial model validation

Water temperature and salinity have a major influence on density circulation and microbial decay processes. Therefore, the model was first validated with measured water temperature and salinity for one year (October 2014–September 2015). Then the model was validated using the measured FIB (*E. coli* and enterococci) concentrations for the same period.The model performance was assessed using two statistical parameters: the Root Mean Square Error (RMSE) and the NSE. A smaller RMSE indicates a better model performance. NSE ranges between–∞ and 1.0; values between 0.0 and 1.0 are usually viewed as acceptable; the closer NSE is to 1.0, the more accurate the model is; NSE >0.90 is excellent, 0.75 to 0.89 is very good, and 0.50 to 0.74 is good (Moriasi et al., 2007).

4.2.5. Impact of different processes on FIB concentrations

To better understand the influence of the different processes and contaminant sources on FIB concentration and its variability in the Betna River, a sensitivity analysis was performed. The model sensitivity was tested with input variables and model parameters such as, boundary condition, FIB inputs from different sources, water temperature, salinity and light intensity. The model was run to generate a time series output of 15 minute resolution for ten days during the wet season (8–17 July, 2015) and ten days during the dry season (21–30 January, 2015). The major processes (wind, decay effect, different contaminant sources) were removed one at a time. For example, to evaluate the influence of wind, the model was run by removing the wind force from the model, while all other forcings and processes were kept the same. In addition, to determine the contribution of different contamination sources to the total concentration, we ran the model with and without upstream boundary concentrations, wastewater discharges and diffuse contaminant sources.

4.3. Results and discussions

4.3.1. Water temperature and salinity distribution in the Betna River

Fig. 4.2 shows an example of validationresults comparing model output with the measured water temperature and salinity at Sampling Site 3 in the Betna River. The RMSE and NSE for water temperature and salinity are 0.51^{0}C and 0.38ppt, and 0.93 and 0.94 respectively. Thus, both parameters suggest an excellent agreement between the modelled and measured water temperature and salinity. The results show temporal variability of the system that are due to the seasonal changes in temperature and salinity. Water temperature remains high, around 30^{0}C, except for the winter months (Fig. 4.2). Salinity starts reducing at the onset of the rainy season in mid-June and reaches near zero ppt during July (Fig. 4.2).

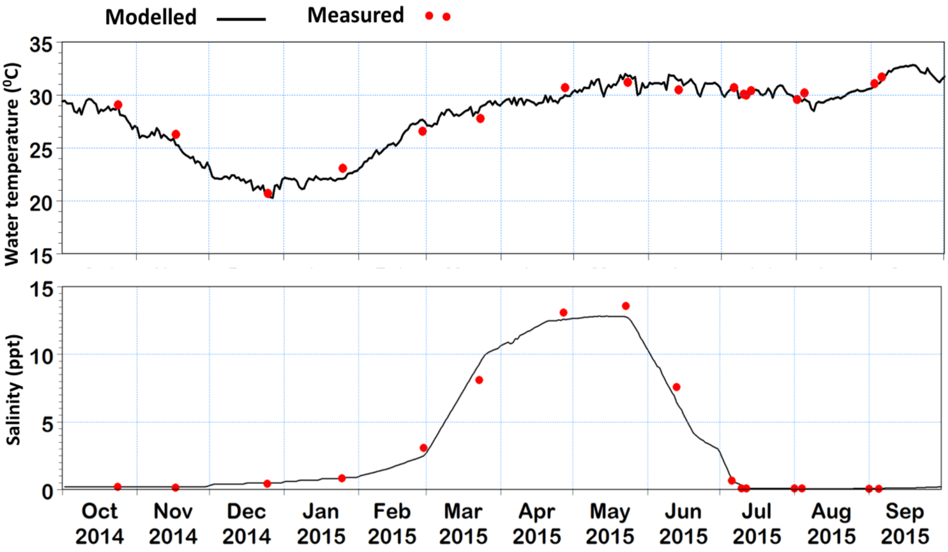

Fig. 4.2. Daily modelled and observed water temperature (upper panel) and salinity (lower panel) at Sampling Site 3 of the Betna River

4.3.2. FIB concentrations in the Betna River

The modelled outcomes were compared to the measured FIB concentrations at Sampling Sites 2, 3 and 4 of the river (c.f. Fig. 4.1 for locations). The model captured the spatial and temporal variations of measured FIB concentrations well (Fig. 4.3). The RMSE and NSE for log-transformed *E. coli* and enterococci concentrations combined for the three sampling sites were 0.23 (log cfu/100ml) and 0.19 (log cfu/100ml), and 0.84 and 0.86 respectively. This is considered a very good performance of the model. The simulated FIB concentrations slightly underestimated the measured FIB in few of the peaks (e.g. July–August). This underestimation indicates that there is more contamination entering the river than we have estimated. This can be due to an underestimation of the load from the identified contamination sources and/or the existence of unknown contamination sources. There is a lack of FIB data measured with high temporal resolution. Also, contaminant loads from septic tank leakage, open defecation, and sediment resuspension data were unavailable. Addressing these data gaps can be recommended to further improve the model performance.

The modelled and measured results showed substantial spatiotemporal variations. The highest concentrations of FIB occurred during the rainy season (July–September) with frequent intense rainfall and associated high flow, while the lowest concentrations occurred in the winter and dry months (November–February). Higher bacterial concentrations during periods of heavy rainfall and high river flow are often reported in the literature (Schilling et al., 2009, Aragonés et al., 2016, Ouattara et al., 2013). During the dry periods, FIB concentrations were low, because the river gets contaminated only by the point sources. During the dry period, Sampling Sites 3 and 4 showed slightly higher FIB concentrations than Site 2, because Sites 3 and 4 receive more wastewater input from the Satkhira town. On the other hand, the peak concentrations at Site 2 were relatively higher than at Sites 3 and 4. The concentrations during peaks are higher at Site 2 because this site receives more diffuse sources contamination from upstream catchments after heavy rainfall events. Both modelled and measured results showed comparatively higher enterococci concentrations than *E. coli* during most of the time, and this is also supported by previous studies (Mishra et al., 2015, Tiefenthaler et al., 2009). The higher levels of enterococci are explained by their longer survival in surface water in comparison to *E. coli* (Liu et al., 2006).

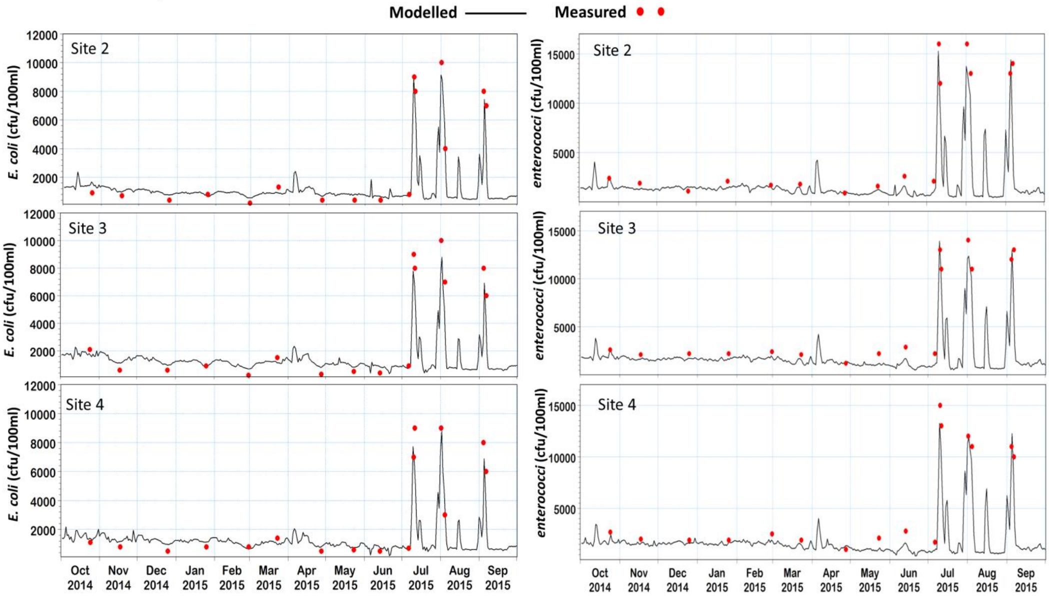

Fig. 4.3. Comparison of daily modelled and measured *E. coli* (left column) and enterococci (right column) concentrations (cfu/100ml) at Sampling Sites 2 (up), 3 (middle) and 4 (bottom).

4.3.3. Impact of different processes on FIB concentrations

The modelling results for the wet season (i.e. 8–17 July, 2015) showed that the FIB concentrations vary along the river (Fig. 4.4). Near the Sampling Sites 2, 3 and 4, the river was found to be highly contaminated, because during wet weather these sites receive both wastewater discharge, and urban and agricultural runoff. The concentrations tend to decrease downstream due to the reduced anthropogenic influence there. During high tide, FIB concentrations were reduced due to dilution effect, but not substantially, because of the high concentrations already present in the river system. Vijay et al. (2016) observed a similar effect in India.

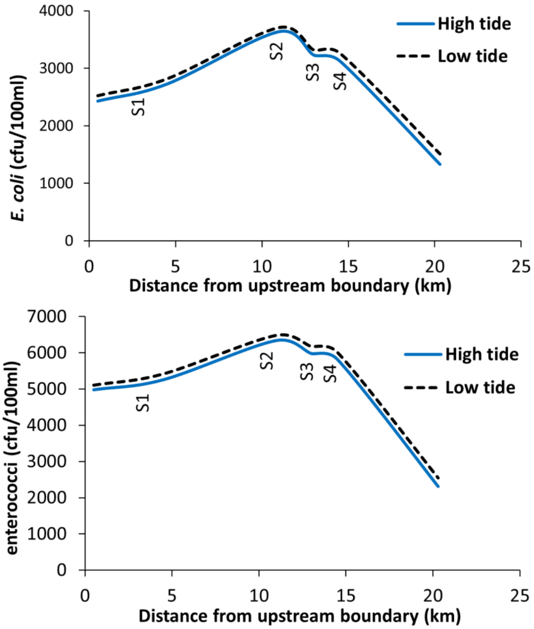

Fig. 4.4. Longitudinal distribution of simulated average FIB concentrations along the Betna River for 8–17 July, 2015 under high and low tide conditions.

