# Modelling pollution hot spots as a result of industrial effluent in Dhaka, Bangladesh

Deltares
Enabling Delta Life

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# Table of Contents

# Summary

Industries in Dhaka, Bangladesh, play a significant role in polluting the waterways. Although effluent treatments plants are required by law for many of the industrial sites, these are in many cases not well monitored and often not used. The result of the lack of effluent treatment is that many of these industries are releasing large amounts of wastewater into the water untreated. There are many issues due to water pollution in Dhaka relating to human health, ecological health and reduction in agricultural production, for example. To improve water quality in the area policies and approaches need to change. Although some parameters have been monitored in the past, there are substances which are potentially overlooked. By modelling emissions from industries, pollution hot spots could be analysed in the area, based on the substance loads industries add to the waterways. Subsequently, the effect of adding industries onto the existing sewage system in Dhaka was modelled to assess the impact this would have on substance load added by industrial effluent in the study area.

The first step in modelling industrial effluent emissions in Dhaka's waterways was categorising the industries for use in the emissions model. The resulting categories textile, tanneries and paper mills were selected based on their wastewater quantity and quality. A further division was made for the textile category, consisting of dyeing, printing, washing and mixed wet processes. Substances also needed to be selected for modelling, which was based on literature data availability and consequences for ecological and human health. The selected substances were arsenic, cadmium, chlorine, nitrate, sulphate and tannins. The wastewater production per individual industry was used as input in the model in combination with typical substance concentrations in the effluent to calculate the substance load.

The emissions model results in substance loads emitted spatially. The industrial effluent locations were then assigned to sub-catchments, which were defined by using a digital elevation map. Using the digital elevation map the outfall points for wastewater from industries were also estimated, to show where the modelled substance load would enter the waterways. Pollution hot spots could subsequently be defined as the outfall points with large substance loads for each of the substances. From the modelled loads the industrial categories which contributed most to the substance loads could also be shown.

Validation of the model was based on the concept of a substance balance. Modelled discharge values for the main stretches of river were combined with substance concentrations measured at various points in the study area. The loads were calculated and compared for nitrate and sulphate, which were the only substances with available concentration data. Although the validation was not fully realised, the next steps were indicated for improving the validity of the model for further use.

The scenario analysis looked at the effects on the substance loads added to the waterways by industries and what the impact would be of connecting the industries to the sewers for the Pagla wastewater treatment plant. The results from this analysis showed this would have very little impact on substance load addition to waterways, with all reductions being under one percent of the total load in the study area.

# Acknowledgements

Especially considering the abnormal year we have had this year I would like to say thanks to Marc Weeber, who has given so much of his time and energy to guide this research. His regular contact and willingness to help has been a great aid in the development and writing of my thesis, and for this I am very grateful. I would also like to say thanks to Walter Schenkeveld, who has been a great guide in writing the thesis and has given me prompt feedback and regular calls throughout the time period.

# 1. Introduction

## 1.1. Background

### 1.1.1. Location

Dhaka, the capital of Bangladesh, is seeing rapid economic growth and consequently severe pollution of its rivers. The densely populated city is nested in central Bangladesh, surrounded by a complex network of rivers, north of the convergence of the river Meghna and the river Padma (Figure 1). The river network surrounding Dhaka is known to be very polluted, but is, nevertheless, used for many purposes such as bathing, drinking, industrial processes and irrigation. The city has a rainy monsoon season from June to September and a dry winter season between December and February, which leads to high levels of variability in seasonal flow. Seasonal flow has significant impacts with regards to pollution effects, due to reduced dilution in times of low discharge.

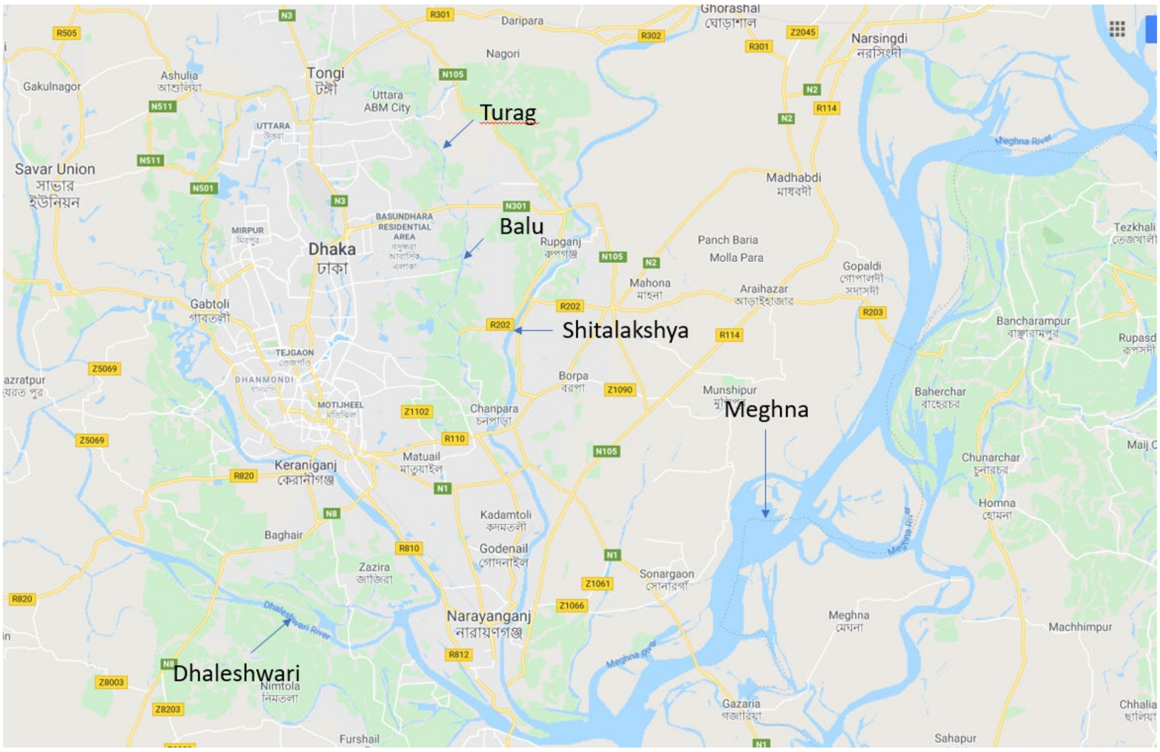

*Figure 1: Map obtained from Google Maps, accessed on 06/02/2020, showing location of Dhaka within Bangladesh, north of the convergence of the Padma River and Meghna river. The Meghna, Dhaleshwari, Shitalakshya, Turag and Balu are some of its major rivers and are labelled on the diagram.*

### 1.1.2. Industrial Presence

Dhaka is one of the most densely populated cities globally and hosts a wide range of industries. Each of these industries is responsible for its individual type of waste production dependent on its materials and processes. Surface water pollution by untreated or poorly treated domestic, industrial and agricultural wastewater causes issues for human health, livelihoods and environment. Water pollution also reduces the fresh water availability for the various industrial processes in place. “In the last twenty years, a convergence of unregulated industrial expansion, rural-to-city migration, overloaded infrastructure, unclear institutional responsibility for water quality management and ineffective enforcement of environmental regulations have all taken their toll on surface water quality” (Whitehead et al., 2018). Currently, a city expansion on the banks of the Meghna river is underway by the name of New Dhaka, which might increase the stress on the river system even further. Dhaka will continue to grow both economically and in population size, and therefore these pressures on its water sources are likely to continue, if not worsen, if no actions are taken.

There are several types of industries to consider in the area. Industrial facilities are clustered in zones, such as the Dhaka Export Processing Zone (DEPZ). Concentrated industrial clusters, due to their lack of adequate wastewater treatment, pose threats to aquatic life and human health (Islam et al., 2016). A report in 2007 estimated that 60% of the pollution in rivers around Dhaka originated from roughly 7,000 industries, releasing 1.5 million cubic metres of wastewater, daily (IWM, 2007). A large part of this industrial wastewater is untreated, and thus industrial waste water management is a key component regarding river pollution in the area.

### 1.1.3. Environmental Legislation for Industries

Industries in Bangladesh are categorised by colour, determined by the Environment Conservation Rules (ECR). These categories dictate where an industrial premise can be located due to the hazardous nature of its industrial effluent, solid waste or air pollution. The ECR also dictates what kind of wastewater processing needs to be in place. Orange and red categories require an Effluent Treatment Plant (ETP) if there is liquid waste generated (*The Environment Conservation Rules* , 1997). ETPs have been made compulsory within environmental compliance due to the severity of impact that certain industries have on the environment, but are difficult for the Department of Environment (DoE) to monitor (Belal et al., 2015). ETPs are also not always implemented, or switched on, especially by small to medium-sized industries, due to lack of funding for initial investment, and running and maintenance costs (Dey & Islam, 2015). This results in industrial wastewater, containing various pollutants that have potential adverse impacts on the environment, being released into the river network without treatment.

## 1.2. Problem description and knowledge gaps

Goal 6.3 in the UN Sustainable Development Goals strives to provide clean water for all (United Nations, 2017). This goal is vital as the consumption of contaminated water harms human health directly. A lack of clean water also impacts livelihoods by affecting income and food production. Dhaka’s rapid economic growth makes it essential to assess present and future estimates for water pollution to find solutions to water issues. Dhaka is largely reliant on groundwater for its drinking water. Overexploitation of groundwater resources has led to an unsustainable decrease in fresh water supply (M. A. Hoque et al., 2007). Surface water could be an alternative source for drinking water. Switching to surface water during the wet season allows for sustainable recharge of groundwater resources. However, pollution of waterways limits the potential of surface water intake and availability for drinking water production. In this way, surface water quality is of societal importance and will determine the future development of Dhaka.

The direct implications of untreated effluent release into rivers are also becoming more apparent. Research suggests that skin issues, allergies and other contact diseases arise due to contact with water for fishing, bathing or agricultural purposes in areas of high industrial presence in Dhaka (Halder and Islam, 2015). It is unlikely that skin issues are the only problem; toxic substances are expected to have further impacts on human health, biological diversity and crop yield. The reduction of crop yield affects nutrition and income for families, who typically do not receive the financial benefits from working in the polluting industries (Akhtar et al., 2016).

Currently parameters such as Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are monitored. Measuring BOD and COD is important due to their indication to depleting oxygen in rivers. Oxygen in rivers is important to aquatic organisms for survival and is, therefore, vital for ecosystem health. Nutrients such as nitrogen and phosphorous are also monitored, as elevated concentrations can lead to eutrophication and algal blooms. Due to a lack of sewage systems, coliform testing has also been of importance as it indicates faecal presence in water sources. There are, however, substances that fall outside of the regular monitored substances that could have their own risks. One of the sources of un-monitored substances is industrial. Due to the large industrial presence in Dhaka with unmonitored effluents, alternative methods of pollution quantification are required.

In summary, the problem considered is industrial effluents causing pollution in the waterways of Dhaka. People will continue to use the waterways for fishing, bathing, irrigation and food production. Continuous use of heavily polluted water causes problems for the local population's health directly, which is likely to be underestimated in severity. Water pollution also has consequences for ecosystems and food production. Due to the socio-economic status of Bangladesh, even the legislation in place to implement ETP use does not enforce adequate wastewater treatment. There is a lack of water quality monitoring, which could lead to an underestimation of certain substances when considering the impacts of water pollution in Dhaka.

## 1.3. Literature Review

### 1.3.1. Parameter Measurement

Previous work of interest in the context of (industrial) water pollution in Dhaka is the collection of water quality data and the subsequent visualisation of this data in line with the problem description. There are several methods to analyse water quality parameters, which vary from using simple hand-held meters for in-situ water testing, sampling and examination in a lab, to using more novel techniques such as biosensors (Rampley et al., 2020). There is a need for long term monitoring of water quality parameters, due to the climatic variations in Bangladesh and subsequent high and low discharge pollution concentrations. Where this is not feasible, due to lack of financial resources or knowledge, modelling may be a viable option to estimate pollution levels.

Several rivers in Dhaka do not meet national water quality standards. The Turag-Tongi-Balu river can be considered anaerobic due to its remarkably low levels of dissolved oxygen (DO) as determined with biosensors by Rampley et al. (2020). Low DO levels are detrimental to aquatic life itself but can also increase the concentrations of metals in water and gases such as methane and hydrogen sulphide, due to changes in reduction-oxidation processes. In other studies on the Turag-Tongi-Balu river (Whitehead et al., 2018), but also on the Buriganga river (Ahammed et al., 2016), similarly low levels of DO were found. The national surface water standards in Bangladesh dictate a minimum DO of 8 mg/L. Ahammed et al. (2016) observed an average DO of 1.11 mg/l in the Buriganga. Readings showed DO levels close to 0 mg/L, likely due to the sampling in proximity to tanneries in the Hazaribagh area. The low level of DO of tannery effluent has been described as being due to a high presence of organic matter in the water (Verma et al., 2008).

### 1.3.2. Modelling Water Quality

A variety of industries uses and emits metals. Whitehead et al. (2019) investigated heavy metal pollution from tanneries, specifically. Heavy metals typically emitted from tanneries consist of chromium, cadmium, lead and zinc amongst others. Heavy metal contamination can seriously affect human and aquatic life. The government relocated the tanneries from Hazaribagh to Savar due to high levels of pollution. The study still found high levels of heavy metals at the old location, even after the effluent release from the industries ceased. A small decrease in heavy metal concentrations in the waterway after changing location of the tanneries suggests a slow recovery from metal pollution. Continuous monitoring before and after decisions, such as policy implementation, to evaluate whether the results are adequate is vital. The policy of moving the tanneries' site away from Hazaribagh has reduced pollution in the area. Modelling, however, showed that the shifting of industries to different locations is insufficient for overall water quality improvement (Whitehead et al., 2019). The value of modelling in policymaking was shown by assessing the impacts of moving tanneries to a different location on water quality using the Integrated Catchment Model (INCA model). Modelling studies have also taken place to assess nutrient and total coliform levels to advise on policy decisions. Whitehead et al. (2018) used scenarios to assess the effects different policies might have on Dhaka's waterways. The scenario analysis led to suggesting two solutions, which were flow augmentation, to dilute concentrations of nutrients and coliforms, as well as pollution control by treating sewage and other types of effluent (Whitehead et al., 2018). A limitation to this study was the infrequency of water measurements to ensure model accuracy.

Factories are required to have an operational ETP by the Environmental Conservation Act (1997) for cleaning effluent before release into the surface water. It is the responsibility of the DoE to monitor the use of ETPs and the water quality of effluent. Both government officials and industry leaders do not perform adequate monitoring of effluent quality and ETP use due to a lack of knowledge, resources and funds (Belal et al., 2015). Field observations of ETP use are consequently more significant than just the presence or absence of an ETP. As the extent of which ETPs are used is unknown, this may limit the predictive value of models. This is a limitation that must be considered and addressed.

There are various ways in which to model water quality data. Geographic Information System (GIS) mapping has been utilised in the past to show water quality by location for policymakers, city planners and as a guiding tool for further modelling (Rahman and Hossain, 2008). More specifically, it has also been used to guide decision makers to optimal location of drinking water production sites, as these require varying levels of treatment, dependent on the quality of water. Drinking water production sites typically benefit from cleaner water sources (Rahman, 2013). Using modelling as a method for policymaking has the benefit of simulating a catchment and applying scenarios, so that potential pathways and solutions could be used to predict outcomes. The impact of factors such as population growth and use of technical solutions on pollution of Dhaka's waterways can be explored in a scenario analysis by adjusting model parameters. It is, however, crucial to verify the validity of the model by checking it against measurements. Long-term parameter measurement of water samples would aid in model calibration.

Data collection in Dhaka for water quality related to industrial wastewater has, until now, mainly focused on traditional parameters such as BOD, COD and DO. Some significant substances linked to industrial processes and wastewater may be unaccounted for and underrepresented in findings.

Underrepresentation of these substances could make a difference in spatial planning and policymaking, as unawareness could lead to suboptimal decision making. Modelling water quality in this river network can aid to assess future scenarios, whether for a policy or process improvements or the effects of economic growth. Presently, research on Dhaka's industrial pollution has been based on concentrations of substances in river water quality specifically. No research has studied what the effect would be if there were better effluent treatment of industries on a larger spatial scale.

## 1.4. Aim

Water pollution in Dhaka due to industrial effluent release is causing issues for human and ecosystem health with further indirect consequences such as crop yield and subsequent financial earnings for locals. Existing literature has covered the impacts of industrial effluents, but knowledge gaps remain, regarding substances that are not currently monitored. Some parameters are monitored in the area, yet there are many more parameters which are overlooked and the impacts on a larger spatial scale in Dhaka. The effluent characteristics and locations of industries have thus far not been mapped and modelled, meaning that there is little understanding where the pollution hot spots are for specific industrial substances. For the remainder of this thesis pollution hot spots are defined as areas where a high load of substances is released into the waterways. There is an information gap concerning substance release by industries, both in the sense of what substances are released and at which locations. This study aimed to fill these knowledge gaps. Firstly, this required mapping of industries in the region. Information about location of industries is vital for mapping of the consequent pollution hot spots based on the type of industry present and what kind of emissions typically come from this kind of industry. By selecting substances and finding their typical concentrations in the effluent of different industries it was possible to make estimations of substance concentrations to enter as input into an emission model. The results from this emission model were used to assess the current state of water quality in Dhaka's waterways. Scenario analysis based on information about the wastewater quality and quantity subsequently predicts the effects of connecting industries on to the only wastewater treatment plant (WWTP) in Dhaka.

## 1.5. Research Questions

Based on the problem description and aim, the following research questions were formulated:

**RQ:** What are the pollution hot spots with regards to substances released by industrial wastewater production in Dhaka, Bangladesh and how would connection to the existing WWTP change this?

> **SQ 1**: What industries are currently present in the study area and how can these industries best be categorized in terms of effluent quantity and substance presence and concentration?
>
> **SQ 2**: What substances can be found in literature that are of importance in industrial wastewater in Bangladesh that are currently not monitored in Dhaka's waterways?
>
> **SQ 3**: Can pollution hotspots of pressing substances as found in sub question two be defined by location of entry the water system and what are the responsible sources?
>
> **SQ 4**: How can the modelled output best be validated, and what information is needed for future calibration of the emissions model?
>
> **SQ 5**: What difference would connecting the industries in the area served by the WWTP to the sewage system make to substance load?

The hypothesis for this thesis is that there are substances which are currently not monitored that are of importance in Dhaka’s waterways due to their impact on environmental and human health. Using the emissions model, it should be possible to analyse the locations of pollution hot spots for these substances in Dhaka’s waterways. Due to the lack of monitoring of these substances in rivers it is hypothesised that validation of the model with current data is insufficient for calibration of the model, and therefore it is likely to show that more data is needed for further validation and calibration of the model for use in policymaking. Connecting the industries in the area served by the WWTP to the sewage system will reduce the amount of substance load into the rivers, but as the area is small, this impact would be limited in reduction of load into the rivers over the whole study area.

