2018

Application of SWMM to analyse the effect of sewage water treatment on water quality in Guwahati, India

MASTER THESIS - RIANNE BOKS

UNIVERSITY OF TWENTE & ARCADIS

AUGUST 21, 2018

Application of SWMM to analyse the effect of sewage water treatment on water quality in Guwahati, India

Master thesis Water Engineering & Management

University of Twente

Faculty of Engineering Technology

Civil Engineering & Management

Author

H.J. (Rianne) Boks BSc
h.j.boks@student.utwente.nl

Graduation committee

University of Twente, Department of Water Engineering and Management
Dr. Ir. D.C.M. Augustijn
Dr. M.S. Krol

Arcadis Nederland, Waterbeheer en Landschap ZW
Ir. K.C. de Vries

Enschede, August 2018

Picture front page

Sewage dumped along water stream in Guwahati. This picture is made by Arcadis on a trip to Guwahati in January 2017

ABSTRACT

Drastic population growth in India in the last decades has resulted in uncontrolled development and urbanisation in many cities. In 2015, the Government of India launched the Smart Cities Mission in which adequate water supply, sanitation and solid waste management are part of the core infrastructural elements of a smart city. Guwahati, the largest city in the state of Assam and situated at the banks of the Brahmaputra River, has been selected for this programme as it has also observed this rapid growth of population. The absence of a sewage treatment plant (STP) in the entire state of Assam results in direct discharge of untreated sewage waste into the open surface waters of Guwahati. Hence, the need for sewage water treatment is high, but due to the complexity of the water system and lack of data in Guwahati, there is a limited overview of how to act to improve the water quality in the most efficient way. This study had two major purposes: (1) to obtain an in-depth understanding of the water quality in the Guwahati water system in relation to how it functions and (2) to identify effective sewage water treatment management scenarios to improve the water quality in Guwahati. Water quality aspects were added to an existing schematisation of Guwahati for quantitative water management in the Storm Water Management Model (SWMM). It was then used for system analysis and to assess the effect of each scenario on improving the water quality in the area.

Considering the population in 2050 can increase by as much as 50% from the reference 2025 population, it will consequently also increase the amount of sewage water being generated, eventually ending up in the water system. Investigated scenarios ranged from projecting the future with both centralised and decentralised STPs to diverting flows and addition of extra capacity to treat part of the storm water runoff, which were compared to a worst-case scenario in which no measures were taken. Results from SWMM revealed that all selected scenarios managed to lower both pollutant load and concentration in the focused water bodies. However, the scenarios were not able to completely fulfil the goals of adequate sanitation and solid waste management, hence not improving the water quality to desirable concentrations.

The distinct seasonality in climate, alternating between large rainfall events in summer and no rainfall in winter, largely influences the flow and water quality in the water system of Guwahati. During dry season the water system is mainly fed by raw sewage water from the city which is reflected in high pollutant concentrations, in contrast to lower pollutant concentrations during monsoon season when pollution is diluted with a large volume of storm water runoff. Especially during dry winter season the water quality is poorest, but in this period all scenarios showed to be most effective in improving the water quality. Furthermore, the addition of extra treatment capacity to treat most incoming flow during monsoon season had little effect, neither was a correlation found between total combined treatment capacity of all STPs and reduction in pollutant load from the complete study area. The location and number of STPs throughout the area, on the other hand, were found to have a measurable impact on pollutant concentrations in the lake as well as the reduction in total pollutant load from the study area. A more decentralised approach would lead to a greater reduction in pollutant load, but not necessarily a large improvement in lake water quality.

To conclude, this study showed that the scenario and STP selection greatly depends on the final goal, whether the local authority prioritises plans to improve water quality in the city or primarily in the selected water bodies. Based on a limited available budget and prioritising improvement in the lakes only, scenario 1, having two centralised STPs, would be the best, but for maximum impact in both lakes as well as the city, scenario 3, with four smaller decentralised STPs in combination with diverting flow to Deepor Beel, shows more potential.

PREFACE

This research has been the final part of my study Civil Engineering and Management, specialisation in Water Engineering and Management at the University of Twente. It has been a pleasure to study at the University of Twente and it helped me to successfully carry out this research. This report gives an analysis of the water quality in Guwahati and the effect of sewage water treatment scenarios to improve the water quality situation in the area. Poor water quality is becoming an increasing and concerning issue for the world's water resources. This research has made me realise the water system in the Netherlands is well organised whereas in many developing countries this is not self-evident.

During my time at Arcadis, I have learned a lot on water quality as well as (sewage) water management in urban and rural areas in India as well as in the Netherlands. The culture difference between India and the Netherlands and working with an unknown model for me, were not always the easiest parts, but made this research a lot more interesting.

I am really thankful for being able to conduct my research at Arcadis which has given me a lot of new insights and possibilities. I want to thank Kees de Vries for guiding me through the process of carrying out this research, especially by providing me feedback and taking me more into the Guwahati project with meetings, introducing me to people and interesting stories. I also want to thank Denie Augustijn and Maarten Krol, my supervisors at the University of Twente, who were always available for answering questions and taking time to reflect on my report and progress. Furthermore, I want to thank my colleagues at Arcadis for giving me a pleasant time in the office and providing all the possibilities to join meetings, activities and excursions. Last, I want to thank my friends and family for helping me, reading my report and being there during the process of writing this thesis.

Rianne Boks

Amsterdam, August 2018

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

BIS – Bureau of Indian Standards

BOD – Biochemical oxygen demand

CPCB – Central Pollution Control Board

DWF – Dry weather flow (also called sanitary flow)

EPA – Environmental Protection Agency

GMA – Guwahati Metropolitan Area

GMCA - Guwahati Municipal Corporation Area

GMDA – Guwahati Municipal Development Authority

LULC – Land Use Land Cover

MLD – Million litres per day

MSW – Municipal solid waste

SWMM – Storm Water Management Model

PCBA – Pollution Control Board Assam

P.e. – Population equivalent

TN – Total nitrogen

TP – Total phosphorous

TSS – Total suspended solids

SDG – Sustainable Development Goals

STP – Sewage water treatment plant

WWF – Wet weather flow (also called storm water runoff)

UN – United Nations

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Background information

In recent decades, India has observed drastic population growth resulting in unplanned development of several large cities which are unsustainable and unfriendly to live in. The increased urbanisation and economic development in the cities has led to overuse of natural resources and increased wastewater generation (Sharma, Yadav, & Gupta, 2017). Many cities are not able to handle the rapid increase of wastewater generation, resulting in water pollution. Water pollution in India is a serious issue considering that almost 80% of the surface water is polluted and an increasing percentage of the groundwater gets contaminated (Sharma et al., 2017). The residential sewage water is considered to be one of the major contributors of this pollution together with industrial and agricultural activities. Inadequate sanitation facilities have been one of the primary reasons for groundwater and surface water pollution. According to the Central Pollution Control Board (CPCB) the available total sewage treatment capacity is only 37% of the total generated sewage in the urban areas (Central Pollution Control Board, 2015). However, based on several reports on the performance of sewage treatment plants (STP) in India, the used capacity for sewage treatment is far lower than its designed capacity. Poor maintenance, inadequate capacity, lack of skilled personnel and absence of underground sewerage connections are reasons for the underutilised capacity of the STPs (Arappor Iyakkam, 2018; Central Pollution Control Board, 2013). In general, sewage water collection and treatment has not been a priority by state governments as compared to water supply (Kamyotra & Bhardwaj, 2011). Additionally, India has to deal with increasing water scarcity in which water pollution also has a large share in decreasing the country's water resources, making sewage water treatment inevitable (Sharma et al., 2017). Wastewater treatment is seen as an essential element for human and ecosystem's health in developed countries, but for most developing countries it is immensely expensive (Kamyotra & Bhardwaj, 2011).

In 2015, the government of India under leadership of prime minister Modi, launched the Smart Cities Mission, a programme that focuses on the comprehensive development of physical, institutional, social and economic infrastructure, so the quality of life and sustainability of Indian cities will be assured. The definition of 'smart city' varies between cities and the government of India has not defined any specific guideline, enabling the local governments to formulate their own vision and plan suitable to their local conditions and ambitions. This could be retrofitting, redevelopment or greenfield development (Ministry of Urban Development, 2015). In this programme adequate water supply, sanitation and solid waste management are part of the core infrastructural elements of a smart city. These aspects are also reflected in the global Sustainable Development Goals (SDG) developed by the United Nations (2015).

Guwahati, the largest city in North-East India, is the only city from the state of Assam selected in this programme. Being located on the southern banks of the Brahmaputra River (Figure 1) it has access to fresh water. However, the significant seasonal flow differences make the water system of the city immensely complex facing dry periods during winter (December-March) and severe vulnerability from flooding during monsoon period (July-September) (Bordoloi, 2015). Additionally, a vast population growth in the last decades, reaching 1 million in 2011, has resulted in uncontrolled development around Guwahati (Census, 2011; Government of Assam, 2016) and nearby storm water storage basins (Ramsar, 2002). The unplanned and uncontrolled urbanisation has reduced the water system's capacity through restricting their areal extent subsequently making the city more susceptible to seasonal floods (Bhateria & Jain, 2016). Additionally, the drainage channels are filled with garbage lowering the storage capacity and transport of storm water even more.

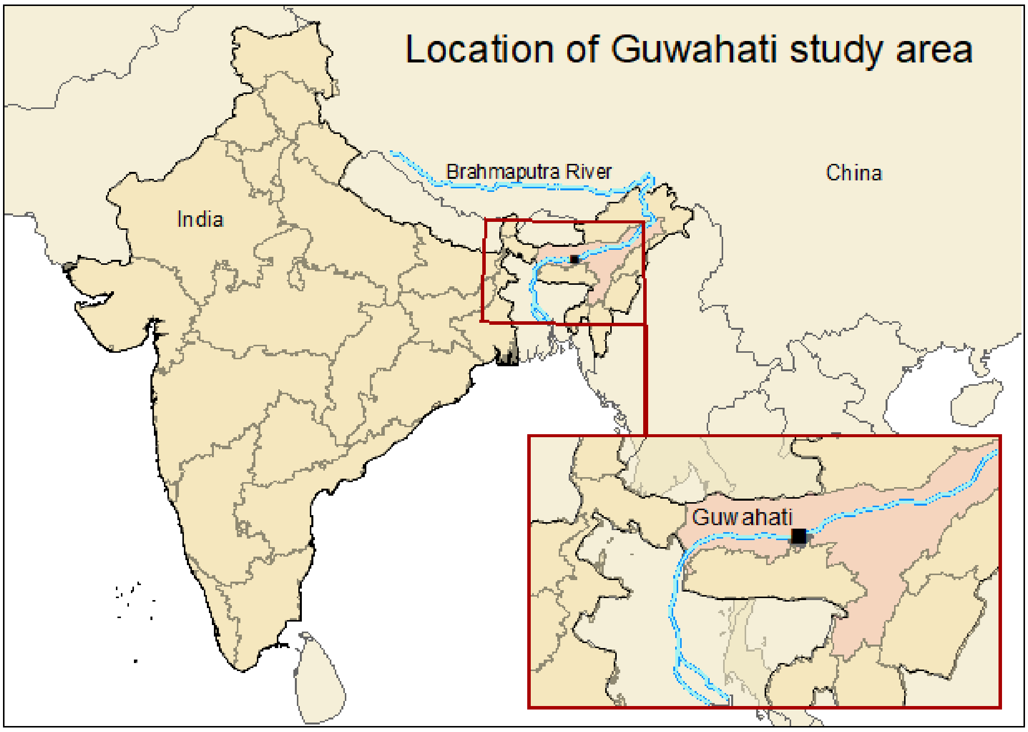


Figure 1: Guwahati is located on the southern banks of the Brahmaputra River in North-East India

The water quality in the Brahmaputra River (Government of Assam, 2016; Ministry of Statistics & Programme Implementation, 2016) as well as in the water system of Guwahati and the nearby wetland Deepor Beel (Bhattacharyya & Kapil, 2010; Dutta, Gogoi, Khanikar, Bose, & Sarma, 2016; Government of Assam, 2016; Sayed, Kumar, & Ajay, 2015; Water Pollution Control Board Assam, 2017) is in a deteriorating state. The main sources of pollution in surrounding water bodies of Guwahati are considered to be domestic sewage, industrial effluents and storm water surface runoff (Government of Assam, 2016). One of the reasons for the deteriorating water quality is the absence of a sewage treatment plant in the entire state of Assam resulting in direct discharge of untreated sewage waste into the water system of Guwahati. Hence, the anthropogenic activities together with the population growth resulting in increased residential land cover, form a threat to the water quality in Guwahati and surrounding areas (Government of Assam, 2016).

1.2 Problem definition

Population growth, the rapid uncontrolled urbanisation and the absence of sewage treatment plant results in sewage water being directly dumped into the natural drainage channels deteriorating the state of water quality in the area (Deka & Devi, 2017). The increase in local people's dependency on the adjacent water bodies also amplifies the importance of addressing the water quality issue and the necessity of sewage water treatment. In accordance with the norms of the Government of India, a city with a population of over 750 000 is obliged to have adequate facilities of sewerage and sewage treatment in the city.

Due to the complexity, size and variety of problems in Guwahati there is a limited overview of how to act and respond best to these problems. Additionally, there is limited availability of information and data on water quality as well as on pollution loads and the impact from specific (point) sources into the water system. In order to improve the water quality in the area, it is necessary to identify these sources and identify effective management scenarios for sewage water treatment in the area and assess the effect of each scenario on the water quality.

1.3 Research objective and questions

This problem definition leads to the following overall objective of this research:

To define sewage water treatment management scenarios, based on the identification of the major sources of pollution for the current situation and future projections, to improve the water quality in Guwahati and to quantify the effect on water quality of these scenarios.

The objective of this research leads to the following main research question:

Which sewage water treatment scenario performs positively in improving the water quality in the long-term in both Deepor Beel, Borsola Beel and Guwahati's water system?

To answer the main question, the following questions need to be answered first:

1. How does the water system in Guwahati work?
    a. How does the distinct seasonality in climate affect water flow and quality?
    b. How does the current water system respond to different pollutant sources?
    c. What are the major sources of water pollution and where are they located?
2. What are future projections for water quality in Guwahati and how robust are these?
3. What are suitable management scenarios to improve the water quality in Guwahati?
4. Which management scenarios will be most effective based on their ability to improve the water quality in Guwahati and what are their associated costs and feasibility?

1.4 Outline of report

In Chapter 2, the study area is introduced in which background information on population, land cover and precipitation patterns is given. The methodology used to answer the research questions is presented in Chapter 3 followed by the model set-up in SWMM in Chapter 4 which represents the framework of this study. Chapter 5 contains the results which can be subdivided into sections consisting of a systems analysis of the current and future situation; the development of scenarios and a scenario comparison to evaluate the effect of each scenario's ability to improve the water quality. In Chapter 6, the results will be discussed and in Chapter 7 conclusion are drawn on which scenario performs the best in improving the water quality in Guwahati. Last, recommendations are given in Chapter 8.

2 STUDY AREA

The study focuses on the Deepor Beel wetland ecosystem, located southwest of the city of Guwahati and the fresh water lake, Borsola Beel, located in the centre of the city (section 2.4). First, a general description of the whole catchment area including important characteristics is given and secondly, the two wetlands will be described in more detail including an analysis on water quality measurements.

2.1 Background information

Guwahati is a city in the state of Assam in North Eastern India which is located at the southern banks of the Brahmaputra River (see Figure 1). The city has an undulating surface with altitudes varying between 49 m up to 55.5 m above mean sea level and is surrounded by hills. It has a humid subtropical climate consisting of dry periods in winter (severe water shortage during the dry months of January to March) and two wet periods due to melt water from the mountains (pre-monsoon period in April-May) and monsoon rainfall during late summer (between June and September) causing a peak discharge in the Brahmaputra River and drainage channels in Guwahati. Especially during monsoon season the city is susceptible to water logging (Bordoloi, 2015).

The mean annual precipitation of Guwahati is approximately 1700 mm, however the values can be as low as 1300 mm in a dry year. The majority of this precipitation occurs in monsoon season which accounts for as much as 90% of the total rainfall (see Figure 2). This distinct seasonality, alternating between large rainfall events and no rainfall, influences the rate of flow through channels and lakes. The evaporation is almost constant throughout the year varying between 4 and 6 mm/day.

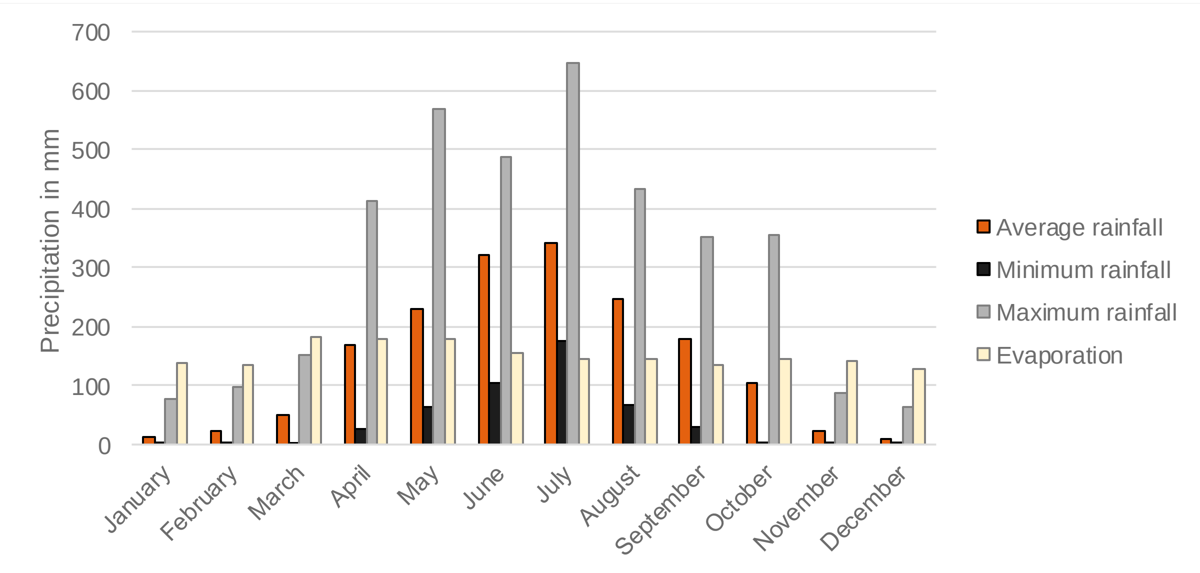


Figure 2: Precipitation and evaporation pattern throughout the year in Guwahati based on 1969-2012 daily rainfall dataset (Indian Meteorological Department)

Drainage system

Various drainage channels flow through the city of Guwahati making it a complex water system to manage. The major channels and their catchments are shown in Figure 3. The Bharalu River flows through the city centre of Guwahati towards the Brahmaputra River of which the total catchment basin is visualized in green colours. The lake Borsola Beel, located in the city centre, as well as Mora Bharalu River join the Bharalu River. During monsoon season high water levels in the Brahmaputra River can cause back waters in the city's water system and will naturally force part of the water from the Bharalu River to flow into Mora Bharalu River which discharges towards Deepor Beel. Additionally, a pumping station is located at the confluence of Mora Bharalu and Bharalu River to divert water to Deepor Beel. A sluice at the outfall can also be closed to prevent these back water flows.

The Basistha River flows from its origin in the Meghalaya Hills to Deepor Beel at which the Mora Bharalu River joins the Basistha River just upstream of Deepor Beel. The catchment area of Deepor Beel is visualized in purple colours.

The Bonda River is located in the Sisola catchment area, east of Guwahati and the Palashbari catchment is located in the west (grey coloured). Both are not considered in this research, because it has no connection with the Deepor Beel or Borsola Beel catchment area.

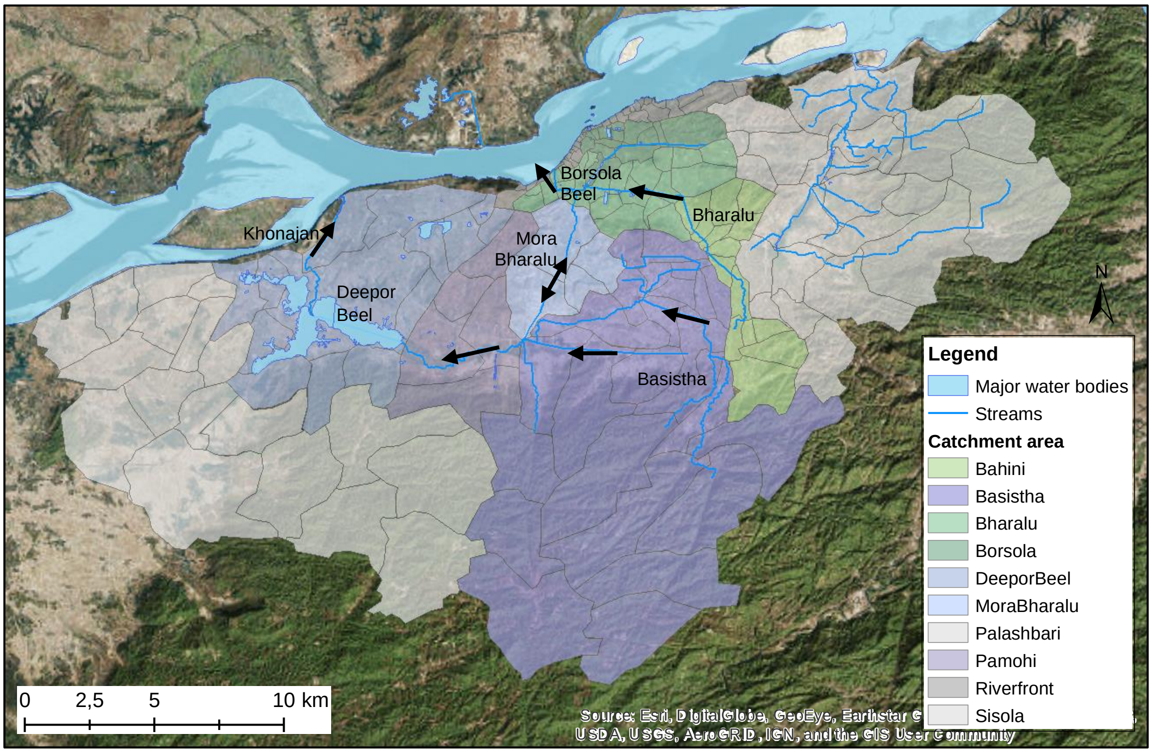


Figure 3: Catchment areas of major drainage channels (GIS)

Water supply and sewage system

Guwahati is situated on the banks of the Brahmaputra River, which serves as major drinking water source for the city. The water will be treated to drinking water conditions in a drinking water treatment plant and subsequently distributed around Guwahati. However, due to unreliable piped water supply, the inhabitants of Guwahati also extract groundwater and depend on commercial water supply agencies. The water consumption is estimated on 90.6 litres per capita per day, being below the average water consumption in other Indian cities (Bhattacharya & Borah, 2014). However, many plans for piped water supply networks in Guwahati are being executed, increasing the water consumption per capita.

Guwahati does not have any integrated sewage system in the city, except for some residential areas (Railway Colonies, IOC Refinery colonies and defence establishments, located in the north eastern part of the Bharalu catchment area) which have their own treatment facilities. The population is connected to a system of open drains which transport the water to the primary natural drainage channels. A large part of the households in Guwahati have septic tanks from which the effluents are not collectively collected. The septic tanks are emptied by the city on an irregular basis and dumped at a large disposal site near Deepor Beel. Still most sewage from the septic tanks is directly going into open drains (Deka & Devi, 2017). Also, (sanitary) waste is dumped along the drainage channels which can be swept off due to heavy rainfall, going into surface waters, subsequently blocking and decreasing the capacity of the drainage channels to discharge water. This blockage is mainly exposed during monsoon period resulting in inundations throughout the city. The city of Guwahati cleans the streets by street sweeping, reducing the contaminants in runoff during rainfall events, but this is done at a very irregular basis.

2.2 Population

Guwahati is the largest city in North-East India with approximately a million inhabitants (Census, 2011). The city has, in recent decades, expanded significantly as people immigrated into the city because of the better educational and commercial facilities offered in the city (Census, 2011; Manta & Rajbangshi, 2015). An increase in built-up area in Guwahati Metropolitan Area (GMA) indicates this rapid growth (Manta & Rajbangshi, 2015; Pawe & Saikia, 2017).

In Figure 4 the population density distribution per sub-catchment is presented. The Guwahati Metropolitan Development Authority (GMDA) estimated a total of 1.7 million inhabitants in 2025. It is visible that the most densely populated areas are located in the city centre as well as along the Basistha River and upstream of Bharalu River. Also, in the southwestern part of Guwahati, near Deepor Beel, more populated areas are visible. People are primarily living in low lying areas and along the main natural drainage channels like Mora Bharalu and Bharalu River, primarily serving as a place to get rid of their waste and as sanitary service.

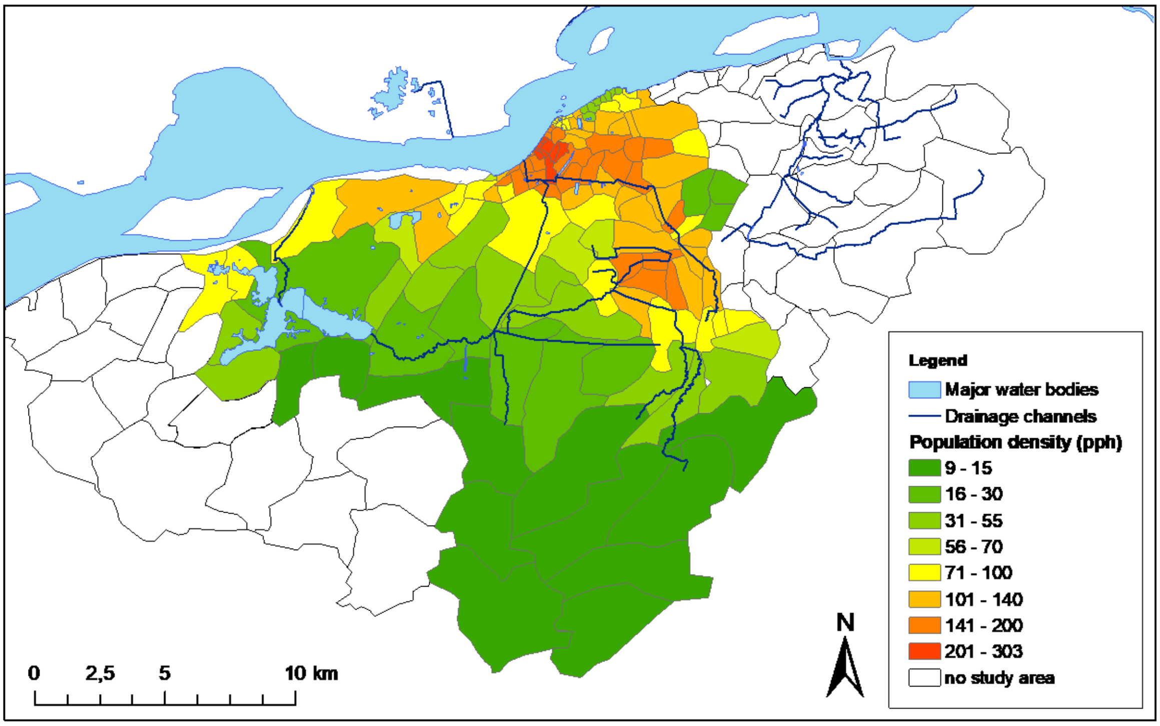


Figure 4: Population density in people per hectare (pph) per sub-catchment for the year 2025 (Guwahati Metropolitan Development Authority, 2009)

2.3 Land uses

Figure 5 presents the land cover change from 2002 to 2015. It shows that a large part of Guwahati is covered with built-up (urban) area, especially along the rivers; which also represents the most densely populated area in Figure 4. The increasing population trend in Guwahati results in a constant need to expand residential area which is often achieved in expense of agricultural and forested land. The built-up land is composed out of residential, industrial and commercial practices including several major industries such as oil refineries, textile industries, stone quarries, pulp and papermills (Bhardwaj, 2005). Agricultural activities mainly take place around Deepor Beel, but this is just a small fraction compared to residential, industrial and commercial practices described as built-up (Pawe & Saikia, 2017).

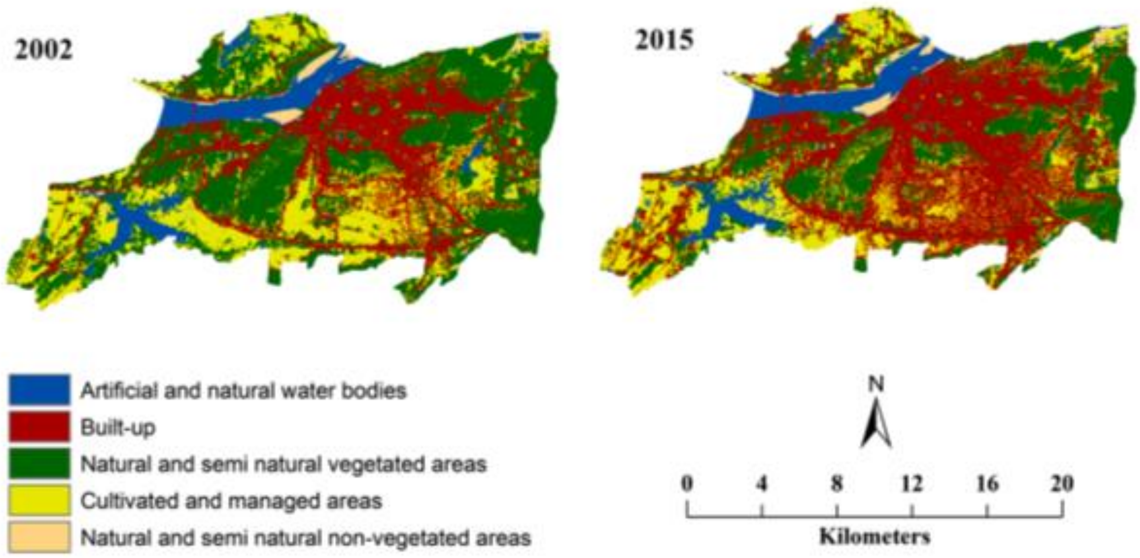


Figure 5: Land use land cover map of Guwahati from 2002 to 2015 (Pawe & Saikia, 2017)

2.4 Case study areas

Guwahati has many small lakes and wetlands including Deepor Beel and Borsola Beel (see Figure 6) which are selected for this research.

2.4.1 Deepor Beel

Deepor Beel (also called Deepar Beel or Dipor Bil) is a permanent, freshwater lake located just south-west of the city of Guwahati and has formerly been a channel of the Brahmaputra River. It serves as a major storm water storage basin for Guwahati and since 2002, the wetland is declared as a Ramsar site, the only one in the state of Assam. It habitats a large amount of residential flora and fauna, as well as migratory birds. Deepor Beel is, similar to Guwahati, surrounded by highlands on the north and south. The wetland is seldom used for drinking purposes but acts as a source of fisheries and agriculture for the local inhabitants (Bhattacharyya & Kapil, 2010; Ramsar, 2002). A major threat to Deepor Beel is the municipal solid waste (MSW) disposal site which was established in 2005 on the eastern banks of Deepor Beel in Boragaon, near Institute of Advanced Study in Science and Technology (IASTT) (Gogoi, 2013). In this municipal disposal site about 420 to 450 tons of solid waste is dumped every day (Choudhury & Gupta, 2017) and leachate of pollutants is considered to be a serious issue.