In order to understand the influence of different process, the model was run with and without wind and the FIB decay rate (Table 4.1). The results revealed that wind has some influence on the bacterial transport in river water. In the simulation without wind, the concentrations decreased by 1.6% to 3.5% (Table 4.1). The faster or slower bacterial transport from different sources is dependent on wind speed and direction (Sokolova et al., 2013). The simulations with and without the decay process produced highly different FIB concentrations, indicating that the decay process is very important (Table 4.1). Without the decay process FIB concentrations were found to be one or two orders of magnitude higher. This is in agreement with the studies by Brauwere et al. (2014) and Ouattara et al. (2013).

The contribution of different contamination sources (upstream boundary concentrations, wastewater discharges and diffuse sources) to the total concentration at the three

Sampling Sites 2, 3 and 4 were analysed. The results revealed that during the wet period upstream concentrations and wastewater discharges through drains had the largest contribution, up to 55% and 42% respectively (Table 4.1). While diffuse sources (urban and agricultural runoff) contributed less, up to 9.3% for *E. coli* and 12.6% for enterococci. Comparatively lower contribution from diffuse sources was also reported in other studies (Ouattara et al., 2013, Sokolova et al., 2012, Gao et al., 2015). During the wet period, a higher contribution from the upstream boundary is expected, because the river here is connected to the Bhairab River in the north and carries contaminated runoffs from the upstream urban and agricultural areas. During the dry period, the wastewater discharges contributed maximally (maximum 89%), because of the continuous wastewater discharge from the drains (Table 4.1). The lower contribution from the upstream boundary (11–36%) during the dry period is due to the absence of precipitation-induced contaminant transport from upstream areas. For the same reason, no contribution from diffuse sources was observed during the dry period (Table 4.1). The results highlight the impact of untreated wastewaters (mostly from Satkhira town) on the microbial water quality of the Betna River. Due to continuous input from the sewerage drains, FIB concentrations were found to be above the USEPA bathing water quality standards (235 cfu/100ml for *E. coli* and 104 cfu/100ml for enterococci) most of the time, even during the dry periods (Fig. 4.3). `

Table 4.1. Influence of various processes on mean FIB concentrations (cfu/100ml) in the Betna River. The simulations cover the wet period 8–17 July 2015 and the dry period 21–30 January 2015.

	Wet period						**Dry period**					
	E. coli (cfu/100ml)			Enterococci (cfu/100ml)			*E. coli* (cfu/100ml)			Enterococci (cfu/100ml)		
	Site 2	Site 3	Site 4	Site 2	Site 3	Site 4	Site 2	Site 3	Site 4	Site 2	Site 3	Site 4
Reference concentration	3641	3176	2778	6185	5732	5341	1089	1398	1287	1492	1673	1577
	Change in concentration (%) of the reference concentration											
Without wind	- 1.8	- 3.2	- 3.5	- 2.1	- 2.4	- 2.2	-2.0	-3.1	-3.4	-1.6	-2.2	-2.8
Without decay rate	+177	+175	+166	+ 81	+ 81	+ 78	+199	+193	+186	+158	+156	+153
Without upstream conc.	- 55	- 53	- 49	- 51	- 49	- 50	- 15	- 12	- 11	- 36	- 35	- 34
Without wastewater drains	- 39	- 39	- 42	- 38	- 39	- 38	-85	- 88	- 89	- 64	- 65	- 66
Without urban runoff	- 3.2	- 4.1	- 4.4	- 5.2	- 5.9	- 6.1	0	0	0	0	0	0
Without agricultural runoff	- 3.5	- 4.5	- 4.9	- 5.9	- 6.7	- 6.4	0	0	0	0	0	0

4.3.4. Influence of wastewater treatment on microbial water quality

The Betna River is highly contaminated due mainly to the continuous discharge of untreated wastewater from sewer drains of the Satkhira urban areas. To improve the microbial water quality of the river, the faecal contaminants that are directly discharged into the river should be treated first. To examine the present system's response to changes in FIB loadings from the sewer drains, the validated MIKE model was applied to predict the microbial water quality during ten days (21–30 January, 2015) in the dry season. The dry season was studied because during this period wastewater discharge from drains are the primary source of faecal contamination in the river. We considered a scenario that (a) wastewater treatment plants (WWTPs) are constructed with the required capacity, (b) the sewernetwork is built to collect and transport the entire volume of wastewater to the WWTPs, and (c) primary and secondary levels of treatment are applied totreat the entire volume reaching the WWTPs. We assume that with the application of the primary and secondary levels of treatment, the concentration of FIB in wastewater will be reduced by two order of magnitude based on Saleem et al. (2000) and George et al. (2002).

Fig. 4.5 presents an example of FIB concentrations under the present condition and after contaminant load reduction by wastewater treatment. The results revealed that the faecal contamination in the river system are largely reduced after introducing primary and secondary wastewater treatment. This is also supported by other studies (Vijay et al., 2016, Liu et al., 2015b, Ouattara et al., 2013). The FIB concentrations substantially improved along with the compliance of USEPA specified bathing water quality standards (*E. coli* 235 cfu/100ml and enterococci 104 cfu/100ml) in many of the occasions. Despite a marked improvement in FIB concentrations, the tested removal still could not help to reach the desired bathing water standards as no tertiary level of treatment was considered due to the exorbitant cost implication, where all facilities have to be newly constructed. With the introduction of wastewater treatment major improvement of water quality would be achieved in the dry season. However, noncompliance of water quality would be prevailed during the wet season due to the contribution from the upstream boundary and diffuse sources. Treatment of wastewaters of upstream urban areas will reduce the concentrations on the upstream boundary and further improve water quality of the Betna River during the wet season.

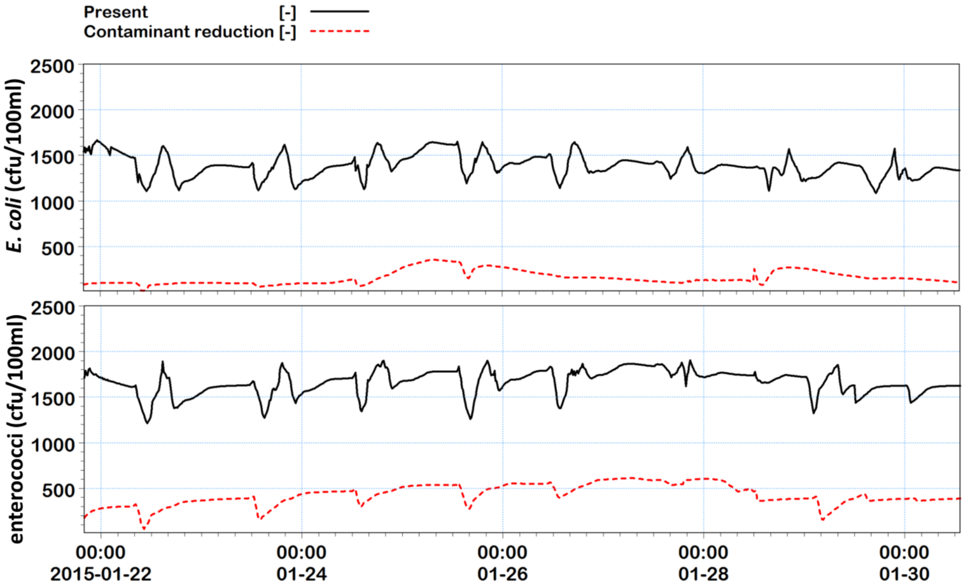

Fig. 4.5. E. coli and enterococci concentrations before and after contaminant load reduction at Sampling Site 3 in the Betna River for 21–30 January, 2015.

The river water is now unsuitable for bathing due to violation of bathing water standards almost all the time (Fig. 4.3). After a heavy rainfall event the FIB concentration become very high (peaks in Fig. 4.3) and reduces after three to four days (although still the bathing water standards are violated). However, some people want to sometimes bathe and fish in the river. Therefore, we suggest that those people do not bathe or fish in the river for at least three to four days after a heavy rainfall event, as long as major improvements of wastewater treatment are not ensured in the surrounding river catchments and upstream areas. Bangladesh's government has already made establishing effluent treatment plants mandatory for industries. However, there is a lack of strict regulation and initiative to implement domestic wastewater treatment before disposal of wastewaters into rivers. This modelling study hopefully creates awareness and provides policy-support information for the government in reducing the widespread faecal contamination of the surface waters of Bangladesh.

4.4. Conclusions

This modelling study provided enhanced understanding of the influence of different processes on the fate and transport of FIB, the contribution of different sources to the total faecal contamination, and the effectiveness of wastewater treatment in the Betna River in

Bangladesh. Based on the obtained modelling results, the following conclusions can be drawn:

- The presented model described the water temperature, salinity and microbial fate and transport in the river very well.
- Bacterial decay, upstream concentrations and untreated wastewater discharges were found to be the dominant factors controlling FIB concentrations in the river, while tide, wind and contamination from the diffuse sources did not have a significant influence.
- Implementation of the primary and secondary levels of wastewater treatment would decrease the contamination of the river during the dry season considerably.
- Treatment of wastewater from upstream urban areas would further improve the microbial water quality in the river during the wet season.

This study underlines the need for treatment of wastewater before it is discharged into the rivers and canals. This study could be a test case for other river basins with similar conditions. The developed model can be used in further studies in order to forecast the future impact of climate and socio-economic changes on FIB fate, transport and dynamics. This modelling study provides information to support decisions by water managers to reduce the widespread faecal contamination and the risks of waterborne disease outbreaks.

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Chapter 5

Modelling the Impact of Future Socio-economic and Climate Change Scenarios on River Microbial Water Quality

Abstract

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 in the Betna River, Bangladesh using a coupled hydrodynamic and water quality model (MIKE21-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 river. 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, as currently is common practice in the Intergovernmental Panel on Climate Change. We used our own assumptions on future local sanitation and waste water treatment. Different future scenarios were found to have a substantial impact on the river's FIB concentrations. An uncontrolled future results in a deterioration of microbial water quality due to socio-economic changes, such as higher population growth, land use change, increased sewage discharges and changes in rainfall patterns. However, microbial water quality improves under a sustainable scenario with improved sewage treatment. By the 2090s, FIB concentrations are expected to decrease by 98% or increase by 75% for the sustainability scenario and uncontrolled scenario respectively. Contaminant loads were more influenced by changes in socio-economic factors than by climatic change. Therefore the socio-economic factors should always be considered in assessing microbial water quality. To our knowledge, this is the first study that combines climate change and socio-economic scenarios to simulate the future microbial water quality of a river. Such approach can be used to assess future consequences for health risks.