## 2. Theory/Site Description

Due to the scope of the project, it is not feasible to model the entire area in and around Dhaka. The Padma river, for example, has not been considered in the model. The areas that are specifically selected for this project are the Dhaleshwari, Buriganga, the lower Shitalakshya, Westbank Meghna River between Bhairab Bridge and the confluence with the Dhaleshwari. This area was predefined as a study area by Deltares. The area considered for data collection is limited by boundaries shown as a black rectangular frame in Figure 2. The selection for this area is in line with the focal area to be most impacted by industry surrounding Dhaka, decided upon by Deltares, Institute of Water Modelling (IWM) and the Centre for Environmental and Geographic Information Services (CEGIS). These institutes are currently working in conjunction on multiple water quality related projects within this area.

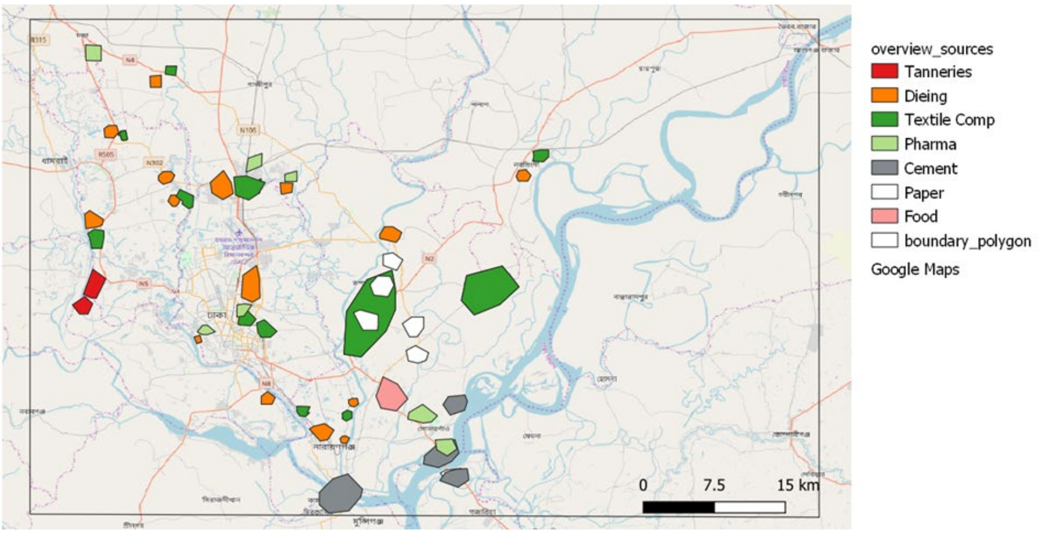

*Figure 2 Presence of different types of industries in the wider Dhaka region. The study area is indicated by the black rectangular box.*

A schematic map of the rivers considered is shown in Figure 3. Each of the river stretches have their own code and have been used for hydrological modelling in Dhaka previously. Some of the river stretches indicated on the map fall outside of the study area but are important to consider for calculation of discharges and substance loads coming into and leading out of the catchment. The catchment has also been divided into sub-catchments, which was estimated from a digital elevation map. The assumption is that the sub-catchments run off by gravity to the nearest river. These sub-catchments then have their own outflow points, which is the estimation of where the substance load enters the waterways (Figure 4). There is one wastewater treatment plant (WWTP) in Dhaka, which services the area shown in Figure 5. There are no industries that are serviced by this WWTP. The WWTP removes between 30 and 40% of substances.

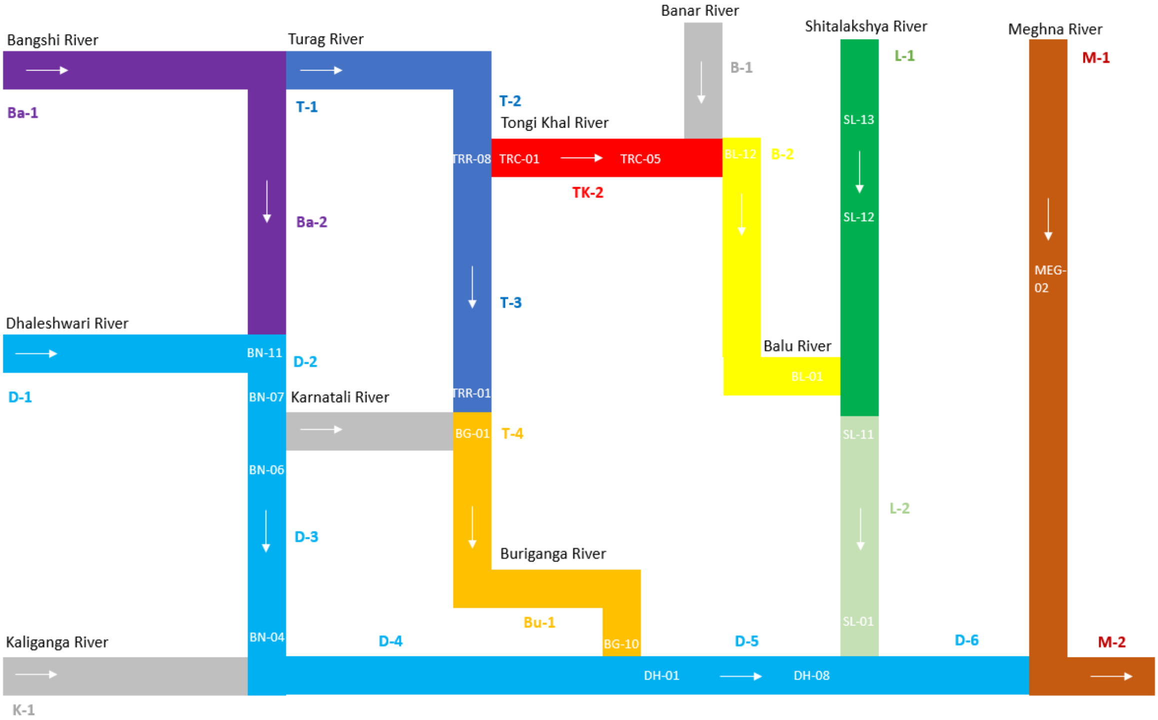

*Figure 3: Schematic map showing the different rivers considered in this study. The river codes are shown in the coloured letters outside the rivers and indicate the river discharges modelled at that point. The white letters within the rivers show the measuring points that have sulphate and nitrate concentrations available at Deltares. This discharge and concentration data could then be used to calculate the nitrate and sulphate loads at these points.*

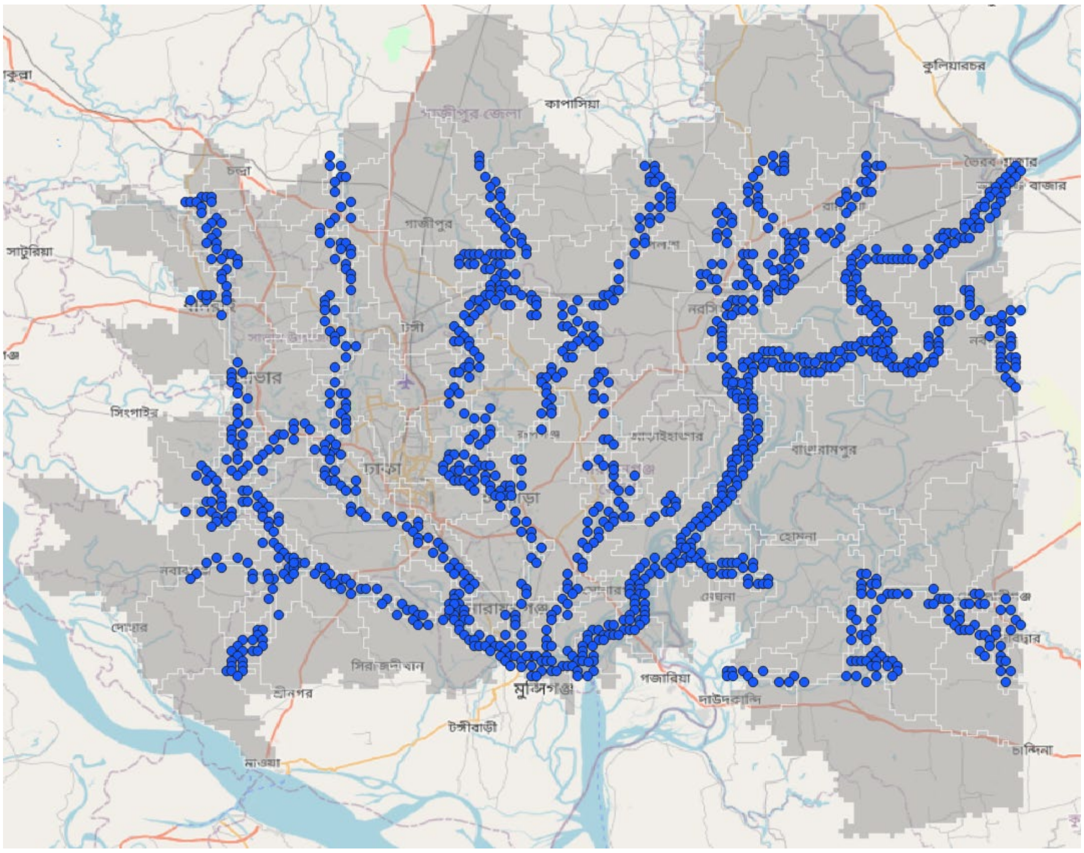

*Figure 4: Map showing the sub-catchments (grey areas) which were defined by an elevation map and their outflow points based on assumptions that the water within these sub-catchments runs into the waterways gravitationally to the outflow points (shown as the blue dots).*

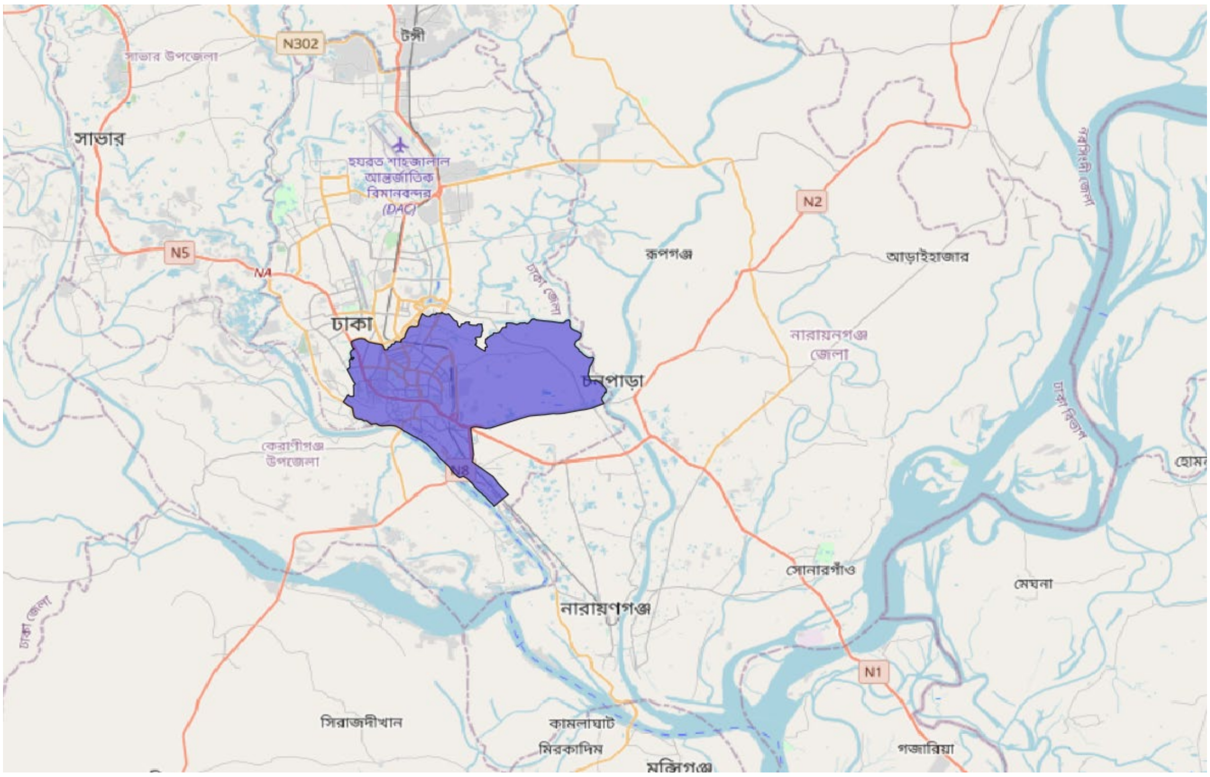

*Figure 5: Map showing the area of Dhaka which is serviced by the WWTP (purple). This only includes the population and no industrial wastewater is processed here. There are no other sewage systems in Dhaka.*

Emission modelling has not been used in Dhaka so far. Emission modelling is a useful tool in estimating substance load addition to waterway by industries, agriculture and domestic waste. The model can then also be coupled in future with a flow model, which could then also simulate the fate of substance loads in the wider river network. Modelling the effects of implementing new sewage treatment plants and industry relocation can be used to influence policy decisions.

# 3. Methodology

## 3.1. Approach

The approach to answering the research questions, and subsequently reach the aim, was to firstly map the location of industries. Due to the quantity of industries present, the industries in the study area had to be separated into categories based on their product and wastewater characteristics. A selection of substances using existing literature data for the designated categories was made for modelling. By modelling the emissions of certain unmonitored substances from industries spatially, pollution hot spots could be found. The resulting modelling data then needed to be calibrated on monitoring data to assess the validity of the model and adjust if needed. What would happen if the industries in the area the Pagla WWTP services were to be connected was then modelled as a scenario to assess what difference this would make to the load. For the setup of the model in this thesis only the industrial effluent is considered, and the substances assessed are assumed to have a purely industrial origin. Domestic and agricultural waste is, therefore, not considered.

## 3.2. Categorization

Data acquisition from the field was needed to map the locations and types of industry in Dhaka. Details of the types of data collected are shown in Table 1. This information was gathered by the CEGIS, although coordinated with Deltares to fill data gaps. Dhaka hosts many industries and it is not feasible to assess each individual industry by its individual effluent quantity and quality. To estimate wastewater characteristics these individual industries were initially grouped in categories based on their final products and raw materials used as listed in the CEGIS database.

*Table 1: Types of data concerning industries in Dhaka received from CEGIS and their uses.*

| **Type of data** | **Purpose of inclusion** |
|---|---|
| Name of industry | Useful for further research for validation |
| Location of industry | Coordinates for plotting on QGIS |
| Final product(s) | For classification into categories |
| Raw materials used | For classification into categories |
| ECR categorization | For selection and classification into categories |
| Production size / wastewater quantity | Where possible, to calculate wastewater and substance quantity |

A literature review was employed to classify the industries in terms of the presence and concentrations of substances, and further wastewater characteristics. The focus of this literature review was the difference between industries for substances present in effluent and in further wastewater characteristics such as quantity. The industries can be process specific, such as dyeing and embroidery under the textile category. Division of these processes into different categories required further specific literature analysis. The classification procedure is further elaborated on in Figure 6. Key words used for the literature search became clear from the CEGIS data available on present industries. The key words used also developed as a snowball effect from literature. Some of the categories have limited impact on waterways or limited literature data on pollution impact. The industries with less impact were omitted to focus on only the industries that have high levels of wastewater production and contain substances that impact the environment.

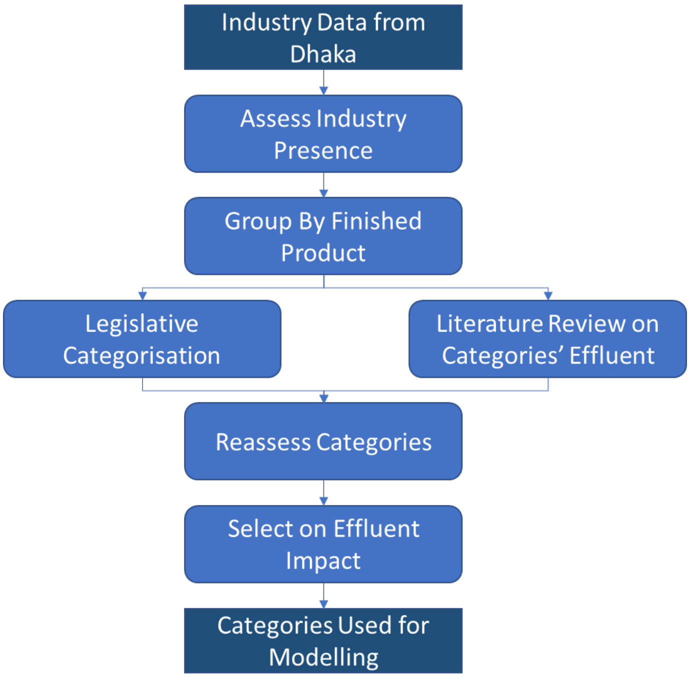

*Figure 6 Flow diagram showing the process used for classification of industries into categories, and refinement processes.*

## 3.3. Substance Selection

The selection of the substances was made after analysis of literature availability and prevalence in industrial wastewater for the selected industrial categories. A database based on literature concentration data in industrial effluent was created. As this resulted in a large database it was further narrowed down to the selected substances by their potential impacts on human and environmental health. The impacts on human and environmental health were investigated by literature review. Each of the categories for the industries resulted in concentrations of each of the six selected substances in untreated effluent.

## 3.4. Calculations

The database created by CEGIS contained some information about wastewater production by each of the individual industries. The wastewater production required validation against literature data, which required another literature review. Based on this validation either the data was used, and data gaps filled based on literature data. Each of the industries in the selected area were allocated their own wastewater production quantity. The wastewater quantities could then also be combined with the substance concentrations to assess where the six selected substances are released and to what magnitude.

Quantum GIS (QGIS), which is a geographic information system software, was used to ensure that the data received from the industries fell within the boundaries for the industry data from CEGIS. By mapping the selected industries and the boundaries outlined for the project outliers could be removed. The industry locations could then also be combined with locations of sub-catchments in the area to assess the points where outfall from the sub-catchments enter the waterways. The sub-catchment outfalls aid in understanding where the substance load release from each of the individual industries can be summed per catchment to better understand fate of substances.

## 3.5. Modelling

The presence and location of pollution hot spots was estimated by utilising an emissions model (D-Emissions). A deterministic emission model is one way to estimate the substance release based on the load emission from the source and estimate the quantity reaching the monitoring location. Models have the advantage over monitoring in that they can present a continuous spatial estimate for the substance load distribution. Where data is lacking, modelling assumptions can be used to fill gaps of which the impact can be gauged by comparison with in field monitoring data. These assumptions are often required as in a deterministic emission modelling study, measurements of (industrial) wastewater treatment plants and pollutants released are often non-existent or unattainable. In addition, deterministic models allow for system understanding, enabling the user to perform scenario analysis.

D-Emissions was developed by Deltares in the European project SOLUTIONS and applied for Europe to estimate presence of pharmaceuticals in rivers (Lindim, Gils and Cousins, 2016), using data from consumption rates, metabolic rates at wastewater treatment rates to estimate emissions. A similar method was used to assess the presence of microplastics in the Seine catchment from tire and road wear particles (Unice et al., 2019).