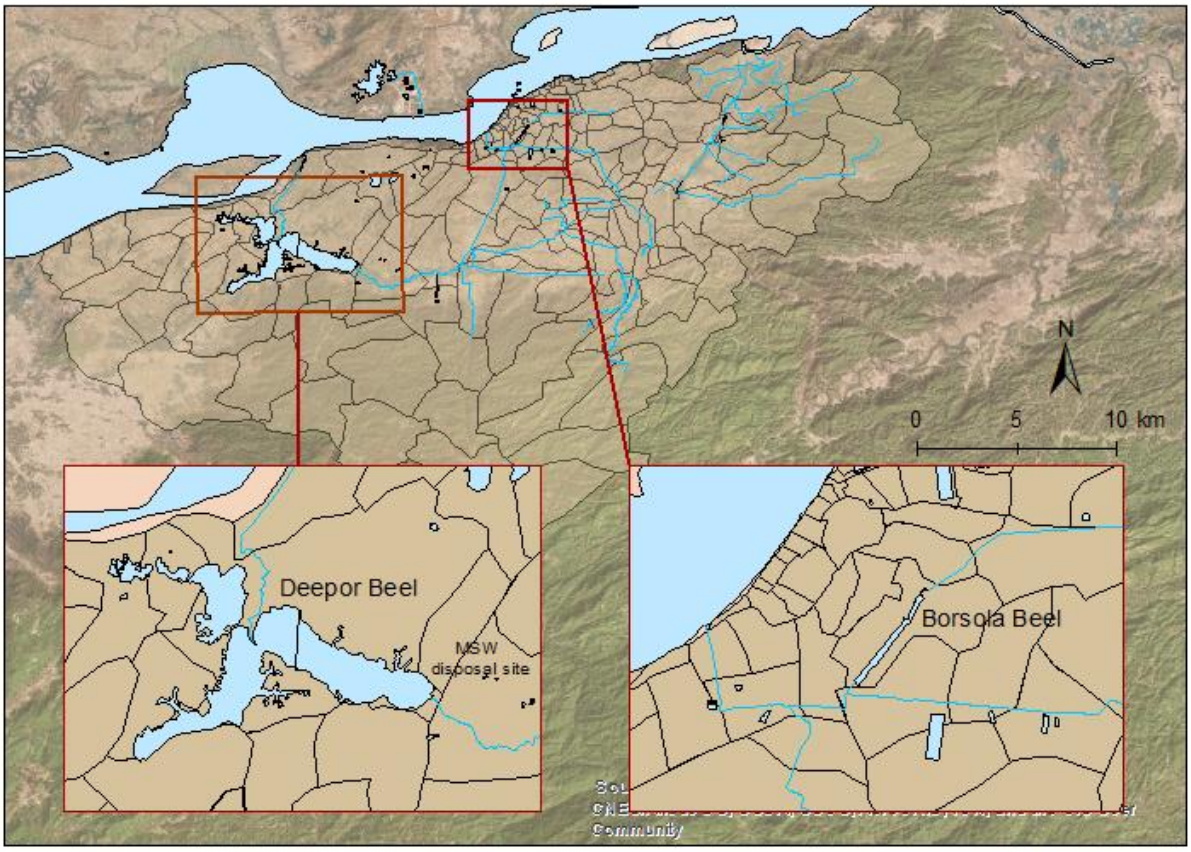


Figure 6: Location of Deepor Beel and Borsola Beel within the water system

Deepor Beel is fed with water from the Basistha River with its origin in the Rani-Garbhanga Forest (Meghalaya Hills) and drains its water into the Brahmaputra River via the Khonajan River five kilometres north. The catchment area of Deepor Beel is relatively large with a mix of densely populated residential areas, but also less populated forested areas.

The water depth in Deepor Beel (average water level at 45 meter above MSL) is influenced by monsoon rainfall, as well as by the water level in the Brahmaputra River (see Appendix A). The water level in the Brahmaputra River gets higher in monsoon season exceeding the water level in Deepor Beel. Hence, Deepor Beel is filling as it cannot discharge its water to the Brahmaputra River. It could even lead to backwater effects in Guwahati and subsequent water logging, which has happened frequently in the last few years. The city tries to prevent this by closing sluices. During highwater, the water depth in Deepor Beel can increase up to four or five meters, expanding its total inundated area (see Figure 7). During dry season the water depth is approximately one meter. Based on the land cover around Deepor Beel a lot of bare soil is present during the dry period which is assumed to be cultivated or just fallow land. During monsoon season, most of this area around Deepor Beel gets inundated as the size in area and volume of Deepor Beel increases (Mozumder, Tripathi, & Tipdecho, 2014). Due to encroachment around the wetland, its natural limits have decreased in a couple of decades from a total area of 40 km^2 to only 10 km^2 (1000 hectares) nowadays (Gogoi, 2013).

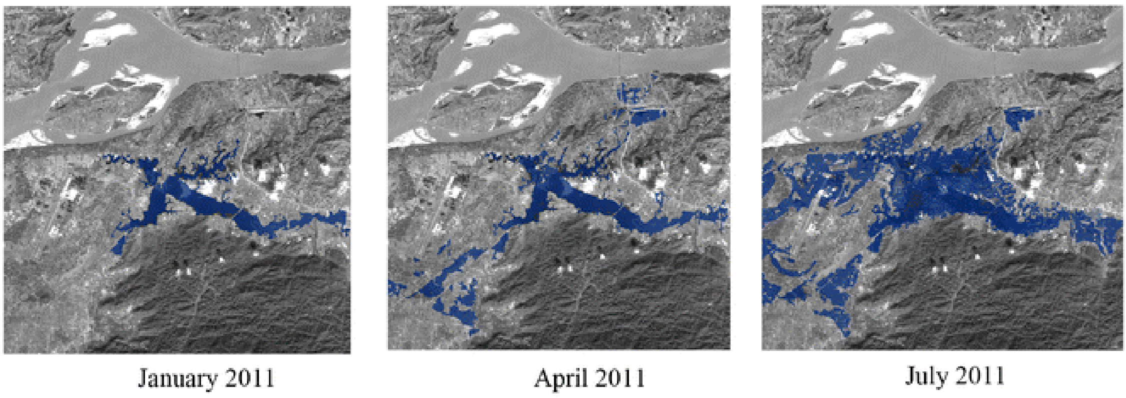


Figure 7: The inundated area of Deepor Beel in different months of the year 2011 (Mozumder et al., 2014)

2.4.2 Borsola Beel

Borsola Beel is a fresh water lake with a rectangular shape covering an area of approximately 10 hectares in the city centre of Guwahati (approximately 1.1 km in length and 60 m in width). Similar to Deepor Beel, it also serves as a storm water storage basin for the city of Guwahati, but due to encroachment its size and capacity has decreased. Next to retaining storm water, it is also used for recreational purposes, but people living near the lake complain about the smell. The water quality is very poor as growth of algae has taken over the lake surface. Borsola Beel's catchment area mainly consists out of urban area (approximately 100 000 inhabitants), so a large part of the inflow comes from sanitary flow mixed with storm water runoff during monsoon season. Furthermore, Borsola Beel acts as a sediment trap which makes it essential to dredge the lake, however it is not dredged on a regular basis.

2.5 Water quality

Several substances, both natural and anthropogenic, are found in the water system of which pollutant concentrations are influenced by many processes and other factors such as inflow, precipitation and degradation. Water quality measurements from literature reviews showed that both Deepor Beel and Borsola Beel have severe pollution of which biochemical oxygen demand (BOD) was found to be higher than permissible limits for class C representing a drinking water source being 3 mg/L (Bureau of Indian Standards, 2012) as well as 5 mg/L which represents the upper limit for moderately clean water (SWRP, 1996; Taua'a, 2018). Both total nitrogen (TN) and total phosphorus (TP) showed excessive concentrations that lead to eutrophication. Total suspended solids is used as an indicator of heavy metals which can be adsorbed. The measurements are presented in Appendix B.

Limited availability of water quality data from the area restricted the study to identify any clear patterns between pollutants and other parameters. However, it was still possible to observe some relationship between water quality parameters and factors such as precipitation and land cover. An overview of pollutant concentrations in both seasons is presented in Table 2.

Table 1: Ranges of water quality parameters concentrations in dry and monsoon season and water quality standards by WHO and BIS

Parameter	Deepor Beel		Borsola Beel*		Water quality standards	
	Dry	Monsoon	Dry	Monsoon	Desirable concentration	Source
Chloride (mg/L)	50-60	40-60	40-60	30-50	250	BIS/WHO (drinking water)
BOD (mg/L)	4-10	0-4	120-150	-	4 (3-5)	BIS/SWRP (drinking/surface water)
TN (mg/L)	1-2	0,5-1,5	-	-	1,5	Eutrophication
TP (mg/L)	0-1	2-5	1-4	0-1	0,05	Eutrophication
TSS (mg/L)	50-100	100-200	400	-	50	WFD

* limited to no available data

First, a clear difference in magnitude of concentrations in Borsola Beel and Deepor Beel is visible, especially for BOD concentrations. The Bharalu River and adjacent Borsola Beel are heavily polluted whereas Deepor Beel is moderately polluted. Secondly, during monsoon season a large part of the pollutant concentrations lower due to dilution with cleaner runoff from precipitation.

This dilution is clearly visible for chloride which is a conservative salt and can thus be used as a tracer since it is relatively inert to any processes except for dilution. A similar process is notable for BOD concentrations, however BOD concentrations are also influenced by degradation of organic matter. Still, its highest concentrations are found during dry periods, indicating high organic load which primarily originates from raw sewage. Furthermore, the highest concentration of pollutants has been found at a location near the incoming flow to Deepor Beel. However, the measurements from further into the water body revealed a lower concentration, suggesting the effect of decay over time.

Regarding TP and TN, both have generally a higher concentration during monsoon season due to wash off with eroding sediments and release of phosphate from bottom lake sediments which is higher during summer periods, because of more favourable conditions (Bhattacharyya & Kapil, 2010). However, during consecutive rainfall the concentrations lower significantly, because of dilution with cleaner water.

The measurements also reflect a correlation between TSS with both precipitation as well as land cover pattern. A higher concentration of TSS was recorded during rainfall especially near both agricultural lands as well as residential areas (Sayed et al., 2015). Furthermore, the measurements of TSS from the middle of Deepor Beel were relatively lower, which may be caused by sedimentation.

3 METHODOLOGY

In order to achieve the objectives of this study, several steps were undertaken. This chapter elaborates the methods carried out in the research. The structure of the steps is shown in the schematization in Figure 8.

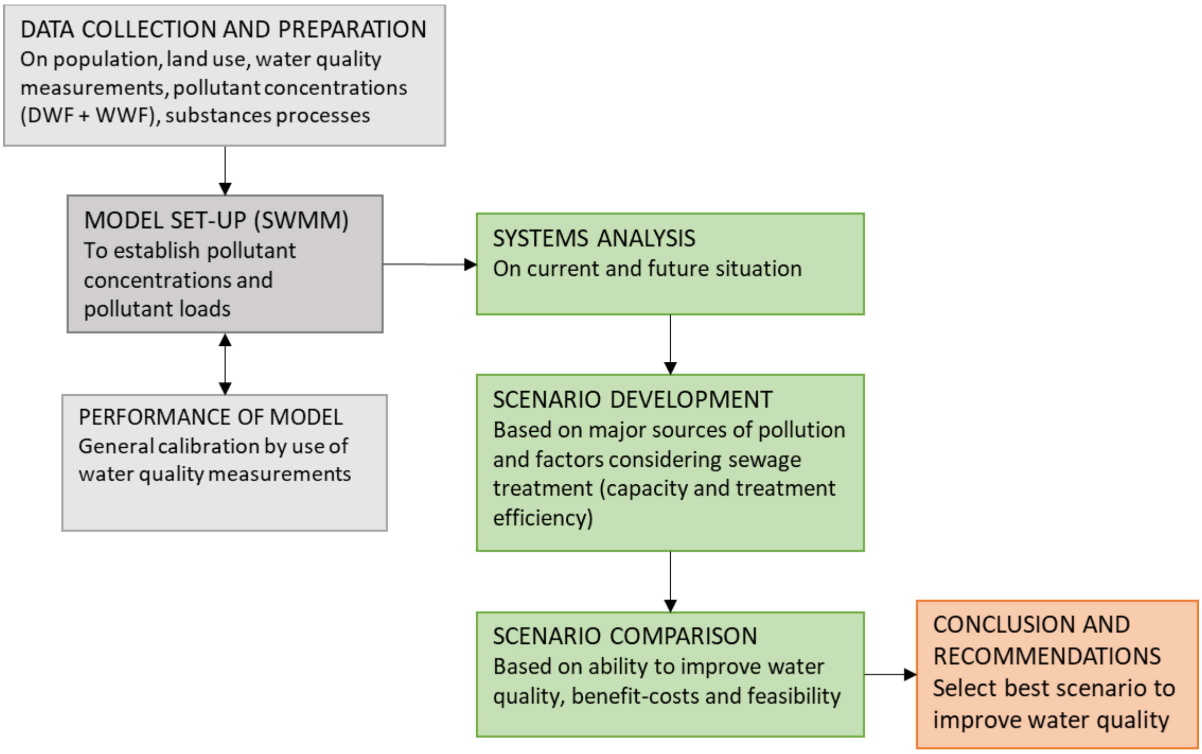


Figure 8: Schematisation of research model of this study

3.1 Storm Water Management Model

In this study, the Storm Water Management Model (SWMM), developed by the Environmental Protection Agency (EPA) (Rossman, 2015), was used to obtain further understanding of the water quality situation and design of alternatives for sewage water treatment in Guwahati. It is a widely used model for urban drainage design, analysis and planning (Niazi et al., 2017). Considering the large percentage of urban area in the study site, SWMM was selected for this study. An existing water quantity (hydraulic) model of the study area, in which the major drainage channels flowing through the study area are modelled by Arcadis in SWMM, has been used.

3.2 Data collection and preparation for SWMM

SWMM is a dynamic hydrology-hydraulic water quality simulation model that allows incorporation of information on pollutants and land use. Due to limited data availability as well as to avoid the risk of over-parametrisation, the number of selected parameters in this study was kept as low as possible. In order to prepare SWMM to model the current as well as future water quality situation of Guwahati, information on pollutant concentrations, population and land use were required as an input to the model.

The substances, modelled in this study, were selected entirely based on data availability and representation of major sources of pollution in Guwahati. Several scientific literature with comparable study sites were reviewed to obtain information on pollutant concentrations in dry weather flow (DWF) as well as in wet weather flow (WWF), also referred to as storm water runoff, in the study area. SWMM combines these flows to calculate the total flow.

The calculation of pollutant concentration and volume of DWF required information on population and water consumption in Guwahati. The population data in India are available at a municipal ward level within Guwahati Municipal Corporation Area (GMCA). Thus, to incorporate this information in the model, it was converted to the sub-catchment level with the help of GIS software. Population density of 10 people per hectare was assumed for the sub-catchments outside GMCA boundary as these areas mostly consisted of forests. The dependency of generated wastewater flow on population and the present growing trend of Guwahati population meant that the study also required to forecast the future population in Guwahati. As the design period for a sewage treatment plant is 15 years, but land acquisition requires a 30 year design period according to the CPHEEO[1] (2012), a total design period of 30 years is used in this study making the design year 2050. In order to estimate the population of Guwahati in the coming decades, several arithmetic functions were used and the mean population from the obtained results was afterwards selected. Based on development zones proposed by the Masterplan of Guwahati, spatial variability in population was considered by applying certain growth rates to different areas.

The model determines pollutant concentrations in WWF, or storm water runoff, by using land use classification information. In order to acquire information on the current land uses in the study area, the study converted satellite images from February 2018 (Landsat 8) to land use land cover (LULC) maps. Afterwards the generated LULC map was converted to understand percentage of different land cover in each sub-catchment and was used as an input to the model. For the future situation, the study also required to provide information on land classes based on the forecasted population. In order to obtain this, the 2025 Masterplan of Guwahati was used and the proposed urbanisation plans (development zones) were taken into consideration. The DWF volume per capita, concentrations in DWF and WWF were kept constant. The predicted population and land use change was then used to calculate the probable sewage generation in the future.

As models are always sensitive to input data as well as the probable errors in data (both instrumental and human), a sensitivity analysis was carried out to understand how each parameter influences the model results and the robustness of scenarios. Generally, a sensitivity analysis is carried out together with an uncertainty analysis as the uncertainty in each input parameter can affect the model result differently. However, due to lack of detailed information on the measured data from the study area, in this research only a sensitivity analysis was carried out.

Also, due to the lack of available data from the study area, neither model calibration or validation were possible. However, some literature from the area provided water quality measurements of pollutant concentrations from different parts of the study area, which were used to calibrate the obtained results by iteration. This could only be done based on the order of magnitudes. Considering this whole study is dependent on SWMM, Chapter 4 describes the model set-up and sensitivity analysis in more detail.

3.3 Scenario design and comparison

In order to design suitable scenarios for the study area several factors considering sewage treatment in India as well as the major sources of pollution in the area have been taken into account. Within the scenarios the capacity, treatment efficiencies and its locations, simultaneously being the service area of the STP, were taken into consideration for design. These factors were varied throughout the scenarios, but the combinations of values were based on assumptions which were compatible and realistic for future situations, not always being the most extreme scenarios. The investigated scenarios ranged from centralised and

[1] organisation which deals with urban water supply, sanitation and solid waste management in India

decentralised to incorporation of diverting flows and extra treatment capacity at the STP. Limiting the complexity in modelling the scenarios, the natural flow of the streams were used in proposing locations and serving area.

3.4 Evaluation methods

Due to distinct seasonal variation as well as parameter values, the water system can react differently under different conditions. Therefore, the whole study investigates both dry and wet season under stationary conditions to understand the response of the water system to pollutant loads, the effect of STPs in different seasons as well as the parameter sensitivity. The dry and wet season conditions are respectively without rainfall and with constant rainfall (300 mm/month representing the average monthly rainfall during monsoon season). For both seasons, a hot start file has been used to account for the warm up time of the model to go to steady-state conditions, which are then used as initial values for the simulations. During the simulation, a period of two months has been used to assure the results were going to an equilibrium.

The basis for formulating scenarios is the reduction of pollutant load and concentration to improve the water quality in Guwahati. The gap between the existing and target situation for the specific functions (recreational purposes and ecological restoration) determines the needed improvement. Hence, the results were analysed on pollutant concentrations in both lakes as well as pollutant loads at the outfalls. As surface waters for recreational purposes are generally measured on faecal contamination to assure human health, the parameters in this study did not have any specific criteria. Concerning the aesthetics and health of the water system, BOD concentrations were analysed based on desirable limits for open surface waters to prevent oxygen depletion and nutrient concentrations were assessed based on lake concentrations preventing eutrophication (Liang et al., 2013). The water quality standards are provided in Appendix B.

In order to compare the effectiveness of each scenario to improve water quality in Guwahati, the concentrations and loads were compared to a reference scenario in which no measures were implemented (worst case scenario). To determine the effectiveness in improving the water quality under varying weather conditions as well, an additional run with non-stationary conditions using a daily rainfall dataset of monsoon season 2008 was performed.

The fact that the most effective measure is often very expensive as well as often not feasible, the research took cost and feasibility into consideration in addition to the ability of the scenario to improve water quality. For cost estimation, the study looked at both construction and operation cost for each scenario. Literature was reviewed in order to have an idea about the predicted costs of each measure and the investment the city has to make. Considering the demand of land in a densely populated country like India being extremely high, availability of suitable land was considered in the feasibility section of the study. Furthermore, the study also considered availability of skilled personnel as that often lacks in developing countries and will determine the final functioning of a STP.

4 MODEL SET-UP

In this chapter, the complete model set-up for incorporating the water quality is described. A description is given on what parameter values are assumed and which processes are included in the model.

4.1 Storm Water Management Model (SWMM)

In past years, researchers from both Arcadis and different universities, have worked extensively in Guwahati region. In 2017, the water quantity situation of Guwahati was modelled using SWMM in which the sanitary flow was not incorporated in the earliest versions, but has been incorporated in later analyses. With the scarce amount of available data, it was found that the model was able to capture the locations where inundations occurred. Thus, this existing model was used as the basis of this study. However, the boundary conditions of this model, representing the Brahmaputra River, were adjusted for this study by lowering the water level in order to prevent the model from having large water quality routing continuity errors[2]. The other parameters and assumptions made in the existing hydraulic model are provided in Appendix C.

In modelling water quality routing, SWMM assumes that conduits and storage units behave as a continuously stirred tank reactor (CSTR) which allows perfect mixing in which no spatial variation in concentrations are to be expected. Hence, within the large fresh water lakes (Deepor Beel and Borsola Beel) no spatial variation will be assumed. Furthermore, SWMM models pollutants as surface runoff concentration or as a direct inflow from nodes introduced to the conveyance system e.g. industrial inflow or dry weather flow (DWF). To simulate these pollutants, concentrations of each pollutant in different kind of inflows, distinction in land uses and wash-off parameter values are needed. These concentrations are based on values used in literature.

4.2 Inflow of pollutants

Multiple sources of pollutant input contribute to the deteriorating water quality in Guwahati. As the city of Guwahati lacks a sewage system, one of the major sources of water pollution in the city is sanitary flow (dry weather flow). Especially during dry periods, this becomes the only flow going through the water system. During monsoon season pollutants from surface areas like streets and even septic tanks get washed off, introducing further pollutant load into the water system. This storm water runoff is considered as wet weather flow in SWMM.

In addition to these sources, the water system in Guwahati also receives constant outflow from different industries, medical, educational and many other facilities. In water quality measurements they were often found to have a large impact on the local water quality. However, Bhattacharyya & Kapil (2010) concluded that in many cases the contributions from urban storm water runoff are higher than those from the point sources such as industrial discharges. Due to scarcity of data on input loads from specific point sources and the focus of this study being on domestic sewage water, these point sources were not considered.

Another large threat to Deepor Beel is the municipal solid waste (MSW) disposal site which was established in 2005 on the eastern banks of Deepor Beel in Boragaon, near Institute of Advanced Study in Science and Technology (IASTT) (Gogoi, 2013). Especially during monsoon rainfall, large amounts of water sweep off garbage from this dumping site (Basistha, 2016). Despite observations by Sayed et al. (2015) which did not reveal that changes in water quality were specifically due to leachate from this disposal site, the site is considered as a

[2] Continuity errors represent the balance of incoming and outgoing mass flow. A low continuity error means the model is converging to a stable solution and is numerically correct. The error, however, does not demonstrate if it is an accurate demonstration of the measured situation.

serious issue and contribution to the water pollution in Deepor Beel (Choudhury & Gupta, 2017). However, this specific site is not taken into account in SWMM due to unavailable data on the size of pollutant load and concentration from this site.

4.3 Pollutant concentrations

Pollutant concentrations differ in dry weather flow (DWF) and wet weather flow (WWF). The sanitary flow from a city is a small constant flow from residential areas, but generally exhibits large pollutant concentrations influencing the overall pollutant load (Pribak & Siegrist, 2015). Storm water runoff (considered as WWF) is generated by rainfall and transports domestic waste from streets and untreated water (excluding sanitary flow) into receiving waters. Pollutant concentrations in WWF are generally more varied than in DWF as it is dependent on rainfall intensity, duration and volume, together with the amount of build-up of contaminants (e.g. antecedent dry days) and the type of land use they originate from. All this leads to variations in the magnitude of pollutant loads.

4.3.1 Dry weather flow

The volume of water introduced by the sanitary flow is modelled using the population in each sub-catchment and the amount of sewage water used per capita. The volume of sewage water is assumed at 125 l/cap/day, being about 80% of the total water supply consumed by a person in a day in India. This value presumes that every inhabitant of Guwahati is connected to a drinking water supply network which is used in several reports for design of sewerage systems (Assam Pollution Control Board, 2013). Based on the current situation, most areas are not connected to drinking water supply, however in the future this will be expected.

The CPHEEO (Central Public Health and Environmental Engineering Organisation) deals with urban water supply, sanitation and solid waste management in India and has set up design pollutant loads (in grams per capita per day) of several water quality parameters. These pollutant loads can be converted to pollutant concentrations in DWF from each sub-catchment using formula 4.1:

$$Concentration_{pollutant}[mg/l] = \frac{Pollutant\ load\ [g/day/cap]}{Sewage\ water\ [l/day/cap]} \cdot 1000 \tag{4.1}$$

Figure 2 presents the design pollutant loads of CPHEEO and the calculated pollutant concentrations in DWF using the given loads and volume of sewage water. An adjustment has been made as the concentrations are relatively high compared to values in other studies and water quality measurements in the area. An explanation for this could be dilution by an unknown water source or primary treatment (e.g. settling of contaminants) which takes place in septic tanks lowering the pollutant concentration entering the open drainage channels. The adjustment is based on the removal fraction of the pollutant in a septic tank assuming 40, 30, 35 and 90% respectively for BOD, TN, TP and TSS (Nelson & Murray, 2008).

Table 2: Pollutant loads and concentrations

Parameter	Pollutant load [g/cap/day]	Range in literature [load in g/cap/day]	Pollutant concentration [mg/L]	
	(CPHEEO, 2012)	Sources*	**Calculated****	**Used*****
Biochemical oxygen demand, BOD	45-54	20-85	362-435	150
Total nitrogen, TN	6-12	2-15	48-96	28
Total phosphorus, TP	0,6-4,5	0.2-6	5-36	3
Total suspended solids, TSS	70-145	40-105	565-1170	100

* Sources: Chapra (1997); Henze et al. (2002); Katukiza et al. (2014); Mesdaghinia et al. (2015)
** Using 125 l/cap/day produced sewage water
*** Based on removal fraction (primary treatment) in a septic tank (Nelson & Murray, 2008)

4.3.2 Wet weather flow

SWMM provides many methods on calculating the wash-off generated by rainfall events. The simplest of these methods and requiring the least number of parameters, is the event mean concentration (EMC). It has the same constant concentration in every volume of runoff from the sub-catchment which is generated by the rainfall event and it is not dependent on the total amount of build-up of a contaminant. Hence, the higher the volume of rainfall, the more pollutant load will be introduced to the system (Nazahiyah, Yusop, & Abustan, 2007). It is commonly used to estimate nonpoint water quality loads and is an appropriate method for evaluating the effects of storm water runoff on receiving waters (Lee et al., 2002).

For the EMC values different land uses are required to make a distinction between storm water runoff from different areas. The used land uses in the study area were obtained from satellite images from February 2018 (Landsat 8) which were converted to land use land cover (LULC) maps. This map is presented in Figure 9. Only percentages of built-up land (urban), agricultural (managed) and forested areas are used in SWMM. This will not always add up to a 100% in each sub-catchment, but the remaining percentage of land use will not contribute to the pollutant load in SWMM.

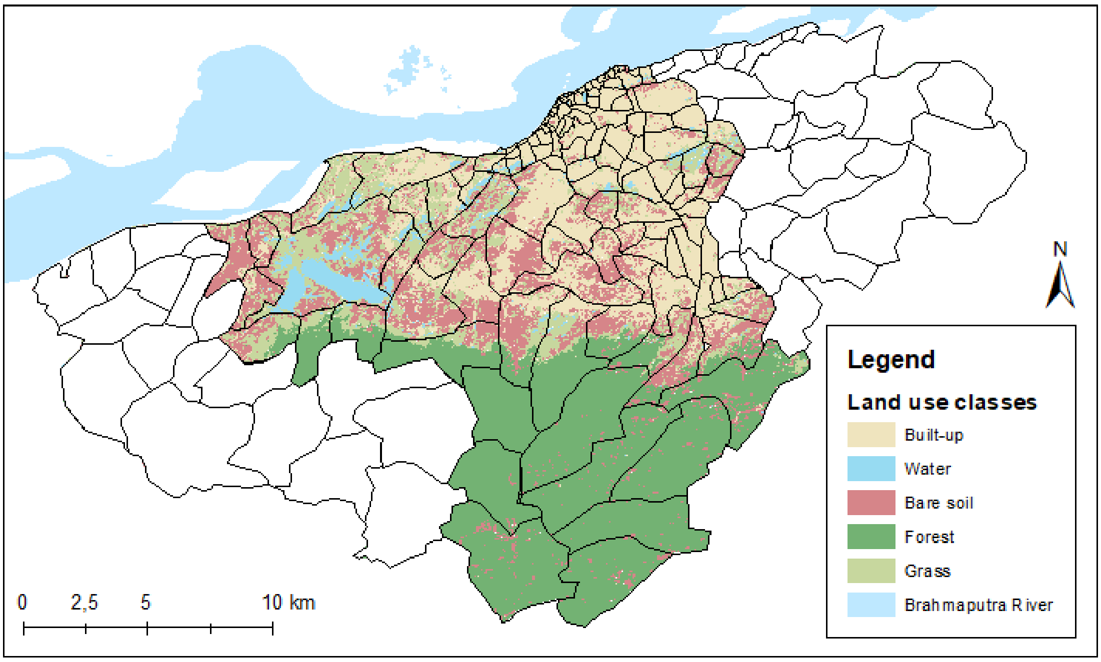


Figure 9: Land use classification based on Landsat 8 data from USGS (February 2018)

In SWMM, the wash off by event mean concentration is defined through the following equation:

$$w = K_W q f_{LU} A \quad (3.2)$$

With w = wash-off load (mg/hr), K_W = event mean concentration (mg/m^3), q = runoff rate over sub-catchment (mm/hr), f_{LU} = fraction of land use (-) and A = sub-catchment area (m^2). Table 3 shows the land class specific event mean concentration values used in this study. The values are based on studies done in subtropical and tropical areas which resemble the climate and/or situation[3] in Guwahati (Chow et al., 2013; Qin et al., 2010; Sharma et al., 2012).

Table 3: Values for event mean concentrations (EMC) for different parameters used in SWMM

Parameter	EMC (mg/L)	Range in literature*
BOD		
- Agriculture (managed)	10	10-20
- Residential (built-up)	30	20-180
- Forest	1	-
TN		
- Agriculture (managed)	2	0,6-3,7
- Residential (built-up)	1,1	1,1-1,2
- Forest	0,7	0,7-1,1
TP		
- Agriculture (managed)	1,5	0,1-2,5
- Residential (built-up)	0,5	0,1-0,7
- Forest	0,1	0,1-0,2
TSS		
- Agriculture (managed)	200	80-250
- Residential (built-up)	50	20-70
- Forest	120	122

* sources: Chow et al. (2013); Qin et al. (2010); Sharma et al. (2012)

4.3.3 Processes

The substances are all subject to biological and chemical processes. The most important processes which are included in SWMM are discussed in this section (see Table 4). The processes are modelled as first order decay rates or as a removal fraction as SWMM is unable to model the interaction and processes between different water quality components in detail. The first order decay rates are based on average values found in literature.

BOD naturally decays over time due to organic matter that is degraded. The waste type in the water (treated-untreated) determines the rate of decay, as well as the temperature (Thomann & Mueller, 1987). The decision is made to use a decay rate of 0,2 day^{-1} (at 20°C) which is within the range found in literature (Costa, Burlando, Liong, & Priadi, 2014; Davis & Cornwell, 1985; Nuruzzaman, Al-Mamun, & Salleh, 2018).

Total nitrogen consists out of organic nitrogen, ammonia and nitrate. The decay of nitrate in total nitrogen is based on the process of denitrification in the nitrogen cycle transforming nitrate into nitrite and finally N_2, a gaseous state. An initial first-order decay rate of 0,1 day^{-1} is used based on literature (Thomann & Mueller, 1987). Total phosphorus consists out of organic and inorganic phosphorus. The phosphorus cycle is one of the slowest cycles and unlike nitrogen, it cannot disappear from the system via a gaseous state. An initial decay rate of organic phosphorus of 0,01 day^{-1} is used (Bowie et al., 1985) which takes into account both uptake by plants and accumulation in sediments.

[3] No sewage system present

One of the processes responsible for a decrease in TSS concentration is settling of sediments. The settling of sediments on the bottom influences aquatic life and if organic, possibly oxygen level as well. This mainly happens in slow moving water like lakes. No initial decay rates are defined, but a settling rate in terms of a treatment removal fraction is assumed at 25% of total incoming load. Resuspension is not taken into account in this model.