Keywords: Modelling; faecal indicator bacteria; socio-economic development; climate change; SSPs; RCPs

Chapter based on:

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5.1. 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 been 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 (Chapter 2). Bathing water-quality criteria were found to be violated year round. 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). 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 also has highlighted the likely impacts of climate change and proposed an approach of assessing future Shared Socio-economic Pathways (SSPs) and how these can be related with climate change to produce a combined effect on catchments, communities health and livelihoods (Whitehead et al., 2015). Developing a new scenario frame work by combining the SSPs and Representative Concentration Pathways (RCPs) have been proposed by the climate community (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 and sanitation) that describe challenges to mitigation and adaptation(O'Neill et al., 2015). 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 to 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 only climate change on river hydrodynamic characteristics (Elshemy and Khadr, 2015, Kuchar and Iwański, 2014) or waterborne pathogens/FIB (Jalliffier-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 waters 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 together with Iqbal et al. (2017) 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 scale. 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 has 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 the Faecal Indicator Bacteria (FIB). *E. coli* and enterococci are the two most widely used indicators of microbial water quality (Lata et al., 2009). Quantitative studies on the changes in FIB concentrations in surface waters for combined scenarios have not yet been published. 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. Then, socio-economic development and climate changes projections for the near (2040s) and far (2090s) future were made. Next, the model was run for these futures using these projections in different scenarios. Finally, the future scenarios were discussed and guidelines were proposed to address changes in microbial water quality induced by climate change and socio-economic developments. This study illustrates the application of future microbial water-quality scenarios in the context of a subtropical river system in a developing country.

5.2. Methodology

5.2.1. Study area and sources of contaminants

The study area covers an area of 107 km^2 inthe Betna River catchment in southwestern Bangladesh (Fig. 5.1). The total length of Betna River is about 192km with an average width of 125m. The maximum water depth is 9m. Our modelling study focuses on the downstream 30km of the Betna River. The study area has a typical 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 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.

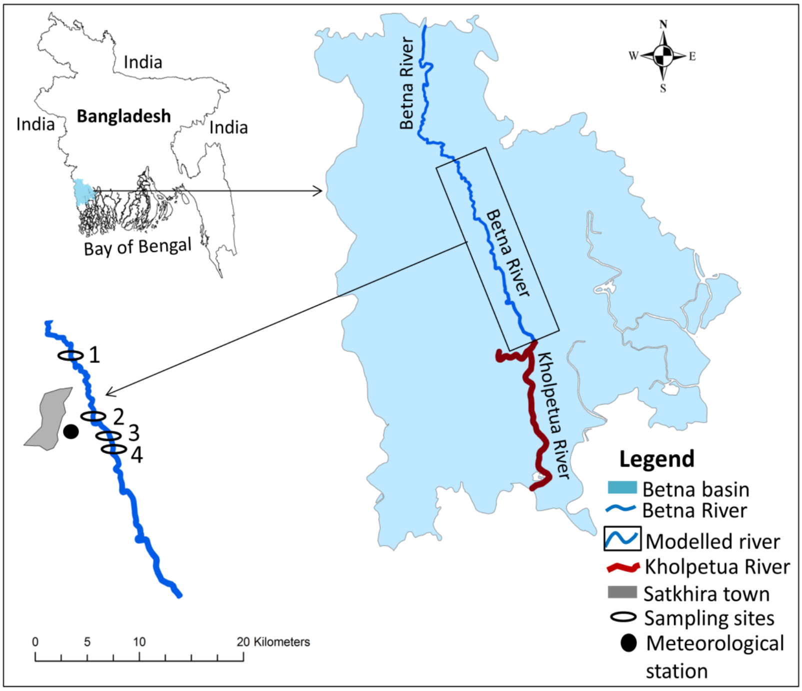

Fig. 5.1. Map of the study area: Betna River basin in the southwest of Bangladesh

Sewage and manure are the main bacteria sources in this catchment. In the study area, sewage is discharged into the river without treatment. The manure sources include manure applied to the agricultural lands 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).

5.2.2. 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. 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. 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 simulate microbial water quality. The calibrated and validated model was applied to simulate daily microbial concentrations from October 2014–September 2015 as the baseline condition. The model output during 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 respectively. 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. 5.1). The detail of the model development, calibration, validation and input data used have been described in Chapter 3.

5.2.3. 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 and uncontrolled) have been developed (details are in Section 5.2.3.3) that are based on the new approach developed for the IPCC (2014), which employs a new generation of scenarios (Moss et al., 2010) that include socio-economic scenarios (SSPs) (O'Neill et al., 2015) 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.

5.2.3.1. 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., 2015). 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., 2015). Our scenarios (S1 and S2), have been based on the two SSPs and our own assumptions. 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. People are aware of environmental conditions and slow degradation. Education, health, sanitation and safe water are improved. Inequalities between and within countries decrease (O'Neill et al., 2015). In this scenario, we assume that the study area's microbial water quality is improved by developing water treatment and other water-management strategies. Wastewater treatment plants (WWTPs) are thus installed and access to sanitation and sewage treatment in the study area is strongly improved. Due to low population growth and an eventual stabilization, in 2040 and 2090 the whole study area population has access to sewer lines. The population that previously caused direct or diffuse emissions is now connected to a sewage system or uses an on-site sewer. 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. We assume 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. These assumptions are based on Saleem et al. (2000) and George et al. (2002). The future upstream FIB boundary data assumed that similar levels of wastewater treatment facilities would be established in the upstream areas of the study area. For this, the current boundary data will be modified based on the assumptions presented in Table 5.1 regarding wastewater treatment, sanitation, and human and livestock population growth.

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, slow developments in technology, health care, safe water and improved sanitation (O'Neill et al., 2015). In this scenario, the population will grow rapidly and urbanisation 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 present condition) but will be established with limited capacity (30% primary and 20% secondary treatment) by the 2090s.

Table 5.1 provides an overview of the changes in the factors that can be varied in the scenarios under different SSPs by the 2040s and 2090s. Five major factors were used as the factors that influence the river FIB concentrations. These include human and livestock population growth, urbanisation, sanitation, wastewater treatment and land use change. We assumed specific changes in sanitation and wastewater treatment that were in line with the storylines and population and urbanisation changes from the SSPs. We used data for human population and urbanisation for the year 2040 and 2090 from the SSP database at IIASA (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about), which is developed by the climate change community. Human population data were obtained from Landscan 2010 (http://web.ornl.gov/sci/landscan) (Bright et al., 2011) and the changes were calculated using data from the SSP database. Current livestock population data were collected from the Department of Livestock, Government of Bangladesh's district office Satkhira in 2014. These data were based on latest Bangladesh agriculture census from 2008 (BBS, 2010), livestock and poultry survey from 2009 (BBS, 2010) and the annual growth rates (Rahman et al., 2014). Future livestock population changes were based on the SSP database. Poultry and ducks are reared mostly in households but they are not commercially grown in the study area. Since poultry and ducks contribute very little to the total contaminants, they are ignored. Land-use data were obtained from the RCP land-use data base (https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage& page=welcome#intro).

Table 5.1. Population growth, urbanisation, sanitation, waste water treatment and land use for different scenarios for base year (2014–2015), 2040 and 2090.

Scenario features	**Source**	**Baseline**	**S1 2040**	**S1 2090**	**S2 2040**	**S2 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’s		0.39	0.41	0.32	0.48	0.58

5.2.3.2. 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). The daily GCM data were downscaled using the ‘Delta change method’ with ‘quantile-quantile’ correction as described by Liu et al. (2015a). 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 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 climate change scenarios: a relatively low emission pathway (RCP4.5) and a high emission pathway (RCP8.5). Table 5.2 summarizes the changes under different RCPs at 2040s and 2090s. The detail of the climate change scenario development and projections are presented in Chapter 3.

Table 5.2. Projected changes in climate variables (precipitation, mean air temperature and sea-level rise) in the study area for the two selected GCMs for RCP4.5 and RCP8.5 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 air temperature increase	2.8%	4.1%	4.6%	5.8%
Mean sea level rise (m)	0.26	0.26	0.44	0.44
Year 2090				
Annual precipitation increase	11.6%	12.2%	13.5%	13.7%
Mean air temperature increase	4.9%	5.7%	10.5%	12.3%
Mean sea level rise (m)	0.42	0.42	0.76	0.76

5.2.3.3. 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 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 2014–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 5.3. Various combinations of SSP and RCP that are impossible globally, are possible regionally. For example, socio-economic trends in scenario SSP3 are such that global emissions cannot reach 8.5 W/m2 due to increasing poverty, economic collapse and scarcity of resources. Similarly, SSP1 with its low population growth, planned urbanization, improved sanitation and rapid technological advancements is unlikely to reach above 6.0 W/m2 (Kok, 2016). We select S1 (SSP1 x RCP4.5) and S2 (SSP3 x RCP8.5) as our main scenarios. Although these combinations may not be appropriate globally, they are logical choices for the study area in Bangladesh. The regional rivalry scenario (SSP3) does not provide sufficient carbon emissions to reach RCP8.5 globally. Reaching the RCP8.5 globally is possible if the world keeps emitting carbon as in SSP5 ('Taking the highway'). However, for a developing country, Bangladesh, where emission will continue to rise, the SSP3 likely keeps emission consistent with RCP8.5. Combining SSP1 with RCP4.5 is a plausible choice for all world regions, including the Betna River basin. We did not consider RCP2.6. Firstly, because such a low emission is very unlikely for the study area and, secondly, daily time series data were not available from the selected GCMs.

Table 5.3. Scenario matrix and assumptions of socio-economic changes

	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	

5.3. Results

5.3.1. FIB concentrations for different scenarios

Fig. 5.2 presents the impact of combined socio-economic development and climate change scenarios (S1 and S2) on FIB concentrations for 2014–2015 (baseline), the near future (2040s) and far future (2090s) at Sampling Site 3 in the Betna River. The results 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/100ml) most of the time (Fig. 5.2, a). The S1 in the far future was an ideal case with 100% wastewater collection and 100% treatment resulted in compliance of bathing standards all the time with the only exception after few heavy precipitation events (Fig. 5.2, b). 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. 5.2).