D-Emissions was amended for Dhaka in a collaboration between IWM, CEGIS and Deltares. This catchment-based model provides an overview of spatial distributed emission input to surface water. The social-economic factors that affect the outcome of the D-Emission model are the industry's location, type and a measure of production size and water management systems in use. This model could then be of further input to a conventional water quality model, like D-Water Quality, that considers processes like advection, diffusion, sedimentation, resuspension and in-river degradation.

The input required for the model to run was the location and category type of industries, their wastewater production and the concentration of each of the substances within its wastewater. The study area in Dhaka was divided up into a grid for this project, so the locations of the industries were matched to segment numbers via QGIS. The segments have a resolution of 500 by 500 metres, and the industries that fall within this segment number are aggregated. The resulting data then reflected the amount of wastewater per category that was released by which specific segment number.

The model also has various layers, which also have their individual numbers (Figure 7). In this thesis only the stormwater layer is considered, and the other layers omitted. As can be seen in Figure 7, the only exchange this has is directly into surface water. The assumption that all industrial wastewater enters surface water from stormwater is based on field observations. The assumption that all industrial wastewater goes to the stormwater layer has the implication that the decay rate in the paved and unpaved layer are omitted. Infiltration into the subsurface and erosion are also assumed to not occur. This means that the load of substances produced by the industries is assumed to go into surface water unchanged.

The model run produces the amount of load for each substance in grams per second per segment. As Dhaka was split into sub-catchments by elevation (Figure 4), the location data for the segments and sub-catchments were joined so that the load per sub-catchment was calculated. The outfall locations of each of these sub-catchments was also available, so the load was also calculated via QGIS at each of the outfall locations. By obtaining the load per outfall location it was estimated at which point the load enters the surface water. The resulting load per outfall location could then be exported as a map or as a database. The model simulates substance load over the course of 2 days to speed up the process. As only the effluent is modelled and none of the travel of the substances in the waterways, this does not need to be considered with the results.

In addition to the previously mentioned assumptions it is also assumed that all industries within a category have the same concentration of substances in their wastewater. The concentration of substances in wastewater cannot be altered for individual industries. Each industry does, however, have its own input data for wastewater quantity. The only source of the substances considered is industrial, so any other sources such as domestic waste and agricultural runoff are not considered.

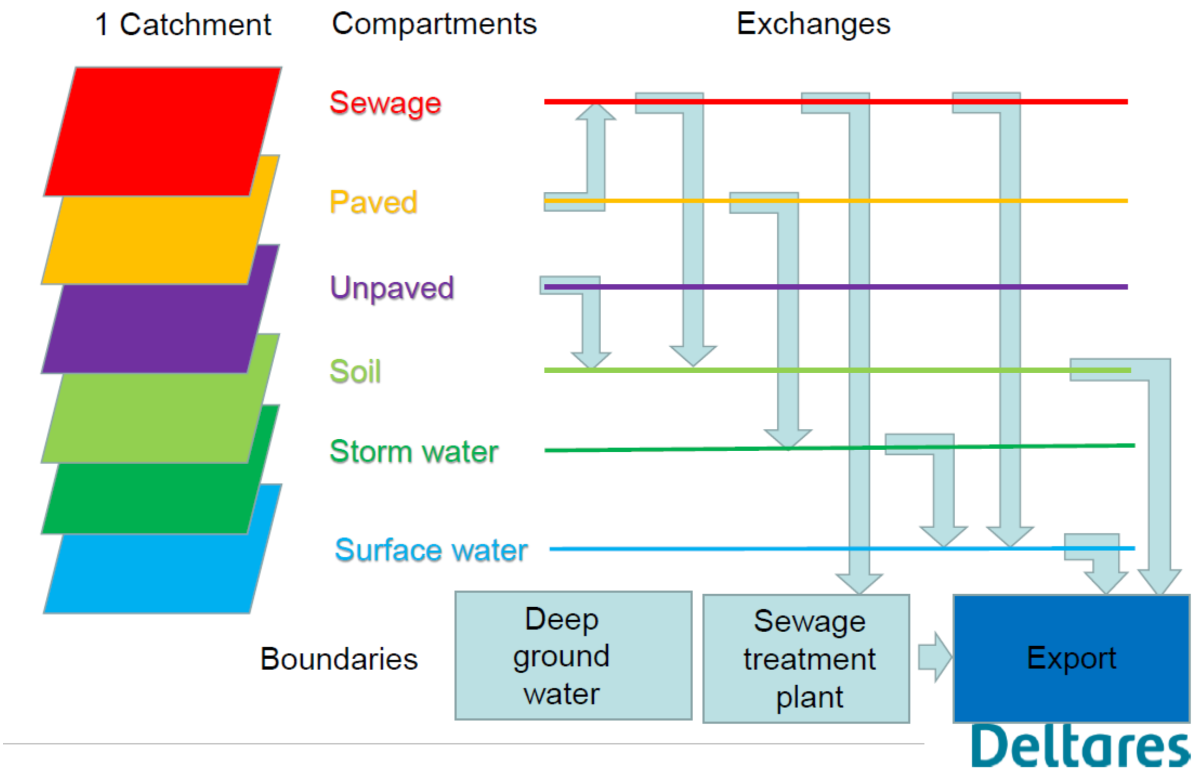

*Figure 7: Diagram showing the various compartments in the emissions model and the exchanges each layer has with regards to their substance load. Although these layers are all used in the model, in the case of this thesis only the storm water layer is considered. This storm water compartment only has an exchange with surface water, meaning that all the water directly runs off into the surface water.*

## 3.6. Validation/Calibration

First the goals of the model were outlined, which were to define where loads enter the waterways based on the sub-catchments and their outfalls from the digital elevation map from WFLOW. The resulting outflow was also quantified with regards to load on the model, to assess the quantity of the substances is typically emitted by industries. The combination of both the location and substance load allow for simulating the pollution hot spots locations. From the modelled load data, the categories that are most responsible for water pollution can also be seen.

As the monitored substance concentration data for Dhaka’s waterways is limited, an additional step is required in order to assess the validity data. The available data are simulated discharge data as provided by IWM ranging from 2006 to 2008. Deltares has concentration data for various locations in the catchment. The load was calculated using the concentration and discharge data. As the discharge data is simulated, it required validation with the schematic map of the river basin previously shown in Figure 3.

The concepts of the validation were the substance and water balance. Based on the schematic map of the river and the measuring points the loads at various points on the map could be calculated for the area. The modelled load could then be compared, by subtracting the load entering and leaving the whole catchment and comparing this to the load generated by industries between these two locations according to the model. The concept of this is outlined in Figure 8. Essentially as there is no other input into the rivers by the model other than industries, the load difference in and out of the catchment should only be the industrial effluent load. This same concept was then used over river stretches using the same method. By comparing the modelled load to the measured load, the model can be validated and calibrated.

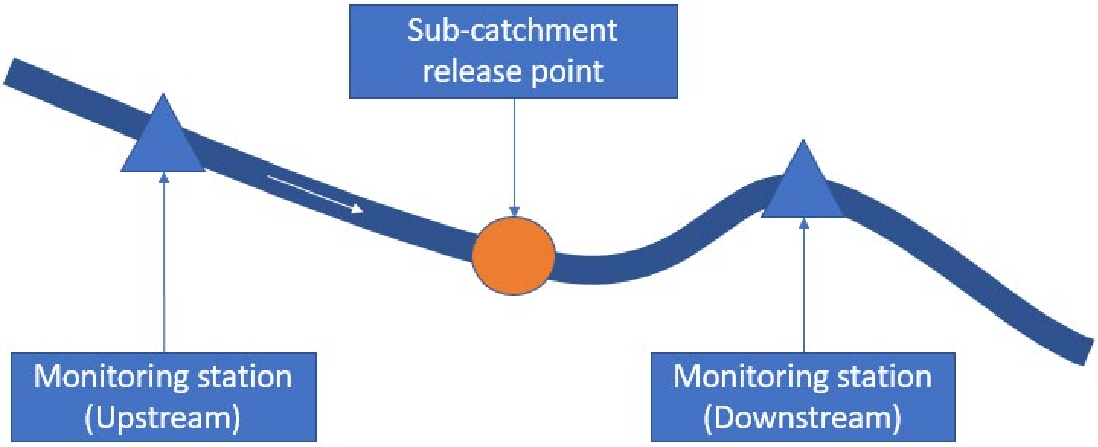

*Figure 8 Diagram showing method of point calibration in the waterways in Dhaka. The sub-catchment release point is a point where modelled data leaves a sub-catchment. The monitoring stations are spread catchment wide, and substance concentration data has been monitored at these points by Deltares. Discharge data is also available from literature (here shown as the white arrow) in m3/s. The data available from the monitoring stations is in mg/l. The substance data at the release point is in g/s. By multiplying the substance data at the release point by the discharge the load is calculated. The modelled load is then compared to the difference between the upstream and downstream modelled data.*

## 3.7. Scenario Analysis

By running this model, predictions can be made for certain scenarios. Scenarios allow for assessment of different policies or land use changes on emissions data. This information could then provide data for policy making and implementation. Using this emissions model allows for direct focus on the effects of industries on water quality, shifting away from existing data of substance concentrations from surface water quality alone. In order to assess the effects of adding industries to the WWTP network the model was run a second time. The WWTP removes between 30 and 40 percent of the substances roughly. A removal rate of 40 percent was assumed for modelling the effects of adding these industries onto the WWTP. The selection of industries that would be services by the WWTP was made by location, simulating the effects of water treatment on the substance loads. The modelled load output could be compared, to assess the difference on a catchment scale.

# 4. Results

## 4.1. Categorization by Data

The field observations by CEGIS provided information on about 17,080 individual industries. Each industry in the target area came with information such as the address, industry name, industry type as per governmental rulings, finished product, what raw materials are used, information about waste disposal, whether the industry is operational and the coordinates. Due to the variety of different industries, these needed to be categorised in order to model. The industries that were listed as non-functional on the CEGIS database were removed from analysis.

## 4.2. Legislative Categorization

The ECR originated in 1997 to aid in implementation of the Environment Conservation Act, 1995. The act aims to conserve the natural environment by maintaining environmental standards. The ECR contains rulings about the categorization of industries by their levels of pollution. Pollution can mean air, water, noise or solid pollution. Environmental clearance needs to be given for each type of industry and project in the region. Industries are separated into Green, Orange-A, Orange-B and Red industries dependent on their pollution levels. The red category is the worst polluting category, and green the least. Certain industries automatically fit within these categories, as seen in Table 2. Industries can also be moved up or down a category dependent on their financial income and physical size. The decision was made to only consider Orange B and Red category industries due to their significant role in water pollution.

*Table 2: Categories as defined by the Environmental Conservation Act, showing the requirements for each of the categories and examples of the types of industries that typically fit into the categories.*

| **Categories** | **Requirements** | **Examples of types of industry** |
|---|---|---|
| Green | Forms and fees for ECR<br>Information about project/industrial site<br>Information on product and raw materials<br>Location in commercial zones | Electronic goods<br>Toy manufacturers<br>Vehicles<br>Medical instruments |
| Orange A (or KA) | Same as green category<br>More information on process, labour and ETP arrangement required | Salt production sites<br>Artificial leather<br>Saw mills<br>Agricultural machinery |
| Orange B (or KHA) | As above but with additional information about the environmental management plan, emergency plan for pollution as well as more information about ETP process | Food processing<br>Water purification plants<br>Soap production<br>Refrigeration repairs |
| Red | Same as for Orange B, but needs more information on environmental compliance terms of reference for an environmental impact assessment report | Fabric dyeing<br>Power plants<br>Tanneries |

## 4.3. Categorization by Final Product

Initial separation based on raw materials and final product resulted in 33 different categories. However, tweaking was required using the information taken from further literature review. Initial separation of the industries in Bangladesh is shown in Figure 9. Over half of the industries listed in the CEGIS data are textile industries, whereas the other categories are much smaller in number.

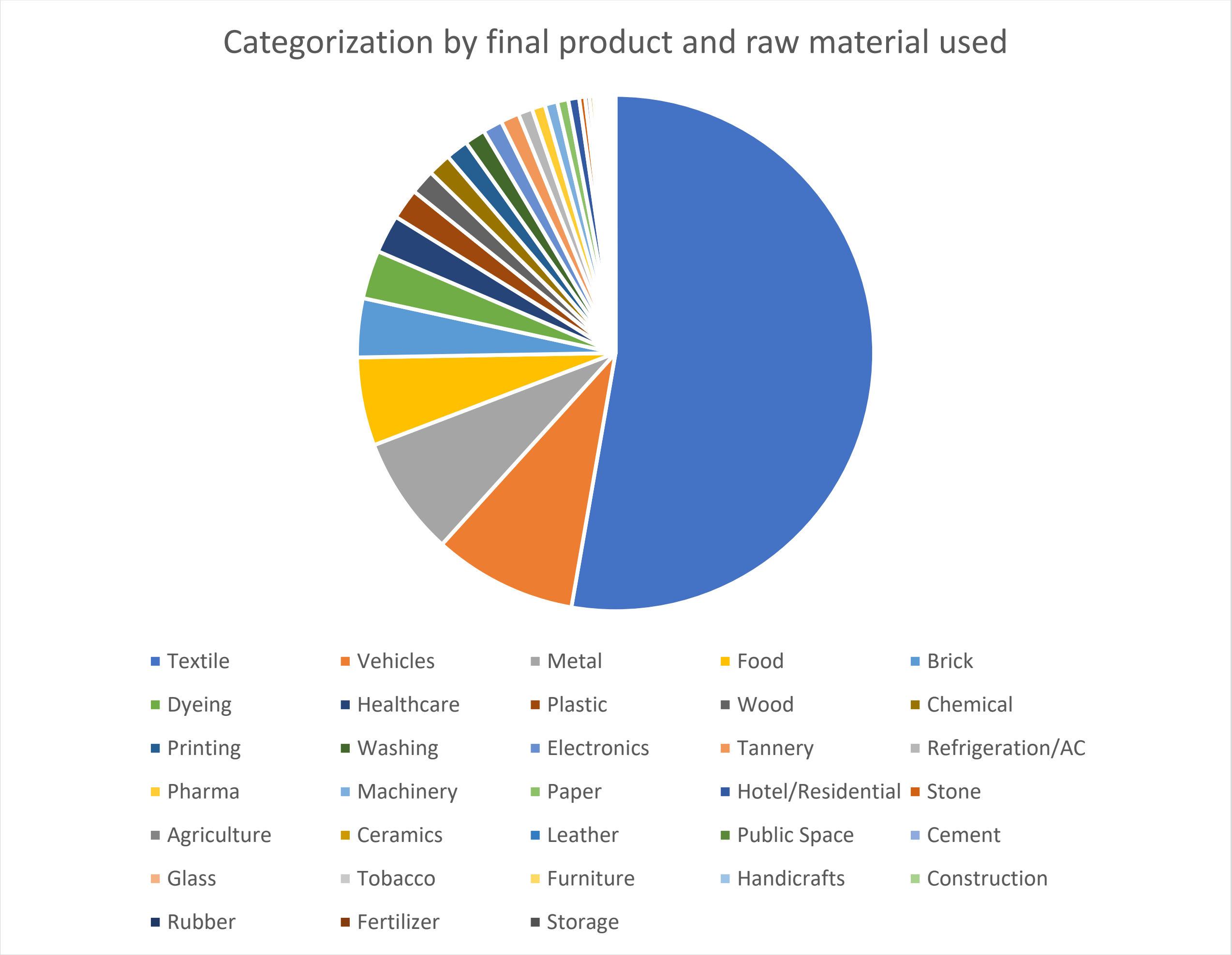

*Figure 9 Initial breakdown of CEGIS data for industries in Dhaka. The categories are separated based on the final product from each of the industries. The pie chart shows the share of the total number of industries each of the initial categories have, which were split initially on raw materials used and final product produced of each of the industries.*

Due to the small quantity of industries, or typically low impact of wastewater, some of these categories are outside of scope for this project. Some of the industries were removed as they aren't defined as industrial, such as healthcare. The resulting categories were selected for further analysis. As the textile industry has many subcategories it was important to specifically review this categorization again for more accurate emission modelling results.

## 4.4. Categorization by Wastewater Quality

Further literature review was needed for categorization of the industries by wastewater impacts. There are different processes within each of the industrial categories, so further investigation was required to assess whether these needed their own categories. Further changes were made to the categories based on the comparison of wastewater characteristics, such as BOD and COD levels, substance presence and effluent quantity.

### 4.4.1. Chemicals

There is much variety within the chemical category. Principal products produced within this category consist of adhesives, minerals, pesticides, cosmetics, soaps and softeners. From a cursory literature review it is impossible to characterise the wastewater that comes from "chemical industries" as a category containing all these subcategories. Typical effluent from some of the chemical subcategories are shown in Table 3, which are also the largest in number in the chemical industries as originally selected from the CEGIS data.

*Table 3: Wastewater quality characteristics from different types of industry within the chemicals category*

| **Type of Industry** | **Characteristics** | **Reference** |
|---|---|---|
| Pesticides | Varied COD and BOD, volatile inorganics, halomethanes, phenols, heavy metals, traces of final product | (Goodwin et al., 2017) |
| Cosmetics | High COD, BOD, TOC, petroleum ether, suspended solids, fats, oils, detergents | (Melo et al., 2013; Naumczyk et al., 2017) |
| Adhesives | High BOD, COD, TDS, (Total Suspended Solids) TSS and oil and grease | (Hassan & Ramadan, 1999) |
| Paint Manufacturing | High BOD, COD, TSS, toxic compounds, Heavy metals, colour | (Aboulhassan et al., 2014; Jolly et al., 2012) |
| Soap/Detergent (like cosmetics) | High COD values, preservatives, dyes, fragrances and cosolvents | (Martins et al., 2011) |

### 4.4.2. Food

There were many different types of food and beverage processing sites listed in the CEGIS data, which were difficult to split into categories based on raw materials and final products. Many industries in the region also combine different types of food processing. The CEGIS data (Figure 10) illustrates that there are many subcategories within food, of which many are too low in industry number to model. From literature, a selection of different specific products was made also based on the data provided from field observations (Table 4) to show the different characteristics of wastewater from some of the more polluting subcategories.