Table 4: Overview of first order decay rates presenting processes of parameters used in SWMM

Parameter	Value	Process
BOD	0,2 day^{-1}	Degradation of organic matter
TN	0,1 day^{-1}	Nitrogen cycle: denitrification
TP	0,01 day^{-1}	Phosphorus cycle: uptake by plants and accumulation in sediments
TSS	0,25*	Sedimentation

* A removal rate of 25% of incoming load (only at Borsola Beel and Deepor Beel)

4.4 Sensitivity and uncertainty analysis

As mentioned earlier, a sensitivity analysis is always carried out to understand the impact of input parameters on the final results. This analysis can both be carried out locally or globally. A local sensitivity analysis changes one variable at a time whereas global sensitivity (Monte Carlo simulation) uses prior defined ranges of all parameters and finds the range of possible model predictions (Niazi et al., 2017). In this study, a local sensitivity analysis has been performed using the one-at-a-time (OAT) technique in which one parameter is perturbed at a time and the other parameter values are fixed. In this way a large set of parameters could be explored on their influence on model results. This method has generally been applied in water quality studies done in SWMM (Niazi et al., 2017).

The parameters used in the sensitivity analysis were the decay coefficient, DWF volume (population is related to this parameter), DWF concentration, WWF concentrations (EMC) and imperviousness of a sub-catchment. Each parameter value has been perturbed with a certain fraction of their initial value. This fraction is based on each parameter's range in literature and its likelihood to occur (see Table 5). The DWF volume was already taken at the higher end of the range, so it was only perturbed to lower values. Furthermore, perturbing the concentration of each pollutant has been done in similar runs as was assumed that the pollutants do not interact with each other. Their effect has been quantified and analysed on the pollutant concentration in both Deepor Beel and Borsola Beel. The WWF concentrations as well as the imperviousness have only been assessed under wet conditions. In Table 5 the ranges in values taken for the sensitivity analysis are presented.

Table 5: Parameter ranges for the sensitivity analysis

Sensitivity parameter	Initial value	Fraction range	Value range
DWF volume	125 l/cap/day	60-80-100%	75-100-125
DWF concentration	BOD = 150 mg/L TSS = 50 mg/L TN = 28 mg/L TP = 3 mg/L	100-150-200%	150-200-250 50-100-150 28-33-38 3-4-5
Decay coefficient	K_{BOD} = 0,2 day^{-1} $K_{nitrogen}$ = 0,1 day^{-1} $K_{phosphorus}$ = 0,1 day^{-1}	50-100-150%	0,1-0,2-0,3 0,35-0,7-1,05 0,05-0,1-0,15
WWF concentration *Urban* *Bare* *Forest*	 BOD = 100 mg/L BOD = 15 mg/L BOD = 1 mg/L	50-100-150%	 50-100-150 10-15-20 0,5-1-1,5
Imperviousness (only Borsola Beel catchment)	Impervious = 50%	50-100-125-150%	50-62,5-75

4.5 Schematisation of sewage treatment facilities

Scenarios were used to determine which management strategy for sewage water treatment performs positively in improving the water quality in the lakes (Deepor Beel and Borsola Beel) and additionally improving the water quality in Guwahati. The scenarios were varied in locations, number, removal efficiencies and capacities (service areas) of STPs. In this way, a centralised and decentralised option as well as diversion of water and adding extra treatment capacity could be investigated. A complete overview of the STPs in each scenario is given in Table 9 and Figure 21 in Chapter 5.

In SWMM, a STP has been modelled according to the simple schematisation presented in Figure 10. The STP has been modelled as a node where treatment takes places. SWMM provides different options to handle pollutant removal (treatment). These options include an empirical function for pollutant concentration with one or more process variables (flow rate, water depth and settling velocity) or a removal fraction (Rossman & Huber, 2016). For simplicity, the removal fraction option was used to model pollutant treatment (Irvine et al., 2015). Using this method, the removal efficiency could be changed easily in the different scenarios as well as differentiating between dry and wet season. Furthermore, a pump (type 2: inline pump relating flow with depth) connects the STP with the natural drainage channels. Each pump has been assigned a certain constant flow (pumping capacity) to divert (part of) the water from the natural drainage channels via the STP where the water is treated. When the maximum capacity of the pumping station is reached, the residual flow will just continue in the natural drainage system untreated, acting as an overflow. As a starting point, the DWF coming from upstream area is used for the design capacity of each STP, but this varies depending on the scenario.

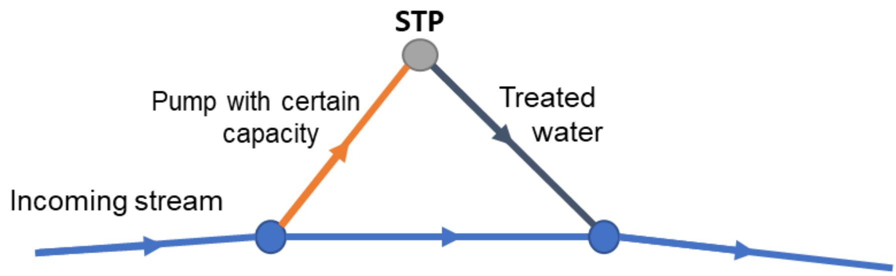


Figure 10: Schematisation of a sewage water treatment plant (STP) in SWMM

5 RESULTS

In this chapter the results are discussed. First, the current water system and corresponding water quality in the study area is analysed based on the results produced by SWMM (5.1). Secondly, the main projections and changes in the future situation are analysed (5.2). Subsequently, the worst-case scenario and four additional management scenarios are designed based on the key problems and projections in the study area (5.3). These are assessed on their effect on water quality using SWMM together with a qualitative description on costs and feasibility for each scenario (5.4).

5.1 Systems analysis: current situation

The water system in Guwahati is largely influenced by the seasonal climatic characteristics of the area represented by a dry winter and a monsoon season in summer. Water quantity plays an important role in water quality as large volumes of water (due to rainfall) can dilute and lower pollutant concentrations in surface waters. This can be expressed in the form of a mixing ratio which defines the percentage DWF of the total flow (DWF plus WWF) in the system. To understand these mixing ratios, water volumes have been quantified based on DWF volumes and WWF volumes during constant rain from sub-catchments (rainfall event of 10 mm/day) in the catchment areas of Borsola Beel and Deepor Beel which are presented in Table 6.

Table 6: Mixing ratio and water volumes in million litres per day (MLD) originating from storm water runoff (WWF) and sanitary flow (DWF) in catchment areas for 2025 situation (mean value)

Catchment area	Area of catchment	WWF volume (MLD)	DWF volume (MLD)	Total volume (MLD)	Mixing ratio
Deepor Beel	23 000 ha	222	105	327	32%
Borsola Beel	700 ha	14	12	26	46%

The values in Table 6 show that, during rainfall, the drainage channels and lakes get flushed with a large volume of water (runoff). It can be concluded that approximately one third of the total water which is directed towards Deepor Beel comes from sanitary flow (DWF) whereas for Borsola Beel almost half of the total inflow is sanitary flow. This makes it easier for pollutants discharging to Deepor Beel, to be mixed with storm water causing dilution and subsequently lowering the pollutant concentration.

Regarding the capacity of a STP to treat the complete flow, these values already show that the total volume of water should be double to even three times the DWF. This, however, is just a rainfall event of 10 mm in a day whereas rainfall events in Guwahati can reach up to 100 mm per day. This will dilute a large part of the wastewater, lowering pollutant concentrations even more in monsoon season. A general calculation on mixing ratios throughout the year, depending on the average monthly rainfall, is presented in Table 7 for both Deepor Beel catchment and Bharalu catchment (Borsola Beel is part of Bharalu catchment area). In Table 7 it is visible that for both catchment areas, especially in the monsoon period, the DWF is diluted with a large amount of runoff from rainfall. During dry season the flow consists for the largest part out of DWF. On the other hand, the two catchments show a difference in percentages of mixing ratios. Especially, the city centre which has a high population density, shows higher percentages in the mixing ratio indicating that a larger part of the total flow consists out of sanitary waste. During dry season this can reach up to 80% (to 100% without rainfall) and during wet season, the portion of sanitary flow will still be minimally 10 to 15%. This is different in Deepor Beel catchment area where more water from rainfall is available to dilute the sanitary flow. Here, in dry periods the mean mixing ratio stays around 50% and will be near to just 4% during wet periods.

Table 7: Mixing ratios for Deepor Beel and Bharalu catchment area based on average monthly precipitation (1969-2012). Note that Borsola Beel is not presented here, but is part of Bharalu catchment area

	Rainfall (mm/ month)	Deepor Beel catchment				Bharalu catchment (city centre)			
		DWF* [m3/s]	WWF** [m3/s]	Total [m3/s]	Mixing ratio	DWF* [m3/s]	WWF** [m3/s]	Total [m3/s]	Mixing ratio
January	14	1,21	1,3	2,5	48%	0,72	0,3	1,0	73%
February	24	1,21	2,1	3,4	36%	0,72	0,4	1,2	62%
March	50	1,21	4,5	5,7	21%	0,72	0,9	1,6	44%
April	169	1,21	15,4	16,6	7%	0,72	3,1	3,8	19%
May	228	1,21	20,8	22,0	6%	0,72	4,2	4,9	15%
June	322	1,21	29,3	30,5	4%	0,72	5,9	6,7	11%
July	341	1,21	31,1	32,3	4%	0,72	6,3	7,0	10%
August	248	1,21	22,5	23,7	5%	0,72	4,6	5,3	14%
September	179	1,21	16,3	17,5	7%	0,72	3,3	4,0	18%
October	105	1,21	9,5	10,7	11%	0,72	1,9	2,7	27%
November	22	1,21	2,0	3,2	38%	0,72	0,4	1,1	64%
December	11	1,21	1,0	2,2	56%	0,72	0,2	0,9	79%

* Based on population in catchment area multiplied with per capita sewage generation of 125 l/cap/day
** Based on amount of rainfall multiplied with catchment area

5.1.1 Response to point or diffuse source

The water system in Guwahati is complex. In order to understand how the system responds to pollutant input during dry as well as monsoon season, both a point and diffuse pollutant source were modelled using SWMM. These were respectively emitted for a day and a week. This analysis gives an indication of the recovery rates of a lake after some pollutant input, also known as the residence time. The residence time gives an indication of the time it takes to remove the polluted water and replace it with non-polluted water (Chapman, 1996). For Deepor Beel the residence time is an order of magnitude higher as for Borsola Beel.

The downstream routes of the three point sources are presented in Figure 11. Here can be seen that Bharalu River (city centre) does not interact with Deepor Beel via Mora Bharalu River during dry periods. However, during periods with high water depths and large rainfall events, part of the water gets diverted to Mora Bharalu from the Bharalu River in the city centre by a pumping station (triangle in Figure 11). In the current situation, the pumping station in the model will start pumping water with an upstream water depth of one meter corresponding to approximately 0,9 mm/h (21,6 mm/day) of rainfall. Thus, in this analysis using stationary conditions with a maximum rainfall of 0,3 mm/h (10 mm/day) no water is pumped from Bharalu River to Deepor Beel.

Point source

In Figure 12, the salt propagating through the system is visualised as pollutant load (mg/s) during a dry and wet period. The pollutant load is highest and most concentrated at the source where the peak of pollutant load spreads and lowers over time the longer it travels. Especially the lowering in the peak height with more than half just after the lake, shows the slow transport through the lake whereas it travels relatively fast to Deepor Beel and Borsola Beel. The pollutant travels fastest through the Bharalu River in which can be seen that the peak stays relatively constant throughout time. It only takes a couple of days for the pollutant to be removed from the system. At Deepor Beel and Borsola Beel it takes a longer time to be removed from the system, respectively in the order of months and weeks. The distinct seasonal characteristics are also visible in the travelling time of the pollutant through the system. Based on the graphs, the peak of the salt is faster during a wet period than in a dry period in which the travel time in wet season is almost half of the time in dry season.

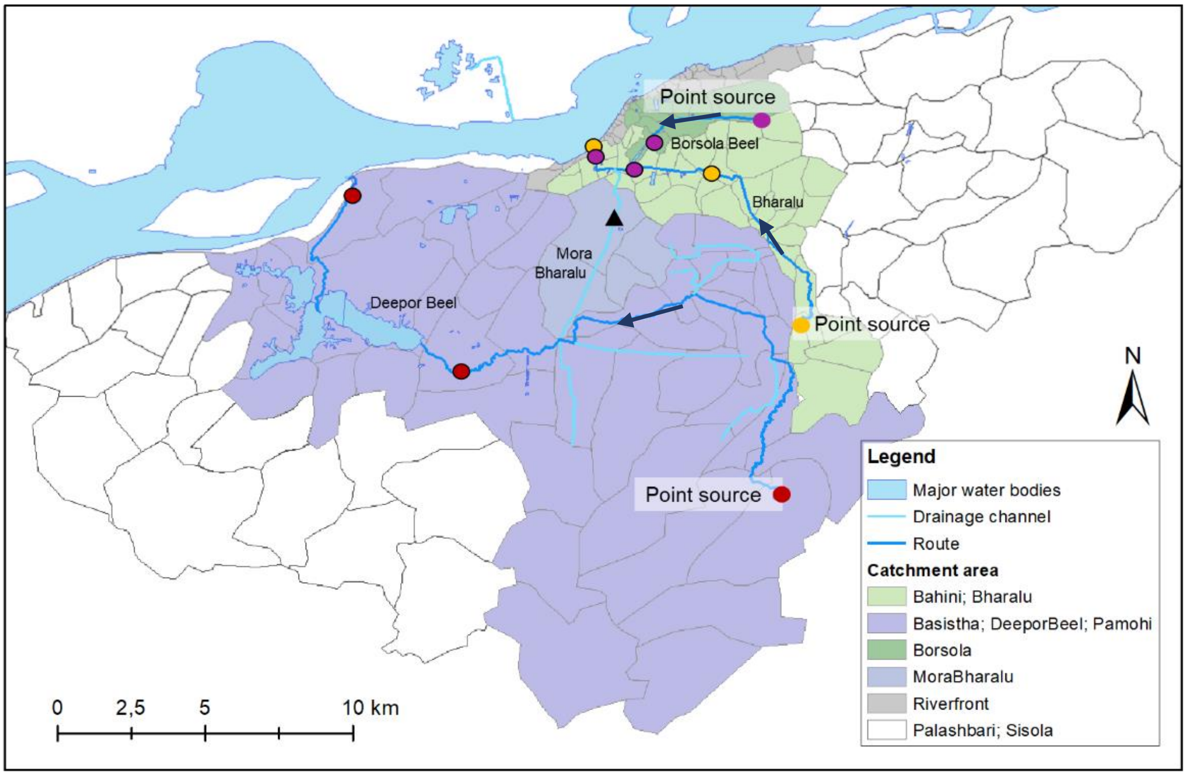


Figure 11: Routes for the point sources through the water system (dots represent the analysed locations)

Diffuse source

A diffuse source is entered in the modelled system for one week (first week of June) based on the DWF distribution throughout the area. It is harder to trace within the system, so only the pollutant load and concentration at the two major outfall locations (one in the city centre from Bharalu River and one at Deepor Beel) are discussed. Based on the total pollutant load at the outfalls, about 40% of the total generated load in the study area is discharged to the Brahmaputra River via the city centre outfall whereas the other 60% travels via the outfall at Deepor Beel showing that more than half of the sanitary flow comes from Deepor Beel catchment area. This area is larger than that of Bharalu and Borsola showing that more load per area is generated in the city centre. This is also reflected by the higher population density. Based on a monsoon season with high intensity rainfall events more water will be leaving the system through Deepor Beel as part of the water is diverted from the city centre with a pumping station.

Furthermore, the results show that the pollutant concentration in the city centre outfall is much greater and spread over a shorter time period than at Deepor Beel indicating the large residence time in Deepor Beel (Figure 13). The rapid reduction in concentration indicates the exact point in time when the pollutant input has been stopped. However, in Deepor Beel the concentration drops and rises after the input has stopped. During monsoon, this increase is much smaller suggesting the faster transportation of pollutants through Deepor Beel. Furthermore, it can be noted that the concentration during rainfall is lower at both outfalls, because of dilution by storm water.

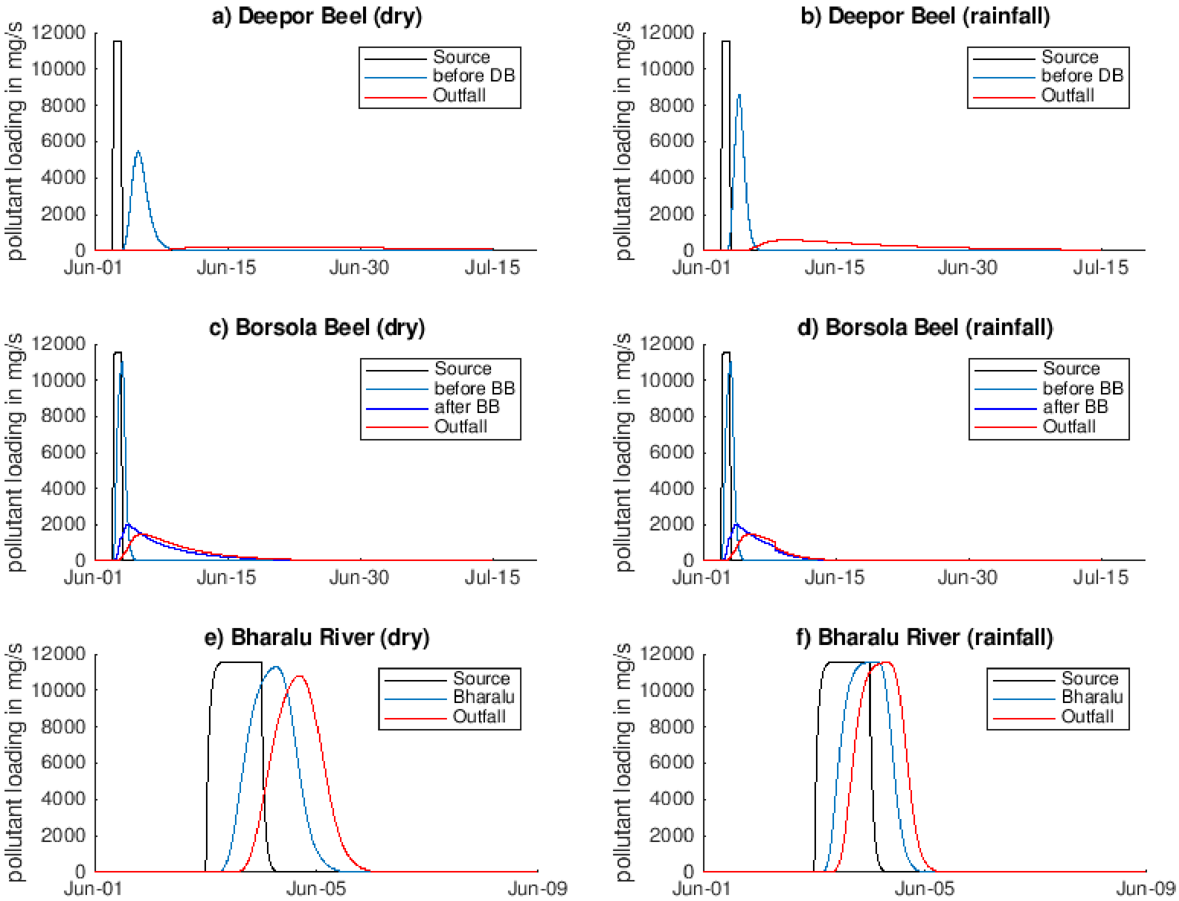


Figure 12: The downstream propagation of the point sources (pollutant load) from different locations. Note: graphs of Bharalu River (e and f) have a shorter time axis (only first week)

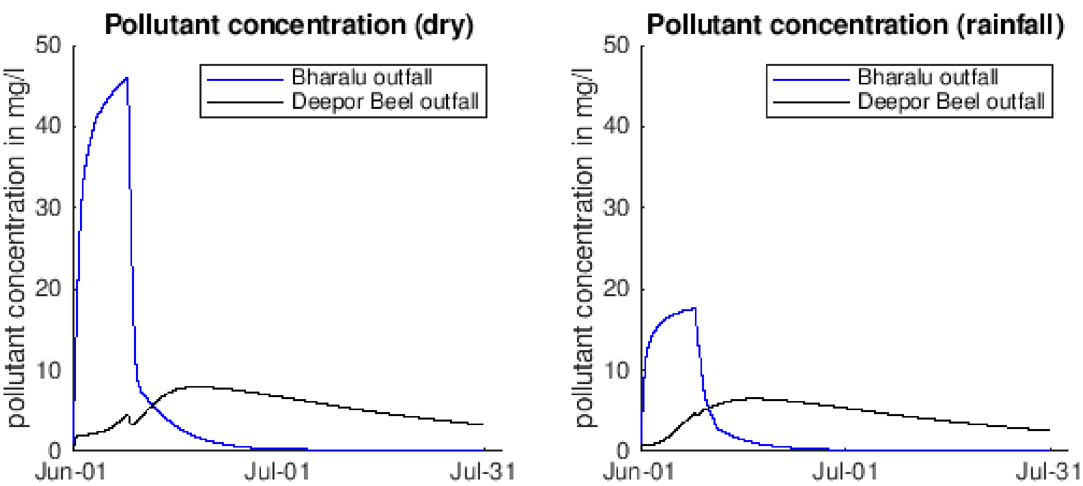


Figure 13: Pollutant concentrations of diffuse source at two major outfalls during dry period (left) and monsoon season (right)

5.1.2 Pollutant sources

The results from SWMM revealed DWF to be the major source of pollution. Except for TSS, a large percentage (above 75%) of the remaining substances were generated from DWF. In Figure 14 the percentage of each origin – DWF or WWF, subdivided into forested, managed and urban area – during wet season is presented.

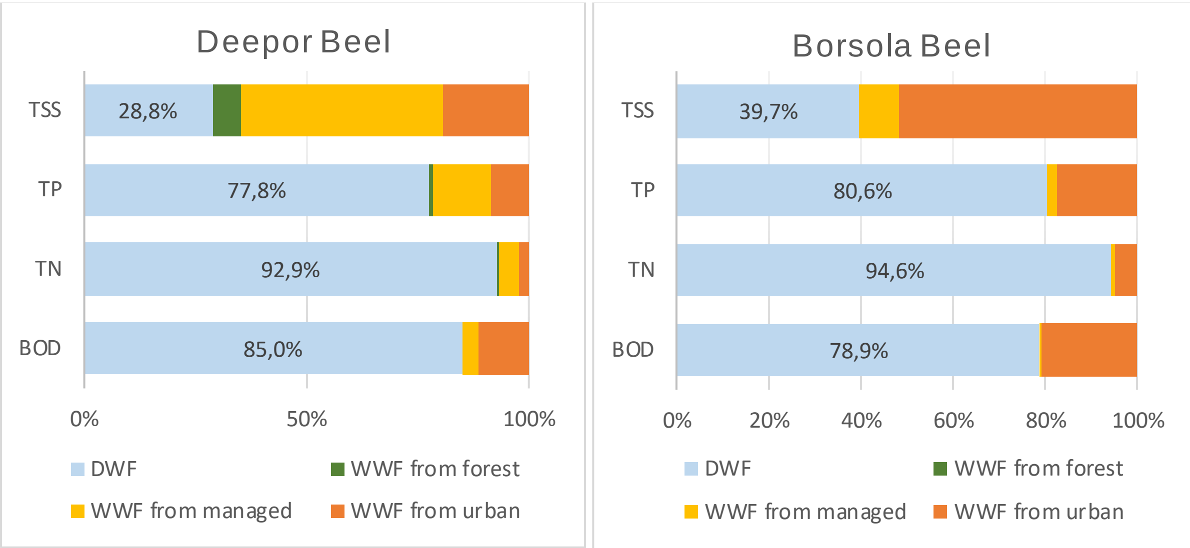


Figure 14: Pollutant load sources for Deepor Beel (left) and Borsola Beel (right) during wet season

During the winter (dry period), almost only the DWF accounts for the total flow in the channels. During monsoon season, rainfall will result in runoff from sub-catchments, hence introducing an extra flow to the DWF. The volume of storm water runoff (WWF) is generally larger than the volume of DWF during monsoon season, but as can be seen in Figure 14 the pollutant load coming from the DWF still contributes to a large part of the total pollutant load. This is mainly because the concentrations in DWF are higher than concentrations in storm water runoff.

Furthermore, the model revealed that the pollution load in Deepor Beel varies more than in Borsola Beel. The pollutant load in Deepor Beel also originates from urban, managed and forest areas, whereas for Borsola Beel it is mostly from urban areas. In addition, the effects from other land uses were clearly visible on the TSS load in both water bodies as it shows that only the majority of sediment and solids is coming from storm water runoff. This can be explained by the fact that sediments are susceptible to erosion. Surface erodibility in this region was already high and was further increased due to deforestation, agriculture and mining activities (Assam State Disaster Management Authority, 2014). This is reflected in the higher EMC values for storm water runoff from the different land uses being in a similar order of magnitude as the DWF concentrations.

5.1.3 Pollutant concentrations

Despite the major source of pollutants being sanitary flow, the concentration is influenced by several other inputs and factors such as evaporation, hydraulic residence time and volume of the lake in combination with degradation processes[4]. In Figure 15 and Figure 16, the concentrations throughout time are presented for respectively Deepor Beel and Borsola Beel during a dry period (shown in red) and a monsoon season with rainfall events varying in duration and intensity (shown in black). The desirable concentration (water quality standard) for each parameter is presented by a dotted line.

[4] Only a first order decay has been taken into account in SWMM

As can be seen in Figure 15, the volume of Deepor Beel increases with higher precipitation. The lower concentration during a rainfall event can be attributed to dilution. This diluting effect is especially notable for the concentration of BOD and also to a lesser extent for both TN and TP, since the nutrient concentrations in both DWF and WWF are in a smaller range. On the other hand, TSS concentrations show a higher concentration during rainfall as sediments are more susceptible to erosion from land. Comparing the model results with water quality measurements taken in the area, the model captures the order of magnitude of each pollutant well, for BOD being 4-10 mg/L and 0-4 mg/L in respectively dry and monsoon season; for TN it ranges between 1-2 mg/L in dry season and 0,5-1,5 mg/L in monsoon season; for TP it ranges between 0-1 mg/L in dry season and 0,5-5 mg/L in monsoon season and for TSS it ranges between 50-100 mg/L in dry season and 100-200 mg/L in wet season (see Table 1).

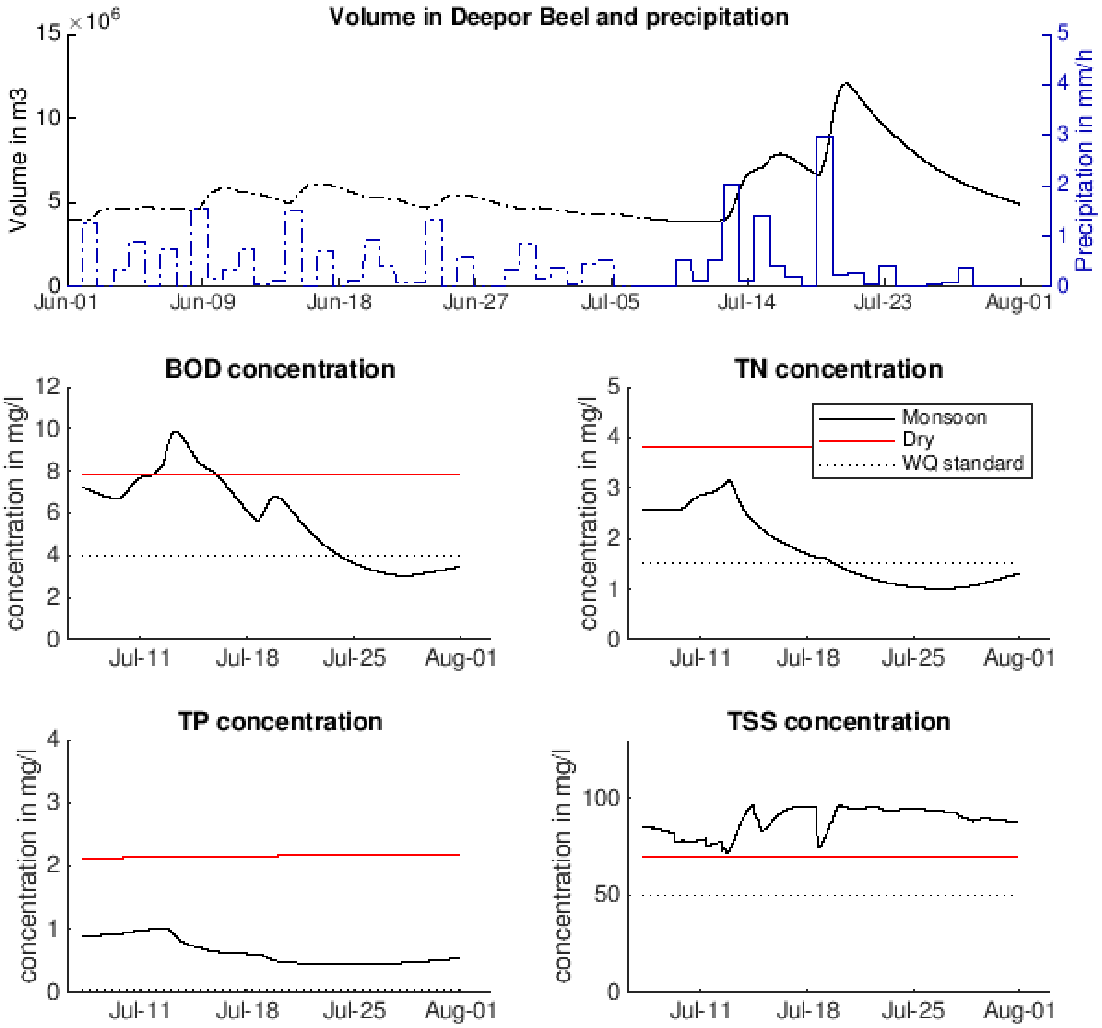


Figure 15: Volume, precipitation and pollutant concentrations throughout time in Deepor Beel. Only the solid part of the upper graph is visualized in pollutant concentrations.

The effect of storm water in lowering the pollutant concentration is distinctly visible in Figure 16 for Borsola Beel as during dry season the pollutant concentration is significantly higher (almost one order of magnitude larger) than in Deepor Beel, but it gets comparable concentrations during rainfall. Also, the model performs sufficiently by capturing the BOD concentrations in the order of magnitude of the water quality measurements which is 120-150 mg/L in dry season. For TP it ranges between 1-4 mg/L in dry season and 0-1 mg/L in wet season, so the model overestimates these concentrations in Borsola Beel. Scarcely available data on TN concentrations in Borsola Beel and concentrations of all pollutants during wet season do not allow this study to say something more on model performance.

Altogether, the results show that both BOD and nutrient concentrations still stay significantly above the permissible water quality standards being 4 mg/L for BOD and 1,5 and 0,05 mg/L for respectively TN and TP (the limit for TP concentrations is hardly visible in Borsola Beel in Figure 16). The high nutrient concentrations imply that both lakes are very eutrophic according to their current concentrations (Liang et al., 2013). The TSS concentration in Borsola Beel is similar in both dry and wet period, most likely because the main source of contaminants in Borsola Beel is residential area which has in general less sediments available for erosion than in the more cultivated and managed areas located in Deepor Beel.