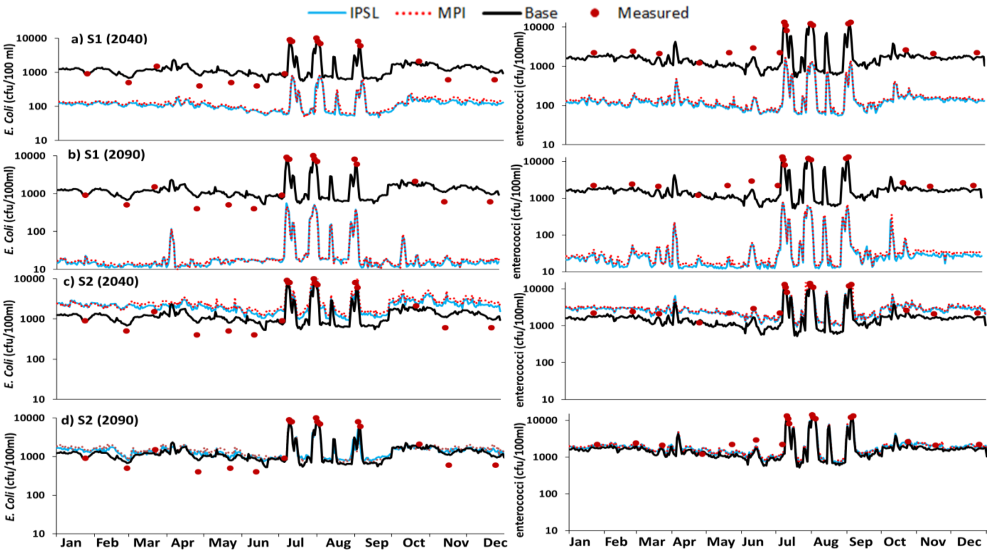

Fig. 5.2. Daily FIB concentrations at Sampling Site 3 in the Betna River under the two scenarios, S1 (a, b) and S2 (c, d) and two future periods, 2040s (a, c) and 2090s (b, d). The scenarios are compared with the baseline condition and measured data in 2014–2015. The left column is for E. coli and right column for enterococci.

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 (RCP8.5) in the 2040s resulted in the highest concentrations of all scenarios. The S2 in the 2090s, which considers 50% treated wastewater, also showed higher FIB concentrations than the baseline conditions (Fig. 5.2, d).

Table 5.4 presents changes in seasonal mean future FIB concentrations along the river. In the S1 scenario, FIB concentrations decreased by 87–91% and 95–98% in 2040 and 2090 respectively. For the S2 scenario, the concentrations increased by 51–75% in 2040 (with no wastewater treatment) and 10–19% in 2090 (with 50% wastewater treatment) compared to the situation in 2014–2015 (Table 5.4). 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.

Table 5.4. Percentage changes of seasonal mean FIB concentrations from baseline to 2040s and 2090s under the two scenarios

GCMs	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	- 88	- 89	- 89	- 89	- 88	- 89
	S1 (2090s)	- 98	- 98	- 98	- 98	- 98	- 97	- 96	- 95	- 97	- 96	- 96	- 97
	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	- 90	- 89	- 88	- 89	- 89
	S1 (2090s)	- 98	- 98	- 98	- 97	- 98	- 98	- 96	- 96	- 97	- 96	- 96	- 97
	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

Because of the little difference in FIB concentrations between the two GCM-based climate-change scenarios and among the sampling sites, their simulated values averaged out. The average daily FIB concentrations were then fitted to a non-parametric cumulative distribution function. FIB concentrations between the simulated baseline (2014–2015) and future scenarios (Fig. 5.3) were varied substantially. The selected sustainable scenario (S1), in near and far future showed a substantial decrease in the FIB concentrations. The uncontrolled scenario (S2), in the 2040s resulted in the highest concentrations of all scenarios. The S2 in the 2090s, despite considering 50% treated wastewater, also resulted in comparatively higher concentrations than the baseline condition.

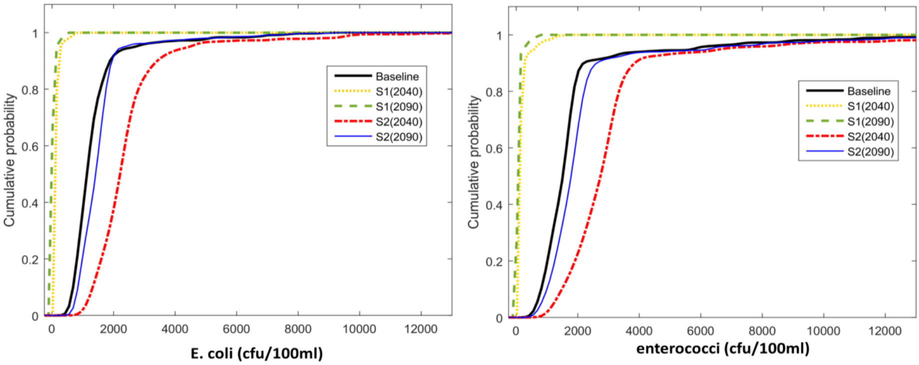

Fig. 5.3. Cumulative distribution function shows the variability of average daily *E. coli* (left) and enterococci (right) concentrations (cfu/100ml) in the Betna River for the baseline year (2014–2015), and in the sustainability (S1) and uncontrolled scenario (S2) in near (2040s) and far (2090s) future. The results are averaged over the two GCMs and three sampling sites.

5.3.2. 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 5.5, Fig. 5.4). 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.

5.3.2.1. Relative importance of Socio-economic and climate change scenarios

The results (Table 5.5) 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 baseline. 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.

Table 5.5. Relative importance of RCP and SSP scenarios for two future periods (2040s and 2090s) 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.

		E. coli (% changes)				Enterococci (% changes)			
		S1 (2040s)	S1 (2090s)	S2 (2040s)	S2 (2090s)	S1 (2040s)	S1 (2090s)	S2 (2040s)	S2 (2090s)
Wet period	Without SSP	+ 730	+ 1820	- 18	- 10	+ 840	+ 2230	- 14	- 11
	Without RCP	- 2.1	-5.2	+ 6.1	+ 3.2	- 1.8	+ 2.3	+ 5.3	+ 3.6
Dry period	Without SSP	+ 890	+ 3250	- 36	- 15	+ 1260	+ 3420	- 21	- 12
	Without RCP	+ 2.2	+ 13	- 7.3	- 9.4	+ 2.5	+ 12	- 8.2	- 6.6

5.3.2.2. Relative importance of different contaminant sources

Fig. 5.4 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 in 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.

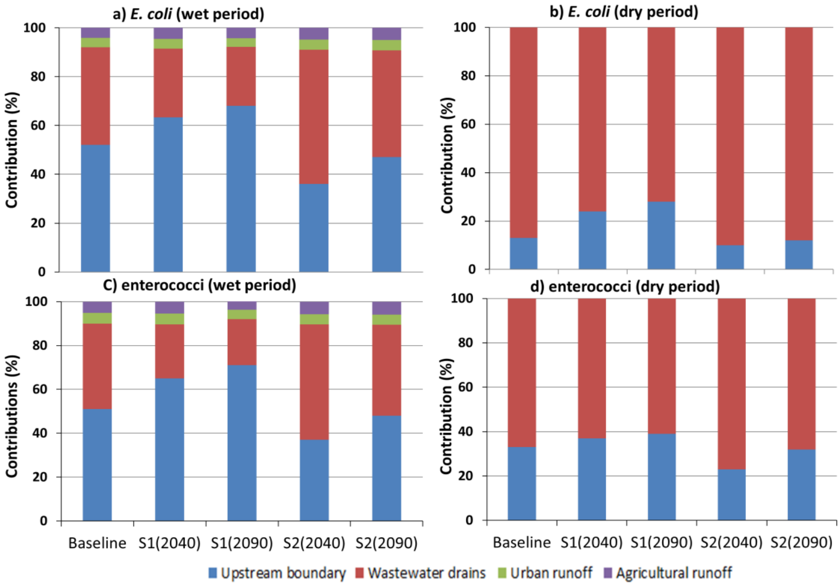

Fig. 5.4. Relative contributions (%) from different sources to the mean *E. coli* (a, b) and enterococci (c, d) concentrations in the Sampling Sites 2–4 (overall), Betna River for two scenarios (S1 and S2) and two future periods (2040s and 2090s). The simulations cover a wet period 6–20 July (a, c) and a dry period 16–30 January (b, d).

5.4. 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 urbanisation 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, urbanisation 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 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 5.5 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 Borris 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 compared to the wet monsoon. The comparatively higher percentage changes in FIB concentrations in the dry season are caused by the relatively low observed concentrations for these months (Table 5.4). The decrease in concentrations in the dry season is likely attributed to the absence of the contribution from diffuse sources. The relative contribution from diffuse sources (urban and agricultural runoff) in the future remains almost the same as the baseline conditions (Fig. 5.4). Currently manure application on lands is not regulated in Bangladesh. Therefore, with the predicted increase in livestock numbers (Table 5.1), 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. 5.4). 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 (Ouattara 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 5.2.3.1). 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.

5.5. 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 to75% 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.
- 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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Chapter 6.

Synthesis

6.1. Introduction

In many countries, poor water quality is a major threat to human health and limited access to clean water continues to act as a barrier of development (Rochelle-Newall et al., 2015). Developing countries often not only lack effective water management facilities due to economic constraints, but also cannot regularly monitor waterborne pathogens and other pollutants in water resources. In addition, the dynamic distribution of pathogens in surface waters in developing countries is poorly known, particularly in the tropics and subtropics. Considering the health risks associated with the consumption of contaminated surface water, factors that influence microbial dynamics in the water bodies in developing countries and in (sub)tropical ecosystems, should be identified. By increasing the knowledge base on these factors, the health risks associated with the use of contaminated surface water in domestic and agricultural and recreational purposes could well be reduced. However, at present most of the studies in the (sub)tropical developing countries have focused on drinking water supplies, while the surface waters have been ignored (Bain et al., 2014). Most of the studies related to surface water microbial water quality have been conducted in developed countries and in temperate systems (Chapter 1, Table 1.2).

Tropical systems are generally characterized by higher and more stable temperatures, higher light intensities and lower variability in day length compared to temperate systems. All these factors probably have strong influence on ecological diversity and activity. This is more applicable for microbes as they strongly determine ecological diversity (Rochelle-Newall et al., 2015). Due to the existing environmental differences between temperate and tropical systems, waterborne pathogens will behave differently in (sub)tropical systems and therefore one of this study's relevancies is its focus on the subtropical developing country Bangladesh.

In Bangladesh access to clean water and adequate sanitation remains a problem despite recent improvements. Due to the country's poor economic conditions and lack of adequate water management infrastructure, most people rely on highly contaminated surface water for household purposes and bathing. This makes the population vulnerable to waterborne diseases and is particularly noticeable both in urban areas where population densities are high, and in rural areas where water supplies are often unregulated (Rochelle-Newall et al., 2015). The study area comprises both urban and rural areas. Therefore access to clean water is a problem for the whole study area.