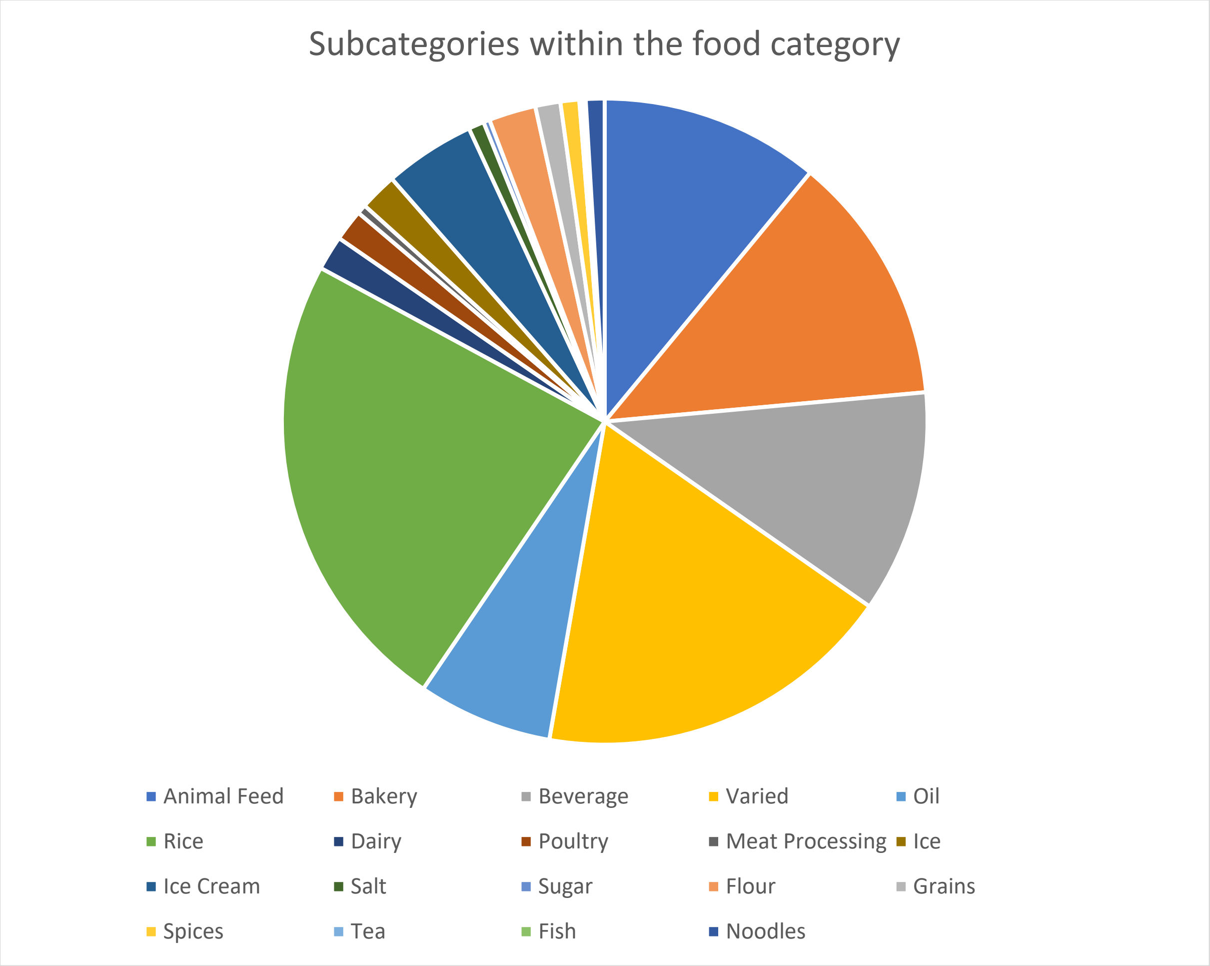

*Figure 10 Pie chart showing the subcategories within the category food in the CEGIS data. The pie chart shows the share of the number of industries each of the subcategories have for the food category.*

*Table 4: Table showing the typical wastewater characteristics and contents from different types of industries from literature review.*

| **Type of Industry** | **Characteristics** | **Reference** |
|---|---|---|
| Palm Oil | High BOD, COD, Solids, total fats, low pH | (Muralikrishna & Manickam, 2017) |
| Dairy | Dissolved organic matter (protein, fat, lactose) | (Muralikrishna & Manickam, 2017) |
| Meat and Poultry Products | Dissolved and suspended organic matter (proteins and fats) | (Muralikrishna & Manickam, 2017) |
| Fish | High BOD, suspended solid, high chloride | (Muralikrishna & Manickam, 2017) |
| Sugar | High BOD, high ammonia content, sulphates, phosphates, fluorides, urea, amines, methanol, hydrogen sulphide | (Muralikrishna & Manickam, 2017; Rasul et al., 2006) |

### 4.4.3. Leather

Generally, the leather industry’s water pollution is largely due to its beam house and tannery operations and the wastewater produced is characterised by a high COD, BOD and Total Dissolved Solids (TDS). Typical tannery wastewater also contains the heavy metal chromium (III) or phenolics such as tannins, dependent on their type of tanning. Bangladesh’s leather industry is mostly (95%) chromium tanning, so it would be assumed that all Dhaka’s tanneries also utilise chromium (III) rather than vegetable tanning. Visually the effluent also has a dark brown colour and a strong odour (Dixit et al., 2015). Further information about what kind of effluent comes from what kind of process is shown in Figure 11. Due to the difference in tannery effluent and the separation of beam house and tannery according to CEGIS data, tanneries were made a separate category from leather finishing.

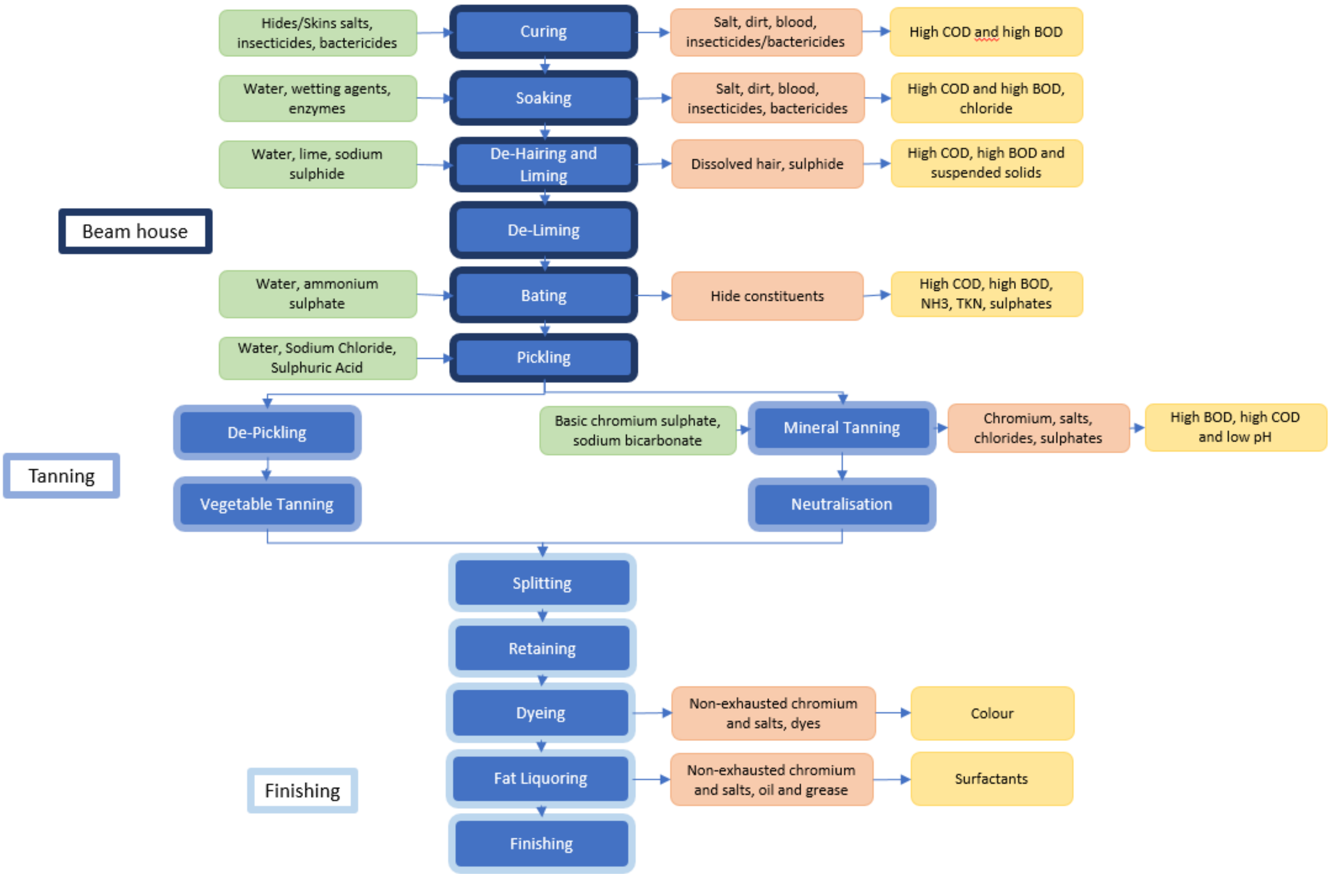

*Figure 11 Process diagram for different stages of leather production, showing the input (green), output (orange) and typical effluent characteristics (yellow) from each process (blue). This figure was amended from information from* (A. Hoque & Clarke, 2013)

### 4.4.4. Metal

Upon further research into the more polluting processes in the metal category such as smelting industries, it was found that most of Bangladesh’s polluting metal industries are based in Chittagong, outside of the study area, due to its proximity to the coast. The metal industries in Dhaka are mostly industries such as metal rollers and finishers, which do not typically emit much wastewater. The metal industry was, for this reason, removed from further analysis.

### 4.4.5. Paper

The processes, wastewater characteristics and materials used in the paper industry are shown in Figure 12. Effluent from pulping facilities has high values of BOD, COD and chlorinated chemicals (Hubbe et al., 2016). The bleaching stage produces chlorine, acid residues, bleach and fillers in the effluent from paper mills (Hoque & Clarke, 2013). Over half of the industries in the paper category convert and print paper, rather than produce paper in a paper mill. Paper mills are the most polluting within the paper industry, where the extraction, de-inking, pulping and bleaching occur. Paper mills are also found separate from finishing processes. Due to their large wastewater quantity and effluent quality only the paper mills were selected for modelling.

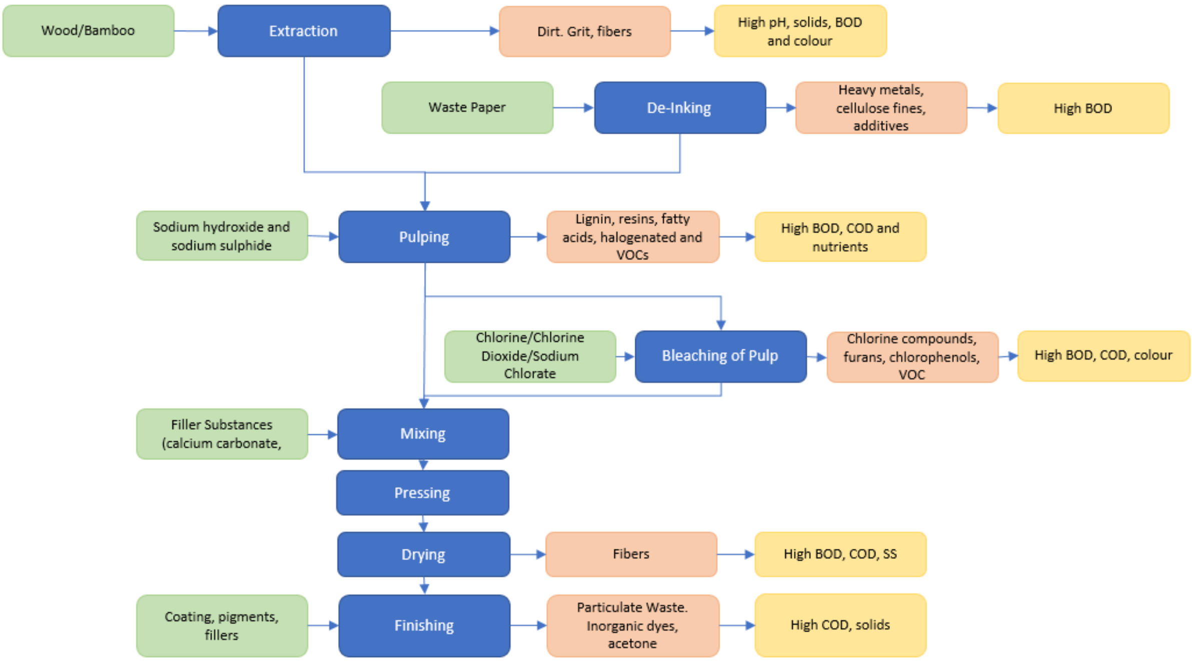

*Figure 12 Process diagram for paper industry showing the input (green), output (orange) and typical effluent characteristics (yellow) from each process (blue). Figure amended from information by* (A. Hoque & Clarke, 2013)

### 4.4.6. Textile

The textile industry is the largest industrial sector in Dhaka. There are different processes within the sector which emit different kinds of effluent. An indication of the difference between effluent characteristics for some of the processes is shown in Figure 13. Generally, the overall process is split into wet and dry steps (Dey & Islam, 2015). The CEGIS data showed that the textile processes are also often spatially separated in Dhaka. Based on the CEGIS data there is also a separation of washing of clothing between stages, which also has its own typical wastewater production. Washing typically takes place between each of the steps, however was omitted from Figure 13 for clarity. Dyeing, printing and washing are typically found separate from other industries based on the CEGIS data and have therefore been selected as categories to investigate further. The remaining industries remain as "textile" for further analysis.

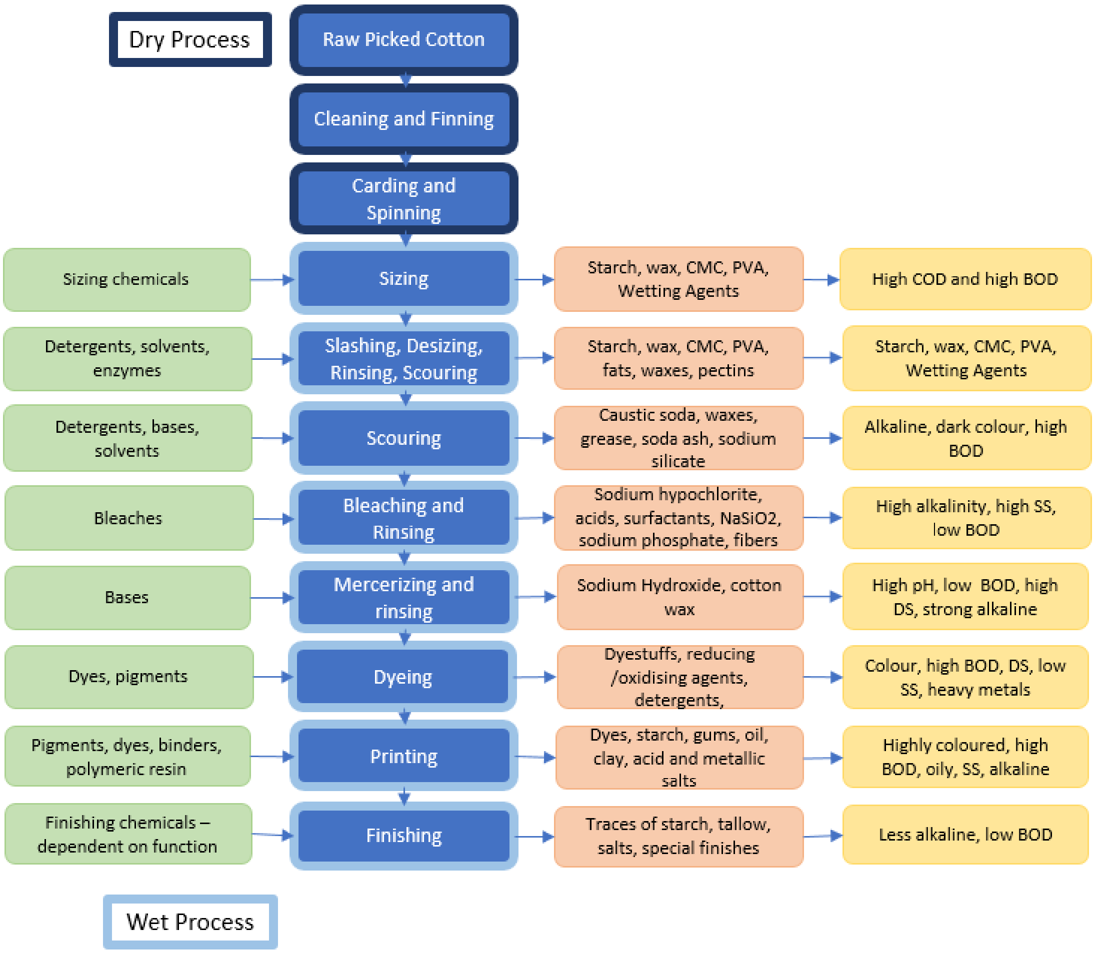

*Figure 13: Process diagram showing the difference in input (green), output (orange) and wastewater characteristics (yellow) for each of the steps (blue) in the textile industry. The figure was amended from process diagrams by* (Dey & Islam, 2015; Mia et al., 2019)

## 4.5. Categorization by Wastewater Quantity

The average and median wastewater quantity of each of the categories is presented in Table 5. There were very large differences between the median and mean values, due to the vast differences in amounts of wastewater produced by each of the categories (Table 5). Many of the industries had very low values for wastewater production in the CEGIS data, with few industries having significantly larger wastewater production. Due to the few extremely high values for wastewater production and many small values for wastewater production (Poisson distribution), the median was used for further analysis. Using the mean value would lead to an overestimation of wastewater production for the industries with data gaps. The CEGIS wastewater data was incomplete and some data was significantly different from literature values. To assess the validity of the wastewater data, and to fill in gaps in the data, validation of data was required. First, where available, the quantity of production was compared to the quantity of wastewater emitted per industry to see whether there was a correlation between an increase in production and the wastewater emission. Some errors could also have been made in data collection as some data was unrealistic, such as no wastewater production for a dyeing industry. The use of median values for data gaps, rather than measured wastewater production, increases the level of uncertainty of the model and could lead to an under or over estimation of the amount of wastewater produced per industry.

*Table 5: Comparison of the wastewater production prior to validation of wastewater production from CEGIS to literature data. Due to the amount of zero values for wastewater production for industries, and it being unlikely that this is the case, the mean and median were also calculated for the data omitting these values.*

| Category | Mean wastewater production ($m^3$/day/site) | | Median wastewater production ($m^3$/day/site) | |
|---|---|---|---|---|
| | **Including 0 values** | **No 0 values** | **Including 0 values** | **No 0 values** |
| **Chemical** | 17.80 | - | 0.10 | - |
| **Dyeing** | 350.72 | 363.77 | 1.66 | 2.00 |
| **Food** | 649.87 | 895.38 | 0.05 | 0.25 |
| **Leather** | 0.44 | 1.10 | 0.00 | 1.10 |
| **Paper Mills** | 32.39 | 36.44 | 1.5 | 5.75 |
| **Printing** | 22.76 | 24.39 | 0.23 | 0.28 |
| **Tanneries** | 8.01 | 9.37 | 1.00 | 1.20 |
| **Textile** | 96.72 | 298.96 | 0.00 | 0.20 |
| **Washing** | 76.75 | 81.77 | 1.50 | 1.70 |
| **Metal** | 3.05 | 10.68 | 0.00 | 0.45 |

### 4.5.1. Chemicals

The difference between wastewater production of chemical sub-categories became clear with literature review, as seen in Table 6. No literature was found on chemical industry as an overarching category and therefore subcategories were selected for further analysis. As the subcategories were small, only the two largest categories, cosmetics and detergents, and chemical processes were selected for further literature review. Very little information was available about the wastewater production per amount of product or raw materials used for each sub-category. Because of lack of data and due to the low quantities of wastewater produced according to the CEGIS data the chemical category was removed from further analysis.