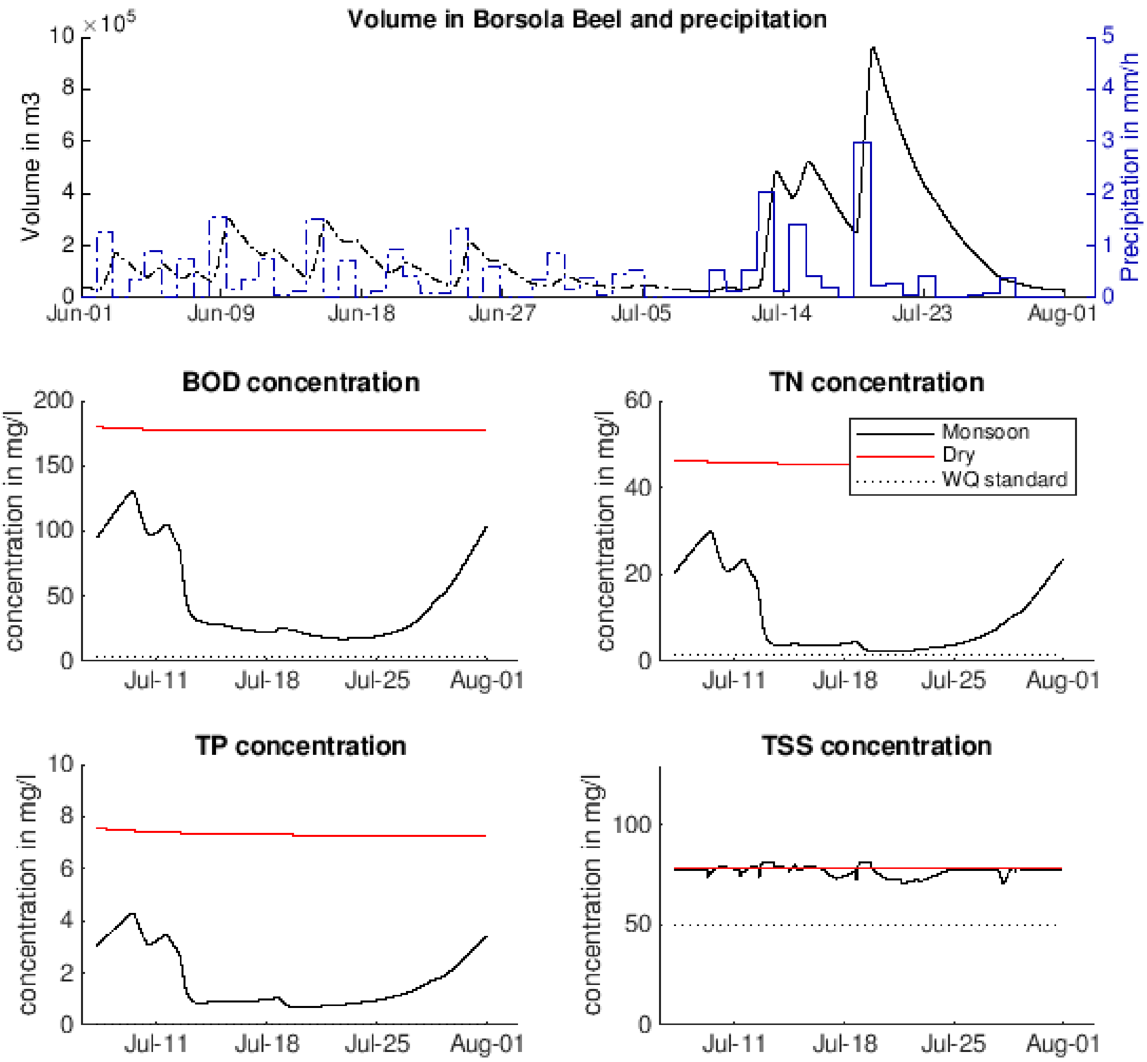


Figure 16: Volume, precipitation and pollutant concentrations throughout time in Borsola Beel. Only the solid part in the upper graph is visualized in pollutant concentrations.

Comparing the results of Deepor Beel and Borsola Beel in general, it shows that Borsola Beel has a flashier behaviour in water volume and pollutant concentrations in response to precipitation events than Deepor Beel has. The volume of Deepor Beel is almost ten times larger than the volume of Borsola Beel whereas the inflow is in a similar order of magnitude for both lakes. Hence, the inflow has a larger effect on the water volume in Borsola Beel than in Deepor Beel. This makes the hydraulic residence time in Deepor Beel also larger, making this wetland more susceptible to different chemical and biological processes like degradation and sedimentation.

5.1.4 Sensitivity analysis

Models are generally as good as the input values used. Based on the underlying functions used in a model, it can exhibit different levels of sensitivity to different parameters. In this study, the model inputs influence the results differently with different weather conditions. Most parameters are found to be more sensitive during dry season and less in wet season, especially DWF volume (and population). Considering the trends were similar for all the input parameters, the following sections only discusses BOD and its sensitivity of different parameters used in the research. The graphs with the other pollutants can be found in Appendix D.

Dry season

During a dry period, only the sanitary flow runs through the water system and no storm water runoff is present. Therefore, the WWF concentration and imperviousness have no effect and are not further discussed. Based on Figure 17, the decay coefficient shows to have a large influence on the concentration in Deepor Beel and to a lesser extent in Borsola Beel. One of the reasons is the difference in hydraulic residence times for both lakes. The hydraulic residence time in Deepor Beel is larger than in Borsola Beel allowing the degradation process to take place longer. Secondly, the population and DWF volume, which are linked to each other, influence the concentration in both lakes. A lower population or DWF volume leads to a lower concentration, however, in Borsola Beel it leads to concentrations going to infinity. This is counterintuitive, but an observation in the model made clear that Borsola Beel emptied over time as a result of a lower constant inflow than initial inflow, hence a decreasing lake volume with a constant incoming pollutant load increases the pollutant concentration. Last, the DWF concentration has a linear relationship to the output concentration in both Borsola Beel and Deepor Beel.

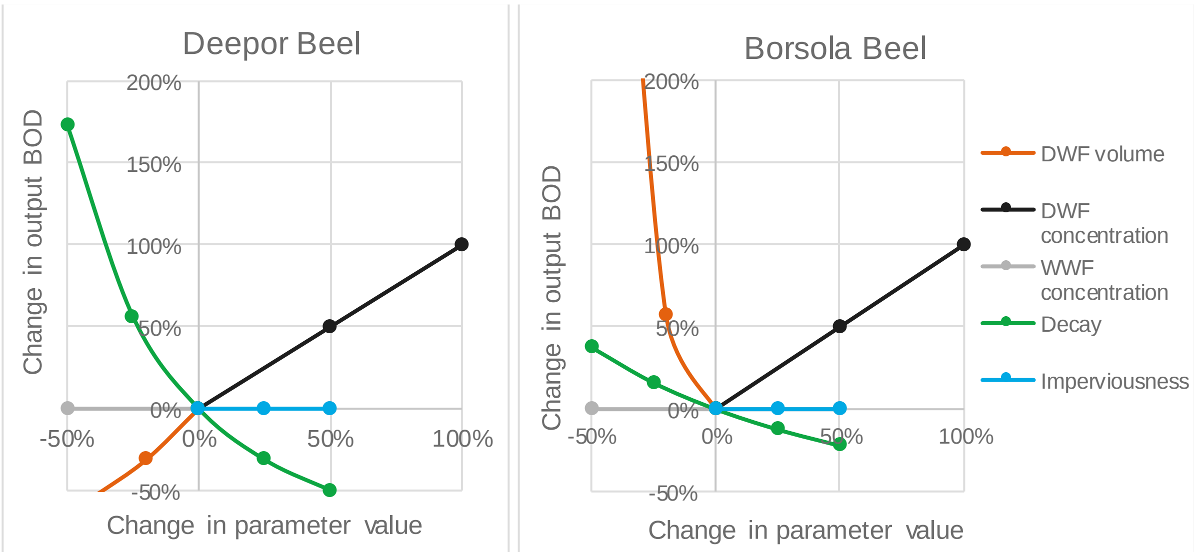


Figure 17: Sensitivity analysis for BOD in Deepor Beel (left) and Borsola Beel (right) during dry weather

Wet season

During a period with constant rainfall a similar pattern for the decay coefficient compared to a dry period is observed in Figure 18 being of a larger influence in Deepor Beel than in Borsola Beel. The same reason of the larger hydraulic residence time in Deepor Beel explains this observation. Furthermore, the change in DWF concentration is of more influence than the change in WWF concentration, but both have a linear relationship to the end concentration. However, the WWF concentration of TSS shows to have a larger influence on the end concentration than its DWF concentration. This can be attributed to the fact that more sediment originates from storm water runoff than from sanitary flow (see appendix D).

The imperviousness has only been changed in the catchment area of Borsola Beel, hence only influencing the concentration here. If the imperviousness is increased, more (urban) runoff will take place and the concentrations increase. Figure 18 shows that it influences the results relatively little compared to other investigated parameters. However, when looking at TP or TN concentrations, the imperviousness has a more distinct effect on the end concentration.

Last, the DWF volume (and population) have a negligible effect on the results in Borsola Beel. The DWF volume and population have a linear relationship to the output concentration for all pollutants. However only for TSS, which has an inverse linear relationship during rainfall due to higher concentration in storm water runoff, the DWF volume suggests that a higher population would lower the end concentration of TSS.

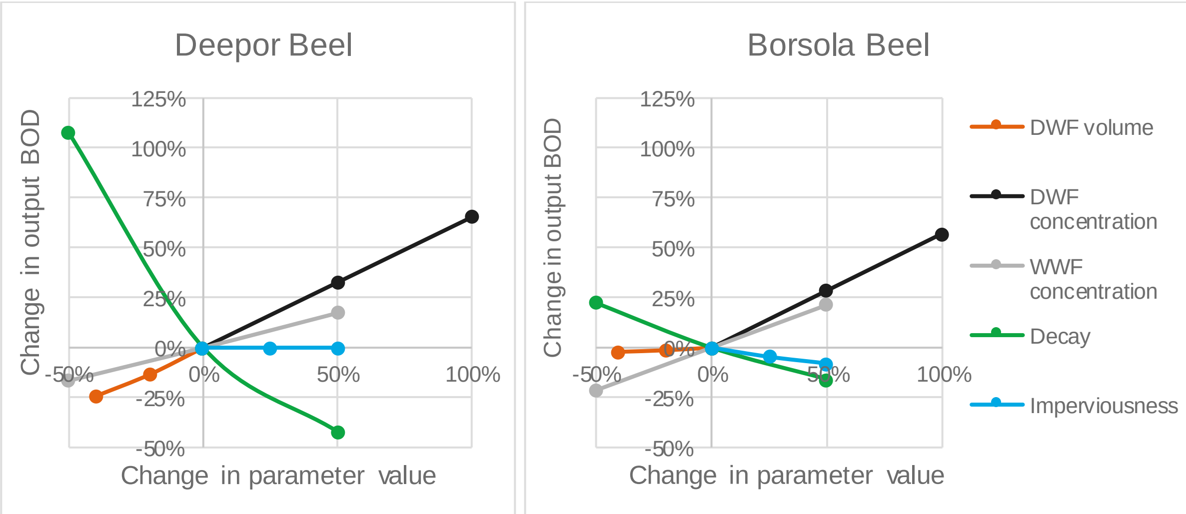


Figure 18: Sensitivity analysis for BOD in Deepor Beel (left) and Borsola Beel (right) with constant rainfall

Land use is not included in the sensitivity analysis. However, it is assumed that increase in urban area also increases pollutant load and concentration as urban runoff generally exhibits a higher pollutant concentration, but this depends on the investigated pollutant.

5.2 Systems analysis: future situation

Wastewater currently generated in Guwahati is one of the major sources of pollution for the water system. Demographic predictions in India show that the growing population trend in Guwahati will continue in the coming decades resulting in both a change in land use composition as well as an increase in wastewater generation. Design for sewage treatment is based on projected population. Any underestimated value will make the system inadequate for the purpose intended and similarly overestimated values will make it costlier (Ghangrekar, 2012). Therefore, predictions and projections for the design period are discussed in this section.

5.2.1 Population growth

The 2025 Masterplan for Guwahati predicts the population to reach 1,8 million by 2025. It is also expected that the city will reach a population of three million by 2050 (in GMC) out of which approximately two million will be living in the combined catchment basin of Borsola Beel and Deepor Beel. Considering the impact of sanitary wastewater on the total pollutant load of both water bodies, this significant increase in Guwahati population will also mean a significant increase in wastewater generation.

The spatial variability in population growth is based on the development intensity zones proposed in the 2025 Masterplan for Guwahati (Figure 19). The main population growth is found to be at the southern side of Guwahati, in Pamohi and at the northern side of Deepor Beel. Large developments near the airport and at the northern side of the Brahmaputra River are proposed, however, as these areas are not connected to either water body, these developments were not further taken into account in this study.

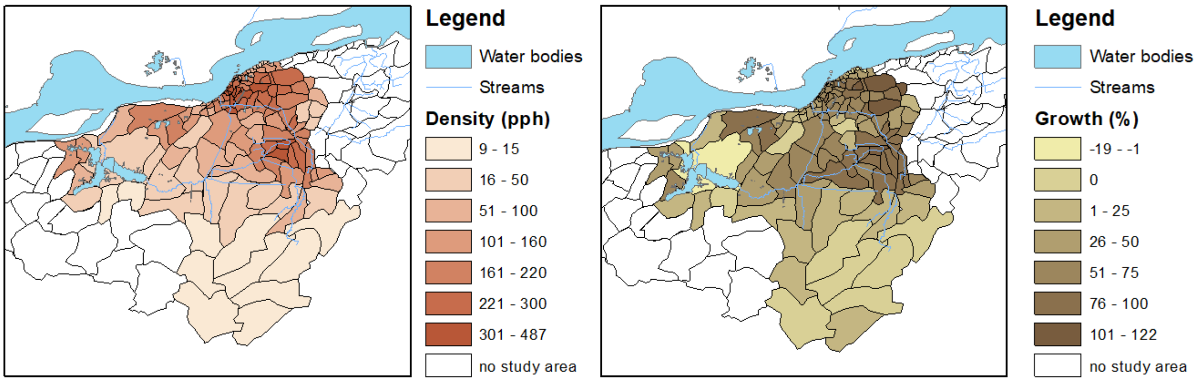


Figure 19: Population density (left) and growth in population (right) per sub-catchment in 2050

5.2.2 Land cover change

Increase in population is always reflected through an expansion of urban land cover. Previous researches suggest that based on historical developments cultivated, managed areas and forested areas in Guwahati may observe a decline (Manta & Rajbangshi, 2015; Pawe & Saikia, 2017) in order to provide residence to the expected increased population. This expected increase in urban land cover will also mean that Guwahati will observe a larger volume of storm water runoff because of the higher imperviousness of urban land cover.

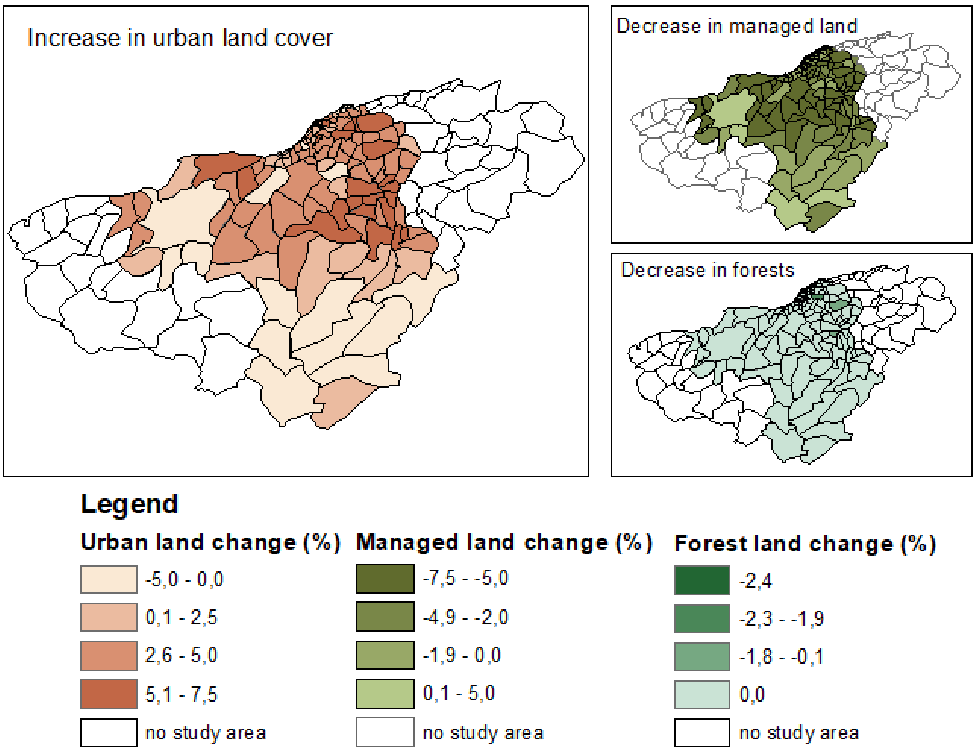


Figure 20: Change in land cover in the study area.
Urban land increases whereas managed and forested land decrease.

It is predicted that urban areas will increase generally along the Basistha River and Mora Bharalu and the (north) western part of Deepor Beel near the airport. The city centre is already densely populated, but a small growth rate is present here as well (see Figure 19 and Figure 20).

5.2.3 Wastewater generation

As a population growth is expected, the wastewater generation in Guwahati will increase as well. The amount of generated wastewater in Guwahati is expected to increase with approximately 50% in the coming decades with the largest increases along the Mora Bharalu and Basistha River and southern part of Pamohi catchment area.

Despite the fact that current and proposed infrastructural development works will improve the drinking water (piped) connectivity in the area eventually increasing per capita water consumption, this value was kept as a constant in this study. Hence, the increase in wastewater per sub-catchment will grow simultaneously with the growth in population throughout the area, visible in Figure 19. Here can be seen that the largest increase in wastewater generation will be along the Mora Bharalu, the Basistha River at the southern side of Guwahati as well as in the city centre.

The wastewater generation in million litres per day (MLD) per sub-catchment for 2025 and 2050 is presented in Table 8. It can be seen that a total of approximately 250 MLD of sewage water is expected in 2050, showing a 50% increase, with the largest increases in Borsola and Mora Bharalu catchment areas.

Table 8: Sewage generation in MLD per sub-catchment in 2025 and 2050 based on model results

	Generated sewage volume (MLD)		Increase (%)
	2025	2050	
Bahini	16,1	25,3	57,1
Basistha	48,2	70,8	46,9
Bharalu	27,9	44,6	60,1
Borsola	12,6	24,1	91,3
Deepor Beel	35,9	49,5	37,7
Mora Bharalu	12,7	20,9	63,9
Pamohi	7,7	9,7	25,9
River front	4,9	6,2	38,3
Total	**166**	**251**	**51,4**

5.3 Scenario development

In an ideal situation, all population of a city is connected to water supply and a sewage system, in which all residential (including industrial and commercial) water will be treated before being discharged into open surface water. In addition to the sources and problems of untreated sewage water, several other factors play a role while designing and building a STP in a developing country. In a country like India, with extreme high population density, it is often a challenge to ensure land acquisition for such a plant, making the location and size of the STP important factors. In addition to the high cost of acquiring the appropriate land, the maintenance of a STP also involves certain cost as well as acquiring an adequate number of people with knowledge about these systems to let the STP functions according to design standards. This makes it essential to know what would be the expected improvement in water quality when a certain amount of money is invested.

In the systems analysis of the current and future situation, the key problems and main projections were identified to help develop scenarios. Growth in population will result in an increased flow of sanitary wastewater. This, coupled with increasing urban land cover will eventually develop more severe problems from wastewater in the city, especially in the densely populated areas in Basistha and Bharalu catchment.

In this study several scenarios have been simulated to understand how water quality of Guwahati, especially in the focused wetlands, will be affected in the future. The factors which are considered most important to vary in the scenarios were location, capacity, treatment efficiency and number of STPs. For Borsola Beel, the location has been fixed as just one inflow is present, but the capacity and treatment efficiency are varied. For Deepor Beel also the number and locations of STPs are varied.

5.3.1 Assumptions in scenarios

This study assumed some fixed values to limit the number of parameters and scenarios; hence to be able to compare the scenarios. Firstly, the future population of Guwahati was considered a fixed value and was not altered during the different scenarios. Secondly, the associated total water usage per capita and generated volume of sewage water was also kept at a constant value throughout the current and future situation.

In addition, the study considered the STP to use activated sludge as treatment method, as it is widely used in both India (CPHEOO, 2012) and other parts of the world. This process presents the secondary and tertiary treatment which respectively remove organic matter (BOD) and nutrients. This specific method provides a removal efficiency of 85%, 60%, 35% and 40% for respectively BOD, TN, TP and TSS (Central Pollution Control Board, 2007; Nelson & Murray, 2008). The primary treatment has already been taken into account when modelling the TSS inflow concentrations. Furthermore, the removal efficiency gets reduced during periods with rainfall as the wastewater gets diluted with storm water runoff and the influent becomes less concentrated (Wilén, Lumley, & Mattsson, 2006). It was assumed that during rainfall the STP will work 10% less effectively than its potential removal efficiency.

Lastly, to limit the complexity of modelling the scenarios and as conveyance systems in India are considered as a large problem of underutilisation of STP capacities - due to unfinished parts or pumps which are not operating (Arappor Iyakkam, 2018; Central Pollution Control Board, 2007), this study considered to only use the natural streams (or open storm water drains) for transporting the wastewater to the STPs. Hence, locations are based on the drainage areas as the sanitary flow will most likely be transported next to, or through the natural streams like Basistha and Bharalu River.

5.3.2 Scenarios

The number, location(s), capacity and treatment efficiency of the STPs are factors which are varied in the scenarios. Since these are multiple factors in multiple dimensions, many combinations can be made. To limit the number of scenarios and design feasible alternatives, the compatibility of the combination of factors is taken into account in the design of the scenarios. For example, a high treatment efficiency with a high capacity at a STP in this area is very unlikely considering unskilled staff and its financial costs. This study primarily focused on options for spatial variations (centralised and decentralised treatment) as well as seasonal variations (diversion of flow during dry season and additional treatment capacity at STP during monsoon season).

Five scenarios, including a worst-case scenario, have been designed and simulated in SWMM to determine the ability of each scenario to improve the water quality. The worst-case scenario in which no wastewater is treated, is used as a reference scenario to compare the improvement in water quality between scenarios.

Starting with two STPs at the main inflows of both lakes, which have a capacity based on upstream generated DWF and which have high removal efficiency, alternative scenarios are made to compare the effects of centralised and decentralised STPs as well as another pumping scheme and larger treatment capacity. An overview of the four proposed scenarios is presented in Table 9 and in Figure 21.

The first scenario focuses on improving the water quality in both lakes. It consists out of two large STPs just before Deepor Beel and Borsola Beel which have a design capacity of respectively 90 and 25 MLD and the highest potential removal efficiency for each pollutant. These STPs only serve the catchment basin of Deepor Beel and Borsola Beel presuming the total flow during dry period, hence, treating all incoming DWF from upstream catchments.

In contrast to scenario 1, scenario 2 consists out of four relatively smaller (decentralised) STPs located closer to the city, thus sources of pollution, and serving a larger part of the city. They treat all incoming DWF from upstream catchments. Hence, the total combined capacity is larger in this scenario. The STPs are located just before Borsola Beel, in the Bharalu catchment area, at the confluence of Mora Bharalu and the northern branch of the Basistha River and additionally one at the northern part of Deepor Beel diverting and treating water from this area to Deepor Beel outfall. Their capacities are respectively 25, 60, 75 and 30 MLD and each STP has a medium removal efficiency, being 25% lower than the potential removal efficiency for all pollutants.

Scenario 3 will investigate if diversion of treated water from the city centre to Deepor Beel during dry period helps to lower concentrations due to flushing the water system of Deepor Beel. The scenario has the same number and locations of STPs as scenario 2 as the diversion of water will help more effectively when it is treated. The STPs have a 25% lower capacity, but high removal efficiency. The lower capacity means it will treat 75% of the total incoming DWF whereas the other 25% will continue untreated. Additionally, another pumping scheme is employed at the Mora Bharalu River where part (±30%) of the treated water of Bharalu River now will be diverted to Deepor Beel during dry periods to flush the lake.

In India it is not common to design a STP with extra capacity, so scenario 4 explores the incorporation of extra capacity for storm water to be treated during rainfall resulting in less overflow with sewage water at the two larger STPs (similar to scenario 1). These STPs have a medium removal efficiency in order to trim costs to compensate for higher capacity. The capacities during dry weather are similar to the first scenario whereas the capacities are 75% higher during wet weather.

Table 9: Overview of varying factors in the scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
	Centralized	**Decentralized**	**Pumping scheme**	**Higher capacity**
Total combined capacity (MLD)	115	195	146	115 (dry) 200 (wet)
Number of STPs	2	4	4	2
Efficiency of STPs*	High	Medium	High	Medium
Separate capacities	25 and 95	30, 25, 60 and 75	22, 17, 47 and 59	*25 and 95 (dry)* 43 and 160 (wet)
Other features	-	-	Diversion of flow during dry period	Extra capacity for storm water

* High and medium efficiency means respectively 100% and 75% of potential removal efficiency

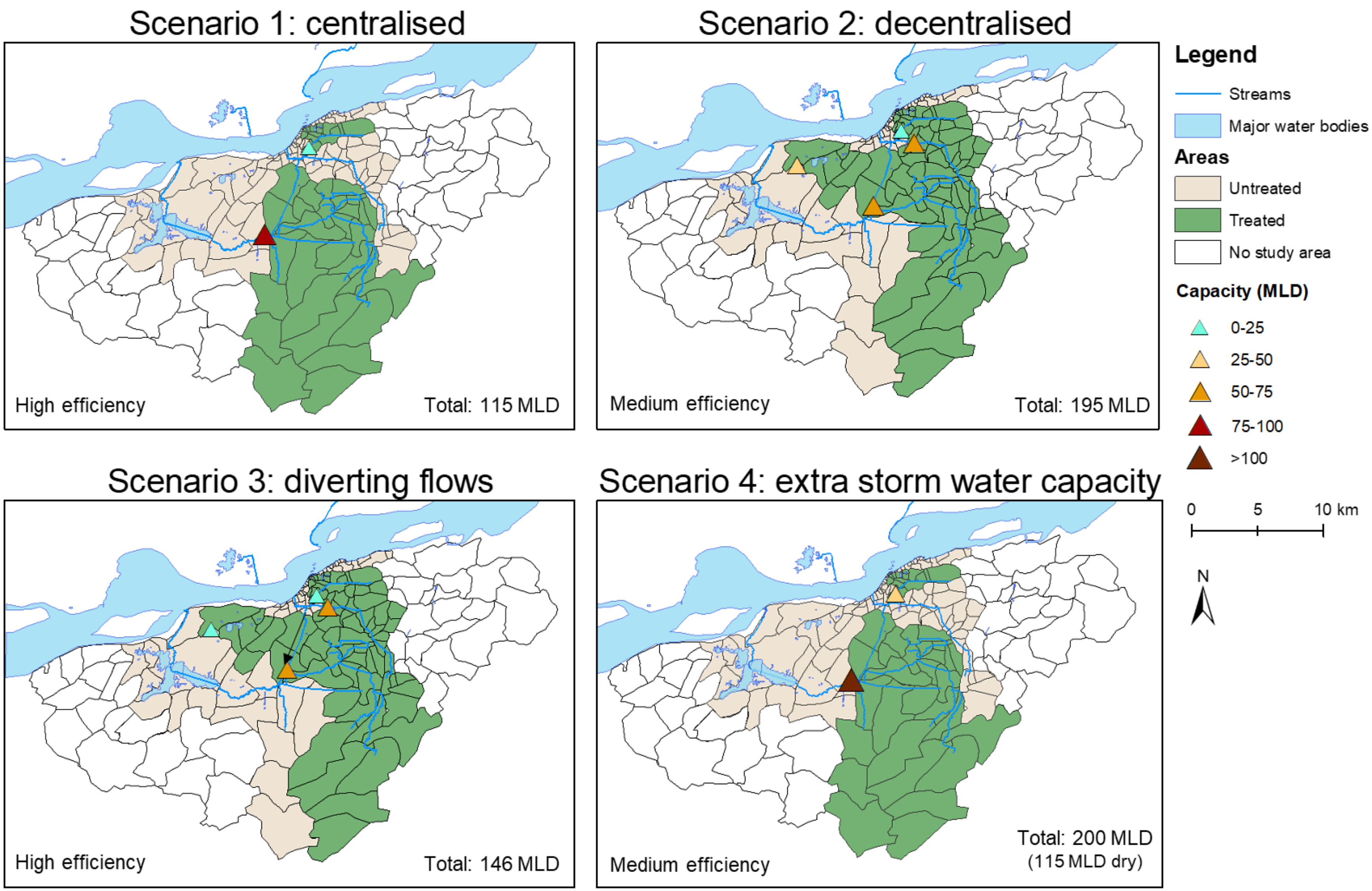


Figure 21: Locations of sewage treatment plants and the served area from which sewage water is treated in the different scenarios

5.4 Identifying most effective scenario

Not all management schemes provide the same level of improvement in the water quality in Guwahati, to be specific in Deepor Beel or Borsola Beel. Neither were the predicted costs the same for the different scenarios. Each scenario is compared to the reference scenario (5.4.1). In this comparison, each scenario was compared on its ability to improve water quality (5.4.2), the cost of implementing that scenario (5.4.3) and its feasibility (5.4.4).

5.4.1 Reference scenario

The reference scenario (worst case scenario) assumes that no management measures will be implemented for sewage water treatment in the area while assuming that the population of Guwahati will continue to increase and subsequently an increase in urban land cover. The increasing wastewater generation due to growth in population, also introduces a higher pollutant load into the water system. An average increase of 30 to 50% for BOD in dry season is observed, whereas this increase is smaller in wet season, being 10 to 30%. This implies that the water quality is rapidly deteriorating when no measures are taken to improve the water quality in the area.

5.4.2 Water quality

The local effects on lake water quality differ from the general effects of reduction in pollutant load in the study area for each scenario. Additionally, the distinct seasonality determines for a large part the effectiveness of the STPs in all scenarios.

Effect on lake water quality

Based on Figure 22 all scenarios show a reduction in pollutant concentration for both lakes, however the effects in Borsola Beel are considerably larger than in Deepor Beel. Especially during dry season, the scenarios show a larger reduction. Figure 22 shows the removal efficiency of BOD at the STP and percentage reduction of concentration in Deepor Beel and Borsola Beel compared to the reference scenario. It can be concluded that the lowering in pollutant concentration in the lakes is clearly larger during dry season than during wet season. This is primarily because the total capacity of the STP is designed on DWF and hence not all incoming flow during rainfall can be treated, leaving a part untreated. Furthermore, the effects of the STPs are clearly more prominent for Borsola Beel than for Deepor Beel when the concentration reduction is compared mutually as well as to the removal efficiency of the STP: in Borsola Beel the percentage reduction in concentration is similar to its removal efficiency of the STP. This large effect in Borsola Beel is primarily because the lake has one inflow contributing to the lake, which is now treated, in contrast to Deepor Beel having multiple inflows around the lake which are not all treated. Only scenario 3 which treats 75% of the incoming flow, leaving 25% untreated, does not comply with the last observation. During a dry period, the effects in Borsola Beel are seemingly related to the capacity as well as treatment efficiency of the STP.

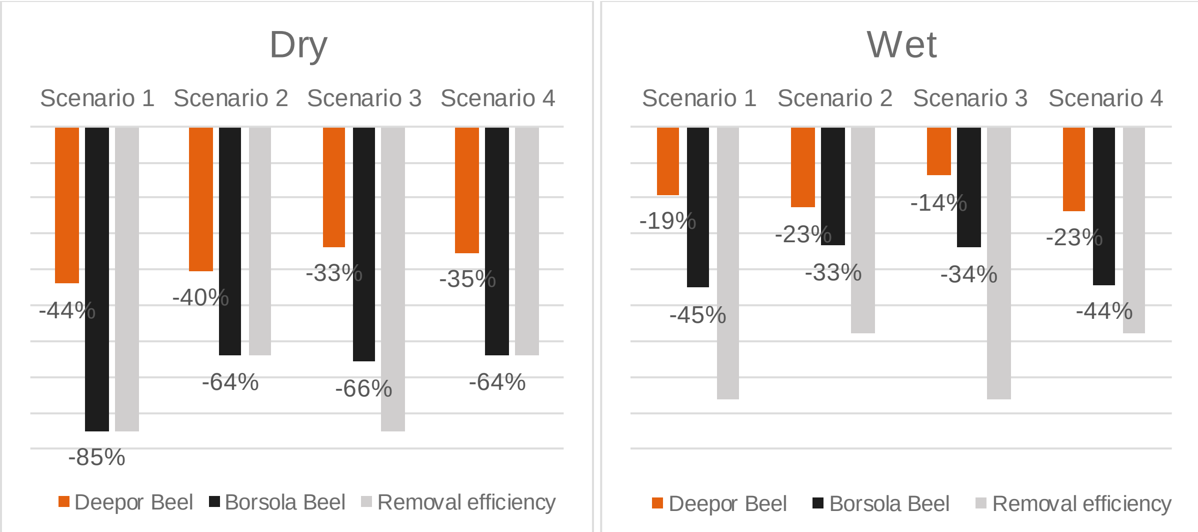


Figure 22: Lowering of BOD concentration in Deepor Beel (orange) and Borsola Beel (black) in each scenario for a dry (left) and wet period (right) compared to removal efficiency in STP (grey)

Regarding the effect of each scenario separately in dry season, Figure 22 shows that scenario 1 with two centralized STPs is most effective in cleaning both Deepor Beel and Borsola Beel presenting the highest reduction in concentration being respectively 44% and 85%. This is mainly due to the high efficiency in pollutant removal and the locations of the STPs, being established just upstream of the lake. For Deepor Beel, scenario 2 – with four relatively smaller STPs of which two serve catchment areas of Deepor Beel with medium efficiency – also has a relatively large effect on Deepor Beel during dry period as the reduction in concentration is 40% compared to the removal efficiency of 64% in the STPs. The STPs are not directly located upstream of Deepor Beel, but an additional part of the catchment area of Deepor Beel (northern) is treated which helps to lower the concentration in Deepor Beel. Furthermore, Figure 22 shows that scenario 3 with a lower total combined capacity and high efficiency has, considering its high removal efficiency, the smallest effect in reducing the concentration in both seasons in Deepor Beel as well as in Borsola Beel. This suggests that the capacity of the STP combined with service area has a large influence. Last, diverting the water from the city centre to Deepor Beel does not seem to have a large influence on the concentration in Deepor Beel either, possibly because part of the diverted flow remains untreated.