Future waterborne pathogen concentrations are influenced by climate and socio-economic changes. Several studies have focused on the impact of climate change on waterborne diseases (Moors et al., 2014, Rose et al., 2001, Freeman et al., 2009). However, very few studies quantified the relationship between changes in climate and pathogen concentrations (Vermeulen and Hofstra, 2013), and no such study has been published so far combining socio-economic development and climate-change scenarios. This thesis research is conducted simultaneously with that of Iqbal (2017), who quantified similar changes for the Kabul River in Pakistan. Our studies for the first time quantify and combine socio-economic and climate change impacts on microbial water quality in a developing country river.

This study aimed to better understand how climatic variables (e.g. floods, precipitation and temperature) and socio-economic developments (population growth, urbanization, land use and sanitation) affect Faecal Indicator Bacteria (FIB) concentrations and dynamics in the surface water of the Betna River through statistical and process-based modelling, and comprehensive scenario analysis. Four research questions (RQs) were defined in Chapter 1 and these were addressed separately in Chapter 2 to 5. The research methodology and flow of inputs used in this thesis are shown in Fig. 6.1. The main results are summarized in Table 6.1. In the next section (6.2) the four RQs and results are discussed and put in a broader context. Then, the scientific contribution and an outlook for future research on this topic are given in Sections 6.3 and 6.4. Finally a general conclusion is presented in Section 6.5.

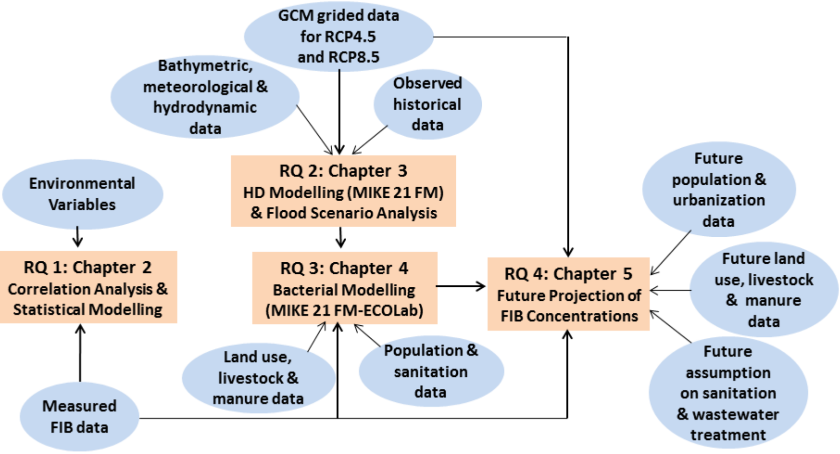

Fig. 6.1. Methodological framework applied in this thesis. Oval boxes are the inputs (data/variables) and rectangular boxes are the research questions and results (Chapter 2 to 5).

Table 6.1. Overview of the main results of four research questions and conclusions

Research Questions	**Main Results and Conclusions**
RQ1: What are the spatiotemporal variability of FIB (*E. coli* and enterococci) and how do environmental variables (water temperature, precipitation and salinity) impact on the FIB concentrations in the Betna River? *(Chapter 2)*	• 88% of the *E. coli* and all enterococci samples exceeded USEPA bathing water quality standards. Therefore, the river is unsuitable for swimming or bathing. • Precipitation sum over three days and water temperature were positively, and salinity was negatively correlated with the FIB concentrations in surface water of the Betna River. The developed linear regression model explained nearly half of the variation in FIB concentration (R^2 = 0.46 for *E. coli* and 0.48 for enterococci) by taking climatic and environmental variables into account. • Under climate change, the projected increased precipitation and associated runoff combined with increased water temperature may further increase the FIB concentrations. It is expected that waterborne pathogens behave similarly to environmental variables, indicating that disease outbreaks could well become more frequent and severe.
RQ2: What would be the impact of climate change on water level, discharge and floods in the Betna River basin? *(Chapter 3)*	• The water level is expected to increase up to 16% by the 2040s and 23% by the 2090s. The monsoon daily maximum discharge is expected to increase up to 13% by the 2040s and 21% by the 2090s. • The duration of water levels above the established danger threshold and extreme discharge events could increase by up to half a month by the 2040s and above one month by the 2090s. When the water danger level will coincide with the extreme discharge event, this could result in disastrous floods in the study area. • This result helps policy makers and water managers in preparation of flood risk mitigation planning and designing hydraulic structures.
RQ3: How do modelled and observed current concentrations of FIB in the surface water of the	• The model output corresponded very well with the measured FIB concentrations in the river and captured the spatial and temporal variations well. • The decay process, upstream concentrations and

river compare? *(Chapter 4)*	untreated wastewater discharge are the primary factors controlling FIB concentrations and their variability in the river. Tide, wind and diffuse sources (urban and agricultural runoff) were unlikely to have a major influence. • The model results also revealed that wastewater treatment could result in considerable improvement of the microbial river water quality. This underlines the need for treatment of wastewater before disposing them in the rivers and canals.
RQ4: What are the future projected FIB concentrations in the river's surface water under climate and socio-economic changes? *(Chapter 5)*	• The river microbial water quality was found to improve under a sustainable climate and an improved sewage treatment scenario. However, an uncontrolled future resulted in a deterioration of microbial water quality due to socio-economic changes, such as higher population growth, land use change and increased sewage discharges and changes in rainfall patterns. • FIB concentrations were found to be more sensitive to changes in socio-economic factors (i.e. human and animal population growth, urbanization, changes in sanitation and land use) than to the climatic changes (i.e. precipitation, discharge and temperature). • Future emission levels will depend on population growth, urbanisation, sanitation coverage, sewage systems and level of wastewater treatment. Major investments to construct wastewater treatment plants are necessary to compensate for the population growth and increased volume of wastewater generation.

6.2. Discussion on the research questions and main results

6.2.1. Spatiotemporal variability of FIB and impact of environmental variables on FIB concentrations (RQ1)

Access to an adequate quantity of clean and safe fresh water is essential to all living creatures. Deterioration of water quality has been a major concern worldwide as a result of population growth, intensive land use and increased industrial activities. Rivers have been treated as a convenient recipient of untreated wastewater, particularly in the developing countries. Besides, due to close linkage of climatic and surface water systems, water quality is affected by different climatic and environmental variables, such as air and water temperature, precipitation, and salinity (Kundzewicz and Krysanova, 2010). However, knowledge on the impact of environmental variables on microbial water quality in surface water sources are lacking worldwide, particularly in developing countries and in (sub)tropical climate. Most of the existing studies regarding the impact on pathogens/FIB have been conducted in developed countries and in temperate region (Chapter 1, Table 1.1). Although few studies have assessed the impact of climatic variables and flooding on cholera disease in Bangladesh (Ali et al., 2013, Hashizume et al., 2010), no studies have been performed on waterborne pathogens or FIB in Bangladesh. Moreover, in most of the existing studies, one environmental variable and one statistical method (either correlation or regression analysis) at a time were used (Chapter 1, Table 1.1). To reduce the knowledge gap and to answer RQ1, monthly water samples over twenty months (and 10 days additional sampling after 3 heavy rainfall events) were collected from different locations along the Betna River and then microbial analysis was performed to measure FIB concentrations. The FIB were measured, firstly to better understand their spatiotemporal variability and level of faecal contamination in the river (Chapter 2). Secondly, to explore the relationship between environmental variables and FIB concentrations by correlation analysis together with statistical modelling (Chapter 2). Finally, the measured FIB concentrations have been utilized to validate the microbial water quality model (Chapter 4).

The measured mean concentrations of *E. coli* (2.9–3.4 log cfu/100ml) and enterococci (3.5–4.0 log cfu/100ml) is comparable to few studies (Liu et al., 2009, Adingra et al., 2012), and slightly lower than few other studies (Lata et al., 2016, Widmer et al., 2013) conducted in developing countries. The measured concentrations are probably relatively low as a consequence of the tidal in and outflowing water and consequent low residence time of the bacteria. Significantly higher FIB concentrations were found during wet weather compared to dry weather. This indicates that diffuse sources contributed more during wet weather than during dry weather. This contribution corresponds with other studies (Ibekwe et al., 2011, Nguyen et al., 2016). Precipitation was positively correlated with FIB, because surface water is likely contaminated with manure through increased runoff from agricultural lands and urban areas (e.g. Satkhira town), leakage from manure storage areas and septic tanks. Other studies (Funari et al., 2012b, An et al., 2002, Abia et al., 2015, Vermeulen and Hofstra, 2013, Martinez et al., 2014, Isobe et al., 2004) reported similar reasons for the positive correlations between FIB concentrations and precipitation.

Most of the studies conducted in the temperate region showed a negative correlation between concentrations and water temperature (Shibata et al., 2004, Walters et al., 2011, Olyphant and Whitman, 2004, Vermeulen and Hofstra, 2013). In this study, water temperature was positively correlated, because the study area is situated in a seasonal subtropical climate, where during June to September frequent rainfall and high summer temperatures coincide. The same positive correlation was reported in other studies conducted in the tropics (Koirala et al., 2008, Kelly-Hope et al., 2007, Huang et al., 2008). These authors also relate it to the coincidence of high temperature and precipitation during the summer period. Therefore, the observed positive correlation with water temperature does not mean that temperature stimulated the increased FIB level in the study area. In some other studies FIB growth was suspected to be a possible reason for the positive relation between temperature and FIB (Byappanahalli et al., 2003, Tiefenthaler et al., 2009, Hong et al., 2010, Abia et al., 2015). However, FIB growth in the natural systems is not evident from literature. In the studied river, the residence time of the bacteria is low and long survival, growth and proliferation are unlikely.

In assessing climate change impacts on water quality, changes in the major climatic variables should be considered together. To assess the influence of temperature increase and precipitation pattern changes separately is not enough as the relative impact of precipitation change could be higher than that of temperature (Kundzewicz and Krysanova, 2010). Simple correlation analysis for each environmental variable separately is inadequate to explore the combined impact of the variables on the total contamination. Therefore, in this study a linear regression model was developed to explore the combined influence of dependant variables (temperature and precipitation) on the independent variable (FIB concentrations). The regression model (Chapter 2) explained nearly half of the variation in FIB concentration ($R^2 = 0.46$ for *E. coli* and 0.48 for enterococci) by taking climatic and environmental variables into account, even without considering other variables, such as locations, land-use, light intensity, decay rate of bacteria.

In most of the measured samples (88% of the *E. coli* and all enterococci) the USEPA bathing water quality standards were found to be violated. These FIB standards for bathing and drinking water are designed to guarantee limited disease risks. Therefore, the river Betna is unsuitable for bathing throughout the year. The potential health risks associated with the river water's use for domestic, bathing and irrigation purposes are too large. The frequent standard failures is not surprizing for the study area as the sewages enter directly to the river without treatment. FIB's are usually not pathogenic, but their presence indicate possible presence of harmful pathogens. Concentrations of FIB together with dose-response data are used to determine health risks. Under climate change, the projected increased precipitation and associated runoff combined with increased water temperature probably further increase the FIB concentrations. Waterborne pathogens behave similarly to environmental variables and this indicates that disease outbreaks could well become more frequent and severe.