*Table 6 Compilation of data for wastewater quantity found in literature data either for the water demand of the industry or for the excess water. The data can either be general for the industry type, or site-specific data as indicated by yes (Y) and no (N).*

| Industry type | Water demand | Unit | Water excess | Unit | Country | General | Reference |
|---|---|---|---|---|---|---|---|
| **Fertilizers** | 15 | $m^3$/ton of product | | | India | Y | (Van Rooijen et al., 2009) |
| **Chemicals Production Facility** | | | 8 | $m^3$/day | Bangladesh | N | (Sarker & Sarkar, 2018) |
| **Paint Production Facility** | | | 120 | $m^3$/day | Bangladesh | N | (Sarker & Sarkar, 2018) |
| **Chemical Industry** | 41.17 | $m^3$/day | 18.33 | $m^3$/day | Vietnam | N | (Thuy et al., 2016) |
| **Cosmetic** | 13.5 | $m^3$/day | 6 | $m^3$/day | Vietnam | N | (Thuy et al., 2016) |

### 4.5.2. Food

Like the chemical industry, the food industry has many subcategories. The available data from CEGIS was further investigated, as there was no literature data on wastewater production for food as an overarching category. When considering the available wastewater data from CEGIS, only edible oil was of note due to the wastewater quantity produced. No literature data was available for the wastewater quantity produced for the edible oil industry in Bangladesh. Additionally, the amount of industries in these categories were not numerous.

### 4.5.3. Leather

The leather category, when omitting the tanning process, generally has very low amounts of wastewater production. Literature data also focuses largely on the tannery and beam house processes, and no literature data was found for the remainder of the leather industry.

#### *4.5.3.1. Tanneries*

The wastewater production in tanneries is well studied in Bangladesh. However, when looking at the production of leather by tanneries in Dhaka it is difficult to compare literature data due to the use of "number" as a unit from CEGIS data.  As there is no indication as to what unit number refers to it was not possible to convert the number without data on the type of product. It is possible that this refers to hides, but there is significant difference between different hides produced in the tanneries industry. The wastewater production is directly proportional to the weight of wet hide in literature data, which is a raw material rather than the product in tanneries. For this reason, the quantity of raw materials was used for literature comparison in tanneries, with information about chemical use added to assess the credibility of the CEGIS data (see Appendix Figure A-1). Dixit et al. (2015) stated that the minimum and maximum wastewater production per ton of raw hide were 17.5 and 23.5 $m^3$ respectively. It is assumed that 452 kg of chemicals are used in turning one ton of raw hides into finished product (L. Hossain & Khan, 2017). The addition of chemicals is important as in this case the weight of raw materials is used to estimate wastewater production, which contains both the hides and the quantity of chemicals used. This is different from other categories, for which the final product was used to estimate wastewater production. The minimum and maximum literature values were used to remove any unrealistic CEGIS data.

### 4.5.4. Paper Mills

Paper mills are known for their large water usage and wastewater excess, making them important for wastewater modelling in Dhaka. The literature data against which the CEGIS wastewater was compared can be found in Table 7. The upper and lower boundaries used were taken from the paper by Rintala and Puhakka (2014). The correlation between the weight of paper manufactured and the amount of wastewater produced was poor (see Appendix Figure A-2).

*Table 7: Compilation of the literature data found for the typical wastewater production per product produced for paper mills. The data can either be general for the industry type, or site-specific data, here shown as general (yes or no).*

| Industry Type | Water Demand | Unit | Water Excess | Unit | Country | General (Y/N) | Reference |
|---|---|---|---|---|---|---|---|
| **Paper** | 30-180 | $m^3$/ ton of product | 20-70 | m3/ ton of product | Global | Y | (Rintala & Puhakka, 1994) |

### 4.5.5. Textile

Where possible a separation of different processes within the textile category was made using the CEGIS data, due to the differences in effluent quantity and quality between them. This was possible for dyeing, printing and washing. The remaining textile industries encompassed a variety of different processes. These were further separated into dry processes, such as embroidery and garment assembly, and wet processes based on raw materials listed in the CEGIS database. The wet processes were selected for further analysis. As the only wastewater quantity data for these processes was available for products with number as a unit rather than weight, a direct comparison with literature data could not be made. A conversion factor could not be applied for number as a unit, as the product ranged from suits to socks. More data would have been needed from the industries to get accurate numbers. For data where the daily weight of final production was available wastewater production of 120L/kg of final product was taken to fill in data gaps for wastewater production (Dey & Islam, 2015).

#### *4.5.5.1. Dyeing*

The literature data on wastewater production by the dyeing industry in Bangladesh is presented in Table 8. The data from CEGIS had a better correlation between weight of product and wastewater produced compared to the literature data than seen in the chemical category. For further analysis the lowest and highest boundaries (80 L/kg of product and 140 L/kg of product) were selected as the upper and lower boundaries for accepting CEGIS wastewater data for modelling (see Appendix Figure A-3).

*Table 8 Compilation of literature data concerning wastewater production by the dyeing industry in Bangladesh. The data can either be general for the industry type, or site-specific data, here shown as general (yes or no).*

| Industry Type | Water Excess | Unit | Country | General | Reference |
|---|---|---|---|---|---|
| **Dyeing (Yarn)** | 80 | L/kg product | Bangladesh | Y | (L. Hossain & Khan, 2017) |
| **Dyeing (Fabric Knit)** | 120 | L/kg product | Bangladesh | Y | (L. Hossain & Khan, 2017) |
| **Dyeing (Fabric Woven)** | 140 | L/kg product | Bangladesh | Y | (L. Hossain & Khan, 2017) |

#### *4.5.5.2. Printing*

The only literature available for the printing industry was in relation to a percentage of the total water excess from the textile industry. The printing industry produces about half the amount of wastewater compared to the dyeing industry (Ntuli et al., 2009). An average from the wastewater quantity data from the dyeing industry (Table 8) was 110 L/kg, half of which is 55 L/kg produced. (L. Hossain & Khan, 2017). 55L/kg was used to compare the CEGIS data to. None of the CEGIS wastewater data were close to this literature data for wastewater production (see Appendix Figure A-4).

#### *4.5.5.3. Washing*

From literature review it was not possible to find any data on the quantity of wastewater that comes from washing in Dhaka. Therefore, a median of the CEGIS data was taken and this was used to fill the gaps for the data points that did not have CEGIS data for wastewater. Any zero values were, however, removed as these are unrealistic for the washing industry.

## 4.6. Source and Substance Selection for Modelling

### 4.6.1. Sources

Categorization and analysis of industry number and wastewater quantity led to the removal of the categories leather, metal, food and chemicals. Removal of these categories was due to a lack of literature data, CEGIS wastewater data or size of industry in Dhaka. The categories selected for further modelling are presented in Table 9, which also shows the final median wastewater quantity used to fill in data gaps for wastewater quantity (see Appendix Figure A-5).

*Table 9: The selected categories for modelling and their median wastewater quantity excluding the unrealistic values that fall either too high or too low compared to literature data. The values that fall outside of the literature data were replaced with other values dependent on data available. The median value was selected over the mean value due to the wastewater data having a Poisson distribution, rather than normal distribution.*

| **Category** | **Final median wastewater quantity ($m^3$/day) per industrial facility** |
|---|---|
| Dyeing | 1200 |
| Paper Mills | 340 |
| Printing | 0.30 |
| Tanneries | 3.00 |
| Textile | 0.20 |
| Washing | 1.70 |

### 4.6.2. Substances

A database was collated for different industries and the concentrations of the selected substances within their effluent. The data for this database came from Bangladesh based literature, or from neighbouring countries when data from Bangladesh was unavailable in literature. The concentration database was used for selection of parameters with concentrations established in literature, which could be used for emission modelling. Selection of the six substances from the database of concentrations was made subsequently on implications with human and ecological impacts. The selected parameters are arsenic, cadmium, chlorine, nitrate, sulphate and tannins.

#### *4.6.2.1. Arsenic*

Arsenic is found in groundwater in Bangladesh but is also added to surface water by industries. Arsenic has many different in- and uptake pathways, like cadmium, which range from direct ingestion through drinking water to inhaling particles and ingesting contaminated foods. Ingestion can affect the central nervous system and cause cancers (M. F. Hossain, 2006). Arsenic concentrations for the industrial categories are presented in Table 10.

*Table 10: Compilation of arsenic concentrations found in literature in the wastewater from the selected industrial categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment. This is the case for all apart from the concentration in the effluent from the washing industry (bold).*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Dyeing** | 9.0 | Bangladesh | (Islam et al., 2016) |
| **Paper Mills** | 3.5 | Bangladesh | (Islam et al., 2016) |
| **Tanneries** | 16 | Bangladesh | (Islam et al., 2016) |
| **Textile** | 4.5 | Bangladesh | (Islam et al., 2016) |
| **Washing** | **0.002** | Pakistan | (Hussain & Khan, 2003) |

### 4.6.3. Cadmium

Heavy metals can be toxic, some even at low concentrations. As heavy metals cannot be broken down, they can also bioaccumulate. Cadmium is also present in wastewater from dyeing industries and tanneries (Zhou, 2003). Within Bangladesh cadmium concentrations in river water tend to be under the limits by Bangladesh and WHO standards. However, bioaccumulation of cadmium in agricultural products, may lead to adverse health effects locally (Hossain et al., 2019). Literature data about the concentration of cadmium found in the wastewater from each of the industries selected is presented in Table 11.

*Table 11: Compilation of cadmium concentrations found in literature in the wastewater from the selected categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment. This is the case for all apart from the concentration in the effluent from the washing industry (bold).*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Dyeing** | 4.7 | Bangladesh | (Islam et al., 2016) |
| **Paper Mills** | 1.75 | India | (Kumar et al., 2015) |
|  | 0.135 | India | (S. Singh et al., 2008) |
|  | 1.3 | Bangladesh | (Islam et al., 2016) |
| **Printing** | <0.005 | Slovenia | (Šostar-Turk et al., 2005) |
| **Tanneries** | 2.9 | Bangladesh | (Islam et al., 2016) |
| **Textile** | 0.08 | Bangladesh | (Islam et al., 2016) |
| **Washing** | **0.001** | Pakistan | (Hussain & Khan, 2003) |

#### 4.6.3.1. Chlorine

There are a variety of processes that release chlorine from industries, such as during bleaching of paper, clothing and leather. For this reason, it was expected to be found in large quantities in paper mill effluent. Details of concentration levels found in literature are presented in Table 12. Although chlorine is not toxic to humans at these levels, it does impact biotic integrity as it is toxic for aquatic life (Karr et al., 1985; Ward and DeGraeve, 1978).

*Table 12: Compilation of chlorine concentrations found in literature in the wastewater from the selected categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment.*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Paper Mills** | 341 | India | (Kumar et al., 2015) |
| **Printing** | 7.30 | India | (Mondal et al., 2013) |
| **Tanneries** | 1363 | Bangladesh | (Rouf et al., 2013) |
| **Textile** | 3500 | General | (R Ananthashankar, 2013) |
| **Washing** | 0.10 | Slovenia | (Šostar-Turk et al., 2005) |

### 4.6.3.2. Nitrate

An excess of nitrate can cause eutrophication and algal blooms, which can have severe impacts on river health. High levels nitrate can also cause issues for children and infants when ingested, such as stunt growth and blue baby syndrome (Ward et al., 2018). Data for nitrate concentrations in wastewater for the different categories is presented in Table 13.

*Table 13: Compilation of nitrate concentrations found in literature in the wastewater from the selected categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Dyeing, Printing and Washing** | 45 - 62 | India | (Husain et al., 2013) |
| **Paper Mills** | 33 | India | (S. Singh et al., 2008) |
| | 3.0 | India | (Nagasathya & Thajuddin, 2008) |
| **Textile** | 0.56 – 3.8 | Bangladesh | (Ali et al., 2017) |
| **Tanneries** | 66 | Bangladesh | (Saeed et al., 2012) |

### 4.6.3.3. Sulphate

Sulphate is discharged from mines, smelters, paper mills, textile mills and tanneries. It tends to bind with other substances such as metals. Like nitrate, sulphate is a nutrient and sulphate salts are typically reasonably soluble. At high concentrations sulphate is toxic to plants and animals and promotes nutrient release from sediment, resulting in eutrophication (Geurts et al., 2009). Literature data for sulphate is presented in Table 14.

*Table 14: Compilation of sulphate concentrations found in literature in the wastewater from the selected categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment.*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Dyeing, Printing and Washing** | 190 | India | (Husain et al., 2013) |
|  | 200 | India | (Husain et al., 2013) |
| *Median* | 195 |  |  |
| **Paper Mill** | 678 | India | (Kumar et al., 2015) |
|  | 217 | India | (Garg et al., 2005) |
|  | 22090 | India | (Singh et al., 2016) |
|  | 39 | India | (Nagasathya & Thajuddin, 2008) |
|  | 1430 | Bangladesh | (Garg et al., 2005) |
| *Median* | 678 |  |  |
| **Tanneries** | 286 | Bangladesh | (Rouf et al., 2013) |
| **Textile** | 800 | General | (R Ananthashankar, 2013) |

#### 4.6.3.4. Tannins

Tannins are found in effluent from the paper industry, forestry, plant medicines and textiles industries and leather industries from vegetable tanning. Tannins colour wastewater and are highly soluble in water. In Bangladesh 95% of tanneries use chrome tanning (Libralato et al., 2011; Temmink et al., 1989), so tannins are likely to come from paper mills. Concentration data is presented in Table 15 and was only found for the category paper mills. No literature data was found for tannins in textile wastewater.

*Table 15 Compilation of tannin concentrations found in literature in the wastewater from the selected categories. The location of the measurement taken is also shown. The concentrations are end of pipe and therefore the water has received no treatment*

| Industry | Concentration (mg/L) | Location | Reference |
|---|---|---|---|
| **Paper Mills** | 500 | India | (Vashi et al., 2019) |

### 4.6.4. Final Calculations Process

The process of filling in gaps in data, or replacing unrealistic CEGIS data, is outlined in Figure 14. There were significant differences in the data available from CEGIS and literature between the categories. With regards to literature values, CEGIS data is deemed unrealistic if it is half the value of the minimum literature data or double that of the maximum literature data based on the industry's production. Unrealistic data was removed and replaced with the median CEGIS wastewater quantity data that did fit between the literature values. The median CEGIS wastewater quantity is also used to fill the remaining data gaps. The wastewater quantity (as $m^3$/day) was then combined with the substance concentrations (mg/L) in the emissions model.

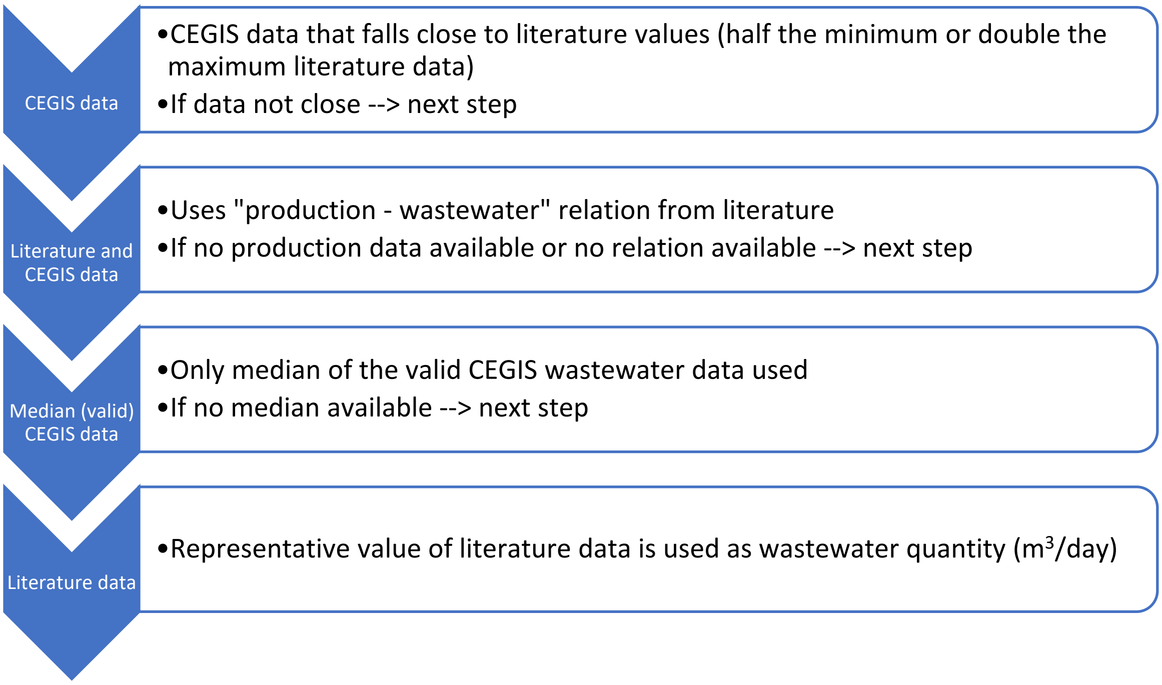

*Figure 14: Schematic process of the wastewater quantity validation from the CEGIS data and filling of data gaps for the wastewater quantity that industries in Dhaka produce.*

A summary of the substance concentrations used for the emissions is presented in Table 16. Like the handling of CEGIS data, there was also a selection process for concentration data. The preference went to data from untreated industrial effluent in Bangladesh. If untreated effluent substance concentrations were unavailable data from surrounding countries were selected. To increase validity of the data more data points were selected if available from India due to the similarities between countries in industrial processes. If this data was not available, then data was selected from other countries. Literature from effluent post-treatment was used if data was unavailable for untreated effluent. Where more concentration data was available a median value was used. If no data was found on concentration for the substance in literature, it was left blank. It is worth noting that leaving the concentration blank does not mean that this substance is not present in the wastewater for the categories, just that it has not been found in data.

*Table 16: Final selected substances used for emissions modelling and the respective concentrations emitted by each of the modelled industries based on literature data. A hyphen indicates that there is no literature data available on the substance and industry.*

| | **Arsenic (mg/L)** | **Chlorine (mg/L)** | **Cadmium (mg/L)** | **Nitrate (mg/L)** | **Sulphate (mg/L)** | **Tannins (mg/L)** |
|---|---|---|---|---|---|---|
| **Dyeing** | 9.0 | - | 4.70 | 15.7 | 195 | - |
| **Paper Mill** | 3.5 | 341 | 1.30 | 17.9 | 217 | 500 |
| **Printing** | - | - | 0.005 | 53.5 | 195 | - |
| **Tanneries** | 16 | 1363 | 2.90 | 40.1 | 286 | - |
| **Textile** | 4.5 | 3500 | 0.08 | 2.41 | 155 | - |
| **Washing** | 0.002 | 0.10 | 0.001 | 53.5 | 195 | - |

## 4.7. Results from Modelling

The results from the modelling show what load is produced by category and where. First an assessment was made as to what loads enter the catchments overall, which could be broken down per substance and per industrial category. The graphs shown in Figures 15-18 indicate the differences in the modelled substance load for each of the industrial categories. There are vast differences between the categories, as expected, as there is much variation between the concentration for the substances in each of the categories' wastewater and variation in the amount of wastewater produced by the industries as well as the number of industries. For the substances selected for modelling, dyeing and textile play the largest role by far for arsenic, cadmium, chlorine, nitrate and sulphate. Only paper mills were modelled to release tannins (18410 kg/day), and therefore no graph has been added for this substance.