In wet season, the right chart in Figure 22 shows that both centralised scenarios (1 and 4) have the most effect in reducing the concentration in Borsola Beel. However, scenario 4 which incorporates extra capacity to treat part of the storm water runoff, is more effective when comparing the reduction in concentration with the removal efficiency of the STP. In Deepor Beel, on the other hand, scenario 2 has a similar effect on reducing the concentration as scenario 4. Since both have a similar removal efficiency, it might be because of their comparable larger combined treatment capacity for Deepor Beel area relative to the other two scenarios. Scenario 2 has a slightly lower capacity, but treats multiple inflows.

The water quality in the lakes are assessed based on acceptable water quality limits. Table 10 shows the achieved percentage by each scenario to lower the BOD concentration to its desired limit of 4 mg/L. This table confirms that the scenarios are more effective during dry season than wet season. The achieved percentages are all higher than 50% with most of the scenarios achieving almost 60 to 70% in the lakes. During wet season, the concentrations are already lower due to dilution, but only approximately 30 to 40% of the concentration which needs to be lowered to reach the target concentration, is achieved by the scenarios. The achieved percentages for the other pollutants are given in Appendix F.

Table 10: Achieved percentage of concentration to be lowered to reach the target concentration

		Worst case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
			Centralised	Decentralised	Diverting flow	Extra capacity
BOD target: 4 mg/L						
Dry	Deepor Beel	0	66,5	60,9	50,6	53,2
	Borsola Beel		87,5	65,8	67,8	65,8
Wet	Deepor Beel		29,2	35,1	21,3	36,2
	Borsola Beel		47,5	35,1	35,6	46,4

Overall effect on water quality in study area

The local effects on the lakes have now been analysed by means of percentage reduction in pollutant concentration relative to the reference scenario, but the overall effect on reducing the pollutant load in the study area differs. The service area in combination with treatment efficiency of STPs mainly determines the overall effect on reducing the pollutant load in the area in which scenario 2 and 3 lower the overall pollutant load the most.

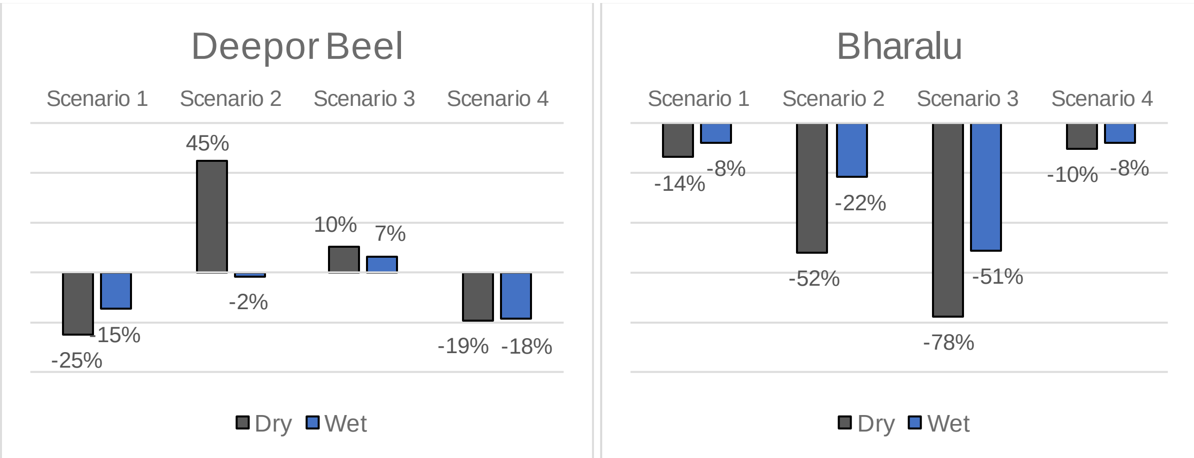


Figure 23: Reduction (negative) and increase (positive) of BOD load at two major outfalls of the study area

Figure 23 shows the reduction in BOD load at the two major outfalls from which can be seen that the pollutant load will be reduced at the outfall of Bharalu River for all scenarios, but the pollutant load is increased at the outfall of Deepor Beel for the scenarios with four smaller STPs. This is primarily because the STP at the northern side of Deepor Beel diverts the treated water directly to the outfall which - according to the model - treats less of the total pollutant load than when the water travels via Deepor Beel to the outfall reducing the pollutants in a natural way. Only during periods with rainfall a small decrease in pollutant load is visible for scenario 2.. On the other hand, both decentralised scenarios (2 and 3) have largest decrease in pollutant load at the city centre, which makes them very effective compared to just two larger STPs in the area. This is mainly because the water from the Bharalu and city centre is treated whereas this is not the case with the two centralised STPs. Additionally, scenario 3 shows the largest decrease in pollutant load at the outfall of Bharalu, because part of the flow is diverted towards Deepor Beel where it is subject to decay in a natural way, however it still causes a small increase in pollutant load at Deepor Beel outfall.

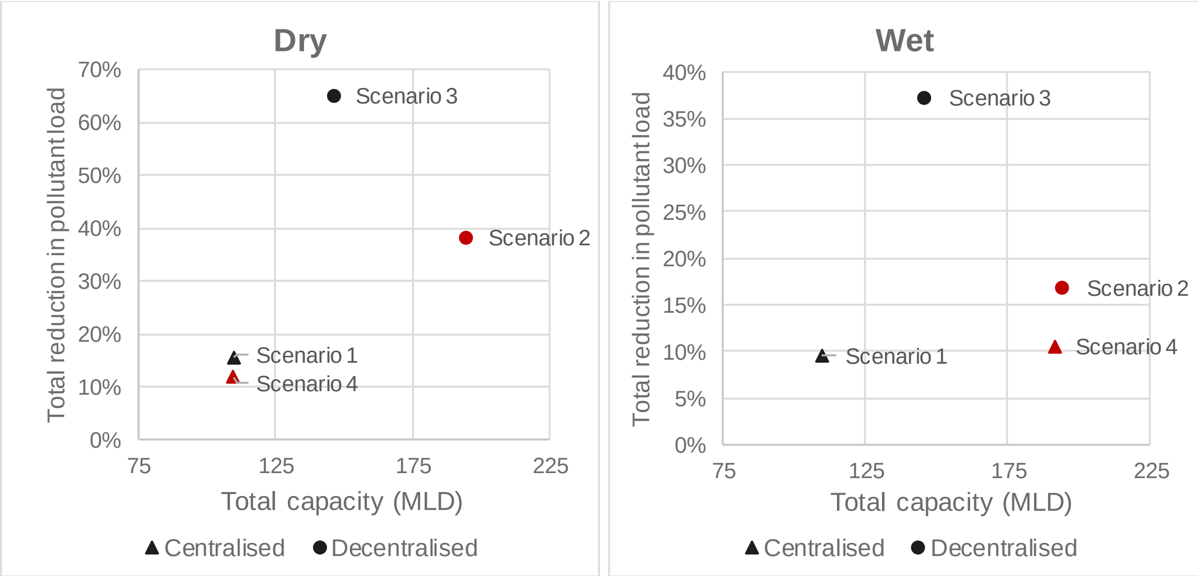


Figure 24: Total combined capacity of STPs (MLD) in study area compared to the total reduction in BOD loads at outfalls during dry (left) and wet season (right). Scenarios 1 and 3 have a high removal efficiency (black) and scenario 2 and 4 have a medium removal efficiency (red)

Based on Figure 24, there is no clear pattern visible between the combined total capacity of the STPs in the study area and the total reduction in pollutant load at the outfalls. However, both scenario 2 and 3 with four smaller STPs (represented by the dots) show a larger total decrease in pollutant load compared to scenario 1 and 4 having two centralised STPs (represented by the triangles) in both dry and wet season. However, in dry season this can also be accounted to the higher total combined capacity in scenario 2 and 3. During a wet period, the difference in centralised and decentralised is well visible between scenario 2 and 4 having a comparable total combined capacity and removal efficiency. The reduction in pollutant load at the outfalls is slightly higher for decentralized STPs (scenario 2) compared to two centralized STPs (scenario 4).

Another striking feature which can be seen is that the STPs having a high pollutant removal efficiency (visualised in black) have a relatively higher total pollutant reduction compared to the scenarios with a medium removal efficiency (visualised in red) and even a larger capacity. This is specifically important with decentralised STPs which suggests it can be valuable to invest in a qualitatively good treatment system when using multiple smaller decentralised STPs.

Based on both dry and wet season outcomes, both decentralised scenarios perform best by having the largest total reduction in BOD loads in the area in both seasons. Considering the total combined capacity, Scenario 3 has, however, a smaller total combined treatment capacity combined with diversion of flow and lowers the pollutant load the most.

Effect on water quality during monsoon season

During monsoon season the varying rainfall intensities show to have a large impact on the effectiveness of each scenario. As can be concluded from the analysis on local and general effect of the STPs, the treatment is less effective during periods of constant rainfall. The main reason would be the larger volumes of incoming water which cannot all be treated. The varying rainfall intensities and higher amounts are found to have even more influence on the effectiveness of the STPs. The rainfall intensities together with the volume and BOD concentrations in Deepor Beel and Borsola Beel for each scenario are presented in Figure 25 with the higher black line indicating the worst-case scenario (reference scenario). The other pollutant concentrations are presented in Appendix F.

As can be seen in Figure 25 the reduction in concentration is largest during periods without or with low intensity rainfall events (first week of July), being more pronounced in Borsola Beel than in Deepor Beel. This corresponds to previous analyses that the STPs are less effective during rainfall. Furthermore, the reduction in concentration in Deepor Beel is relatively similar for all scenarios with the decentralised scenario (scenario 2) lowering the concentration the most. This is in conflict with the analysis under stationary (wet) conditions in which the two larger STPs performed better, however the difference remains minimal for BOD.

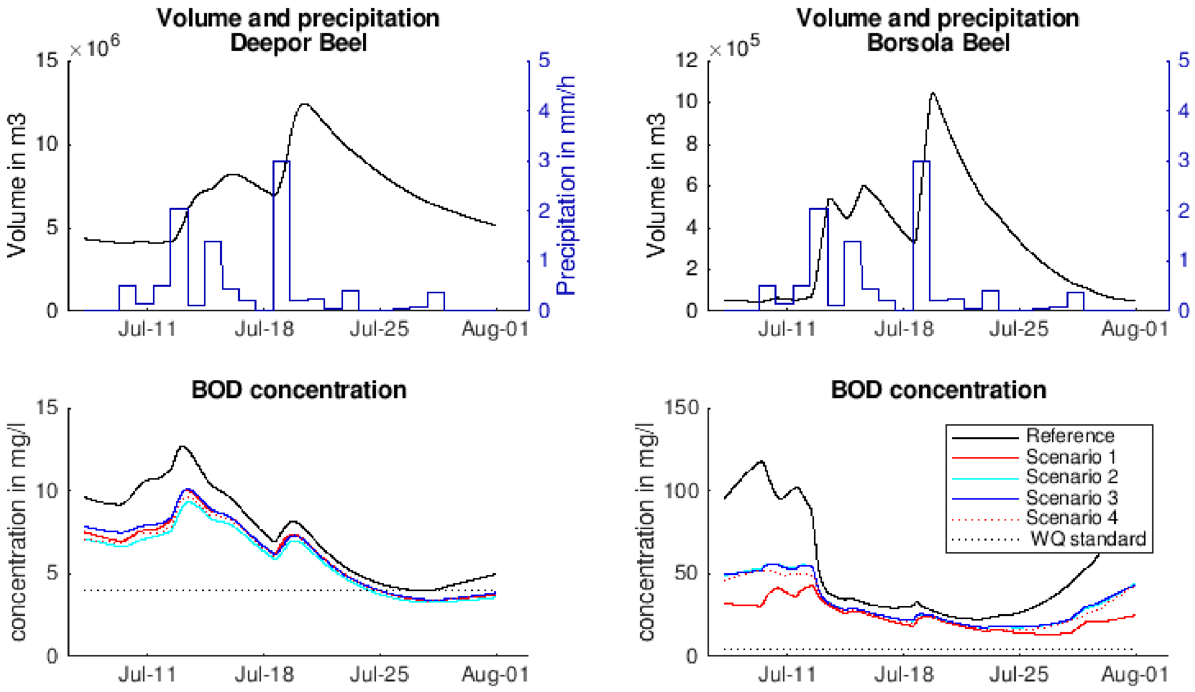


Figure 25: Volume, precipitation and BOD concentration over time together with maximum permissible BOD concentration for the different scenarios in Deepor Beel (left) and Borsola Beel (right)

In Borsola Beel, a larger difference between the scenarios is visible during a relatively dry period in monsoon season (first week of July). Here, the centralised scenario 1 with a high removal efficiency lowers the concentration the most. It is remarkable that scenario 4, treating a larger volume of incoming flow does not lower the concentration as much as scenario 1 which only treats the DWF volume. However, the removal efficiency in scenario 4 is lower, so this could suggest that a higher removal efficiency (scenario 1) is more effective than treating a larger volume with a lower removal efficiency (scenario 4). A reason for this could be that the volumes of storm water runoff are five to ten times larger than the volume of DWF which will make the 75% extra capacity upon DWF capacity have a negligible effect. The capacities of the STPs possibly need to be upgraded even more to have a large effect during monsoon season. However, it can be noted that the sanitary flow gets diluted with storm water runoff making treatment almost unnecessary, especially in Deepor Beel (lower left graph in Figure 25).

Eutrophication

Lakes can be classified on their biological activity ranging from low (oligotrophic, TP <4,6 µg/L) to moderate (mesotrophic, TP<0,01 mg/L) and high biological activity (eutrophic to hypereutrophic, TP>0,05 – 0,55 mg/L). These classes consider the water quality to be respectively good, fair and poor (Carlson, 1977). For shallow lakes, TP is generally the limiting factor for eutrophication and is therefore used for defining the eutrophication levels in Borsola

Beel and Deepor Beel. Both lakes were already considered to be hypereutrophic as in both lakes the TP concentrations were above 0,55 mg/L. Based on TP concentrations in each scenario (see Appendix D), both lakes will stay very eutrophic, even after implementation of sewage treatment in each scenario. Only in Deepor Beel, the lowest concentration observed during monsoon season (being 0,5 mg/L) will change from hyper eutrophic to eutrophic level in the lake. Hence, it can be concluded that none of the scenarios are sufficient to lower the nutrient concentrations below eutrophication levels.

Table 11: Eutrophication levels before (reference) and after implementation of scenarios

	Deepor Beel		Borsola Beel	
Scenario	**Dry**	**Monsoon (lowest)**	**Dry**	**Monsoon (lowest)**
1	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic
2	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic
3	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic
4	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic

5.4.3 Costs

In developing countries, costs are considered as an important criterion for structural works as it requires investment from the government. The number of STPs, total combined capacity and treatment efficiency largely influence the costs of each scenario. The scenarios investigated in this study will cost at least 4 to 6 billion Indian rupees (INR), being 50 to 75 million euros, considering both capital costs and operational costs for 30 years. Scenario 2 and 4 will have the highest costs compared to scenario 1 being the cheapest option. The costs will need to be paid by the government and subsequently through fees by inhabitants of Guwahati. Considering a total paying population of two million will bring the annual fee per capita to treat sewage water on 70 to 100 INR, or 0,85 to 1,20 euros.

The costs are qualitatively described and compared between scenarios in the following sections. The costs consist for the largest part out of construction costs and operational costs. In this study, these costs are primarily based on the size of the STP and the treatment efficiency (technology).

Construction costs (capital costs)

According to the Planning Commission's report on water sector for 12th Five Year Plan (2012-2017), the cost of constructing a STP is 3 million to 10 million Indian rupees per MLD. A study carried out in India regarding the cost of different sized STPs using activated sludge, found that medium sized STPs (5-40 MLD) had the lowest cost per unit whereas the cost for both smaller and larger STPs were relatively higher, but both ranging between the 8 and 9 million Indian rupees per MLD (Pannirselvam & Gopalakrishnan, 2015). Using the average grouped unit costs of this study combined with the designed capacities of the STPs in the scenarios the total construction costs for each scenario were found and presented in Table 10.

Table 9 shows that scenario 1 has lowest construction costs whereas scenario 2 and 4 have comparable construction costs. However, considering the smaller STP just north of Deepor Beel is not fully able to use gravity to get the water to the STP, this STP requires a partly pressurized system. This raises the costs for both scenario 2 and 3, concluding that scenario 2 will have the largest construction costs.

Operational costs

The operational costs are greatly influenced by personnel and energy costs. In this analysis only the energy costs are considered as section 5.4.3 discusses about personnel. The energy usage is highly dependent on the treatment system used which is similar in all scenarios. For the activated sludge process, the annual maintenance and operational costs are estimated on

0,5-0,7 million Indian rupees per MLD (Majumder, 2016). Generally, it is considered that the greater the level of treatment the higher the costs (Tsagarakis, Mara, & Angelakis, 2003). Taking the 30 year design period and treatment efficiency into consideration, operational costs have been estimated for each scenario (see Table 12). Both scenario 1 and 3 have a high potential treatment efficiency, but as scenario 3 has a higher capacity it will have the highest costs.

Other costs

In scenario 3, part of the water in Bharalu River is diverted to Deepor Beel via a pumping station in the Mora Bharalu River. This will also increase costs, but it is assumed to be negligible compared to the total costs of constructing and operating the STPs.

Table 12: Capital and operational costs for each scenario in million INR (million € in between brackets)

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Total combined capacity (MLD)	115	195	146	200
Construction costs (Pannirselvam & Gopalakrishnan, 2015; Planning Commission's report on water sector for 12th Five Year Plan (2012-17))				
Medium sized STPs (8.3 million INR/MLD; 0,1 million €/MLD)	208	458	716	358
Large sized STPs (8.9 million INR/MLD; 0,11 million €/MLD)	840	1193	522	1335
Total construction costs	*1048 (13,4)*	*1651 (21)*	*1238 (15,8)*	*1693 (21,6)*
Operational costs (Majumder, 2016; Tsagarakis et al., 2003)				
Operational costs for 30 years (0,7 million INR/MLD/yr; 9000 €/MLD/yr)	2415	4095	3066	4200
*Total operational costs**	*3019 (38,4)*	*4095 (52,2)*	*3833 (48,8)*	*4200 (53,5)*
Total costs	**4067 (51,8)**	**5746 (73,2)**	**5070 (64,6)**	**5893 (75,1)**

* Costs are increased for higher efficiencies (linear relationship assumed: 25% higher efficiency than medium efficiency, so 25% higher costs)

Total costs

To conclude, scenario 2 and 4 have been found to be the most expensive scenarios, whereas scenario 1 was the least expensive, but in conclusion, cost differences are minimal, regarding that the highest costs are just 50% more than the lowest costs.

To put it in perspective to the worst-case scenario, in which no wastewater management taken into consideration, and hence no associated construction or operational costs, the costs for a deteriorating water quality are also high. It is expected that the city will suffer economic losses as further deterioration of water quality will lead to unhealthy living and working conditions in the city, increasing the vulnerability to different diseases. These are indirect costs, but will certainly influence the overall (long term) economy of the city. Despite the fact that the scenarios with sewage water treatment are not sufficient to improve the water quality to the water quality standards, sewage water treatment has been proven to be an essential element to prevent further deterioration of the water system.

5.4.4 Feasibility

Feasibility of an infrastructural development project depends on both land acquisition for the relevant project and the number of skilled personnel to operate the plant to its full capacity. Especially in a developing country, the availability of skilled personnel can be scarce. These two factors have been considered to determine the feasibility of each management scenario.

The required land in the scenarios is primarily based on the size of the STPs in the area, but the location also determines its feasibility. Generally, acquiring land in urban areas is more difficult and more expensive than acquiring land in a more rural area. Furthermore, Tsagarakis et al. (2003) concluded that small to medium sized STPs could require 20 to 75% more area per population equivalent (p.e.) or MLD than a large sized STP, depending on the treatment method. Considering the size, lowest total combined capacity and its location near the outskirts of the city, scenario 1 with only two STPs requires the least amount of land, followed by scenario 3 and 4 who have a larger total combined capacity and more urban locations, finally ending with scenario 2 needing the largest amount of land in urban area. This makes scenario 1 the most feasible option.

Considering the required personnel, a similar conclusion can be drawn. Based on the economy of scale achieved in larger sizes of installations, smaller STPs need more personnel per MLD than larger STPs (Tsagarakis et al., 2003). This results into a similar ranking as for required land: scenario 1 requires the least personnel followed by both scenario 3 and 4 which require relatively more personnel to remain operational. Scenario 2, with four STPs require the largest number of personnel.

Overall, scenario 1 will be the most feasible option regarding land availability and the lower amount of skilled people needed compared to the other scenarios. Scenario 2 scores lowest on feasibility.

5.4.5 Overview

Each scenario has its advantages and disadvantages in different aspects. The following score table can give more insight in making a choice based on which factor is prioritized most. It gives an overview on which aspect each scenario scores good and on which aspects it scores less. The scores are divided into --, -, + and ++ showing respectively a low to high (good) score for each criterion.

As can be seen in Table 13, both centralised scenarios (1 and 3) score well on improving the water quality in the lakes, whereas both decentralised scenarios have a high score on reducing the pollutant load in the complete system, especially scenario 3. This scenario also scores well on costs and is considered to be a feasible option regarding land requirement and skilled personnel. In order to decide which scenario to implement, the costs can be considered to be less important than the other aspects as the costs are not far apart between the scenarios and improvement in water quality is urgent, making a certain investment inevitable.

Table 13: Score table with scores for different aspects of each scenario (++ means it scores good and -- means it scores low on that aspect)

	Scenario 1 Centralised	**Scenario 2** Decentralised	**Scenario 3** Diverting flow	**Scenario 4** Extra capacity
Water quality in lakes				
Deepor Beel (dry)	+	-	-	-
Deepor Beel (wet)	--	-	--	-
Borsola Beel (dry)	++	+	+	+
Borsola Beel (wet)	+	-	-	+
Eutrophication	-	-	-	-
Overall water quality				
Overall (dry)	-	+	++	-
Overall (wet)	-	-	+	-
Other aspects				
Costs	++	-	+	-
Feasibility	++	-	+	+

6 DISCUSSION

The purpose of this research was to determine which sewage water treatment management scenarios are most promising to improve the water quality in Guwahati. In this study a water quality model was developed with limited availability of reliable data. Hence, the research required several assumptions to be made. In this chapter the most important assumptions which influence the obtained results are discussed.

6.1 Existing hydraulic model

Water quality is closely linked to the water quantity and hydraulics of a water system. The water system of Guwahati has been modelled in SWMM in which assumptions were made for several parameters representing sub-catchments, stream dimensions and functioning of engineering structures in the area. This existing model is the starting point in this study, but the lack of data on discharge volumes and water levels restricted the study to further calibrate and validate this model. Voortman (2017) revealed that sub-catchment width (influencing runoff volume), specifically in combination with imperviousness and sub-catchment area were the most sensitive hydraulic parameters in this modelled study area. These factors influence the runoff and final pollutant load introduced to the system.

Boundary conditions along the perimeter of the model are important, as they affect the results of the simulation. The boundary conditions at the outflows (representing the water level in Brahmaputra River) have been lowered to reduce the water quality routing continuity error in the model. In this study, the water has been able to continually discharge to the Brahmaputra River during rainfall whereas in reality backwaters might occur and continuous outflow is restricted to a certain amount. Additionally, there are sluices and weirs present in Guwahati to prevent large backwater flows into the city, however no exact information was found on the functioning of these structures. Hence, fixed assumptions regarding the precise functioning were used in the model which influence the response of the lakes and total water system as well. Although the response of the water system is uncertain, the pollutant concentrations in the model showed agreement with water quality measurements, hence the model was able to capture the general responses of the water system.

Lastly, the sanitary flow (DWF) and the precipitation resulting in storm water runoff (WWF) are the only water inputs to the water system in the model. Due to lack of data on inflows, the volume of sewage water was assumed on 125 l/cap/day and applied to the complete study area based on the number of people living in a sub-catchment. This value presumes a connection to a drinking water supply network. However, this can be disputed as rural areas and slums located in the city are less likely to be connected to the network. Also, the increasing water scarcity, the implementation rate and final operation of the drinking water network will influence the final volume of water reaching the inhabitants.

6.2 Water quality model

The spatial and temporal variation in water quality makes it a difficult part to model. Within the research area a lack of reliable measured data about diffuse as well as point sources decreases the simulation accuracy of the pollutant concentrations and loads. Therefore, many assumptions on processes and concentrations in all flows were required.

6.2.1 Substances

Limited availability of data restricted the study to focus on just four substances. The modelled substances are all subject to many biological and chemical processes, but SWMM is unable to capture the specific processes that the substances go through. SWMM allows incorporating a first order decay rate, but it revealed to be a sensitive parameter. The first order decay rate was found adequate for BOD, but the detailed nutrient cycles of nitrogen and phosphorus could not be fully captured through a first order decay rate, making the results from SWMM uncertain for these two nutrients. Additionally, unlike the process of sedimentation, resuspension is not able to be modelled by SWMM. These limitations hinder the robustness of the model as they can underestimate or overestimate some of the pollutant concentrations as well as they might not capture the varying effect over time under non-stationary conditions or over a longer period.

6.2.2 Pollutant inflows and concentrations

Pollutant concentrations were only incorporated in DWF and WWF as no other sources were considered such as the MSW disposal site (landfill) near Deepor Beel. Disregarding any other sources has most likely underestimated the loads and concentrations in the lake and water system, but as was concluded in this study and confirmed by other studies, the largest contribution of pollutants came from the sanitary flow generated by the inhabitants (Bhattacharyya & Kapil, 2010; Gogoi, 2013). Thus, this study took into account the major pollutant sources.

The pollutant concentrations in DWF were determined using pollutant loads per capita according to the CPHEEO related to the volume of sewage water used per capita. The calculated concentrations were lowered, so concentrations in the modelled water system were in the same order of magnitude as the water quality measurements during dry season. However, used values in this study were lower than concentrations used in literature (Chapra, 1997; Rossman & Huber, 2016). Hence, this possibly underestimates the total pollutant load by DWF in this study, disregarding the fact that the amount of sewage water generation per capita might be overestimated.

In general, pollutant concentrations in storm water runoff are site specific and cover a large range of values adding uncertainty to the model results which was also revealed in the sensitivity analysis. In this study, the pollutant concentrations in WWF were based on EMC values from studies in comparable locations as no data was available from the study area. These EMC values were chosen at the lower end of the ranges found in literature, however the EMC values for both nutrients (TN and TP) were still taken above the concentrations associated with eutrophication levels. This made it impossible for the nutrient concentrations to go below this level as storm water runoff was the major source for dilution and lowering of pollutant concentrations. There are other more advanced methods available in SWMM which take into account the first flush phenomena. This phenomenon is considered as an important feature in storm water runoff, because the maximum concentration generally precedes peak flow and retains a smaller pollutant concentration afterwards, having a diluting effect on the surface water (Gupta & Saul, 1996). However, using the more advanced method requires sufficient available data to reduce the uncertainty in the model which was not available for this study. Despite EMC being a simple method, which does not account for variability in concentration through time, it is able to evaluate the effects of storm water runoff on receiving waters and track variations in pollutant concentration based on its source, making it a suitable method for this study.

6.3 Obtained results

The results of this study are the outcomes of the modelled study area in SWMM. These results have been verified using water quality measurements which were not taken systematically, meaning random in both time and space. Consistency has been found between measurements, but lack of data strongly reduces the strictness of the scrutinization. The calculated outcome is within the same order of magnitude as the water quality measurements, but it is possible that the modelled pollutant concentrations deviate from the actual concentration in the water system.

This study assessed the effect of sewage water treatment scenarios to improve the water quality in Guwahati considering the core infrastructural elements of adequate water supply, sanitation and solid waste management in the Smart Cities Mission as well as the SDGs. Based on the results, the goals cannot be obtained through establishing STPs only. However, STPs effectively contribute for a large part in improving the water quality in the study area as they show relatively large reductions in pollutant concentrations.

Furthermore, this study investigated a limited number of scenarios which all considered sewage water treatment mainly based on applications in developed countries. It also looked at the possibility of establishing large scale (centralised) STPs in the study area, being widely applied in developed countries. However, these centralised STPs also include the establishment of an extensive network of pipes in order to transport the wastewater to the centralised STPs. Despite the fact that the study considered the centralised option, it neglected the establishment of the vast conveyance network, resulting in a further increase in costs as well as a probable lower efficiency of this management scenario, as when it is constructed it might not be finished or properly maintained.

Last, this research did not look further into other water quality improvement measures such as constructed wetlands or DEWATS (on-site sanitation). In developing countries, these can also be effective measures considering costs (Mara, 2003; Wen, Schoups, & Van De Giesen, 2017). Regarding these alternatives, this study confirmed that treating sewage water closer to the source might help to improve water quality more efficiently. In the long term Deepor Beel might potentially get its cleaning function back when the largest part of sewage water is treated before it reaches the wetland. Despite that this study did not investigate other alternatives than establishing STPs, it still gives a general overview of which alternatives can be more effective than others in this area. Hence, this study can support in guidance for policies and design decisions.

7 CONCLUSIONS

In response to the future projections of an increased amount of generated sewage water ending up in the water system, inducing a deteriorating water quality in the area, the government of India as well as Guwahati municipality has embarked on water quality management initiatives. This research has investigated a number of sewage water treatment management scenarios within the context of population growth, urbanisation and data scarcity. SWMM was applied to represent Guwahati's water system and to examine the impact on water quality of alternative scenarios for sewage water treatment management.

The model results revealed that all scenarios, ranging from centralised to decentralised STPs as well as diverting flows and increased treatment capacity, managed to lower both pollutant load and concentration in the study area and specifically in the focused water bodies. It was found that it is necessary to invest in STPs in order to achieve the goals of adequate water supply, sanitation and solid waste management set by both India's Smart Cities Mission as well as UN's SDGs, irrespective of the fact that the scenarios do not completely fulfil the targets and goals.

Furthermore, this study showed that the scenario and STP selection greatly depends on the final goal, whether the local authority prioritises plans to improve water quality in the city or primarily in the selected water bodies. Additionally, the available skilled personnel and financial investment which the government is able to make, determines this final choice. Based on a limited available budget and prioritising improvement in the lakes only, scenario 1, having two centralised STPs, would be the best, but for maximum impact in both lakes as well as the city, scenario 3 with four smaller decentralised STPs in combination with diverting flow to Deepor Beel, shows more potential.