6.2.2. Impact of climate change on water level, discharge and floods (RQ2)

Under climate change, the projected changes in precipitation patterns, increases in temperature and sea-level rise (SLR) increase the likelihood of future flooding in river basins. Process based modelling has recently been frequently applied to understand hydrodynamics of a basin and to assess the future flood potential (Jin et al., 2015, Kuchar and Iwański, 2014, Apurv et al., 2015, Ghosh and Dutta, 2012). However, these studies were based on mainly two climate change parameters (temperature and precipitation) and outputs of those studies were on river flows and floods. While water level is an important indicator of flooding, this has been ignored in those studies. In-depth studies assessing combined impacts of climate change and SLR on both water level and discharge are lacking. Moreover, quantifying climate change impacts on a relatively small basin like the Betna River have not previously been performed. Therefore, what climate change means for water level and discharge at the local scale remains poorly known.

In this study, the consequences of climate change on water level, discharge and associated floods in the river were addressed using the MIKE 21 FM hydrodynamic model. The hydrodynamic modelling is important mainly for two reasons. Firstly, in the coupled MIKE hydrodynamic and water quality model framework, a hydrodynamic module acts as a basis for the water quality module. Output of the hydrodynamic model is used as inputs to the water quality model (Chapter 4). Secondly, hydrodynamics (water level and discharge) are simulated because increased water level and discharge are responsible for floods in the river. Moreover, flooding is relevant with microbial water quality because direct contact with contaminated flood water is a plausible route of transmission of waterborne diseases (Kunii et al., 2002, Qadri et al., 2005).

The model results reveal a substantial increase in water level (16% by the 2040s and 23% by the 2090s) and monsoon discharges (13% by the 2040s and 21% by the 2090s) (Chapter 3). The combined influence of the increased water levels and discharges potentially causes major floods in the study area. Previous studies also reported similar results. For instance, Whitehead et al. (Whitehead et al., 2015) reported that the 15% increase of discharge in the Ganges, Brahmaputra and Meghna River systems by the 2050s potentially increases flood risk within Bangladesh. Increasing trends of water level and monsoon discharge of rivers in this region are also evident from other studies (Billah et al., 2015, Kirby et al., 2016). Our study further investigates the future scenarios of water levels, discharges and flood potentials in the Betna River. The results revealed that the duration of water levels above the established danger threshold and extreme discharge event could increase by up to half a month by the 2040s and above one month by the 2090s. When the water danger level coincides with the extreme discharge event (Chapter 3, Table 3.3, Fig. 3.6), it would cause disastrous floods in the study area.

Identifying trends and future scenarios of hydrodynamic characteristics is required for the effective management of water bodies. This is particularly important for the Betna River basin that experiences frequent flooding due to combined effects of extreme precipitation events and storm surges from the Bay of Bengal. This severely affects the surrounding agricultural land by prolonged inundation during monsoons and cause losses in terms of lives and livelihoods. Due to climate change more frequent and intense flooding is expected and this would exacerbate the already problematic situation in the basin. This signifies the importance of our climate change impact assessment on the river hydrodynamics and flood potentials. The results of our study increase the knowledge base on climate change influence on local water levels and discharges and are valuable for water managers in flood risk mitigation and water utilization. This information on present and future hydrodynamic conditions can thus assist policy makers and water managers to prepare for flood risks and designing hydraulic structures. This approach and results can potentially also be useful for the other areas of the world with similar geographic settings.

In this study, the applied process-based model (MIKE 21 FM) was forced with climate model output. Although this is a standard approach and the best we currently can do, this likely results in multiple uncertainties, because uncertainty accumulates throughout the process of climate-change projections and by making the necessary assumptions. We used bias-corrected data from only two global climate models for the climate change (RCP) scenarios. This may not suffice to substantially reduce uncertainties. The use of a larger number of climate models would better address the uncertainty in climate models (Zaman et al., 2016). The availability of the bathymetric and discharge data were limited. Therefore, to use more data and climate models is recommended to further improve the scenarios and increase their robustness. However, the comparison with the available data demonstrated a very good agreement between the observed and modelled water level and discharge. The MIKE model and the scenarios has been applied as the basis for rest of my thesis. The model and results can potentially be useful for other river basins in the world with similar geographic settings.

6.2.3. Modelling the fate and transport of FIB in the river water (RQ3)

The water-sample measurements in the Betna River during 2014–2015 revealed very poor microbial water quality due to widespread faecal contamination (Chapter 2). The present contamination level is a serious public health concern and needs to be addressed immediately. To mitigate the faecal contamination of the river water and to prevent the consequent health risks, knowledge on fate and transport of faecal contaminants, influences of different processes and contribution from different sources to the total contamination is essential. Some recent studies have published on the use of process-based models to assess microbial water quality in surface water (For a review see Chapter 1, Table 1.2). However, most of these studies have been conducted in the developed countries and the models mostly exclude contributions from different processes and sources, such as nonpoint (diffuse) sources. To increase the knowledge base and address RQ3, the fate and transport of FIB (*E. coli* and enterococci) within the Betna River were simulated using the coupled MIKE hydrodynamic and water quality model. Our study for the first time models Bangladeshi microbial water quality of a surface water source. The model effectively includes both point (untreated wastewater through sewer drains) and diffuse sources (urban and agricultural runoffs) of contaminants. The model calculates FIB concentrations in the river from human and animal populations, hydrology and die-off processes.

Generally, FIB die-off or decay rates depend on several environmental factors, such as sunlight intensity, temperature and salinity (Mancini, 1978). Usually, FIB decay rates increase with the increase in light intensity, temperature and salinity. Sunlight and temperature have the greatest impact on faecal coliform and *E. coli* (Gao et al., 2015, Liu et al., 2015b, Ouattara et al., 2013). However, due to lack of input data, the decay processes of FIB have been modelled using a constant decay rate in most studies (Bedri et al., 2014, Vijay et al., 2016, Menendez et al., 2013). In this thesis the decay rates of FIB were estimated based on all the three environmental parameters (temperature, salinity and sunlight intensity) measured at the study sites.

The model output corresponded very well with the measured FIB concentrations in the river (Chapter 4, Fig. 4.3). This validated water quality model was then applied for simulation of future microbial water quality scenarios in the next chapter (Chapter 5). According to the model results, the untreated wastewater from sewer drains and FIB inputs from the upstream river boundary are major polluters of the river. After heavy rainfall events a sudden high input of FIB were found (Chapter 4, Fig. 4.3) that can lead to severe contamination but only during a short period (around 3 days). A constant input of FIB through sewer drains during the dry period caused a lower contamination but the USEPA bathing water standards are still violated. So the river Betna is always unsuitable for bathing and domestic use (as also found from the measured data in Chapter 2).

The substantial variability of FIB concentrations (revealed both from the modelled and measured data) can hardly be assigned to a single process. Therefore, the model was also applied to test the influence of different processes and contributions from different sources by removing one process or source at a time from the model. These simulations revealed that the decay process, upstream boundary FIB inputs and untreated wastewater discharge are the primary factors controlling FIB concentrations and their variability, while tide, wind and diffuse sources (urban and agricultural runoff) were unlikely to have a major influence. Comparatively lower diffuse source contributions are also reported in other studies (Ouattara et al., 2013, Sokolova et al., 2012, Gao et al., 2015). Finally, the model was applied to investigate the influence of wastewater treatment on FIB concentrations. It revealed that wastewater treatment resulted in considerable improvement of microbial water quality of the Betna River and this is also evident from other studies (Vijay et al., 2016, Liu et al., 2015b, Ouattara et al., 2013). The high FIB inputs through the upstream open boundary is the contribution from untreated point source discharges from upstream urban areas and accumulation of small amounts of diffuse contaminants from the large upstream areas. Therefore, this study underlines the need for establishment of wastewater treatment plants both in the studied basin and upstream urban areas.

Our study provides insights in bacterial fate and transport mechanism and the contribution of different sources to the faecal contamination, and consists of an innovative scenario analysis in a subtropical river of a developing country. However, high temporal resolution measured FIB data and adequate discharge data are missing. Contaminants load from septic tank leakage, open defecation and sediment resuspension data were also unavailable. These essential data unfortunately limit the full evaluation of the model's performance. However, the model captured the measured FIB variability well. This suggests that the model can be applied to microbial water-quality assessments in the other watersheds of the world with similar characteristics. Using more input data is recommended to further improve the model's performance. The developed model could be an appropriate tool to forecast future impacts of climate change and socio-economic development on FIB fate, transport and dynamics (as is done in Chapter 5). It provides a basis for the water managers in reducing the widespread faecal contamination and the risks of waterborne disease outbreaks, which are the leading cause of deaths in developing countries like Bangladesh.

6.2.4. Impact of socio-economic and climate changes on FIB concentrations (RQ4)

Concerns over surface water quality have been growing in recent years due to widespread faecal contamination of surface water sources. The Betna River is already highly contaminated and this is expected to deteriorate further due to climate change. Future waterborne pathogen concentrations and consequent health risk are also related to socio-economic conditions. Several studies have focused on the impact of climate change on waterborne diseases (Moors et al., 2014, Rose et al., 2001, Freeman et al., 2009). However, changes in socio-economic conditions are often not adequately incorporated in such climate change impact assessment studies (Berkhout et al., 2002). Some studies focused only on impacts on river hydrodynamic characteristics due to future climate changes ignoring socio-economic changes (Kuchar and Iwański, 2014, Elshemy and Khadr, 2015, Liu and Chan, 2015). Some studies assessed the future impacts of climate change and socio-economic changes on water flow or nutrient flux, but no study focused on microbial water quality (Whitehead et al., 2015, Jin et al., 2015). Moreover, most studies developed the scenarios separately without consistently combining socio-economic and climate change variables. Only few recent studies have applied a more consistent approach. For instance, Boris et al. (Borris et al., 2016) used this approach to assess urban storm-water quality (focussing on suspended solids and heavy metals) and Zhuo et al. (Zhuo et al., 2016) to quantify agricultural water availability. However, no quantitative study on surface water microbial water quality under socio-economic and climate changes scenarios has been published so far.