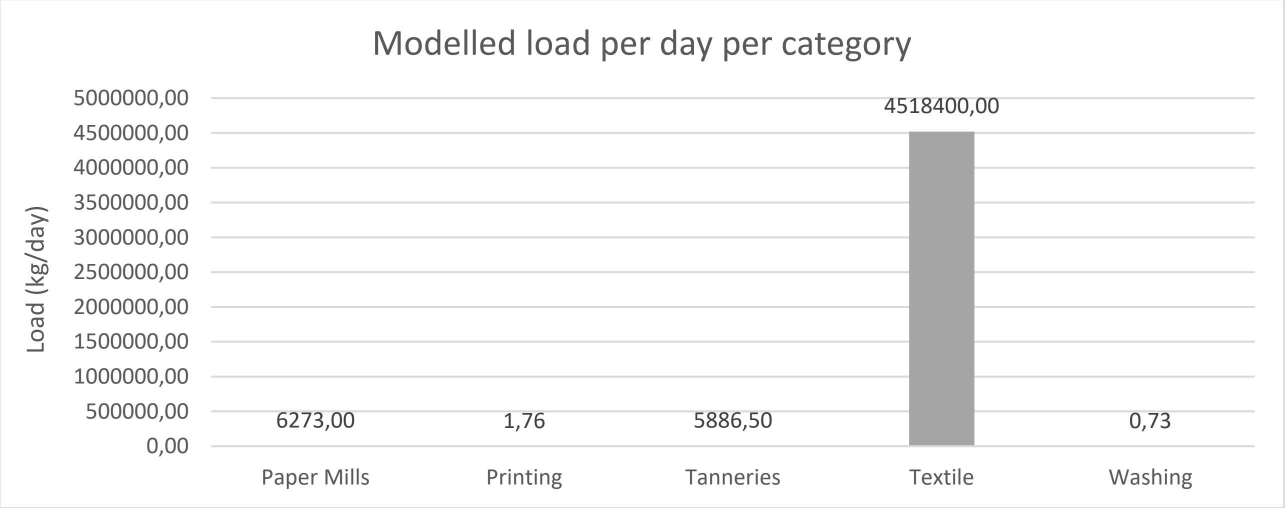

*Figure 15: Graph showing the chlorine load simulated per day by each of the industries in the study area.*

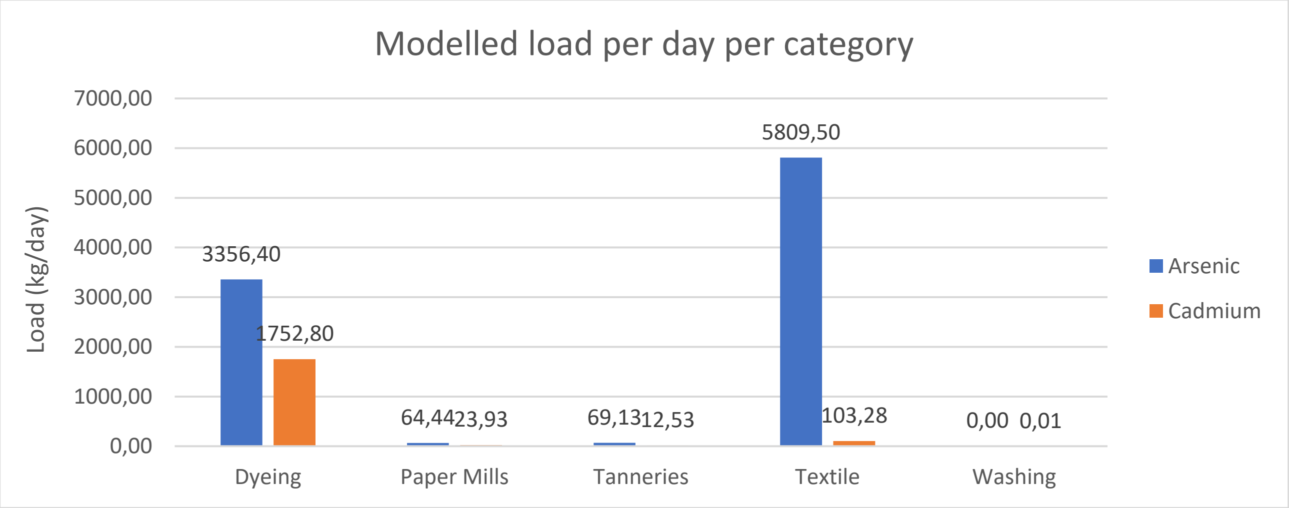

*Figure 16: Graph showing the arsenic and cadmium load simulated per day by each of the industries in the study area.*

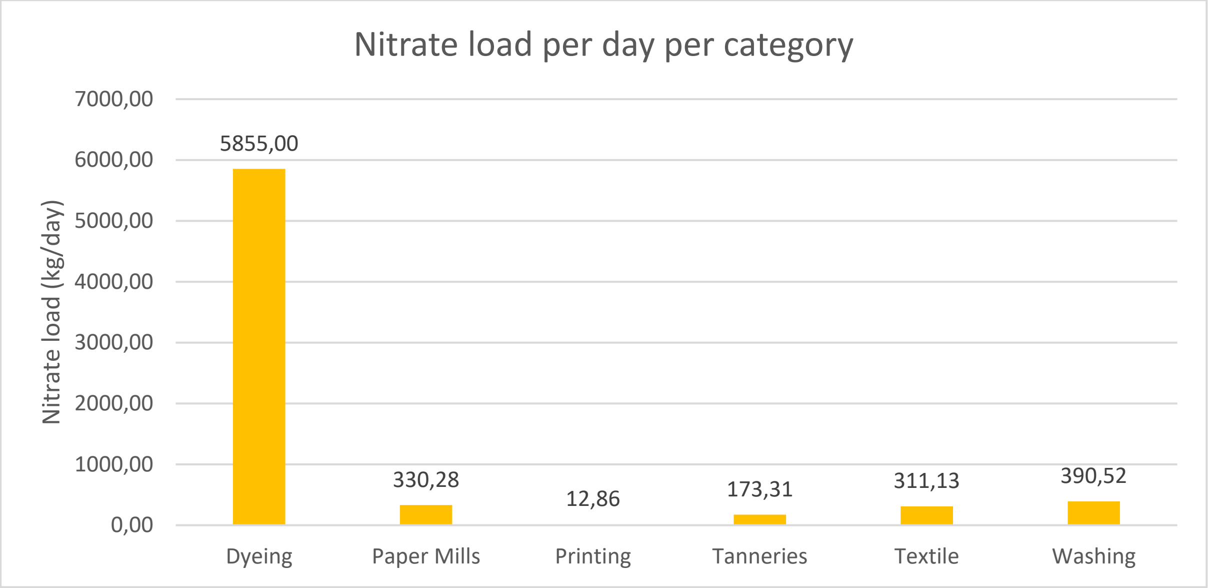

*Figure 17: Graph showing the nitrate load release simulated per day by each of the industries in the study area.*

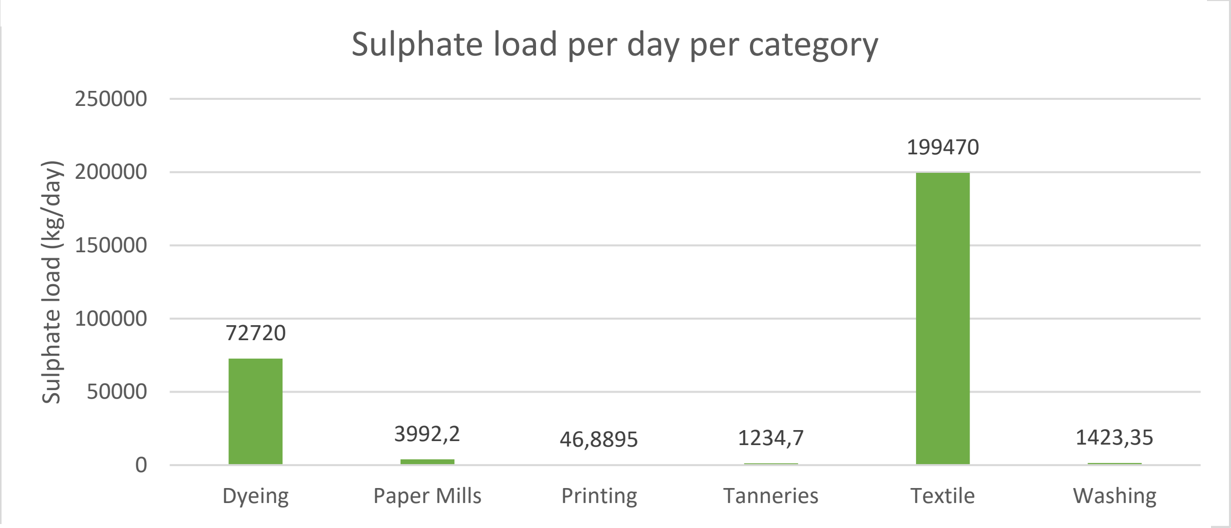

*Figure 18: Graph showing the sulphate load release simulated per day by each of the industries in the study area.*

Although it is of interest to assess which categories are responsible for what share of substance load added to the catchment, what is also important is the spatial spread of the substance load addition to the waterways. This is due to some rivers, such as the Meghna, being much larger and would be able to dilute more than other small periphery rivers. Spatial spread of load release into waterways is also important for policy analysis and highlights the pollution hot spots for each of the substances. The resulting substance loads were combined with the location of sub-catchments. Each of the sub-catchments have their own outlet point, a point at which the effluent released by that sub-catchment enters the waterways. The pollution hot spots, from the visualisation of the points of entry of the substances, can be seen (Figures 19-24). When comparing the load between the catchments there is an overlap between the different substances in location. For further analysis industrial zone locations were compared with the sub-catchments. The sub-catchments in which industries emitted arsenic, cadmium, chlorine, sulphate load were located where the industrial zones are present. This is logical, as clustered industries increase the wastewater quantity. Tannin load is less widespread, as literature data on substance concentration was only found for paper mills.

Comparing load data to locations of industrial effluent zones could show which industrial zones emit the most substances, which for arsenic, for example, seems to be the Tarabo industrial site (See Appendix Figure A-6). It also shows that there are catchments which have higher levels of substance loads, but do not have one of the main industrial zones there. Catchments that do not contain industrial zones could be host to a series of smaller industries which collectively produce enough wastewater to cause issues. This is also of importance as the smaller to medium industries are less likely to be on a central effluent treatment plant. By looking at these catchments and consequently at the outfall points of each of these catchments an estimation of the pollution hot spots was made.

### 4.7.1. Arsenic

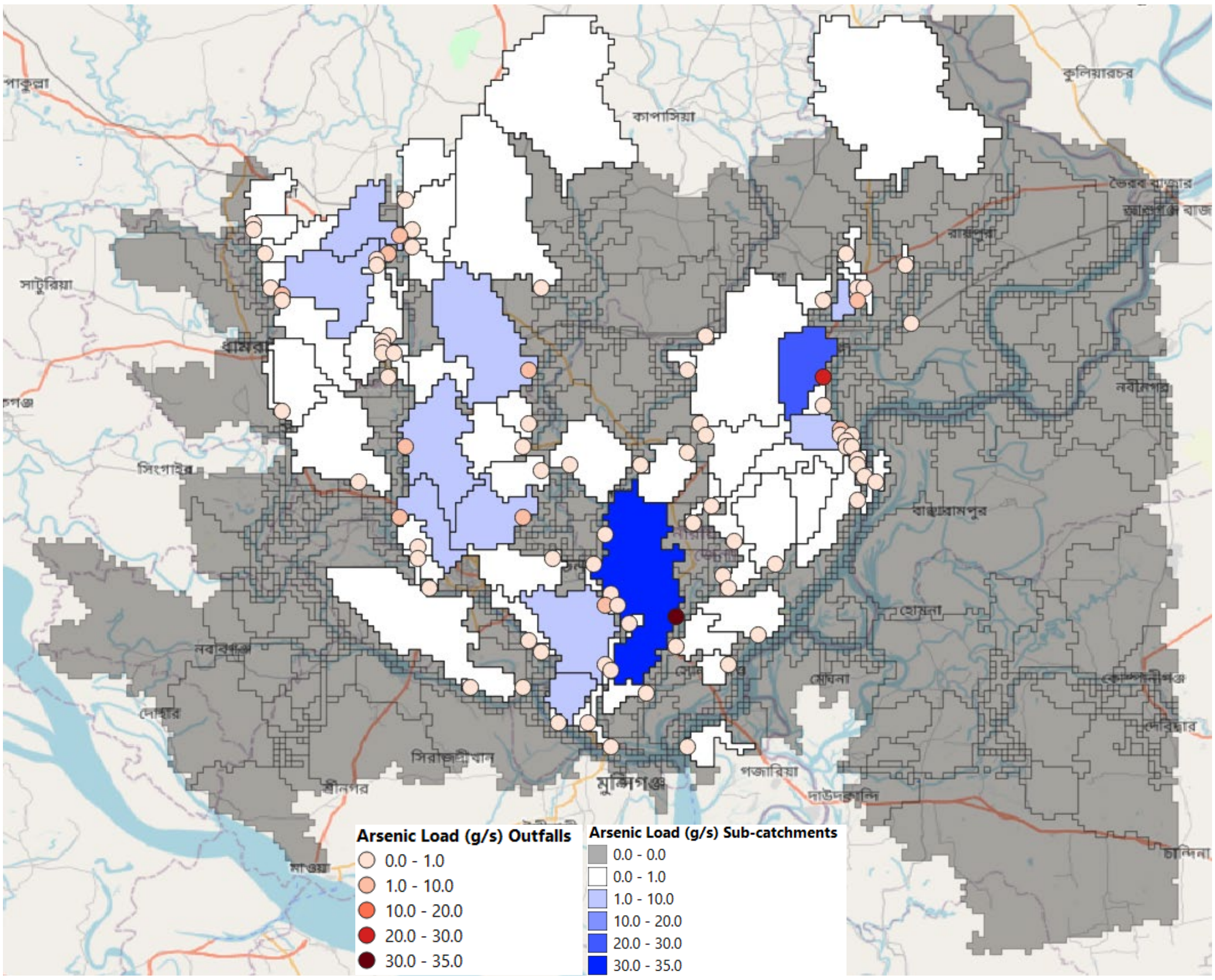

*Figure 19: Map showing the arsenic load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

### 4.7.2. Cadmium

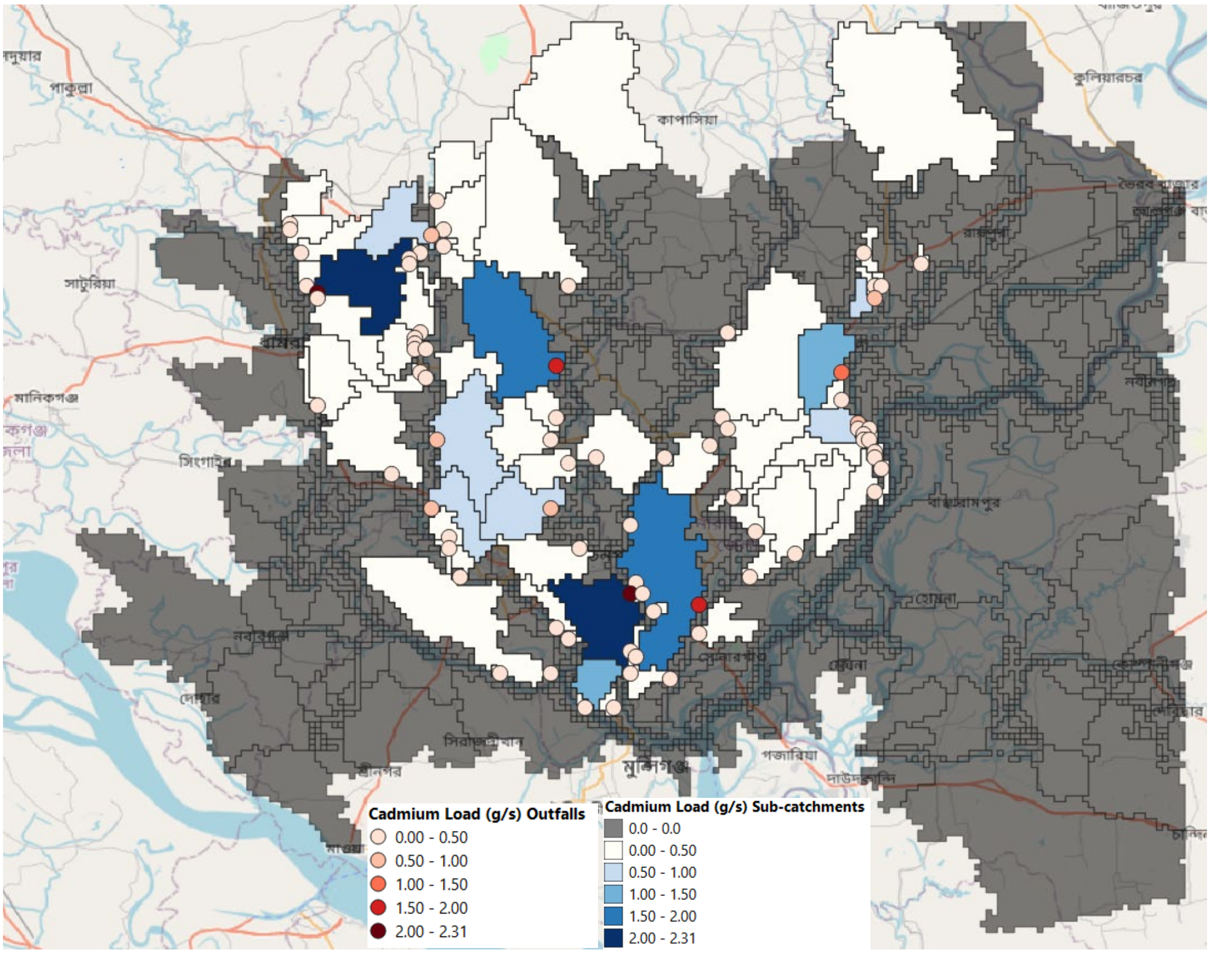

*Figure 20: Map showing the cadmium load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