The local effects on lake water quality differ from the general effects of reduction in pollutant load in the study area for each scenario. Additionally, the distinct seasonality determines for a large part the effectiveness of the STPs in all scenarios. Some other noteworthy conclusions can be drawn from this study which can help in urban planning decisions:

- **Sewage water treatment most effective during dry season**

  The model results revealed that all scenarios were more effective during dry season than during wet season. The most serious pollution was also found to be present during dry season, thus the largest water quality problems are treated most effectively. From the systems analysis it was found that the distinct seasonality, alternating between large rainfall events and no rainfall, largely influences the flow and water quality in the water system of Guwahati. The model results showed that during dry weather, the flow through the water system solely consists of a sanitary flow whereas during monsoon season, the storm water runoff was found to increase the total flow by as much as two to tenfold the sanitary flow. This storm water runoff dilutes the sanitary flow, lowering the pollutant concentrations in monsoon season. Due to the lack of storm water runoff in dry season, the flow in Guwahati's water system is only coming from raw sewage water resulting in a larger water pollution in dry season.

- **No extra storm water treatment capacity needed to improve water quality**

  An increased capacity at STPs to additionally treat part of the monsoon storm water runoff, was found to be less efficient due to the extreme quantity of the storm water runoff. Hence, it can be concluded that designing a STP for only DWF will possibly be a more realistic solution for Guwahati as the storm water runoff already improved water quality by dilution. Additionally, this study did not reveal any correlation between total combined treatment capacity of all STPs and reduction in pollutant load from the total study area at the outfalls. Hence, it can be concluded that the water quality in the area is not necessarily improved more with a higher total treatment capacity.

- **Decentralised scenario covers a larger part of the study area**

  No correlation was found between total treatment capacity and reduction in pollutant load from the study area, but both decentralised scenarios (four smaller STPs) were able to treat a larger part of the study area than the centralised scenarios with two large STPs, hence also reducing a larger amount of pollutant load from the study area. The location as well as the number of STPs highly influenced the improvement in water quality as the systems analysis revealed that the majority of pollution comes from the sanitary flow from the city of Guwahati. In both decentralised scenarios the STPs were closer located to the city. Especially, the densely populated areas along the Bharalu River, Basistha River and Borsola Beel showed to have a large share in the wastewater generation in the city.

  Furthermore, the proposed STPs were found to have a larger effect on improving water quality in Borsola Beel than in Deepor Beel as pollutant concentrations in Borsola Beel were reduced to a larger extent. Hence, it can be concluded that treatment at the source is more effective in Guwahati.

- **Treatment efficiency and diverting flows**

  The treatment efficiency has been found to be larger with decentralised STPs than with two larger centralised STPs. The diversion of flow is found to be generally effective in reducing the pollutant load at the outfall of the study, but it is not as effective in reducing pollutant concentrations in the lakes. Still, it can be concluded that it might be an effective measure in combination with other measures. Especially, when sewage water from the city is treated, Deepor Beel's potential to have a cleaning function for the city's sewage is increased.

Despite having a complex water system as well as the ever-constant challenge to acquire suitable land and skilled staff, it is of significant importance to establish STPs in Guwahati to reach the goals of adequate sanitation in the city. Additionally, a large financial investment together with coherent governmental management policy on sewage treatment and increasing awareness on healthy living conditions by inhabitants are essential aspects to fulfil the goals.

8 RECOMMENDATIONS

Based on the discussion and conclusion for this research several recommendations can be formulated. These recommendations are formulated for further research and development of the model as well as the scenarios.

8.1 Data collection and model improvement

Modelled results are only as good as the data used in the model as well as how the model represents the processes. Hence, lack of reliable data had their roles on the robustness of this model. In addition, the data that were found in different literature were not always comparable to Guwahati. In order to improve the design of different scenarios, it is recommended to collect more data on both water quantity and quality in Guwahati. In this way, the model can be calibrated and validated which will help to improve the outcome of the model leading to a more reliable result.

Further research on water depths, associated volumes in Deepor Beel and inflows (discharges) from streams will help to make a better estimate on the hydraulic residence time of the water in the lakes, hence giving a better indication on which processes are dominant. It is recommended to measure these parameters systematically to capture seasonal patterns in the area. Preferably these measurements will be done continuously, but to minimize the costs, daily or weekly measurements should suffice as well. This recommendation also applies for measuring the water quality (pollutant concentrations). However, considering the cost of collecting water quality data being relatively higher, measurements need to be taken at least at a monthly interval, but weekly or daily measurements are preferred. The locations and time of the measurement should be kept similar to reveal any spatial and temporal patterns. Proposed locations are the in- and outflows of both Deepor Beel and Borsola Beel, the outfalls to the Brahmaputra River and a couple of points along Mora Bharalu, Bharalu and Basistha River. These locations should be carefully chosen as being in the vicinity of large pollutant inputs can highly influence the concentration measured.

Secondly, further research on population densities and volume of discharges from pollutant sources will provide a more detailed understanding and quantification of the pollutant load from each source and help in future management plans. To improve the reliability of the model, more (detailed) information for input parameters such as land cover, population per sub-catchment, processes of pollutants (such as the interaction with other pollutants, e.g. BOD interacts with dissolved oxygen and nutrients are also highly dependent on surrounding conditions and availability of other substances) as well as pollutant concentrations in combination with the volume of sewage water is needed. Especially, the volume of sewage water in combination with population was considered to be a sensitive parameter in this study. Furthermore, there has been made no distinction between rural and urban areas in the volume of sewage water generated per capita, but it is recommended to do so as this can improve the analyses.

Furthermore, the study has only taken a general STP into account whereas the selection of treatment method is often site specific and dependent on the desired capacity of the STP. It is therefore recommended when designing the STPs to do further research on site suitability and most suitable treatment method for each STP separately.

8.2 Scenarios

This study showed that the implementation of sewage treatment in the area will considerably improve the water quality in the short (when STP is in operation) and long term considering the major part of pollution comes from sanitary waste. Considering the obvious health hazards of pollution, establishment of STPs cannot be overlooked. It can be recommended to mainly focus on treating the generated sewage water from the city in a decentralised approach to tackle the major source of pollution.

The results of this study also showed that the concentrations in the lakes will lower in each scenario, however they did not go below the levels of eutrophication or water quality standards. This means that each of the considered scenarios separately is not able to improve the water quality sufficiently. As described in the discussion, this study investigated only a limited number of scenarios to improve the water quality in Guwahati. Addition of other water quality measures to the proposed scenarios are therefore recommended to consider and to further explore whether the addition of other measures will significantly improve the water quality can be helpful. Examples of proposed measures are usage of pipelines to convey sewage water to the STP (including proper maintenance); control on nutrient usage in agriculture and use of constructed wetlands.

Lastly, a limitation of this study has been the modelling of the nutrient cycles, specifically the phosphorus cycle. As phosphorus gets accumulated in the lake sediments and can be released slowly over time, phosphorus concentrations in lakes are not always lowered when the external input has stopped due to treatment or reducing other external inputs (Søndergaard, 2007). Thus, it is expected that the investigated scenarios will never fully resolve the problem of eutrophication in Deepor Beel or Borsola Beel on the short term. It is therefore recommended to combine these scenarios with other measures such as dredging the lakes in which the sediment with the adsorbed phosphorus is removed, reducing the internal loading of phosphorus. For the long term, management and control on nutrient usage should be combined with these measures.

9 REFERENCES

Arappor Iyakkam. (2018). *Why Chennai Stinks? Citizens' effort to understand and solve the Sewage problem*. Chennai.

Assam Pollution Control Board. (2013). *Conservation of River Bharalu, City Sanitation Plan*. Guwahati.

Assam State Disaster Management Authority. (2014). *Review of Studies on Urban Floods in Guwahati From Flood Knowledge to Urban Action*. Guwahati. Retrieved from http://sdmassam.nic.in/download/Guwahati floods.pdf

Basistha, P. S. (2016). *Assessment of impact of urbanisation on Deepor Beel wetland*. Guwahati. Retrieved from http://asmenvis.nic.in/WriteReadData/UserFiles/file/Parangam Internship.pdf

Besluit kwaliteitseisen en monitoring water 2009 (2009). Nederland. Retrieved from http://wetten.overheid.nl/BWBR0027061/2017-01-01

Bhardwaj, R. M. (2005). *Water Quality Monitoring in India - Achievements and Constraints*. *International Work Session on Water Statistics*.

Bhateria, R., & Jain, D. (2016). Water quality assessment of lake water: a review. *Sustainable Water Resources Management*, *2*, 161–173. https://doi.org/10.1007/s40899-015-0014-7

Bhattacharya, P., & Borah, R. (2014). Drinking Water in Guwahati City: Its Past, Present Status and Associated Problems. *Space and Culture, India*, *1*(3), 65–78.

Bhattacharyya, K. G., & Kapil, N. (2010). Impact of urbanization on the quality of water in a natural reservoir: a case study with the Deepor Beel in Guwahati city, India. *Water and Environment Journal*, *24*, 83–96. https://doi.org/10.1111/j.1747-6593.2008.00157.x

Bordoloi, P. K. (2015). Guwahati City Waterlogging - Disaster or Problem? In *International seminar at Guwahaty on Diaster Management – issues and challenges* (pp. 2–20). https://doi.org/10.13140/RG.2.1.4182.3766

Bowie, G. L., Mills, W. B., Porcella, D. B., Campbell, C. L., Pagenkopf, J. R., Rupp, G. L., … Gherini, S. A. (1985). *Rates , Constants , and Kinetics Formulations in S urface Water Quality Modeling*. *United States Environmental Research And Protection Laboratory Agency* (2nd ed.).

Bureau of Indian Standards. (2012). Indian Standard for Drinking Water - Specification IS 10500. New Delhi. Retrieved from http://cgwb.gov.in/Documents/WQ-standards.pdf

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361–369. https://doi.org/10.4319/lo.1977.22.2.0361

Census. (2011). *Census of India 2011*. New Delhi. Retrieved from http://censusindia.gov.in/

Central Pollution Control Board. (2007). *Evaluation Of Operation And Maintenance Of Sewage Treatment Plants In India*. *Control of Urban Pollution Series*. New Delhi.

Central Pollution Control Board. (2013). *Performance Evaluation of Sewage Treatment Plants under NRCD*. New Delhi.

Central Pollution Control Board. (2015). *Inventorization of Sewage Treatment Plants*. *Control of Urban Pollution*. New Delhi.

Chapman, D. (1996). *Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring* (Second Edi). London: E&FN Spon.

Chapra, S. C. (1997). *Surface Water-Quality Modeling*. Boston: McGraw-Hill.

Choudhury, D., & Gupta, S. (2017). Impact of waste dump on surface water quality and aquatic insect diversity of Deepor Beel (Ramsar site), Assam , North-east India. *Environmental Monitoring and Assessment*, *189*(11), 1–17. https://doi.org/10.1007/s10661-017-6233-7

Chow, M. F., Yusop, Z., & Shirazi, S. M. (2013). Storm runoff quality and pollutant loading from commercial, residential, and industrial catchments in the tropic. *Environmental Monitoring and Assessment*, *185*, 8321–8331. https://doi.org/10.1007/s10661-013-3175-6

Costa, D., Burlando, P., Liong, S., & Priadi, C. (2014). Modelling dominant processes affecting the transport and fate of domestic pollution in highly contaminated urban rivers. The case of the Ciliwung in Jakarta. In *Proceedings of the 7th International Symposium on Environmental Hydraulics (ISEH)* (pp. 415–418). Singapore.

CPHEEO. (2012). Design and construction of sewage treatment facilities. In *Manual on Sewerage and Sewage Treatment* (pp. 1–219). New Delhi.

Davis, M. L., & Cornwell, D. A. (1985). *Introduction to Environmental Engineering*. McGraw-Hill Education.

Deka, P. P., & Devi, M. K. (2017). Problems and Prospects of Development in Guwahati, Assam. In *Sustainable Smart Cities in India - Challenges and Future perspectives* (pp. 109–122). New Delhi: Springer International Publishing. https://doi.org/10.1007/978-3-319-47145-7

Dutta, S., Gogoi, R. R., Khanikar, L., Bose, R. S., & Sarma, K. P. (2016). Assessment of hydrogeochemistry and water quality index (WQI) in some wetlands of the Brahmaputra Valley, Assam, India. *Desalination and Water Treatment*, *57*, 27614–27626. https://doi.org/10.1080/19443994.2016.1177598

Ghangrekar, M. M. (2012). Wastewater Management. National Programme on Technology Enhanced Learning (NPTEL). Retrieved from http://www.nptel.ac.in/courses/105105048/

Girija, T. R., Mahanta, C., & Chandramouli, V. (2007). Water quality assessment of an untreated effluent impacted urban stream: The Bharalu tributary of the Brahmaputra River, India. *Environmental Monitoring and Assessment*, *130*(1–3), 221–236. https://doi.org/10.1007/s10661-006-9391-6

Gogoi, L. (2013). Degradation of Natural Resources and its Impact on Environment: A Study in Guwahati City, Assam, India. *International Journal of Scientific and Research Publications*, *3*(12), 1–7.

Government of Assam. (2016). *Performance Audit of Environmental degradation in the greater Guwahati area with special emphasis on the role of the Pollution Control Board, Assam (PCBA)*.

Gupta, K., & Saul, A. J. (1996). Specific relationships for the first flush load in combined sewer flows. *Water Research*, *30*(5), 1244–1252. https://doi.org/10.1016/0043-1354(95)00282-0

Guwahati Metropolitan Development Authority. (2009). *Master Plan for Guwahati Metropolitan Area - 2025*. Guwahati. Retrieved from http://www.gmda.co.in/maps/part2.pdf

Henze, M., Harremoes, P., Jansen, J. C., & Arvin, E. (2002). *Wastewater Treatment: Biological and Chemical Processes*. Springer-Verlag Berlin Heidelberg.

Irvine, K., Sovann, C., Suthipong, S., Kok, S., & Chea, E. (2015). Application of PCSWMM to Assess Wastewater Treatment and Urban Flooding Scenarios in Phnom Penh, Cambodia: A Tool to Support Eco-City Planning. *Journal of Water Management Modeling*, *C389*, 1–13. https://doi.org/10.14796/JWMM.C389

Kamyotra, J. S., & Bhardwaj, R. M. (2011). *Municipal Wastewater Management in India*. *India Infrastructure Report*. New Delhi. Retrieved from http://www.idfc.com/pdf/report/2011/Chp-20-Municipal-Wastewater-Management-In-India.pdf

Katukiza, A. Y., Ronteltap, M., Niwagaba, C. B., Kansiime, F., & Lens, P. N. L. (2014). Grey water characterisation and pollutant loads in an urban slum. *International Journal of Environmental Science and Technology*, *12*, 423–436. https://doi.org/10.1007/s13762-013-0451-5

Lee, J. H., Bang, K. W., Ketchum, J. H., Choe, J. S., & Yu, M. J. (2002). First flush analysis of urban storm runoff. *Science of the Total Environment*, *293*(1–3), 163–175. https://doi.org/10.1016/S0048-9697(02)00006-2

Liang, S., Wu, H., Li, H., & Wu, Y. (2013). Assessment of the Spatial and Temporal Water Eutrophication for Lake Baiyangdian Based on Integrated Fuzzy Method. *Journal of Environmental Protection*, *4*, 120–125.

Majumder, A. (2016). STP technologies & their cost effectiveness. Jadavpur University. Retrieved from https://cdn.cseindia.org/userfiles/arunabha.pdf

Manta, R., & Rajbangshi, D. (2015). Population Growth and Forest Degradation in Guwahati City: A GIS Based Approach. *International Journal of Interdisciplinary Research in Science Society and Culture*, *1*(1), 84–93.

Mara, D. D. (2003). *Domestic Wastewater Treatment in Developing Countries* (1st Editio). London: Routledge.

Mesdaghinia, A., Nasseri, S., Mahvi, A. H., Tashauoei, H. R., & Hadi, M. (2015). The estimation of per capita loadings of domestic wastewater in Tehran. *Journal of Environmental Health Science and Engineering*, *13*(25), 1–9. https://doi.org/10.1186/s40201-015-0174-2

Ministry of Statistics & Programme Implementation. Government of India (2016). *Compendium of Environment Statistics India*. New Delhi.

Ministry of Urban Development, Government of India. (2015). *Smart Cities: Mission Statement & Guidelines*. Retrieved from http://smartcities.gov.in/upload/uploadfiles/files/SmartCityGuidelines(1).pdf

Mozumder, C., Tripathi, N. K., & Tipdecho, T. (2014). Ecosystem evaluation (1989 - 2012) of Ramsar wetland Deepor Beel using satellite-derived indices. *Environmental Monitoring and Assessment*, *186*, 7909–7927. https://doi.org/10.1007/s10661-014-3976-2

Nazahiyah, R., Yusop, Z., & Abustan, I. (2007). Stormwater quality and pollution loading from an urban residential catchment in Johor, Malaysia. *Water Science and Technology*, *56*(7), 1–9. https://doi.org/10.2166/wst.2007.692

Nelson, K. L., & Murray, A. (2008). Sanitation for Unserved Populations: Technologies, Implementation Challenges, and Opportunities. *Annual Review of Environment and Resources*, *33*, 119–151. https://doi.org/10.1146/annurev.environ.33.022007.145142

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B. R., Tryby, M., & Massoudieh, A. (2017). Stormwater management model: Performance review and gap analysis. *Journal of Sustainable Water in the Built Environment*, *3*(2), 1–32. https://doi.org/10.1061/JSWBAY.0000817.

Nuruzzaman, M., Al-Mamun, A., & Salleh, M. N. B. (2018). Experimenting biochemical oxygen demand decay rates of Malaysian river water in a laboratory flume. *Environmental Engineering Research*, *23*(1), 99–106. https://doi.org/10.4491/eer.2017.048

Pannirselvam, R., & Gopalakrishnan, A. N. (2015). Development of Cost Functions for Sewage Treatment Plants based on Conventional Activated Sludge Process. *Indian Journal of Science and Technology*, *8*(30), 1–6. https://doi.org/10.17485/ijst/2015/v8i30/76062

Pawe, C. K., & Saikia, A. (2017). Unplanned urban growth: land use/land cover change in the Guwahati Metropolitan Area, India. *Geografisk Tidsskrift-Danish Journal of Geography*, *118*(1), 88–100. https://doi.org/10.1080/00167223.2017.1405357

Pribak, M., & Siegrist, J. (2015). A Simplified Approach to Pollutant Load Modeling. *Journal of Water Management Modeling*, *C387*, 1–10. https://doi.org/10.14796/JWMM.C387.

Qin, H. P., Khu, S. T., & Yu, X. Y. (2010). Spatial variations of storm runoff pollution and their correlation with land-use in a rapidly urbanizing catchment in China. *Science of the Total Environment*, *408*, 4613–4623. https://doi.org/10.1016/j.scitotenv.2010.07.021

Ramsar. (2002). *Information Sheet on Ramsar Wetlands (RIS)*. Retrieved from https://rsis.ramsar.org/RISapp/files/RISrep/IN1207RIS.pdf

Rossman, A. (2015). Storm Water Management Model User's Manual Version 5.1.

Rossman, A., & Huber, W. C. (2016). Storm Water Management Model Reference Manual Volume III – Water Quality. USA.

Sayed, A., Kumar, S. R., & Ajay, K. S. (2015). Water quality analysis of Disposal site and its adjacent area of Guwahati, Assam, India. *International Research Journal of Environment Sciences*, *4*(5), 12–17.

Sharma, D., Gupta, R., Singh, R. K., & Kansal, A. (2012). Characteristics of the event mean concentration (EMCs) from rainfall runoff on mixed agricultural land use in the shoreline zone of the Yamuna River in Delhi, India. *Applied Water Science*, *2*, 55–62. https://doi.org/10.1007/s13201-011-0022-1

Sharma, R. K., Yadav, M., & Gupta, R. (2017). *Water Quality and Sustainability in India: Challenges and Opportunities*. *Chemistry and Water*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-809330-6.00005-2

Søndergaard, M. (2007). *Nutrient dynamics in lakes - with emphasis on phosphorus, sediment and lake restoration. Doctor's dissertation (DSc)*. Aarhus, Denmark: National Environmental Research Institute, University of Aarhus.

SWRP. (1996). *Student Watershed Research Project: a manual of field and Procedures. 3rd Edition*. Portland.

Taua'a, S. (2018). Exploring the Practicability and Applicability of Payment for Ecosystem Services in the Protection of Samoa's Selected Watershed Areas. In W. Leal Filho (Ed.), *Climate Change Impacts and Adaptation Strategies for Coastal Communities* (pp. 357–371). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-70703-7_19

Thomann, R. V., & Mueller, J. A. (1987). *Principles of Surface Water Quality Modeling and Control*. New York: Harper & Row.

Tsagarakis, K. P., Mara, D. D., & Angelakis, A. N. (2003). Application of cost criteria for selection of municipal wastewater treatment system. *Water, Air, and Soil Pollution*, *142*, 187–210. https://doi.org/10.1016/S0026-0576(98)80320-6

United Nations. (2015). *Sustainable Development Goals*. *United Nations Development Program*. https://doi.org/10.1017/CBO9781107415324.004

Voortman, P. (2017). *The Guwahati basin modeled in SWMM*. Arcadis. Amsterdam.

Water Pollution Control Board Assam. (2017). Analysis report of water samples collected from different locations of Deepor Beel. Guwahati.

Wen, Y., Schoups, G., & Van De Giesen, N. (2017). Organic pollution of rivers: Combined threats of urbanization, livestock farming and global climate change. *Scientific Reports*, *7*(43289), 1–9. https://doi.org/10.1038/srep43289

Wilén, B. M., Lumley, D. A., & Mattsson, A. M. (2006). Rain events and their effect on effluent quality studied at a full scale activated sludge treatment plant. *Water Science & Technology*, *54*(10), 201. https://doi.org/10.2166/wst.2006.721

APPENDICES

A. Brahmaputra River
B. Water quality measurements
C. Model set-up
D. Sensitivity analysis of other WQ parameters
E. Population forecast
F. Scenario comparison

APPENDIX A: BRAHMAPUTRA RIVER

The Brahmaputra River is one of the major river systems flowing through India. Its origin lies in the Himalayas in Tibet and by making its way through North-East India, joining with the river Ganges, it flows into the Bay of Bengal via Bangladesh. It has a total length of about 2900 km and a width ranging from 1 km at the city of Guwahati to approximately 10 km where it has multiple braided channels.

With an average discharge of approximately 19 800 m^3/s and a maximum discharge of about 100 000 m^3/s during floods it is one of the largest rivers in the world. Furthermore, the Brahmaputra River is characterized by its high sediment load which counts up, combined with the Ganges, to around 1.8 billion tonnes per year. The discharge and water level of the Brahmaputra River are highly affected by snowmelt from the Himalayas in spring, but also by monsoon rainfalls during June until October. A plot of the water level of the Brahmaputra River is presented in Figure 26. This water level influences the outflowing discharge of Deepor Beel as Deepor Beel the water cannot flow out from Deepor Beel when the water level in the Brahmaputra River is higher. This mostly occurs during monsoon season resulting in water logging in the city of Guwahati.

The water quality in the Brahmaputra River is in a deteriorating state (Government of Assam, 2016; Ministry of Statistics & Programme Implementation, 2016). Already in 2005, Bhardwaj gave an overview of the water quality in all major rivers in India which showed that the Brahmaputra River has high values for total coliform and faecal coliform, a value less than 6 mg/L for BOD, but COD values between 6 and 11 mg/L. These values have only increased over the years 2010 to 2014, showing a deteriorating trend (Government of Assam, 2016).

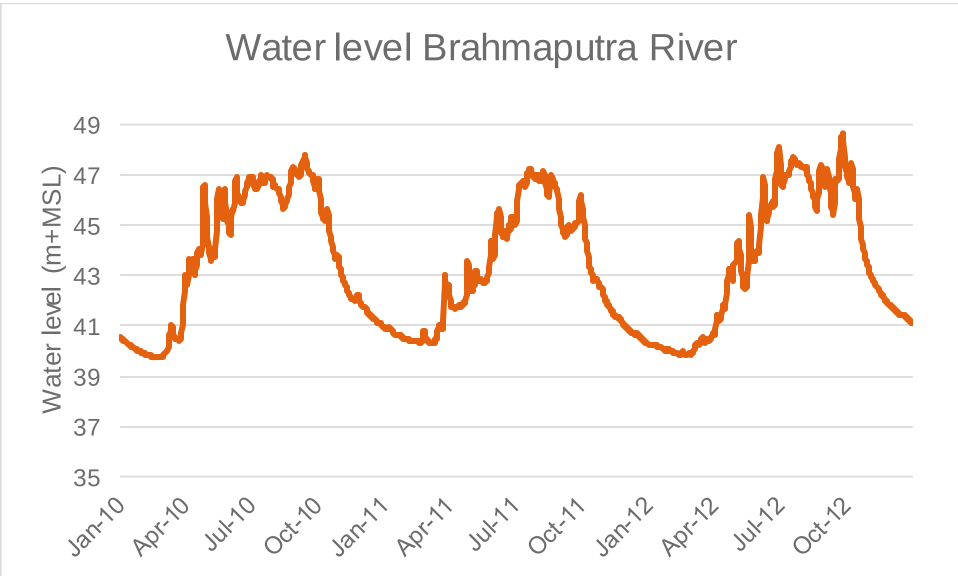


Figure 26: Water level measurements of Brahmaputra River at Khanajan outflow

APPENDIX B: WATER QUALITY

In this appendix, background information on the four investigated substances being biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS), is given, followed by water quality standards by BIS (2012) and eutrophication levels for lakes. Last, the water quality measurements in the area are discussed.

B.1 Water quality parameters

Biochemical oxygen demand (BOD)

The biochemical oxygen demand measures the amount of oxygen in water which is taken up by bacteria to degrade organic matter (expressed in mg/L). Organic matter comes as pollution into the river and comprises carbohydrates, proteins and fats which originate from domestic sewage, urban runoff, industrial and agricultural activities. A low value of BOD does not necessarily mean the water is not polluted, but the present organic matter might not be able to be (fully) degraded or is hampered by other toxic pollutants. BOD naturally decays over time as organic matter is broken down.

Nutrients

Nutrients like phosphorus (P) and nitrogen (N) are needed by aquatic plants to grow. Ambient concentrations of these nutrients are low, but due to anthropogenic activities larger quantities are being introduced to the water system, causing eutrophication[5] in lakes. The increase in nutrients originates from domestic and industrial sewage water and usage in agriculture (Bhattacharyya & Kapil, 2010).

Total nitrogen consists out of organic nitrogen, ammonia and nitrate. The decay of nitrate in total nitrogen is based on the process of denitrification in the nitrogen cycle transforming nitrate into nitrite and finally N_2, a gaseous state.

Total phosphorus consists out of organic and inorganic phosphorus. The phosphorus cycle is one of the slowest cycles and unlike nitrogen, it cannot disappear from the system via a gaseous state. Phosphorus can be taken up by plants, but it is generally accumulated in the soil as it can be adsorbed to (suspended) sediment which deposits in a lake. Based on the surrounding conditions like temperature, pH, concentration gradients and sediment composition, phosphorus in lakes gets released again after some time, also called internal loading (Penn et al., 2011). Researches showed that the phosphorus release from sediments mainly comes from surface sediments and the influence of this source is larger in shallow lakes than in deeper lakes (Søndergaard, 2007). Especially total phosphorus is a limiting factor for eutrophication in shallow fresh water lakes.

Total suspended solids (TSS)

Total solids is comprised out of suspended and dissolved solids. Total suspended solids are part of the organic matter being loaded into water bodies representing the insoluble parts suspended in the water; the total dissolved solids (TDS) represent the soluble parts (both expressed in mg/L). It contains organic and inorganic matter originating from urban runoff, domestic and industrial wastes or from agricultural land.

[5] Eutrophication is a process in which an excess of nutrients results in rapid growth of plants and algae, causing oxygen depletion for other plants. It could finally lead to anaerobic circumstances with less diversity and a few dominant species which survive. Eutrophication is especially a large problem in standing or slow moving water (Liang et al., 2013; Thomann & Mueller, 1987).

TSS influences the amount of light penetrating through the water for photosynthesis impacting the amount of oxygen produced. Next to this, it could also settle on the bottom influencing aquatic life and if organic, possibly oxygen level as well. One of the processes responsible for a decrease in TSS concentration is settling of sediments. Based on the chemistry of the solids other contaminants like heavy metals or nutrients can adsorb itself to the particles and pollute the environment where sedimentation occurs.

B.2 Water quality standards and eutrophication levels

The water quality in Deepor Beel, Borsola Beel and the water system of Guwahati needs to be improved. Water quality criteria have been determined for traditional water quality parameters including BOD and nutrients. In countries with severe organic pollution these criteria are very helpful for strategies on improving the status of the water, preventing oxygen depletion.

In general, there are no specific classes defined for recreational water (boating and swimming) considering BOD, nutrients or TSS. An average desirable BOD level of 4 mg/L is used as a study done by Student Water Research Project (1996) concludes that 3-5 mg/L indicates a moderately clean river. In India, BIS (2012) defines water quality standards and a maximum permissible concentration for BOD is defined on 3 mg/L for class C representing drinking water source after conventional treatment and disinfection. No permissible concentrations for BOD are defined for lower classes. This is fairly strict for the recreational purpose. BOD concentrations in the Netherlands have a desirable limit of 6 mg/L for water which can be treated for human consumption and is considered of good water quality (Besluit kwaliteitseisen en monitoring water, 2009). For TSS, in most countries no water quality standards are defined, but a desirable limit of 50 mg/L is used in the Netherlands for similar water usage as BOD.

No specific standards for nutrients are defined, but eutrophication is undesirable because of its effects on the aquatic environment. So, in this study the objective is to prevent eutrophication in the lakes. The nutrient concentrations associated with eutrophication levels in lakes (Liang et al., 2013) are given in Table 14 below.

Table 14: Nutrient concentrations associated with eutrophication levels in lakes

Eutrophication level	TP (mg/L)	TN (mg/L)
Oligotrophic	0,0046	0,3
Mesotrophic	0,01	0,6
Eutrophic	0,05	1,5
Hypereutrophic	0,55	4,6
Seriously hyper-eutrophic	1,2	

B.3 Water quality measurements

In the study area there have been taken water quality measurements randomly over time and multiple locations. The locations of the measurement campaigns are presented in Figure 27. In and around Deepor Beel most measurements have been taken. Sayed et al. (2015) measured TSS and chloride using gravimetric method four times throughout one hydrological wet year (2010-2011) around sites at Deepor Beel whereas the Water Pollution Control Board (WPCB) started measuring BOD, TSS, phosphate, nitrate and chloride via APHA and BIS methods from the year 2016. Choudhury & Gupta (2017) measured BOD, nitrate and phosphate throughout one hydrological year (2013-2014) using APHA methods.

Only Girija et al. (2007) and the Pollution Control Board of Assam (PCBA) have carried out water quality measurements of BOD, TDS, TSS, total phosphorus and chloride along the Bharalu River and near Borsola Beel using APHA methods in respectively the year 2004/2005 and December 2013 (both years with average rainfall).