To reduce this knowledge gap and to address the final research question (RQ4), this study explores the future impacts of socio-economic and climate changes on FIB (*E. coli* and enterococci) concentrations in the river using the coupled hydrodynamic and microbial model (MIKE 21 FM-ECOLab). The scenarios comprise changes in population, urbanization, land use, sanitation, sewage treatment, temperature, precipitation and sea level rise for the 2040s and 2090s. Two scenarios (S1 and S2) are based on Shared Socio-economic Pathways: SSP1 and SSP3, and Representative Concentration Pathways: RCP4.5 and RCP8.5. These SSPs and RCP are combined in a matrix, as is currently common practice in research that informs the Intergovernmental Panel on Climate Change (IPCC). This approach also allows to interpret our own storylines. Two global climate models (MPI-ESM-LR and IPSL-CM5A-LR) were selected to provide the potential change in future climates. We have made our own assumptions on sanitation and waste water for the 2040s and 2090s (c.f. Table 5.1 in Chapter 5). The two scenarios had a strong impact on FIB concentrations in the river. An uncontrolled future scenario deteriorated microbial water quality due to higher population growth, land-use change, increased sewage discharges and changes in rainfall patterns. However, microbial water quality improved considerably under a sustainable climate and improved sewage treatment.

In general, FIB concentrations were more sensitive to changes in SSPs (e.g. human and animal population growth, urbanization, change in sanitation and land use) than to the RCPs (e.g. precipitation, discharge and temperature). This is in agreement with the study of Boris et al. (Borris et al., 2016) and Sterk et al. (Sterk et al., 2016). While, processes like die-off, pathogen release, surface runoff fluxes and dilution were (positively or negatively) affected due to the influence of climatic factors, the net influence on the pathogen concentration in surface waters was limited (Sterk et al., 2016). In other words, climate change has little overall impact and socio-economic developments drove most impacts on the FIB concentrations in the river water. This underlines the importance of socio-economic factors in assessing and improving microbial water quality. Since the climatic factors have a lower influence on the concentrations, microbial water quality in the river can be improved substantially by applying adequate wastewater treatment both in the Betna basin and upstream areas.

The scenario analysis also suggests that future FIB emission levels are mostly, but not only, influenced by population growth. Other factors, such as urbanisation, sanitation coverage, sewage systems and level of wastewater treatment also contribute substantially to the elevated FIB concentrations in the studied basin. This underlines the importance of improvements in sanitation and wastewater treatment in the Betna River basin to ensure lower future FIB concentrations in the river within the standards of USEPA bathing water quality. Major investments to construct wastewater treatment plants are necessary to compensate for the population growth and increased volume of wastewater generation. Although the current contamination level is already too high, without wastewater treatment the water quality will further deteriorate. As a result, domestic water use, aquaculture and recreation/swimming will increasingly be affected. This could lead to shellfish contamination and thus cause serious health risk to the people by their consumption of contaminated shellfish.

Assessing microbial surface water quality is important, as it is related to public health risk when the people are exposed through drinking, recreation or consumption of shell fishes and irrigated vegetables (Rochelle-Newall et al., 2015). The microbial surface water quality is expected to change with socio-economic development and climate change. Climate change induced increased flooding increases exposure of people to the polluted surface water. Climate change may also impact the natural balance between environmental variables and host-pathogen relationships. Climate change induced new environmental stressors which probably expedite the spread of waterborne diseases, exacerbate disease where they already exist, or result in the occurrence of new pathogens (Vogelbein et al., 2008). Disease arises in an individual or population as a result of the interactions between environment, pathogen, and host. Outbreaks of a disease occur when one of the components shifts (Vogelbein et al., 2008). Therefore, knowledge on present and future river microbial water quality is important and has a strong significance for public health.

Under current situation, disease risks in the study area are already high, and the risks are unlikely to increase with increase in FIB concentrations. Moreover, the results show that socio-economic development and climate change did not cause a strong increase in FIB concentrations. However, in the sustainable future scenario, strong reductions in the concentrations were found, and the concentrations even reduce to below the bathing water standards. The bathing water standards have been set to ensure safe bathing water, therefore under the sustainable future scenario, the reduction in concentrations would likely lead to a lower disease risk. This finding signifies the importance of the future scenario analysis of FIB concentrations. The results provide valuable information for water managers to reduce the widespread faecal contamination and the risks of waterborne disease outbreaks.

6.3. Contribution to science and policy implication

The thesis assesses the present and future hydrodynamics and FIB concentrations in the Bangladeshi Betna River. While hydrodynamic modeling approaches have been applied for larger basins in South Asia (Jin et al., 2015, Kuchar and Iwański, 2014, Apurv et al., 2015, Ghosh and Dutta, 2012), no such studies have been performed for a relatively small basin like the Betna River. Exploring present hydrodynamics and future flooding potential in a changing climate and sea-level rise in such a basin is also new. This study thus reduces the knowledge gap on climate change influence on future local flooding scenarios.

Quantitative information on microbial water quality is lacking worldwide, particularly in developing countries and in (sub)tropical climate. Our study's results contribute to increasing the knowledge base on the dynamic distributions of FIB in surface water in a developing country in a subtropical system. While most previous studies focused on assessing only climate-change impact on microbial water quality, our study assessed the influence of combined climate and socio-economic scenarios (using scenarios based on the new SSP-RCP scenario matrix framework) on FIB concentrations in surface water. We have made assumptions for future sanitation and wastewater treatment, scenarios that are lacking worldwide and that do not exist for Bangladesh. Robust estimates were obtained using process-based modeling and scenario analysis under climate change and socio-economic developments. This approach shows considerable impacts on microbial water quality. The study provides improved quantitative information on the present and future hydrodynamics and FIB concentrations in the river. We show that the impact socio-economic developments on the river faecal contamination is higher than climate change and microbial water quality in the river can be improved substantially by applying adequate wastewater treatment. The developed model is an ideal tool for quantifying the future influence of climate change and socio-economic developments on FIB fate, transport and dynamics. The findings of this study on the present and future FIB concentrations will be helpful for water managers and public health professionals because they provide the necessary insights in present and future microbial water quality. The obtained concentrations along with dose-response and exposure data, can be used to determine health risks associated with the use of untreated surface water. Moreover, the scenarios and model can also be used in related fields, such as water pollution caused by heavy metals, nutrients, industrial effluents etc. These results can be utilized by a broad scientific community involved in water, climate, food security and socio-economic research.

This study is also very relevant and important for Bangladesh. Its results contribute well to the national government initiative to develop appropriate flood and health risk management strategies. It clearly assessed the impact of socio-economic development and climate change on flood and faecal contamination in Bangladesh. In addition to disseminating the results through posters, conferences and research publications, my position as an employee in the Ministry of Planning, Government of Bangladesh will be helpful to disseminate the results to the policy makers and non-governmental organisations (NGOs) in Bangladesh. My insights and information will be helpful to formulate policy and manage the increased flood risk and reduce the elevated health risk caused by faecal contamination. The findings on present and future river faecal contamination would be useful for formulation and implementation of the proposed water safety plan for southern Bangladesh.

6.4. Outlook for further research

This thesis focussed on the combined impacts of climate and socio-economic changes (based on the new SSP and RCP scenarios integrated in a matrix) on local river hydrodynamics and microbial water quality. The developed model in this study has the potential to include the impacts of water availability and water use changes (e.g. construction of upstream reservoir/dam, future water extractions). The next research step could be testing of adaptation strategies, for instance, to test the appropriateness of flow regulation (construction of reservoirs) to regulate low flows during dry periods. Similarly, to quantify the influence of future water transfer plans (e.g. India and China’s proposed dams in the upstream rivers of Bangladesh, India's national river linking project) on the high flows during monsoon. The river flows are important because increased flows are responsible for floods and decreased flow can cause droughts. Flooding is relevant for microbial water quality too, because direct contact with contaminated flood water can cause waterborne diseases (Kunii et al., 2002, Qadri et al., 2005).

Implementation of the coupled hydrodynamic and water quality models at the larger regional scale could be another next step to obtain more realistic projections of coarse-scale water quality and availability in transboundary and regional watersheds. Not only sufficient water availability (quantity) but also suitable water quality is required for the water use sectors and for sustainable water supply. Improved understanding of how global change (climate, socio-economic and land-use changes) will affect water resources (water availability and quality) and cross-sectoral water uses will be important for sustainable water supply and development. Water-use scenario analysis is challenging, because it needs to project the society, industry and future technological development. The water-use scenarios development should reflect both quantitative (e.g. population, irrigation) and qualitative (e.g. degree of technological change) socio-economic factors (Hanasaki et al., 2013). Substantial efforts are needed to combine storylines of these different factors to better project future water use consistent with socio-economic developments.

Considering the growing consensus on the need for information about climate and socio-economic change impacts on water quality (Kundzewicz and Krysanova, 2010, Whitehead et al., 2015) and consequent health risks, an extension of the modelling framework to other water quality parameters which affects FIB (e.g. salinity, dissolved oxygen, nutrients and chlorophyll-a), could be an important next step. Although salinity and nutrient concentrations have direct impact on agricultural and domestic water uses, they only have an indirect impact on waterborne pathogens/FIB. Therefore, a multi-pollutant (nutrient, plastic, chemical and pathogens) modelling approach as proposed by (Kroeze et al., 2016) could be an advanced next step to explicitly address the combined exposure of surface waters to multiple pollutants and to better understand and manage water resources. Future studies may also consider accumulation of pollutants (e.g. microplastics, phosphorus and metals) in soils and sediments.

The developed model can also be applied for a quantitative microbial risk assessment by combining inputs of pathogens, faecal indicators, and microbial source tracking markers. Data on pathogen concentrations is much more sparse than FIB data. To quantify and model waterborne pathogen distribution and dynamics and to perform such risk assessment for climate change by incorporating pathogens instead of relying solely on indicator bacteria should be an interesting next step.

6.5. Conclusions

Microbial surface-water quality is expected to change with socio-economic development and climate change. Identifying trends and future scenarios for microbial water quality caused by socio-economic and climate changes are required to assess health risks and effectively manage surface water sources. However, quantitative information on future river microbial water quality is lacking worldwide. This thesis reduces this knowledge gap and provides enhanced understanding on the present and future FIB dynamics in the Betna River. This thesis provides better understanding on the application of fate and transport modelling of faecal contamination in surface water in the context of a subtropical developing country Bangladesh, where this type of study is completely new. For this, simultaneous measurement, statistical and process-based modelling and scenario analysis were performed. This study combines the new climate and socio-economic scenarios to simulate future microbial water quality of the river. The present and future river hydrodynamics and flood potential are also explored as a related and complementary study with microbial modelling. This information on the present and future hydrodynamic conditions can assist policy makers and water managers to prepare for flood-risk mitigation planning and design adequate flood protection structures. 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 applicability of the model to assess the impact of land-use changes and wastewater-treatment planning on microbial water quality in the rivers. The methodology developed in this study is likely useful for water managers in planning climate change adaptation strategies based on local situations. Microbial pollution is a major concern all over the world. So the results of this study will also serve as a test case for other regions of the world especially for the areas with similar climate and socio-economic conditions.