### 4.7.3. Chlorine

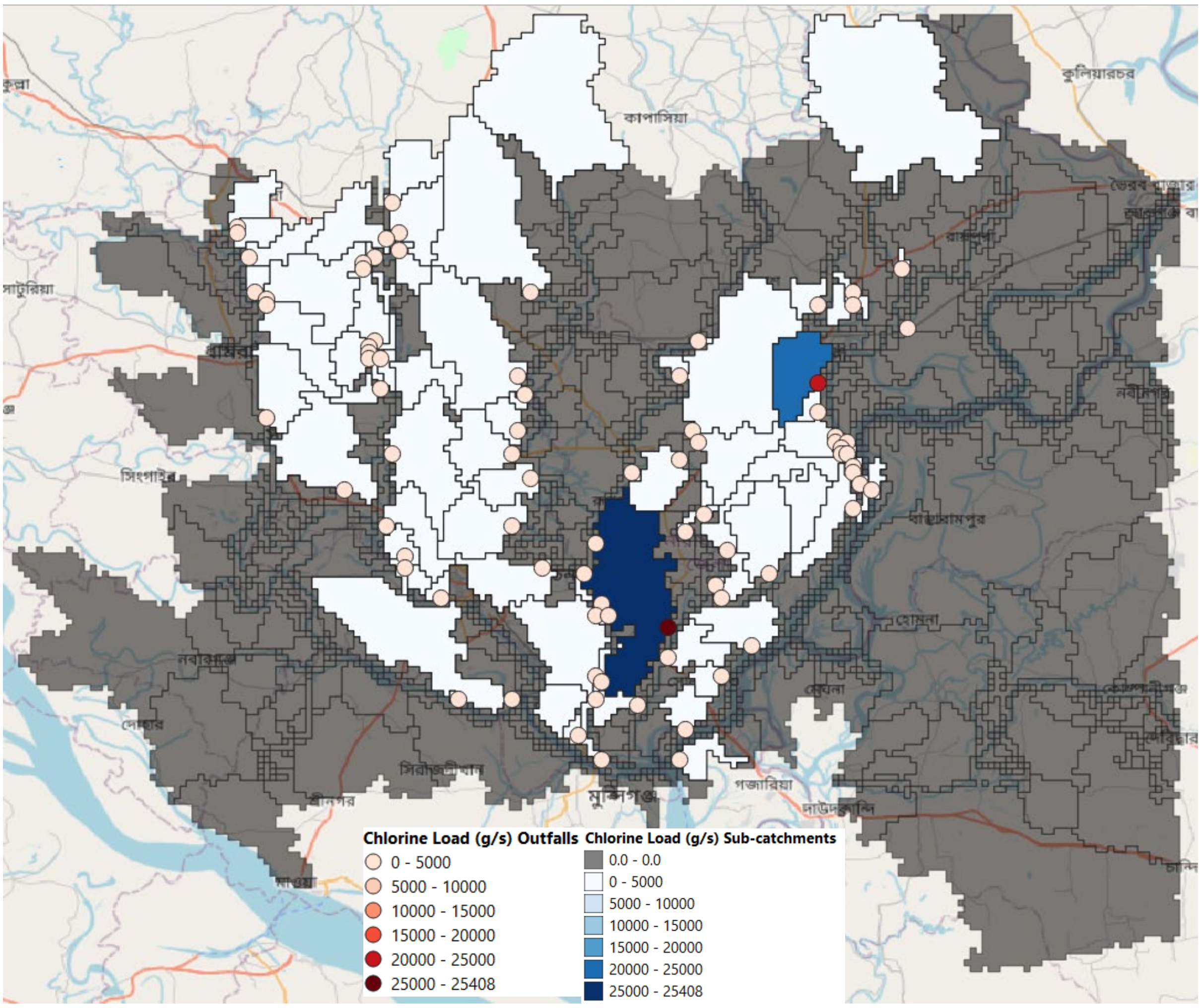

*Figure 21: Map showing the chlorine load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

### 4.7.4. Nitrate

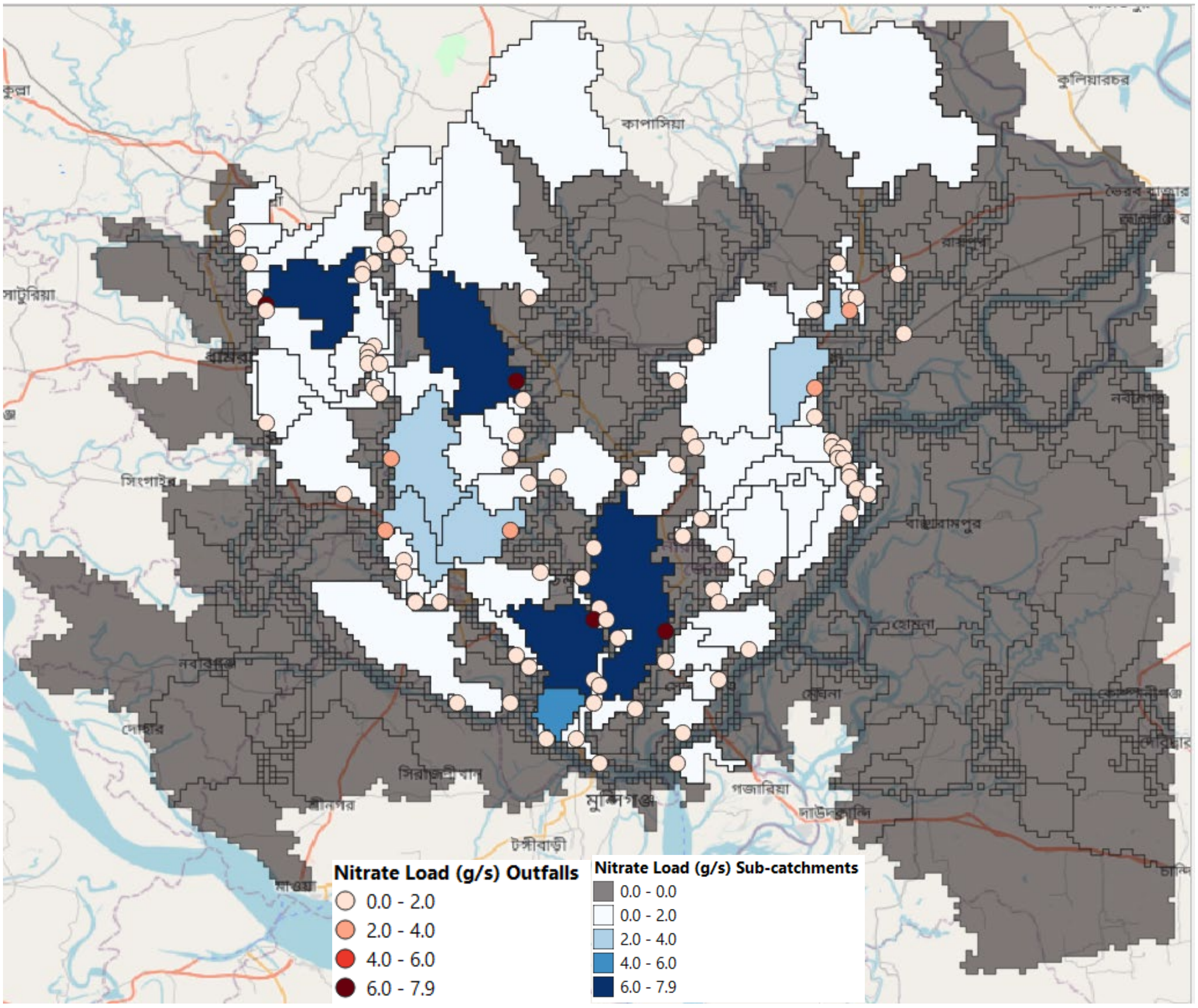

*Figure 22: Map showing the nitrate load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

### 4.7.5. Sulphate

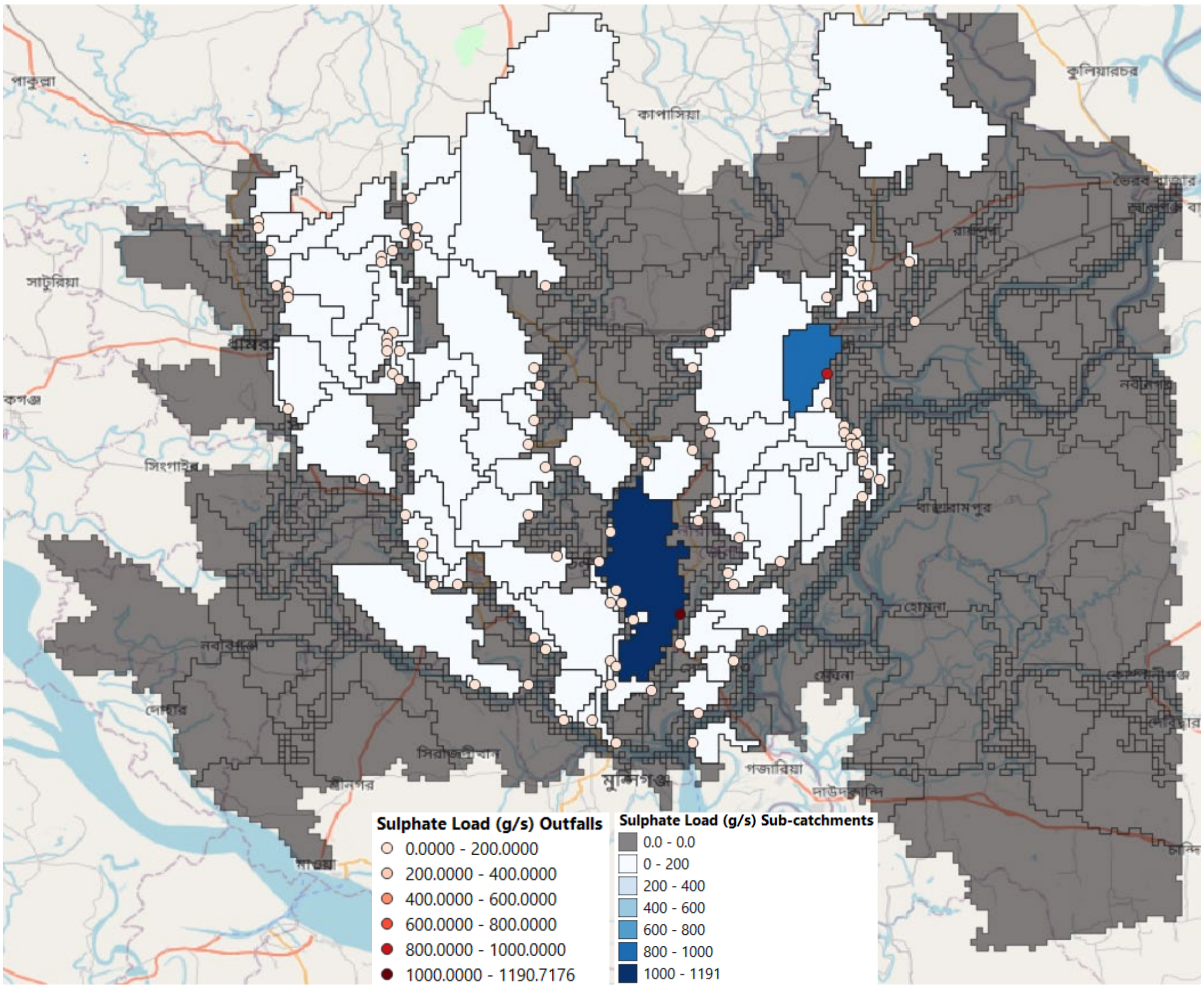

*Figure 23: Map showing the sulphate load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

### 4.7.6. Tannins

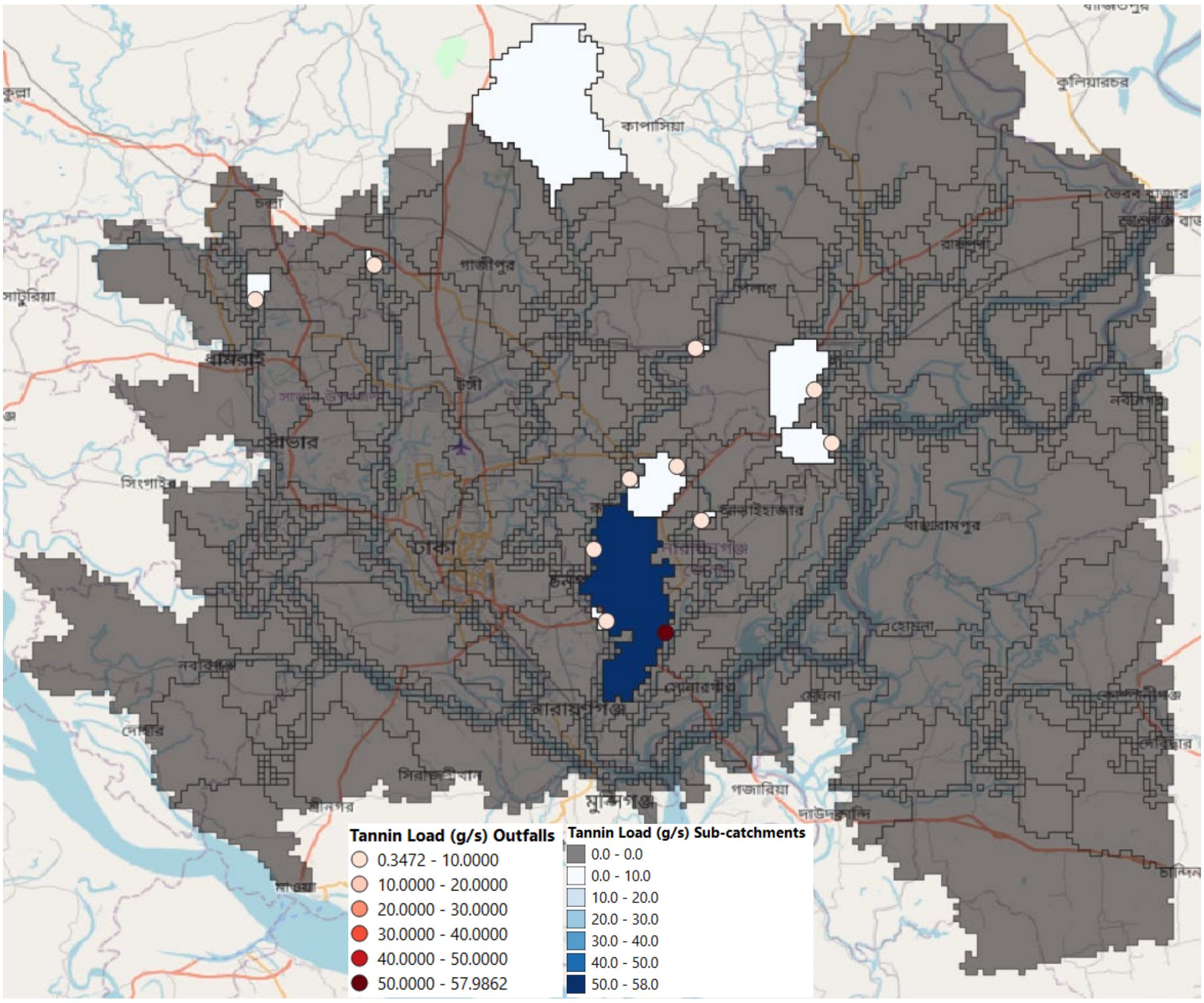

*Figure 24: Map showing the tannin load release points for different sub-catchments into waterways. The sub-catchments are shown by the white to blue sections on the map, and the grey areas signify 0 values for the sub-catchments. The colour of the red dots represents the modelled load (g/s) of arsenic released from industries in the sub-catchment into the waterways at outfall points. Any 0 values have been omitted from this map for the outfalls.*

## 4.8. Validation/Calibration of Model

### 4.8.1. Data Availability

Deltares has a log of all the substances modelled in this thesis apart from tannins and chlorine. Some of the monitored concentration data dates back 20 years, and measurements span over the course of the year. The spread of measurement concentrations over the year is vital due to the changes in substance concentrations in the wet and dry season in Bangladesh. Arsenic and cadmium data was only available for the Meghna, whereas nitrate and sulphate measurements were more widespread with measuring points on the Buriganga, Balu, Bangshi, Dhaleshwari, Meghna, Shitalakshya, Turag River and Tongi Canal (more information on measuring station locations in appendix Figure A-7).

Additional data was required for the discharge of the rivers in the catchment. Measured discharge data was not available. Available simulated hydrodynamic data initially came from literature (Hafiz et al., 2017; Rezaie et al., 2014) and further simulated data was added by IWM. The Tongi Khal stretch (TK-2) of the river was not modelled. In order to calculate discharge data for this river an assumption was made that what did not flow into the T-3 stretch from T-2 went to TK-2 (stretches shown in Figure 3). The D5 stretch of the Dhaleshwari was considered separate from the rest of the Dhaleshwari due to the geographical differences. The D-5 stretch of the Dhaleshwari is also near the Meghna river and sees tidal influences which can affect water quality measurements. The discharge of individual stretches of the waterways is important, as the concentrations and discharge data had to be combined to get load values for comparison to the modelled data.

There was a discrepancy in the year of discharge and concentration measurement data. There were available modelled discharge results spanning between 2004 and 2008, however, the only abundant water quality measurements were available for 2015. The hydrological year 2007-2008 matched best when considering rainfall data with 2015 (See Appendix Figure A-8). The concentration data was not available for the full hydrological year, and therefore only the months May to December could be compared, meaning January to April had to be omitted from comparison to modelled data. Due to the combination of discharge and substance concentration data available for calibration, only nitrate and sulphate could be compared for the river network.

### 4.8.2. Measured load analysis

Using the previously mentioned schematic map of the rivers the measured load in and load out of the river system were checked for the dry months. Due to a substance balance the load out of a system should be equal or greater than the input. To check this, the entrance points were selected, the loads added together and then compared to the loads coming out. Because not all the discharges or concentrations were known for the entry points, some assumptions had to be made (Table 17). The dry months November and December were compared for load in and load out for nitrate and sulphate, results of which can be found in Table 19 and 20. The loads in are consistently larger than the loads out, and in most cases considerably larger. This reduction in load could be due to various factors such as the simplification of the river network, as there are many periphery rivers. Another factor of this reduction could be due to the difference in years between the substance concentration measurements and the discharge data. Due to the reduction in nitrate and sulphate load this data cannot be used to calibrate on the scale of the entire catchment.

*Table 17: Assumptions used for the load input of rivers based on the schematic diagram of the river network in the selected area*

| **Unknown** | **Assumption** |
|---|---|
| **K-1** | Difference between BN-03 and BN-04 |
| **D-1** | Difference between BN-10 and BN-11 |
| **B-1** | Difference between TRC-05 and BL-12 |

*Table 18 Nitrate loads for November and December in and out of the catchment.*

| **November** | | | | **December** | | | |
|---|---|---|---|---|---|---|---|
| **In** | | **Out** | | **In** | | **Out** | |
| **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** |
| **BN-11** | 5888 | **SL-01** | 2171 | **BN-11** | 9497 | **SL-01** | 994 |
| **SL-13** | 5398 | **DH-08** | 6171 | **SL-13** | 1787 | **DH-08** | 590 |
| K-1 | 153 | | | K-1 | -51 | | |
| D-1 | -564 | | | D-1 | -737 | | |
| B-1 | 444 | | | B-1 | 201 | | |
| **Total** | 11319 | **Total** | 8342 | **Total** | 10696 | **Total** | 1584 |
| | | **Difference** | -2977 | | | **Difference** | -9112 |

*Table 19 Sulphate loads for November and December in and out of the catchment.*

| **November** | | | | **December** | | | |
|---|---|---|---|---|---|---|---|
| **In** | | **Out** | | **In** | | **Out** | |
| **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** | **River Code** | **Load (g/s)** |
| **BN-11** | 70861 | **SL-01** | 3871 | **BN-11** | 29981 | **SL-01** | 1503 |
| **SL-13** | 2013 | **DH-08** | 6831 | **SL-13** | 1328 | **DH-08** | 3609 |
| K-1 | 12414 | | | K-1 | 6295 | | |
| D-1 | -6913 | | | D-1 | -2295 | | |
| B-1 | 661 | | | B-1 | 785 | | |
| **Total** | 79037 | **Total** | 10702 | **Total** | 36094 | **Total** | 5111 |
| | | **Difference** | -68335 | | | **Difference** | -30983 |

As shown in Table 19 and 20, a catchment wide substance balance does not make sense with the data and schematisation available due to the substantial load reduction between inflow and outflow. For further investigation the factor difference between the loads in and the loads out were compared for the different river stretches, to assess whether these are suitable for validating and calibrating the model. The factors shown in Table 20 and 21 show that some of the rivers do have an increase in load when considering the start and end points as shown by the black rather than grey numbers in the table. There is, however, inconsistency between the factors not only between the months but also between rivers (see also Appendix Figures A-9 to A-22). It would be expected that all the factors should be above one, as the nitrate and sulphate loads should not decrease downstream. For this reason, the load for nitrate and sulphate are subsequently compared per river stretch to the modelled data.