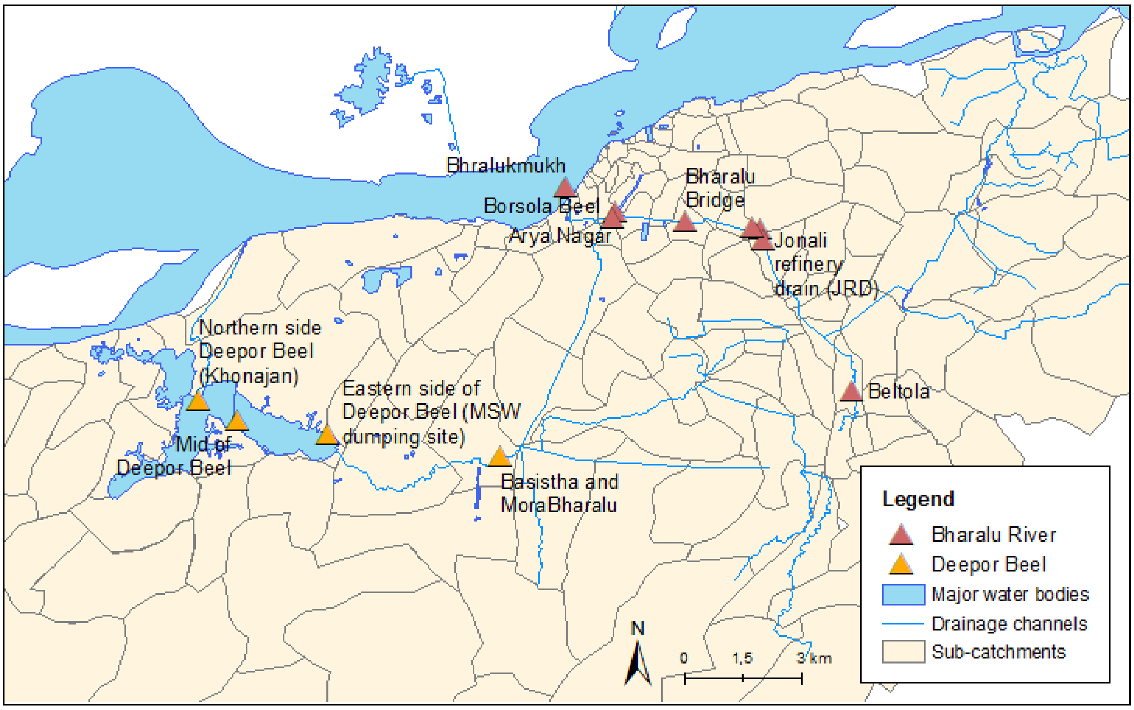


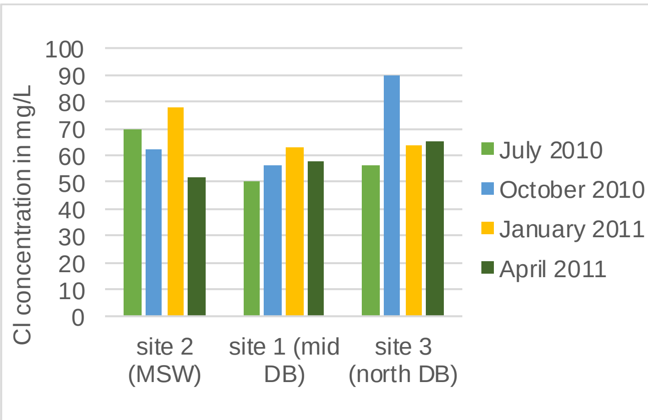
Figure 27: Locations of water quality measurements in Deepor Beel and along the Bharalu River

1.1.1 Deepor Beel

The water quality measurements in and around Deepor Beel will be discussed on seasonal and spatial variations per parameter.

Chloride

Chloride is inert to most processes, so it gives a good indication on how the water system responds. Based on measurements by Sayed et al. (2015) a minor increasing trend from monsoon to post monsoon season is visible (Figure 28). This minor increasing trend in the middle of the lake could be explained by decreasing amount of rainfall from monsoon to winter period (dry) resulting in a decreasing lake volume and subsequently raising the concentration. In measurements from WCPB also dilution occurs, however the Basistha River shows the opposite suggesting chloride mainly originates from urban areas. Also, concentrations are lower in 2016 than during 2010/2011 measurement campaign by Sayed et al. (2015), but this difference might be due to the use of different measurement techniques.



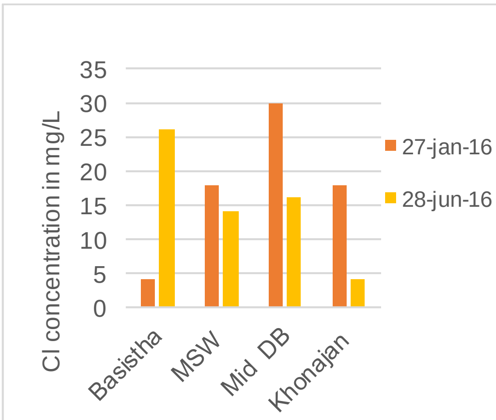


Figure 28: Chloride concentration measurements by Sayed et al. in 2010-2011 (left) and WPCB in 2016-2017 (right) at locations around Deepor Beel

Biochemical Oxygen Demand

Regarding BOD it is generally lowest during monsoon season because of dilution with clean water (except for the inflowing water from Basistha River coming from urban area). The concentration generally lowers (improves) when flowing into the lake. In the Bharalu River (see next section), a similar process is visible in BOD concentrations which are lower during wet months and are higher during dry months (see Figure 29).

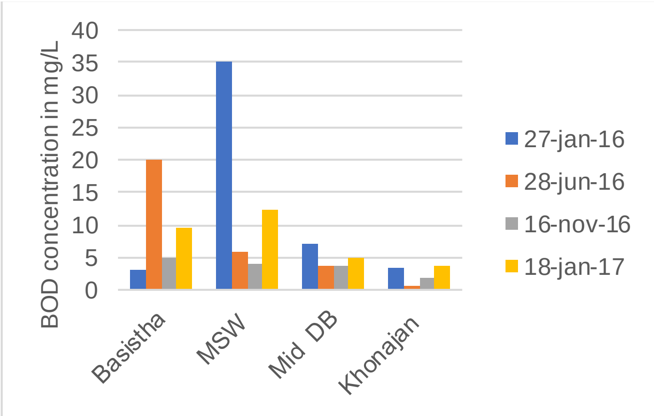


Figure 29: BOD concentration measurements by WPCB in 2016-2017

Nutrients

Nutrients like nitrogen and phosphorus give an indication of the level of eutrophication in a lake. In both measurement campaigns nitrate has generally higher concentrations during dry period and lower concentrations in monsoon season (see Figure 30 and Figure 31). For phosphate a similar observation can be made in measurements from Choudhury & Gupta (2017) where high concentrations in pre- and post-monsoon indicate utilisation by algae and release from sediments. During monsoon period the concentrations are low, because of dilution with rain water. The opposite pattern is visible in measurements from WPCB, but in this measurement campaign both measurement days did not have any rainfall (the month June had a total of 208 mm). June is in the summer period which has higher temperatures possibly creating more favourable circumstances for eutrophication and release of nutrients from lake sediments. Furthermore, this data also suggests that a wide variety of nutrient inputs and processes like dilution, release and adsorption of nutrients to sediments are present in this area which make it difficult to interpret the few number of measurements. Another possibility for the high concentration of phosphate during June 28th might be due to a certain input into the water system at that time raising the concentration.

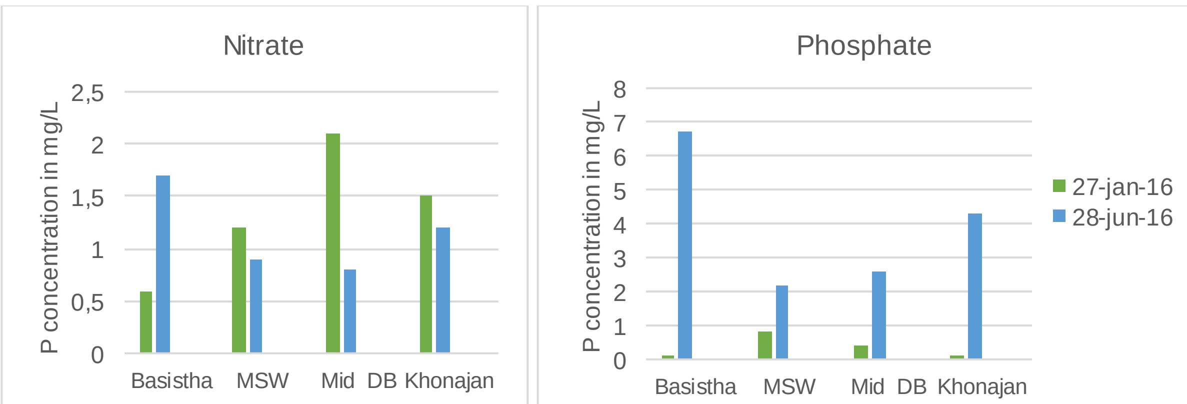


Figure 30: Nitrate and phosphate concentration measurements by WPCB in 2016-2017 at Basistha River, MSW disposal site, mid part of Deepor Beel and the outlet of Deepor Beel (Khonajan)

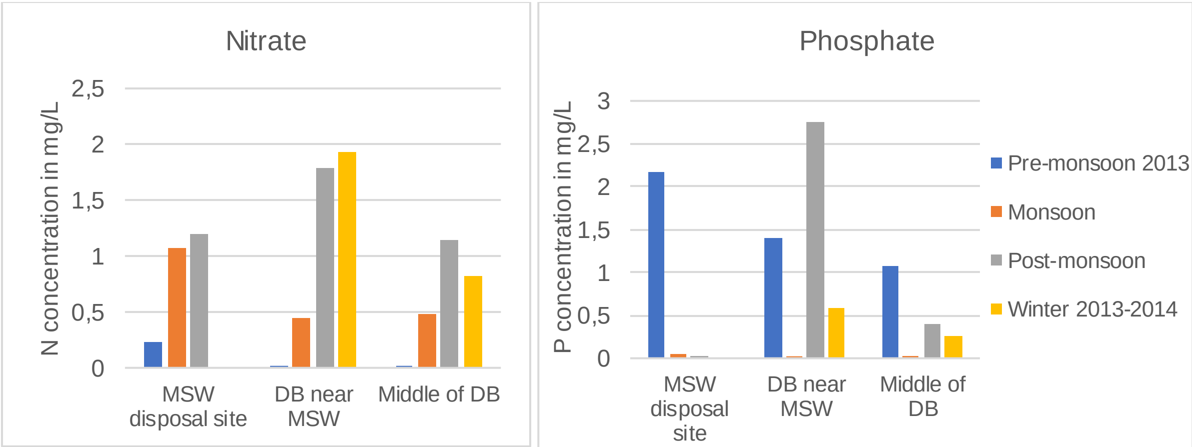


Figure 31: Nitrate and phosphate concentration measurements by Choudhury & Gupta (2017) during 2013 monsoon season at different locations in Deepor Beel

Total suspended solids

Regarding TSS (Figure 32), June shows generally highest concentrations in the adjacent channels (inflow and outflow) and lower concentrations in the lake according to WPCB's measurements. This could be due to storm water runoff and high discharges in the streams which are surrounded with agricultural or urban land, whereas sedimentation of the solids in the middle of the lake cause lower concentrations. From measurements by Sayed et al. (2015) a decreasing trend of the concentration from pre- to post monsoon season is visible suggesting that TSS is correlated with the amount of rainfall and surrounding land use (MSW disposal site has highest concentrations).

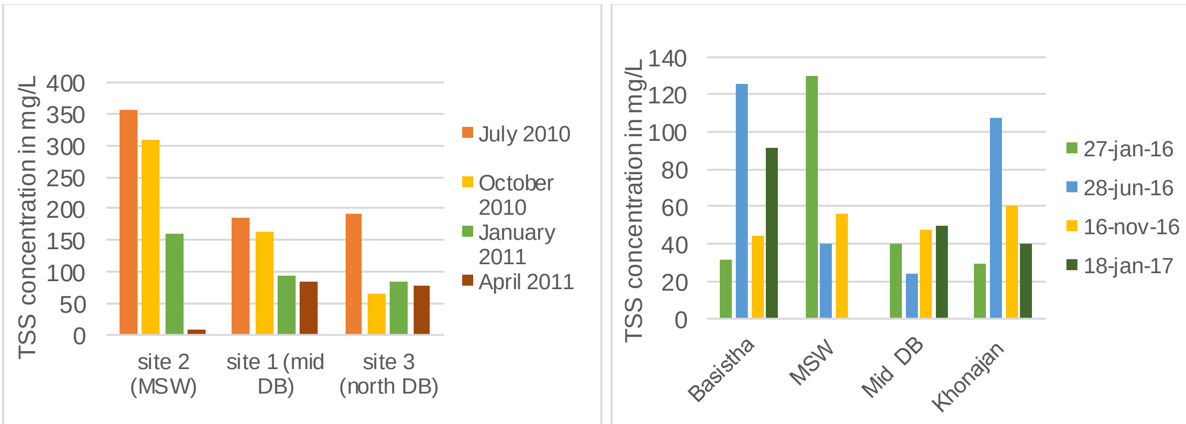


Figure 32: TSS concentration measurements by Sayed in 2010-2011 (left) and by WPCB in 2016 (right) at different locations in Deepor Beel

1.1.2 Borsola Beel (Bharalu River)

Two measurement campaigns have been done along the Bharalu River. Measurements done by PCBA are presented in Figure 33 and are considered sanitary flow only as no rainfall has fallen in the preceding month. Girija et al. (2007) measured in different months throughout the year 2004-2005 also showing the seasonal change in concentrations. These measurements are presented in Figure 34.

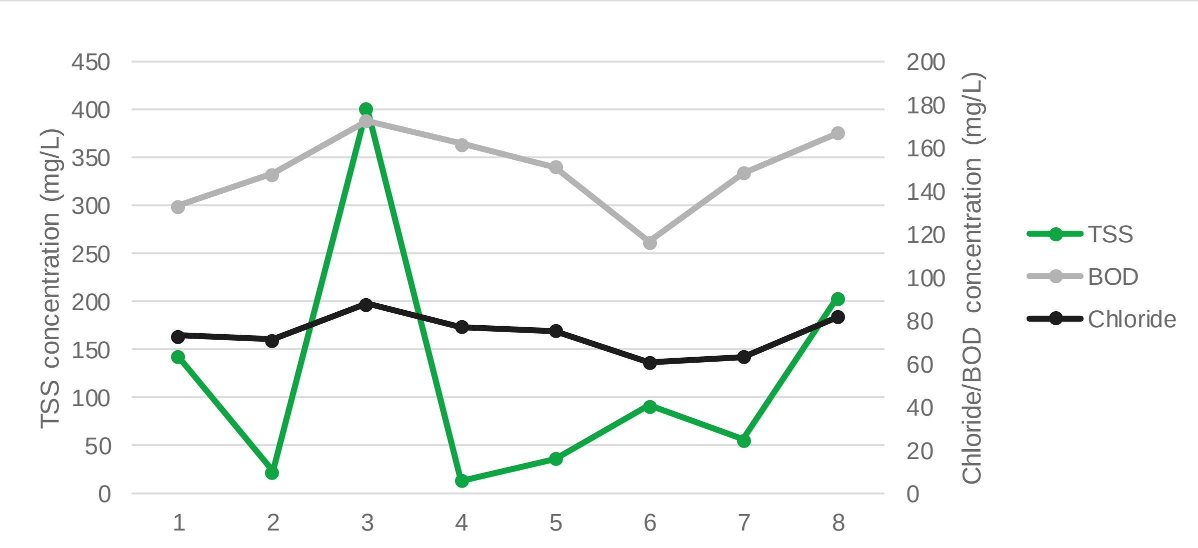


Figure 33: Measured concentrations along the Bharalu River in downstream direction in December 2013 (note: BOD and chloride concentrations are based on right vertical axis)

The measurements along the Bharalu River by PCBA (Figure 33) show no clear pattern regarding concentrations, however some locations can be explained by certain activities or processes taking place. At the Jonali refinery drain an increase in concentration can be found for all parameters (TSS concentration showing largest increase) and a decrease in concentration just downstream of this drain. An explanation is that the water coming from the refinery drain is heavily polluted and will be diluted with cleaner water from upstream. At the outflow point of Borsola Beel the concentration of all water quality parameters is lower than their surrounding concentrations. This could highlight the important self-purification function of wetlands, however this function is reduced by high input of wastewater (Choudhury & Gupta, 2017). Further downstream the concentration of all parameters and especially TSS and BOD increases again indicating the contamination from domestic waste and other urban sources. Chloride is the only parameter which has a relatively constant concentration along the Bharalu River.

A similar trend in concentrations is visible in measurements done by Girija et al. (2007), however these measurements are already taken in 2004 in Figure 34. Here, local increases in concentrations are due to drainage from the market area (location 7b) and drainage outflows from high density residential areas (locations 3 to 8). The oil refinery drain (location 4) does not show an increase in concentrations indicating it was not yet a distinct source of pollution at that time. Chloride concentrations are generally highest during dry periods and lower during monsoon season. For phosphorus and BOD concentrations, similar processes to chloride take place along the Bharalu River as dry periods show higher concentrations and monsoon season shows lower concentrations. No measurements on total suspended solids were taken.

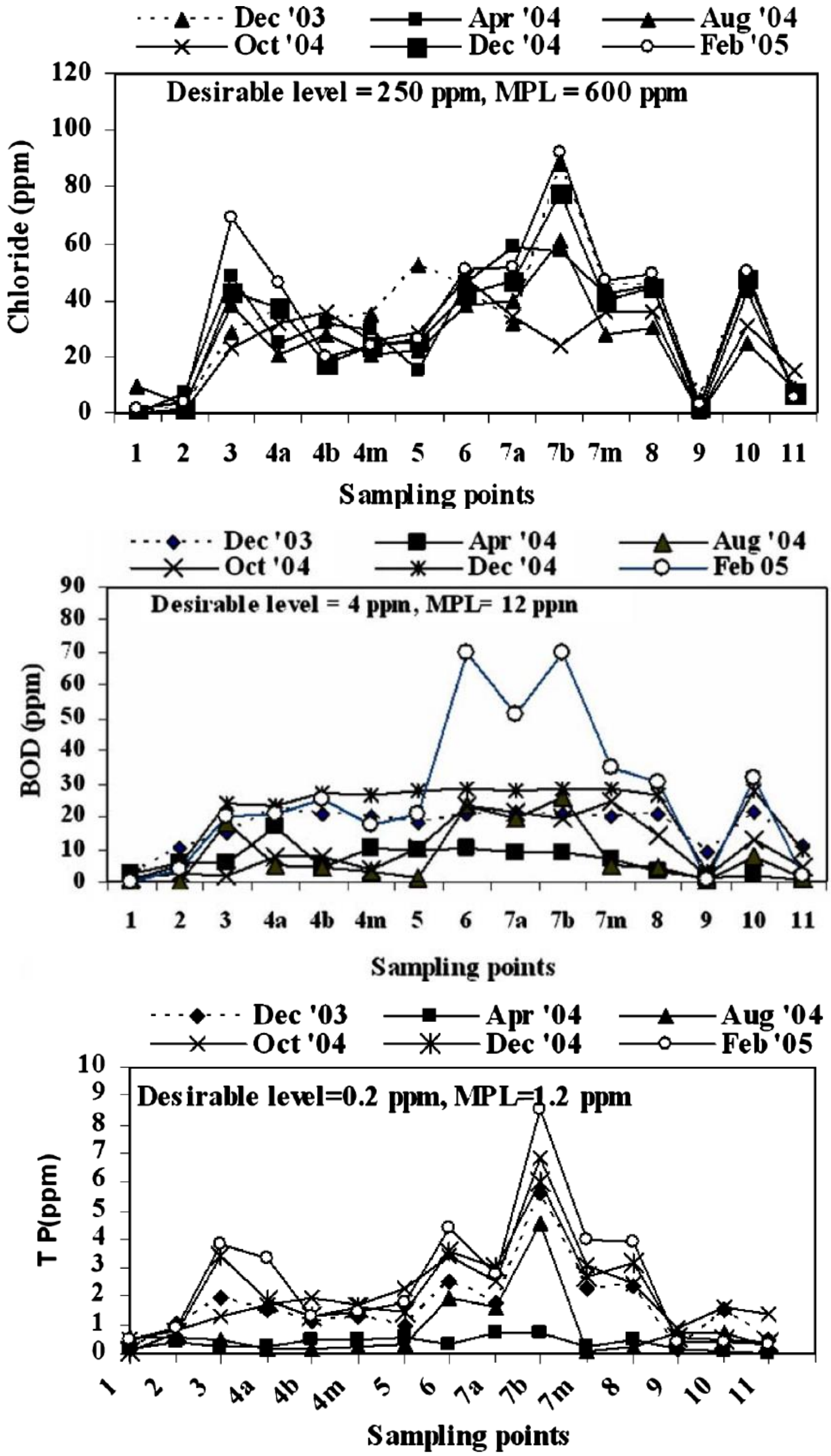


Figure 34: Water quality measurements along Bharalu River by Girija et al. (2007) from upstream direction. From upper to lower graph: chloride, BOD and TP concentrations (ppm = mg/L)

APPENDIX C: MODEL SET-UP

The Storm Water Management Model (SWMM) is developed by the U.S. Environmental Protection Agency (EPA) and is a widely used model for urban drainage design, analysis and planning (Niazi et al., 2017). SWMM is a hydrologic-hydraulic water quality simulation model, which uses a single-event or long term (continuous) simulation and consists out of an atmosphere, land surface, sub-surface (groundwater) and conveyance compartment which interact with each other (Rossman & Huber, 2016). In Figure 35 a flow chart of the model is presented. In this research, PC-SWMM will be used to analyse the overall water quality situation in Guwahati and assess the effects of measures and management scenarios on the water quality.

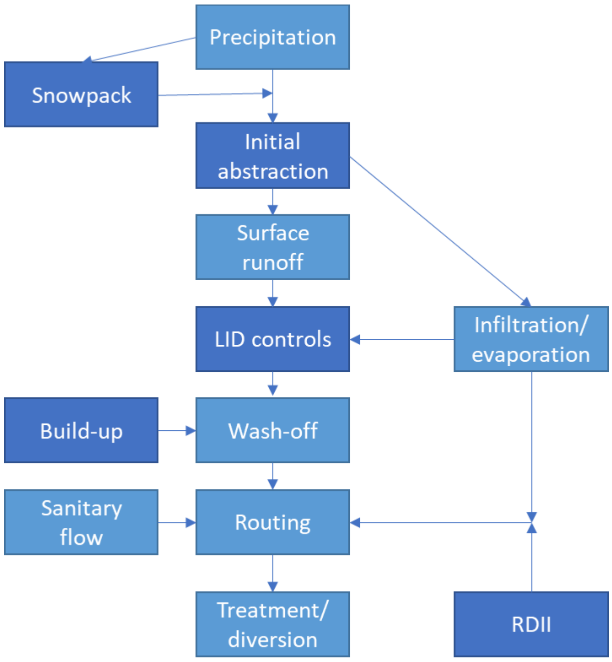


Figure 35: PC-SWMM flow steps (light blue steps are used in this study)

C.1 Hydrologic modelling

The hydrology in a study area is modelled by rain gauges, sub-catchments, aquifers, snow packs and unit hydrographs. A rain gauge is a source of precipitation data which will be converted into runoff using the non-linear reservoir method at a sub-catchment which then flows into another node or sub-catchment. The unit hydrograph describes the response of the amount of sewer inflow/infiltration generated over time per unit of direct rainfall (Rossman & Huber, 2016).

C.2 Hydraulic modelling

The hydraulic component in SWMM accounts for the hydraulics of the system. It keeps track of the runoff quantity and quality through a system consisting of pipes, channels, pumps, regulators and storages (Rossman & Huber, 2016). This system is modelled using junctions (to connect different nodes), outfalls (end point of conveyance system), dividers (to divide flow), storage nodes, regulators or pumps which are all linked through conduits representing pipes and channels. The sub-catchments are used as input, generating runoff and various pollution loads and concentrations as output.

The model uses the one-dimensional shallow water equations (Saint Venant) represented by the momentum and continuity equation. The continuity equation is solved at the mid-point of a link and the momentum equation is solved at each node during each time step. A simulation can be run using different flow routing settings being steady state, kinematic wave and dynamic wave, being a uniform and steady flow (steady state) to taking into account back water effects (dynamic wave). A choice has been made to use the kinematic wave as this routing method accounts for back water effects.

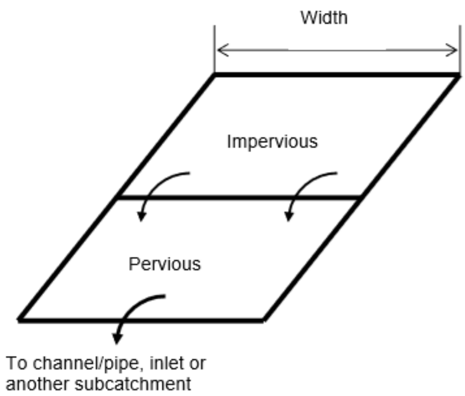


Figure 36: Diagram of conceptual model for rainfall – runoff relations

In sub-catchments, several features can be adjusted to find the best representation of each sub-catchment in the area. The parameters all influence the volume of runoff from a sub-catchment which is based on the nonlinear reservoir method. In this method, the sub-catchment is considered as a very shallow reservoir and is assumed to be a nonlinear function of the water depth of the reservoir.

Table 15: Parameters which describe the characteristics of the sub-catchments

Parameter	**Description**
Width parameter	Width parameter influences the runoff hydrograph which represents the rate at which water is transferred overland. The width is the collection length of the overland flow of the watershed area, thus an increase in width will decrease runoff volume.
Percentage slope	The slope percentage represents the steepness of the sub-catchment. The larger the slope, the faster the water will run off.
Manning roughness coefficient (impervious and pervious)	Manning equation is used to express the relationship between flow rate, cross-sectional area, hydraulic radius and slope in all conduits. - A constant Manning N of 0.011 has been used for impervious areas (Voortman, 2017) - Per land use classification a Manning N obtained from Engman (1986) and Downer et al. (2002) is used.
Percentage imperviousness	The percentage imperviousness determines the amount of water which will not infiltrate in the ground, but which becomes runoff. The remaining percentage of perviousness will infiltrate in the subsurface. The percentage of urban land use per sub-catchment was determined to get the 'percentage imperviousness' in SWMM.
Infiltration	The infiltration in the ground influences the amount of runoff which will be represented by Horton. This is an empirical method which starts with a constant rate and decreases exponentially with time until some saturation level is reached.
Storage height	The depression storage (mm) represents the ability to store water in the sub-catchments preventing it from running off. A certain depression storage is assigned to the impervious and pervious part of a sub-catchment.

Storage units

The fresh water lakes and wetlands in the study area are represented by storage units. These storage units are assigned a user-defined storage curve which represents how the lake fills up regarding water depth and surface area. For the lakes in the case study areas there are no measurements available, but the storage curves have been defined with knowledge retrieved from local observations of people and experts. The water depth in Deepor Beel has a high variation between a dry and wet period whereas Borsola Beel has less fluctuation in water depth. In Figure 37, the used storage curves of Deepor Beel and Borsola Beel are presented.

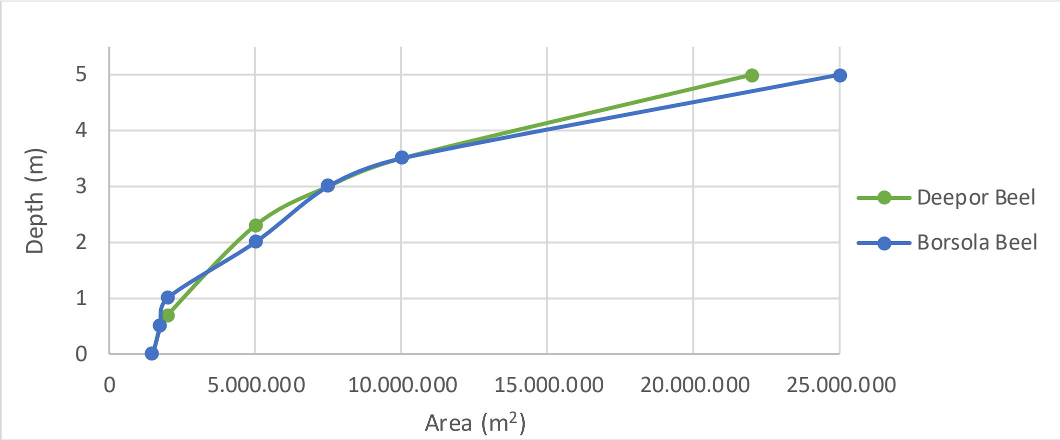


Figure 37: Storage curves for Deepor Beel and Borsola Beel

Pumps and other structures

Within the study area there are several outlet structures and sluices present which are modelled through orifices. The major outlet structures and sluices are located at the outlet of Borsola Beel and at the outlet point of Deepor Beel (Khonajan) to prevent backflow from the Brahmaputra River. Each of these orifices have their own dimensions, but are assigned a discharge coefficient of 0.65.

Just one pumping station has been modelled which is located at the Mora Bharalu River and depending on the water level at the inlet node a certain amount of water is pumped from Bharalu River to Mora Bharalu directing to Deepor Beel.

Initial and boundary conditions

In this model the outflows have a fixed water level which represent the Brahmaputra River. This value will be fixed on 45.45 m above MSL at the outflow point of Deepor Beel. Each outflow has a fixed value which is larger upstream. These values are based on measured water levels in the Brahmaputra River along the river front of Guwahati and remain fixed during all simulations so the water quality error will remain low. This does not represent the real situation as the water level in the Brahmaputra River fluctuates resulting in back flows. Furthermore, the evaporation is set to a constant value per month. The values are presented in Chapter 2.

The simulations are run using initial hot start files which account for the spin up time of the model to get to equilibrium concentrations and water levels throughout the water system. The spin up time is approximately a week for Borsola Beel and a month regarding Deepor Beel. A period of two months without rainfall and a period of two months with constant rainfall are initially run. The equilibrium end concentration and water depths are then used in the simulation runs in this study.

APPENDIX D: SENSITIVITY ANALYSIS

In this appendix the additional graphs of the water quality parameters which are not discussed in the main report are presented here in Figure 38, Figure 39 and Figure 40 on the next pages.

Except for TSS, both nutrients show a similar response in the water system as BOD regarding the sensitivity of each parameter. In dry period, most parameters show to be more sensitive than during wet weather. The DWF volume and concentration show to have a large influence on the final concentration, whereas WWF concentration has little influence. For TSS, the WWF concentration is of more influence on the final concentration. This can be explained by the fact that the main part of sediments originates from storm water runoff represented by WWF. Decay has no influence as it has not been incorporated for TSS.