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Summary

Consumption of water that is contaminated with pathogens still causes high numbers of death and disease. Understanding the factors that influence the dynamic distribution of waterborne pathogens is important, as this will help understanding improvements and possible solutions. Such understanding is particularly important in a developing country like Bangladesh, where large proportions of the population often have little or no access to clean water. Despite the high relevance for public health, few studies currently exists on the fate and transport of pathogens and the so-called Faecal Indicator Bacteria (FIB, e.g. *E. coli,* enterococci) in (sub)tropical systems. FIB are susceptible to shifts in water flow and quality. The predicted increases in rainfall and floods due to climate change will exacerbate the faecal contamination scenarios. This could be further compounded by the rapid change in socio-economic conditions (population growth, urbanization, sanitation and agricultural management) in the developing countries. Therefore, to reduce future health risks, understanding the influence of changes in socio-economic conditions and climate on microbial dynamics is important.

Very few studies have quantified the relationship between the waterborne pathogens/FIB concentrations and climate and socio-economic changes. In this study a process-based model was developed and a scenario analysis was performed based on the new combined climate and socio-economic changes scenarios, to assess the present and future river hydrodynamics, FIB sources, die-off processes and concentrations. We used FIB, because measuring FIB are cheaper than pathogens. FIB are usually not pathogenic but their presence indicates the likely presence of waterborne pathogens. These pathogens are expected to respond to climate change in a comparable way to FIB. The present study is based on the Betna River basin in southwestern Bangladesh, where faecal contamination is not monitored and very little knowledge exists on the distribution of contaminants.

First of all, FIB concentrations of the river water were measured to identify the river's faecal contamination levels that can be used to validate the water-quality model. In the study area, wastewater is not treated and this untreated wastewater is discharged directly into the river. This is evident from the measured FIB data. In 88% of the *E. coli* and all enterococci samples, the USEPA bathing water quality standards were violated (Chapter 2). Such violation indicates potential health risks associated with the use of the river water for domestic, bathing and irrigation purposes. The correlation between environmental variables (water temperature, precipitation and salinity) and FIB concentrations was also

determined. A positive correlation was found with water temperature and precipitation, and a negative correlation with salinity. The positive correlation with temperature is due to the co-occurrence of high summer temperature with abundant monsoon rainfall. The positive correlation with precipitation can be explained by the increased runoff from agricultural lands and urban areas. This runoff contains many bacteria. In the study area, during the rainy season (July to September) precipitation increases and as a result water salinity decreases. The observed negative correlation with salinity is more likely due to the typical weather patterns during the rainy season when low salinity coincides with increased precipitation and high temperature, than to salinity dependent die-off of bacteria. A regression model was applied that explained almost half of *E. coli* and enterococci variability in river water. This, however, only considers water temperature and precipitation (Chapter 2).

Then, the present and future hydrodynamics of the river were simulated using a two-dimensional hydrodynamic model (MIKE 21 FM). Although the main goal of this thesis is to assess the river's present and future FIB concentrations, the reasons for this hydrodynamic modelling are twofold. Firstly, outputs of the hydrodynamic model are used as input into the water-quality model (Chapter 4). Secondly, hydrodynamics (i.e. water level and discharge) are simulated because increased water level and discharge together with sea level rise stimulate floods in the river basin. These floods are related to outbreaks of waterborne diseases. The modelled results corresponded very well with the measured water levels and discharges. The model was applied to simulate baseline and future water levels and discharge for Representative Concentration Pathway RCP4.5 and RCP8.5 scenarios using bias-corrected downscaled data from two climate models (IPSL-CM5A and MPI-ESM). The model results showed an expected increase in water level up to 16% by the 2040s and 23% by the 2090s (Chapter 3). The monsoon daily maximum discharge was expected to increase up to 13% by the 2040s and 21% by the 2090s. These model results also showed that the duration of the water level above the danger level and extreme discharge periods can increase by half a month by the 2040s and over a month by the 2090s. The coincidence of the water danger level with extreme discharge may cause disastrous floods in the study area.

Next, the hydrodynamic model was coupled with a water-quality module (ECOLab). The fate and transport of FIB was simulated, the influence of different processes tested and the contribution from different sources to the total contamination quantified (Chapter 4). The model outputs corresponded very well with the measured FIB data. The present river microbial water quality based on measured and simulated results indicated, once again, noncompliance with bathing water standards. Primary and secondary levels of wastewater treatment were not sufficient to reach the standards most of the time, and discharges from sewer drains and incoming concentrations from the upstream boundary were found to be a major cause of water contamination. Tide, wind and diffuse sources (urban and agricultural runoff) contributed little. The high FIB inputs from the upstream open boundary come from untreated point source discharges from upstream urban areas and accumulation of diffuse contaminants from the large upstream areas. Therefore, this study underlines the need for establishment of wastewater treatment plants both in the studied basin and upstream urban areas. This study provides insight into bacterial fate and transport mechanisms, contribution of different sources to the faecal contamination and applicability of wastewater treatment in a river of a subtropical developing country where this type of study is lacking. Uncertainties are related to the lack of high temporal resolution measured FIB data and the lack of available data for contaminant loads from septic tank leakages, open defecation and sediment resuspension. However, the model well captured the measured FIB variability, suggesting that it can be applied for microbial water quality assessments in other watersheds of the world with similar characteristics. The developed model could be an ideal tool to forecast future impacts of climate and socio-economic changes on FIB fate, transport and dynamics.

Finally, future FIB concentrations were simulated using the coupled hydrodynamic and microbial model (MIKE 21 FM-ECOLab) and scenario analysis (Chapter 5). Scenarios have been developed building on the most recent Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) scenarios from the Intergovernmental Panel on Climate Change (IPCC). We developed a baseline scenario (October 2014–September 2015) reflecting the current conditions and two future scenarios, S1 (sustainability scenario) and S2 (uncontrolled scenario) mimicking different future developments of socio-economic (population, urbanization, sanitation, wastewater treatment development, land use) and climate-change factors (temperature, precipitation and sea-level rise). In S1 RCP4.5 was combined with socio-economic scenarios SSP1, and for S2 RCP8.5 was combined with SSP3 (S2). Assumptions on sanitation, waste water treatment and agricultural management in line with the storylines were made to quantify future changes in FIB concentrations and consequent health risk. Different future scenarios were found to have substantial impact on FIB concentrations in the river. By the 2090s, FIB concentrations are expected to decrease by 98% or increase by 75% for the sustainability scenario and uncontrolled scenario respectively. An uncontrolled future resulted in a deterioration of microbial water quality due to socio-economic developments, such as higher population growth, land-use change and increased sewage discharges and changes in rainfall patterns. Microbial water quality strongly improved under a sustainable climate and improved sewage treatment. FIB concentrations were much more sensitive to changes in socio-economic factors than to changes in climatic factors. This underlines the importance of socio-economic factors in assessing and improving microbial water quality.

The results show the importance of improvements in sanitation and wastewater treatment in the Bangladeshi Betna River basin to ensure that future FIB concentrations in the river comply with the US-EPA bathing water quality standards. Major investments to construct wastewater treatment plants are necessary to compensate for the population growth and increased the volume of wastewater treatment. Although the current level of contamination is already too high, without wastewater treatment the water quality will further deteriorate.

The thesis assesses the present and future FIB dynamics in the Betna River through sampling, statistical and process-based modelling, and scenario analysis. The results contribute to increase the knowledge base on the dynamic distributions of the FIB in surface water in a developing country and in a subtropical system, where this type of study is lacking. It also reduces the knowledge gaps regarding future flooding scenarios at the local scale. While some earlier studies focused on only assessing climate-change impacts on microbial water quality, this study for the first time assessed the influence of combined climate and socio-economic scenarios (using scenarios based on the new SSP-RCP scenario matrix) on river FIB concentrations. This combined modelling and scenario approach enables the assessment of faecal contamination sources and dynamics at present and in the future. The developed model and scenario analysis approach provides a basis for the water managers to reduce the widespread faecal contamination and the risks of waterborne disease outbreaks, which are still a leading cause of deaths in developing countries.

About the Author

M. M. Majedul Islam was born in a small village in Khulna, Bangladesh. He started his career as a research assistant in a project entitled “Estimation of Environmental Capacity and Management of Shrimp Culture in Southwest Bangladesh” just after getting his bachelor degree in Fisheries and Marine Resource Technology from Khulna University, Bangladesh.

He got masters in the same discipline and the same university in 2005. For his master’s thesis, he studied on the “Nutrient Budget of Shrimp Culture Ponds in Southwest Coastal Region of Bangladesh.” He then joined the Bangladesh Civil Service in 2006. While working with the Ministry of Planning as an Assistant Chief, he got ADB-JSP fellowship in 2007 to study Masters of Environmental Studies at the University of Tokyo, Japan. In this second masters, he studied “Modelling Combined Sewerage Overflow Induced *E. coli* and Adenovirus Transport in the Odaiba Area, Tokyo Bay.” After completion in 2009, he again joined the Bangladesh Civil Service. He got promoted as a Senior Assistant Chief and joined the Ministry of Agriculture in 2012.

In July 2013, he started his PhD study at the Environmental System Analysis Group of Wageningen University with a fellowship from Government of Bangladesh. During his PhD, he has been collaborated with Department of Civil and Environmental Engineering, Chalmers Institute of Technology in Sweden and the Environmental Sciences Discipline of Khulna University in Bangladesh. He has attended workshops and conferences in different countries, including Sweden, Germany, Italy and Portugal. For his PhD research, he modelled hydrodynamic and microbial water quality in the Betna River basin in southwest Bangladesh. This is an important new study in the Bangladeshi context. Its results contribute well to the national government initiative to develop appropriate flood and health risk management strategies. His position as an employee in the Ministry of Planning, Government of Bangladesh will help to disseminate the results to the policy makers and non-governmental organisations (NGOs) in Bangladesh. The findings on present and future river faecal contamination would facilitate the formulation and implementation of the proposed water-safety plan for southern Bangladesh.

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The SENSE Research School declares that **Mr M.M. Majedul Islam** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 32.6 EC, including the following activities:

SENSE PhD Courses

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- Techniques for writing and presenting a scientific paper, Wageningen University (2013)
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