Total Nitrogen

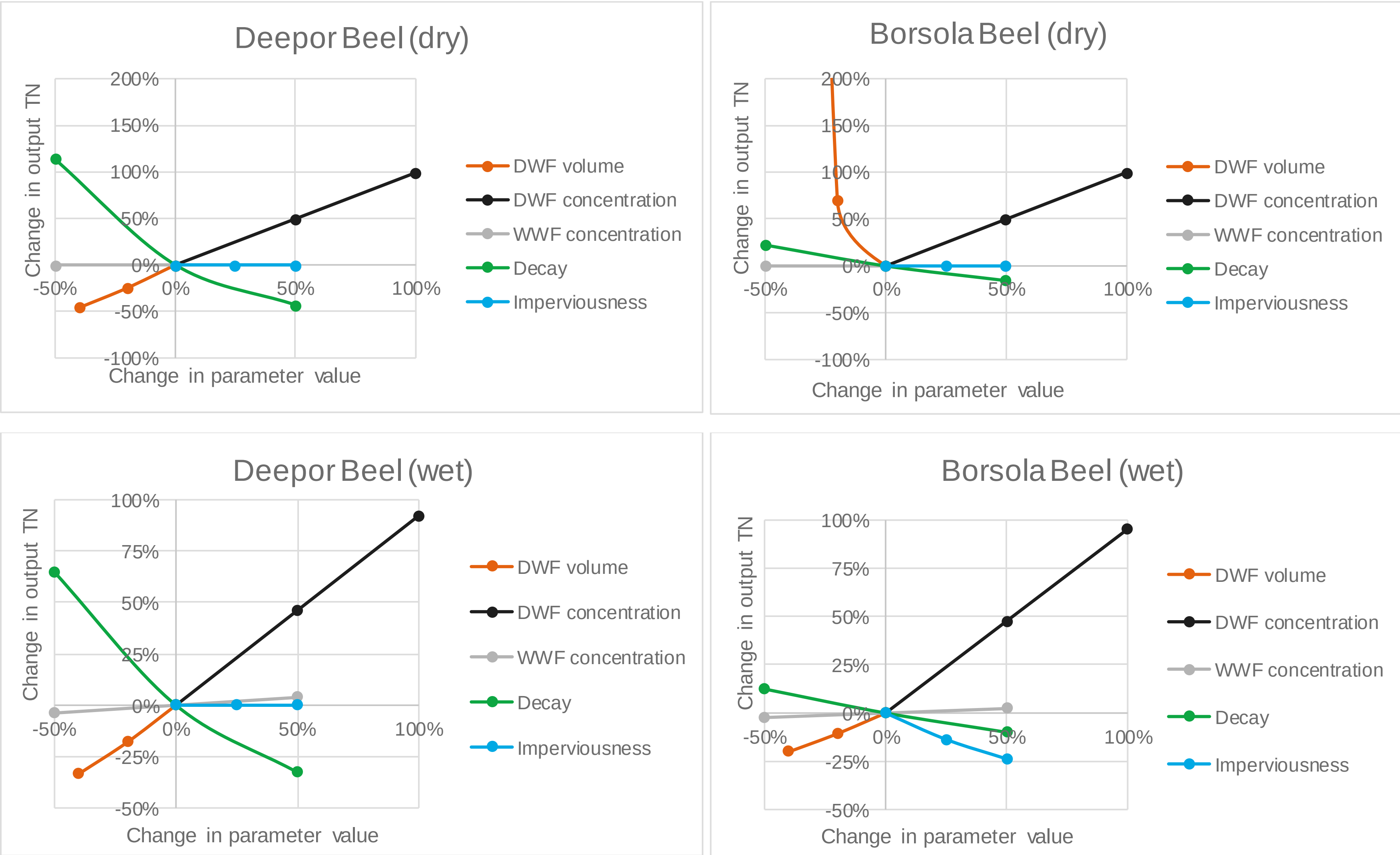


Figure 38: Sensitivity analysis considering TN concentrations in Deepor Beel (left) and Borsola Beel (right) during both dry (upper) and wet weather (lower)

Total Phosphorus

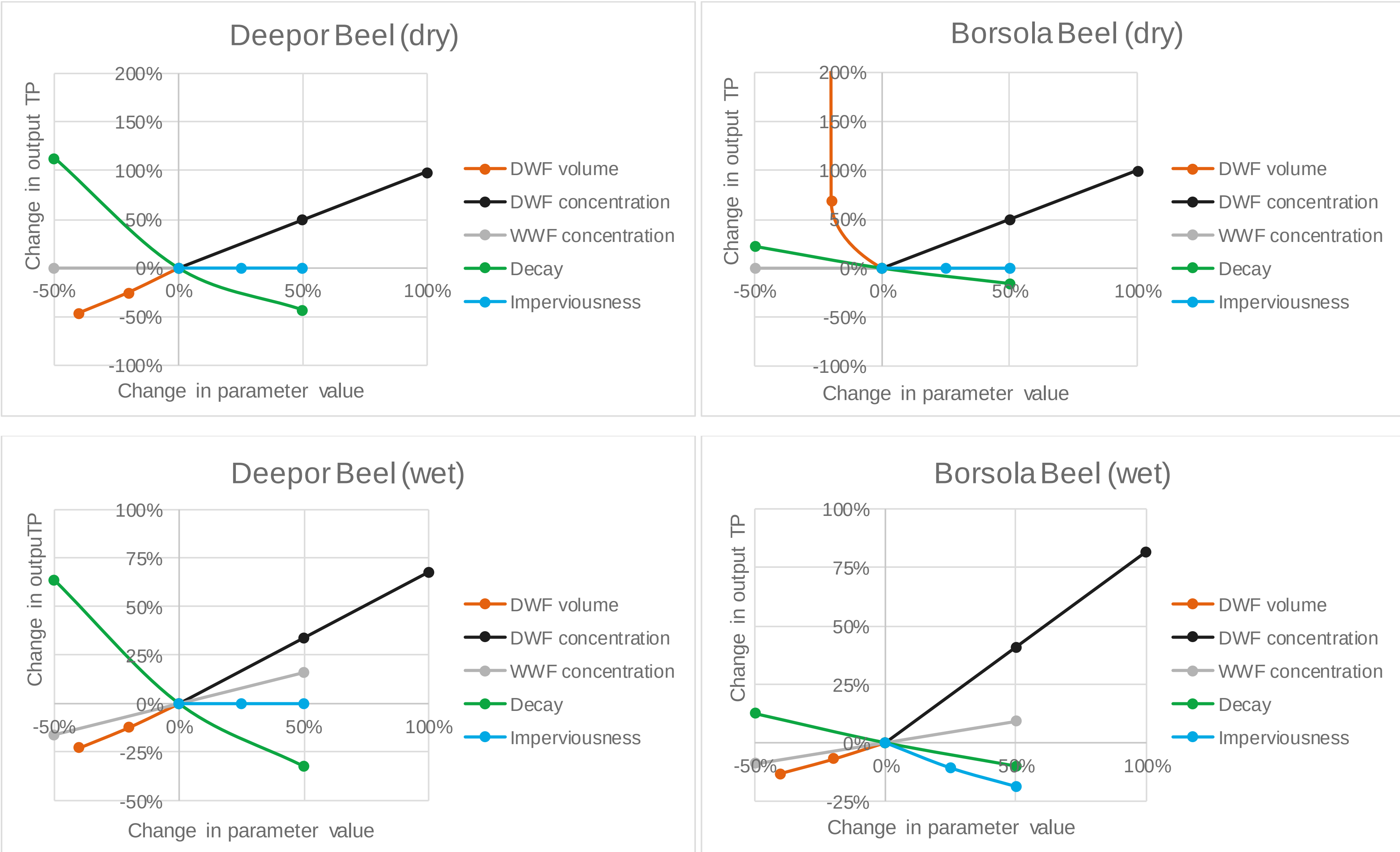


Figure 39: Sensitivity analysis considering TP concentrations in Deepor Beel (left) and Borsola Beel (right) during both dry (upper) and wet weather (lower)

Total suspended solids

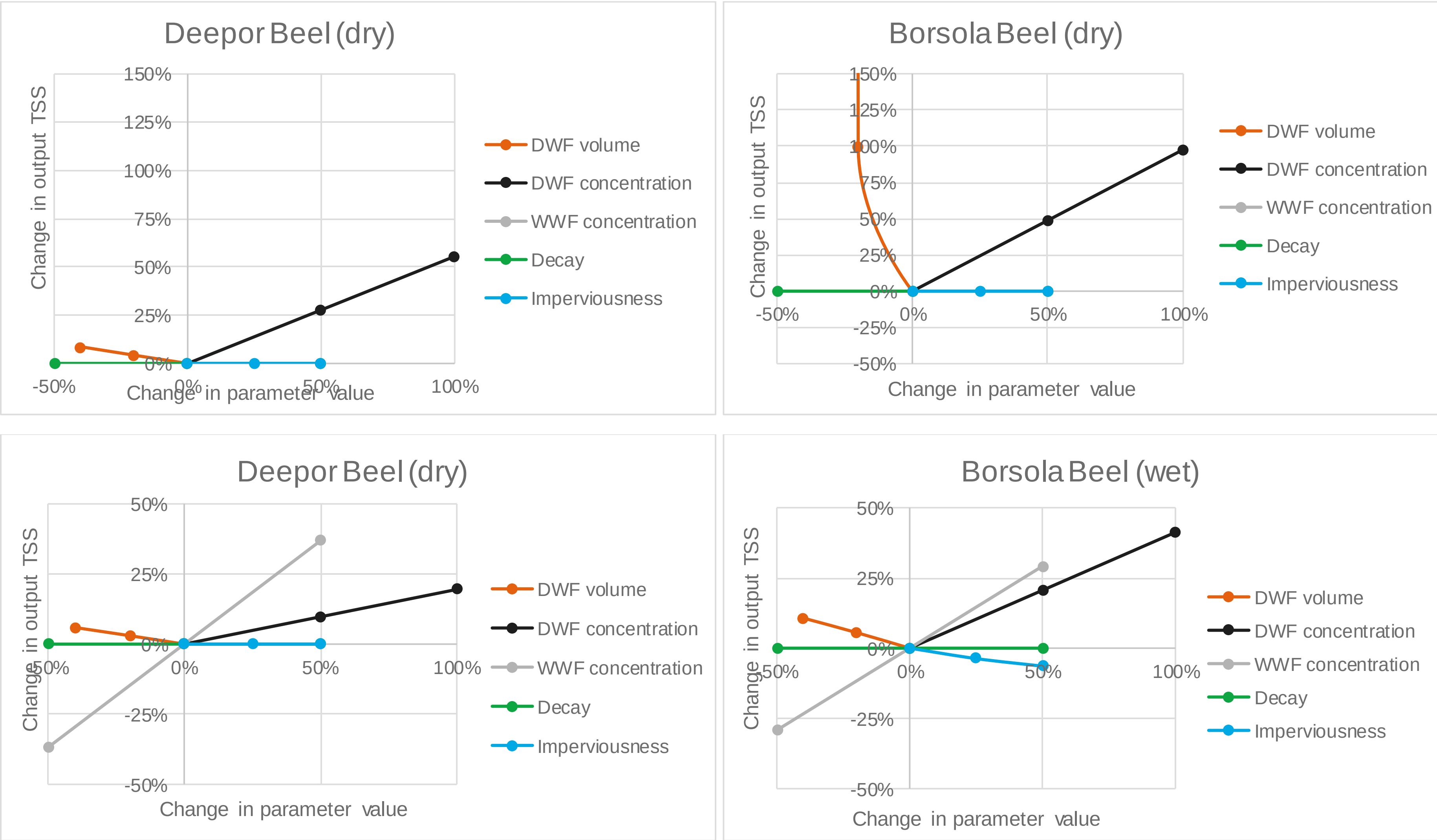


Figure 40: Sensitivity analysis considering TSS concentrations in Deepor Beel (left) and Borsola Beel (right) during both dry (upper) and wet weather (lower)

APPENDIX E: FORECASTING POPULATION GROWTH

The mean population growth is based on different forecast methods. The forecast methods used are arithmetic increase, geometric increase, declining growth rate, incremental increase and graphic method. Reports on design for sewage systems in Guwahati have used these methods, so similar methods are used in this research.

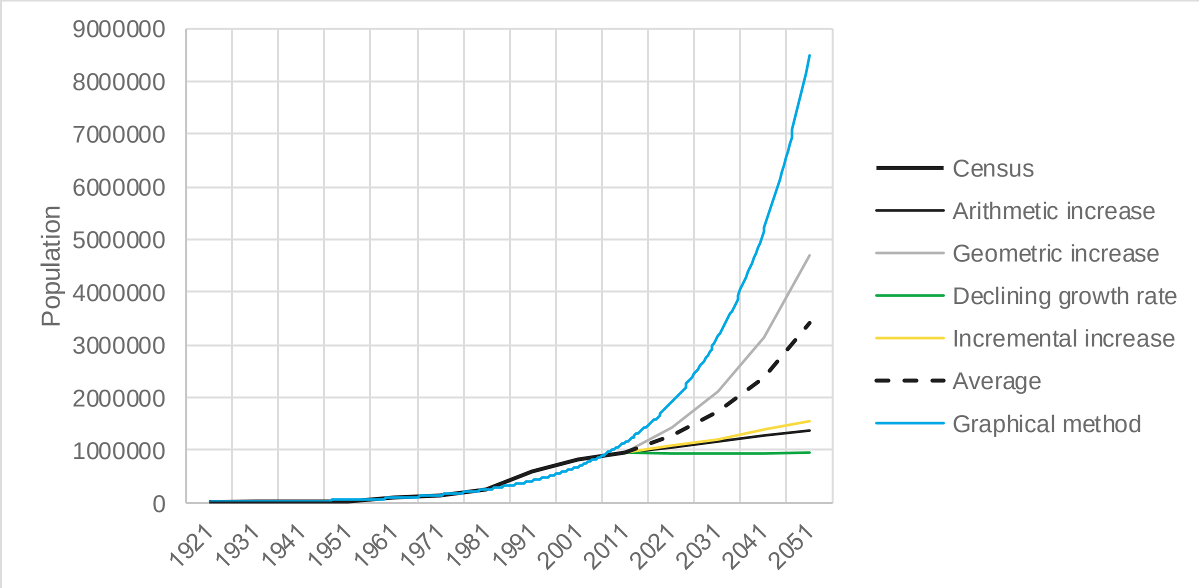


Figure 41: Population growth based on different forecast methods

The total population for Guwahati in 2025 is expected to be approximately two million people according to the Masterplan 2025. This is best reflected in the geometric increase method as can be seen in Figure 41 and Table 16. However, this method together with the graphical method show a very large increase which is unrealistically high. The graphical method does not show a good correlation over the period until 2011 as well, but only the last few decades the population has grown significantly which is expected to continue. However, an exponential growth as it shows now is unrealistic. Therefore, the mean value of all used methods is taken for the year 2050. The mean average population for Guwahati will then be approximately 3.4 million of which two million people are living in the combined catchment area of Deepor Beel and Borsola Beel which is used in this research. There have been assigned development zones outside the study area which explains the difference.

Table 16: Population (million people) in every decade using different forecast methods

	Arithmetic increase	Geometric increase	Declining growth rate	Incremental increase	Simple graphical*	Mean
2011	0,96	0,96	0,96	0,96	0,96	0,96
2021	1,06	1,43	0,96	1,08	1,90	1,28
2031	1,17	2,12	0,96	1,22	3,13	1,72
2041	1,27	3,16	0,96	1,38	5,16	2,38
2051	1,38	4,70	0,96	1,55	8,50	*3,42*

* Simple graphical: based on exponential trendline, because it showed best R-value

APPENDIX F: SCENARIO COMPARISON

In this appendix, complementary graphs and tables of TN, TP and TSS are presented. In general, the reduction in concentrations and loads of the presented pollutants is similar to the pattern of BOD presented in the main report.

F.1 Lake water quality

This section presents the reduced concentrations for TN (Figure 42), TP (Figure 43) and TSS (Figure 44) in each scenario in both Deepor Beel and Borsola Beel in both seasons.

Total nitrogen (TN)

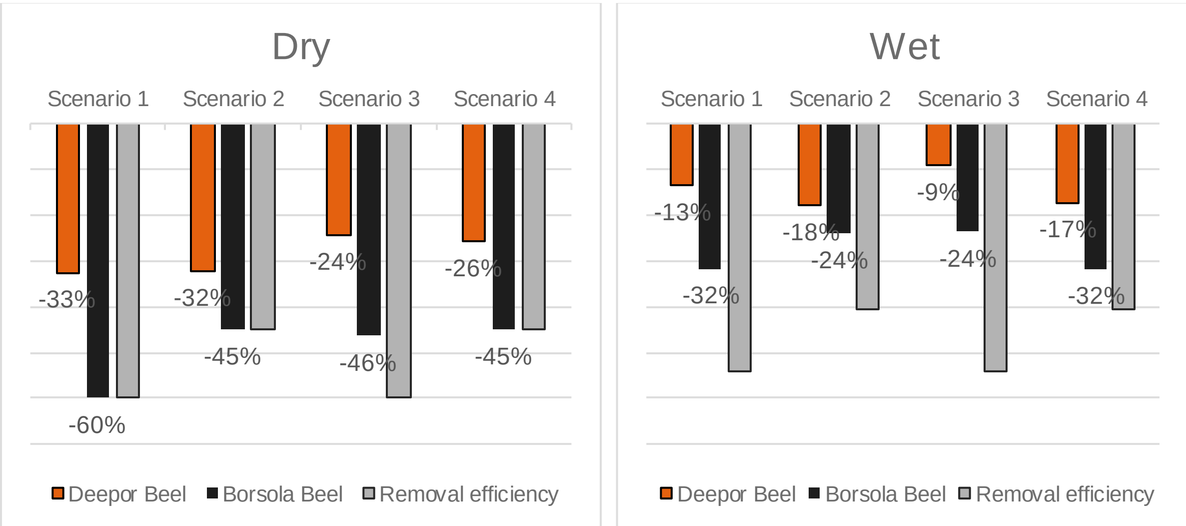


Figure 42: Lowering of TN concentration in Deepor Beel (orange) and Borsola Beel (black) in each scenario for a dry (left) and wet period (right) compared to removal efficiency in STP (grey)

Total phosphorus (TP)

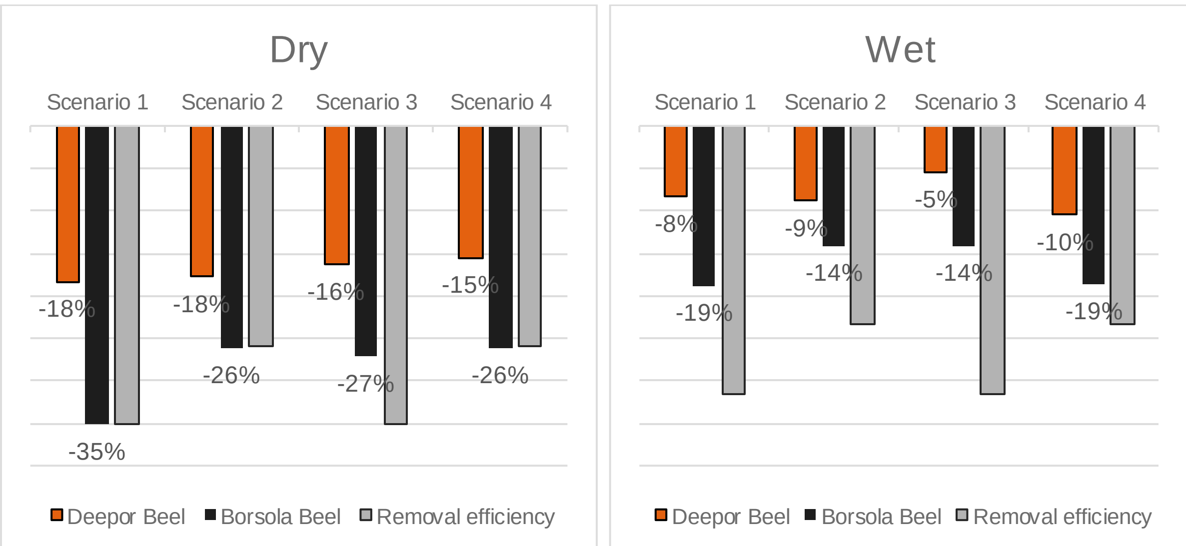


Figure 43: Lowering of TP concentration in Deepor Beel (orange) and Borsola Beel (black) in each scenario for a dry (left) and wet period (right) compared to removal efficiency in STP (grey)

Total suspended solids (TSS)

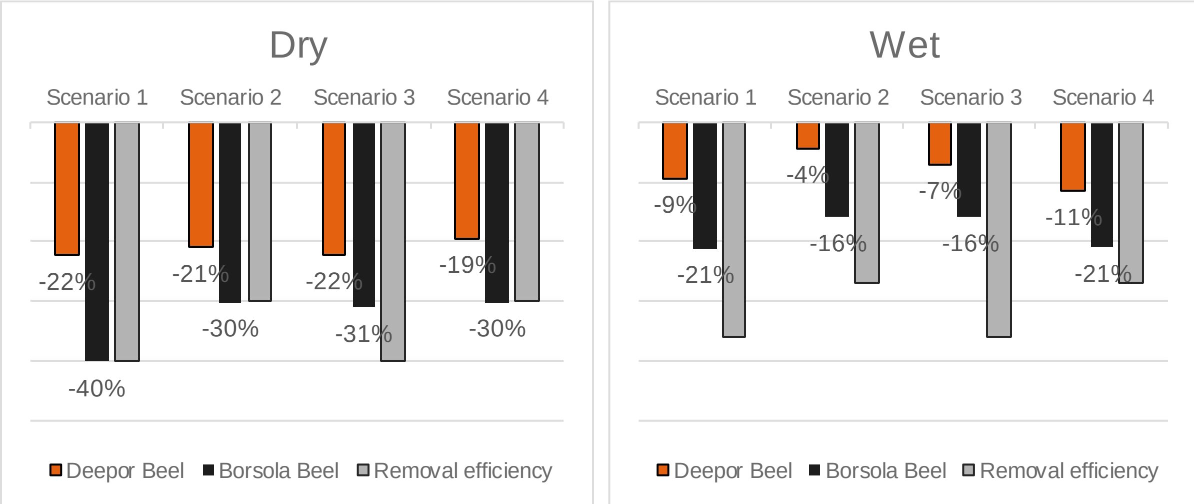


Figure 44: Lowering of TSS concentration in Deepor Beel (orange) and Borsola Beel (black) in each scenario for a dry (left) and wet period (right) compared to removal efficiency in STP (grey)

F.2 Achieved reduction in concentration

In Table 17, Table 18 and Table 19, the achieved percentage of concentration to be lowered to reach the target concentration for each water quality parameter is presented. A similar observation can be made as for BOD: in all cases the achieved percentage is higher during dry period than during wet season. In general, scenario 1 performs best.

Table 17: Achieved percentage of TN concentration to be lowered to reach the target concentration

	Worst case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
TN target: 0,5 mg/L					
Deepor Beel (dry)	0	45,3	44,8	33,8	35,8
Deepor Beel (wet)		21,9	29,1	14,9	28,1
Borsola Beel (dry)		63,0	47,2	48,7	47,2
Borsola Beel (wet)		34,8	26,4	26,1	34,9

Table 18: Achieved percentage of TP concentration to be lowered to reach the target concentration

	Worst case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
TN target: 0,05 mg/L					
Deepor Beel (dry)	0	18,7	18,1	16,7	15,8
Deepor Beel (wet)		8,7	9,2	5,7	10,9
Borsola Beel (dry)		35,5	26,4	27,4	26,4
Borsola Beel (wet)		19,2	14,4	14,4	19,0

Table 19: Achieved percentage of TSS concentration to be lowered to reach the target concentration

	Worst case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
TN target: 50 mg/L					
Deepor Beel (dry)	0	73,8	69,3	73,6	64,5
Deepor Beel (wet)		24,6	11,5	18,5	30,2
Borsola Beel (dry)		**115,2**	86,5	88,9	86,5
Borsola Beel (wet)		62,1	46,6	46,6	61,6

F.3 Overall water quality

This section presents the reduced loads of each pollutant, TN (Figure 45), TP (Figure 46) and TSS (Figure 47), at the outfalls of Deepor Beel and Bharalu River. Only TSS shows a different pattern in reduction or increase of load at the two major outfalls of the study area.

Total nitrogen (TN)

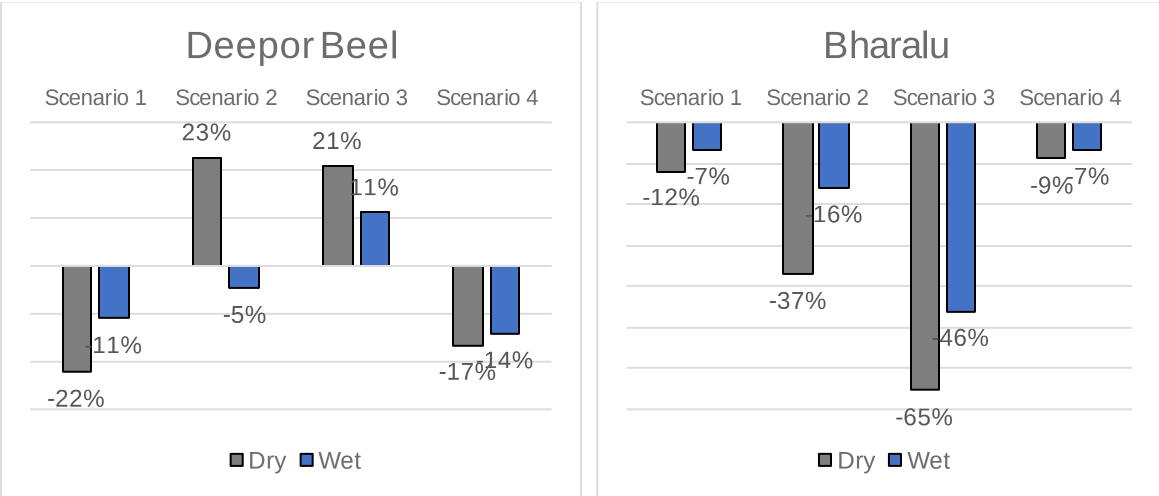


Figure 45: Reduction (negative) and increase (positive) of TN load at major outfalls of the study area

Total phosphorus (TP)

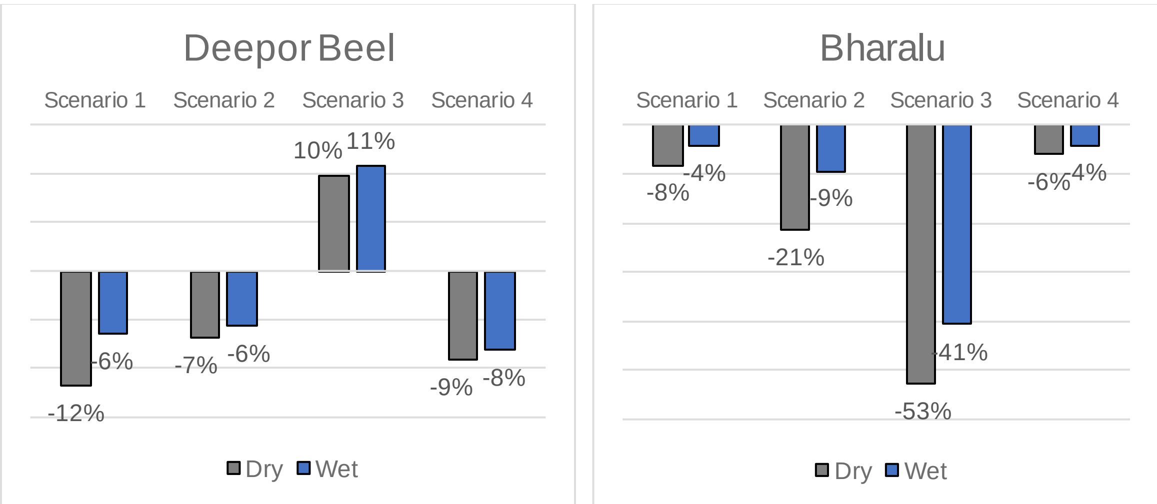
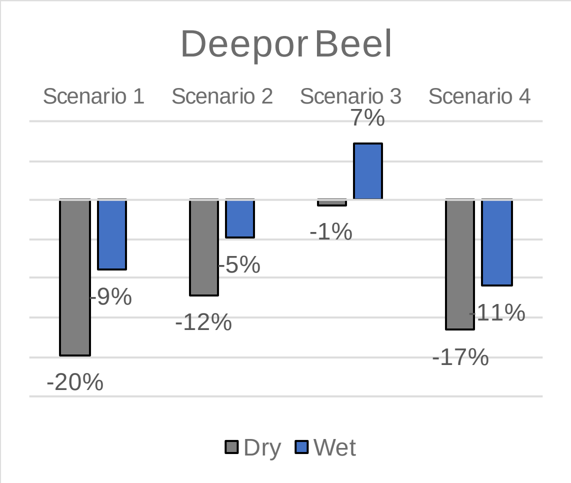


Figure 46: Reduction (negative) and increase (positive) of TP load at major outfalls of the study area

Total suspended solids (TSS)



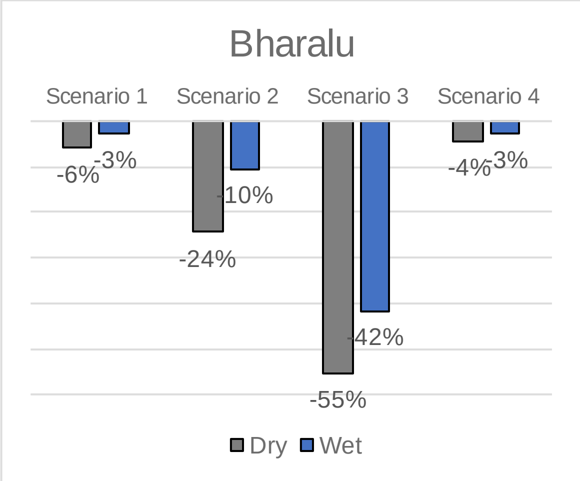


Figure 47: Reduction (negative) and increase (positive) of TSS load at major outfalls of the study area

F.4 Concentrations during monsoon season

Figure 48 presents the concentrations in Deepor Beel and Borsola Beel during monsoon season with varying rainfall intensities for different scenarios. Here it can be seen that during periods with large rainfall events (from 15th of July up to 25th of July), a smaller decrease in concentration is achieved than during periods with smaller rainfall events or even dry periods.

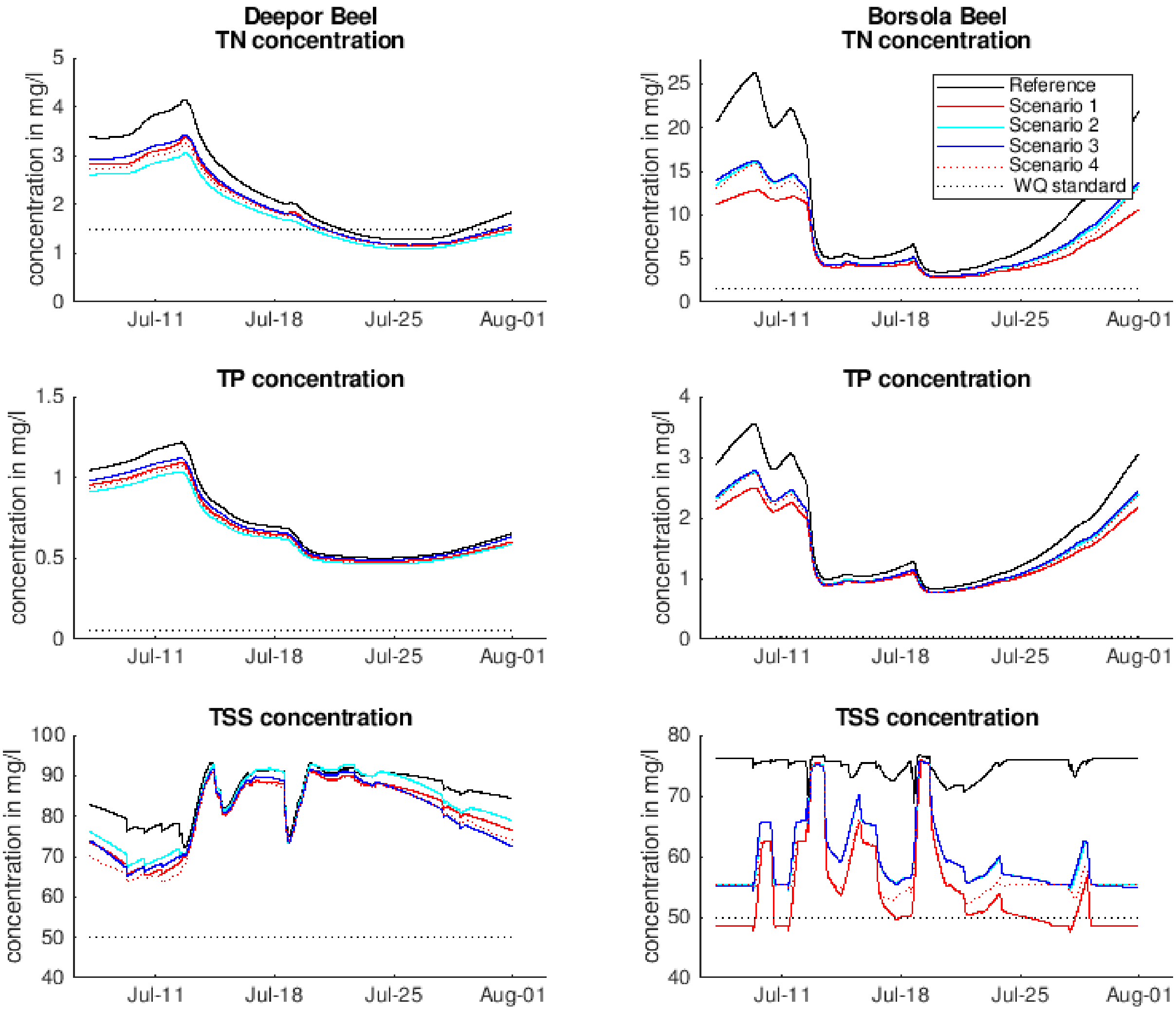


Figure 48: TN, TP and TSS concentration over time together with desirable concentration for the different scenarios in Deepor Beel (left) and Borsola Beel (right)