*Table 20: Factors difference between the end nitrate load and start nitrate load of the rivers. This value was calculated by dividing the end load at the downstream end by the start load on the upstream end. The grey coloured numbers indicate that the end load was smaller than the start load. Higher factors are found in the Dhaleshwari in the wet months in the Shitalakshya and the Dhaleshwari.*

| | Shitalakshya | Dhaleshwari | Dhaleshwari (D5) | Balu | Buriganga | Turag | Tongi Khal |
|---|---|---|---|---|---|---|---|
| **May** | 91.21 | 0.28 | 0.68 | 1.33 | 1.05 | 0.81 | 0.71 |
| **June** | 96.43 | 0.05 | 1.04 | 0.61 | 1.64 | 2.50 | 0.38 |
| **July** | 3.65 | 0.04 | 0.54 | 1.29 | 1.38 | 2.08 | 0.12 |
| **August** | 0.46 | 1.54 | 0.70 | 0.30 | 0.72 | 0.85 | 1.25 |
| **September** | 6.99 | 1.10 | 0.79 | 2.30 | 1.69 | - | 1.01 |
| **October** | 1.43 | 0.05 | 1.70 | 0.83 | 2.11 | 2.19 | 2.20 |
| **November** | 0.72 | 8.04 | 1.05 | 0.23 | 0.98 | 0.75 | 1.31 |
| **December** | 0.84 | 11.49 | 1.79 | 2.60 | 0.56 | 7.42 | 1.01 |

*Table 21: Factors difference between the end sulphate load and start sulphate load of the rivers. This value was calculated by dividing the end load at the downstream end by the start load on the upstream end. The grey colour numbers indicate that the end load was smaller than the start load. Higher factors are found in the Dhaleshwari in the wet months in the Shitalakshya and the Dhaleshwari.*

| | Shitalakshya | Dhaleshwari | Dhaleshwari (D5) | Balu | Buriganga | Turag | Tongi Khal |
|---|---|---|---|---|---|---|---|
| **May** | 2.43 | 173.52 | 0.68 | 1.09 | 0.88 | 1.06 | 1.00 |
| **June** | 1.12 | 29.19 | 1.93 | 0.50 | 0.70 | 0.43 | 1.32 |
| **July** | 1.79 | 51.57 | 2.32 | 1.24 | 1.56 | 0.85 | 0.54 |
| **August** | 1.42 | 7.14 | 0.84 | 0.53 | 1.26 | 0.50 | 1.27 |
| **September** | 1.42 | 13.45 | 0.63 | 1.06 | 0.90 | - | 0.46 |
| **October** | 1.18 | 22.22 | 0.76 | 2.86 | 1.05 | 1.11 | 1.76 |
| **November** | 1.92 | 4.06 | 0.70 | 1.39 | 0.52 | 0.72 | 0.90 |
| **December** | 1.13 | 5.49 | 0.45 | 0.32 | 0.61 | 0.90 | 0.96 |

To compare the modelled and monitored load data each of the river stretches, the difference between the loads for both sulphate and nitrate were taken at the measuring point most upstream of the river and most downstream. By doing this the difference in load between these points was calculated for each month which saw an increase over the river. The outflows were then added up between these two measuring points, and the difference in measured load and the modelled load could be compared (Table 22). Most of the rivers had a much higher measured load difference compared to the modelled load added, indicating that either industrial wastewater is underestimated in quantity or concentration, or that there are other factors at stake that are not included in the model. The modelled sulphate load in the Shitalakshya, Buriganga and Turag are close to the difference in measured data. The modelled nitrate load for the Buriganga is also close. This could make the Buriganga a possible river for further analysis for calibration on a smaller scale. The Tongi Khal is also be of interest for further analysis, due to the increase in nitrate and sulphate load over the river when there is no industrial presence nearby. Especially for nitrate, however, it is important to note that the load difference over the stretches of river that it is very likely that there are other sources for nitrate such as agricultural runoff and domestic waste that are adding load into the system. For this reason, it is likely to be better to use sulphate as a validation as Table 22 shows that the modelled load is not as far off the difference over the measured load (see also Appendix Table A-1 and A-2).

*Table 22: Table showing the factor difference between the minimum measured load for nitrate and sulphate and the modelled load input for each of the river stretches. The factor difference was calculated by dividing the minimum measured load by the measured load.*

| | **Shitalakshya** | **Dhaleshwari** | **Dhaleshwari (D5)** | **Balu** | **Buriganga** | **Turag** |
|---|---|---|---|---|---|---|
| **Factor difference between measured nitrate load and minimum measured load (minimum measured difference/modelled load)** | 72.30 | 267.19 | 357.38 | 47.80 | 0.50 | 131.28 |
| **Factor difference between measured sulphate load and minimum measured load (minimum measured difference/modelled load)** | 1.08 | 24.35 | 1922.07 | 47.9 | 1.99 | 1.78 |

### 4.8.3. Calibration

As shown in the previous section the data used for validation is currently not adequate for validating or calibrating the substance loads modelled in this research. It is, however, possible to guide towards what factors could be calibrated if validation was possible. An overestimation of substance load could be due to the selection of industries which may not be functional, as a selection was made for industries which were functional, temporarily closed or had an unknown functionality. Further research could also show that ETPs are in place in certain areas, and therefore have some level of substance load reduction. Validation could also show areas which have input from categories or industries that were not selected for modelling that might have been omitted. Reassessment of wastewater production or typical wastewater substance concentrations may also be required. The addition from substance loads from other sources such as human waste or agricultural runoff may also have to be considered if substance loads are overestimated.

## 4.9. Scenario Analysis

Tanneries and paper mills are not found in the area serviced by the WWTP and therefore the scenario does not change their effluent release into the waterways (Figure 25). Tannins are, therefore, not reduced in load by connection to the WWTP as they are only released in the model by paper mills. The only industries that would have their water treated by the WWTP are dying, textile and printing industries. Only one printing industry is in this area, so the load from the printing industry is also not likely to be reduced by much. The simulation showed that although the WWTP removed some of the load, the percentage fell below 0.01% (see Appendix Table A-3). It is difficult to say with accuracy exactly how this load would be affected, as the resolution of the output of the model is too small to show such a small decrease. This indicates that the industries that fall into the area that the Pagla WWTP would only remove minimal quantities of substance load.

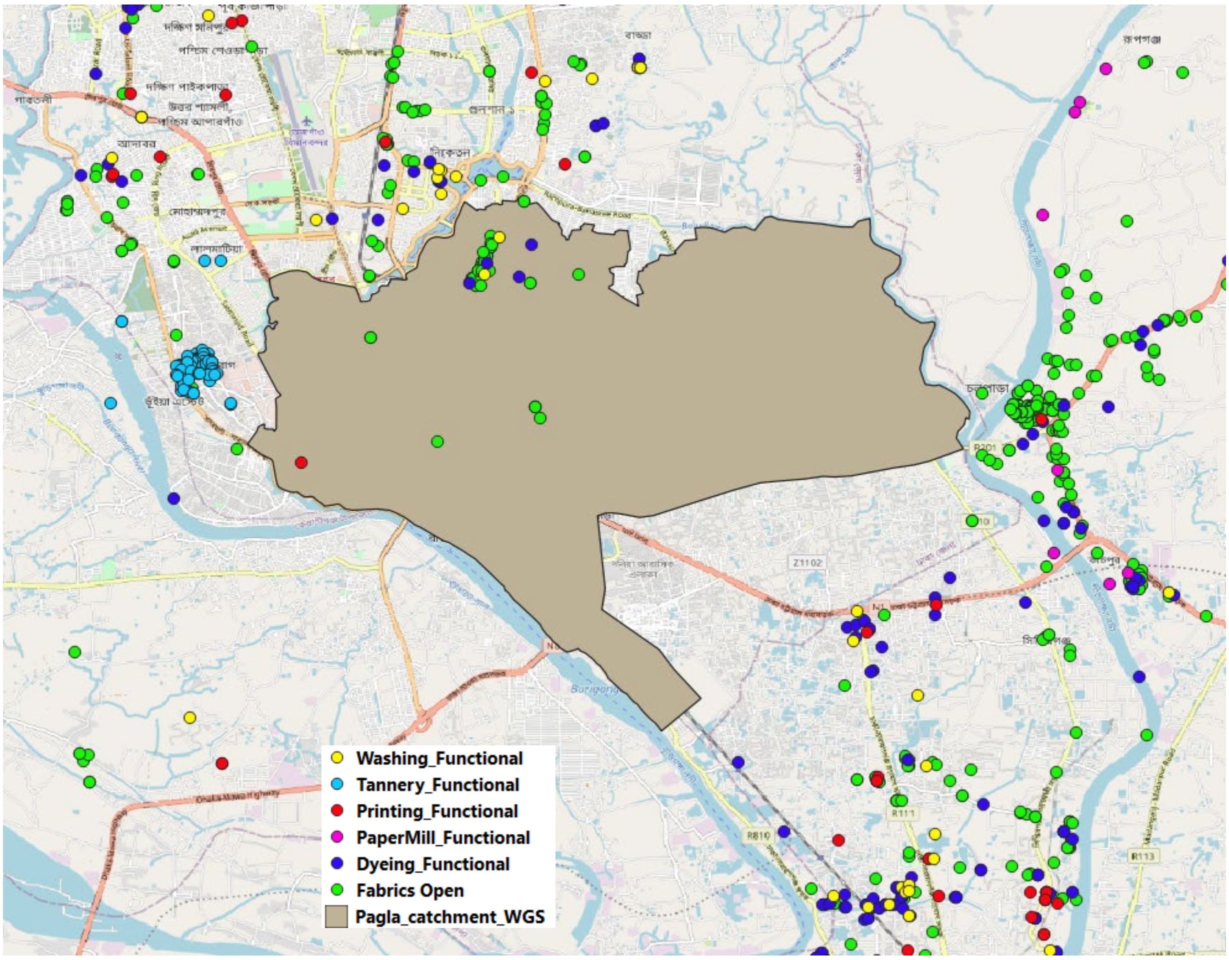

*Figure 25: Map showing the location of the Pagla WWTP area serviced, and the modelled industries that fall in this area.*

# 5. Discussion

## 5.1. Reliability and Limitations

Modelled data is only as accurate as its input data and the underlying assumptions made. For validation of model outputs, the optimal data available was used but there is much room for error due to the amount of assumptions made. There remain gaps to be filled in order to produce reliable emissions data, as calibration is currently not possible for the substances modelled. These initial model runs do, however, give an indication of pollution hot zones in Dhaka. The modelled data also highlight further data requirements for emission modelling in Dhaka for policy decisions for industrial effluent, such as expansion of WWTP capacity to treat industrial wastewater.

It is important to critically reflect upon the limitations within this research. The categorisation of industries needs further fine-tuning. Local knowledge on industries would shed more light on individual industries, or categories of industries, that typically release more pollutants in the area. Categorisation of the wrong industries into groups could lead to an over or underestimation of its contribution in substance load release. Similar estimation issues are possible due to modelling industries that have unknown functionality, or are temporarily closed, which would need assessment on whether they are functional. From conversations with IWM the categories food and fertiliser production were named as likely contributors to water pollution, neither of which have adequate literature data to model currently. If there is knowledge on the typical wastewater that either the food or fertilizer industry emit, for example, these could also be added to the emissions model.

The units of production collected were also a limitation, as often the literature available states the amount of wastewater produced per weight of product. Many of the relationships for wastewater production by industries in literature were based on weight and therefore wastewater could not be based on production for units that did not match. A better understanding of individual industries, such as the typical product weight, would lead to more accurate wastewater data. As literature data on wastewater per industry in Bangladesh is limited, especially on typical processes, knowledge on typical wastewater production per industry is vital and would be beneficial for the fine tuning of input into the modelled data and could be collected in country. Better understanding of local products may also give more of an insight as to what wastewater is produced by what kind of industry. The production weight and wastewater production were compared between the categories considered there was little correlation between the two. An example of where the use of literature data to estimate wastewater production might especially be an issue is the tanning process. The wastewater production per raw material was used to estimate tannery effluent, however, it is likely that a better understanding of whether chemicals are considered a raw material or just raw hides is required.

Industrial data was also no longer up to date. Tanneries have, as explored by Whitehead et al. (2019), moved from Hazaribagh to Savar in recent years, meaning the effluent now enters another river. The move impacts surrounding waterways and data surrounding this move is needed for modelling. The assumption that there was no ETP use for any of the industries was also made, thus validation of data and knowledge on ETP use and location would help calibrate this within the model.

Local knowledge on direction of flow and location of rivers of importance would also be beneficial when considering the schematic drawing of the river network and its use for validation. Some stretches, like the Karnatali river, had an unknown direction of flow. Any peripheral rivers or canals that are of importance but have been omitted could also be added to the schematic diagram of the rivers. Impacts such as the release of water in lakes into the rivers at times of high discharge during wet season, which would delay substance load entering the main rivers, also requires further inspection. The emissions model used in this thesis can be coupled to a water quality model that also considers rainfall-runoff, so this information about ponds, for example, would be especially beneficial for further analysis. The data for canals, small rivers and ponds that lead on to the main rivers was not available but are important to consider in future. It is also difficult to discern the specific location of measuring points on differing stretches of river. Further discussion with IWM on the comparison of the schematic map and the points of data collection for substance concentration would improve on the accuracy of load calculation.  There was insufficient data for validation for any of the other remaining substances modelled. The results from the modelling could therefore not be calibrated for arsenic, cadmium, chlorine and tannins. Additional monitoring has also been a recommendation based on other modelling research in the area (Whitehead et al., 2019). It is important to validate arsenic, cadmium, chlorine and tannins as they could be under or overestimated in industrial effluent. Additionally, there could be sources of these remaining substances that are not modelled in the emissions model, such as groundwater.

The use of nitrate as a modelled substance in the industrial emissions in this thesis was a problem, as nitrate also originates from domestic waste and agricultural runoff. In this thesis modelled nitrate load was compared to measured nitrate load over Dhaka's waterways and it was shown that the measured nitrate load was much higher than the modelled nitrate load. The large difference between the modelled and measured nitrate load suggests that the domestic and agricultural source may in effect be much greater than that of the industrial source. To further investigate nitrate load in the area the other sources and their typical emission factors would need to be added to the model.

The assumptions and limitations of this model's impact requires further analysis for the model to be used. Validation using different parameters that are more frequently tested such as BOD and COD is underway. This validation also includes impacts from agricultural runoff, domestic waste and landfills and gives a more complete overview of the catchment. For BOD and COD validation in the other model run by Deltares, the values were closer to the measured values and could therefore be used for further analysis. As the method for validation of the model is based on the concentrations of parameters in the waterways and the discharges of the rivers, it is essential to also model the other sources of these substances.

When locating pollution hot spots, the outfall locations are themselves an assumption, as these were located based on elevation map. Locations of various outfalls are known but which industries connect to these outfalls is unknown. This would require further investigation as it likely means that the current pollution hot spots are in the wrong place due to the network of pipes currently present in Dhaka. Satellite imaging to assess areas with increased temperature in comparison to the rest of the river could be used to indicate outfall areas which are not yet known to get a clearer overview of location. Comparison of existing knowledge on outfall point locations of the network and sub-catchment outfall points based on elevation can already, however, be performed. Testing the water quality at these outfall points could potentially be used as calibration for the industries assumed to be connected to them.

## 5.2. Policy significance

Although there were difficulties in validating and calibrating the model, the process of this initial model run highlights the need for data and existing knowledge gaps requiring investigation in order to improve accuracy. With further fine-tuning the model will, however, have valuable use in policy. As there is limited measured data in Dhaka it is difficult to make assessments on policy decisions based on measurements, therefore modelled data is a good way in which to assess the effects that certain policies might have. Emission modelling rather than other types of modelling used previously, such as INCA modelling, allows for testing the effect of ETP placement, for example. Emission modelling is especially beneficial when considering the coupling of the model to a model that would simulate the travel of substances to other parts of the catchment.

Especially the coupling of emission and water flow models would allow for indication of areas that might have more problems than others and need solutions for water pollution issues. Steps need to be made in order to reduce the impact industrial wastewater has in Bangladesh. The use of ETPs are not widespread or controlled adequately. The resulting industrial effluent makes its way directly into waterways. Once validated the model utilised in this thesis can provide information for industrial wastewater specifically, which could be used for industry-specific policies. Adaptations of the model could also extend to other substances of importance in the geographic area.

Currently there are more WWTPs and an increase in capacity for the current Pagla WWTP in the pipeline in Dhaka. The scenario analysis showed the potential impact that fitting industries onto the sewer system would have on load reduction, and the effects of these plans could be modelled in this model to assess the impact of industrial water pollution hot spots in Dhaka. The scenario analysis in this thesis is related to these plans and could be expanded on to involve more factors such as sources of substances. Further coordination will take place with IWM and CEGIS, and their in-country knowledge of the waterways and industrial wastewater production will help with achieving more accuracy in modelled output. Better local understanding of the hydrodynamics such as direction of flow and flow in and out of periphery rivers would also give a better understanding of the accuracy of results.

The next steps to follow on from this thesis and other modelling in parallel in this project are as follows. The locations of pollution hot spots would first need to be checked and compared with where the outfalls are from this elevation data to outfalls of pipes. The industrial data will need updating to get more up-to-date information, alongside some fine tuning of units, functionality and whether any categories have been wrongly omitted. Substance loads can be validated with the data available, which will need further investigation for model calibration. The sources such as the population, landfills, agricultural runoff also need to be added and validated for, as some substances also come from those sources. Known ETP locations and use should then also be considered, either by knowledge of their location or by finding an underestimation of load in the rivers and checking ETP presence locally.

# 6. Conclusion

The main research question in this thesis aimed to understand the locations of the pollution hot spots with regards to substances produced by industries in Dhaka and how the loads of substances originating from industries would change when connected to the WWTP in Dhaka. The pollution hot spots were simulated, and their locations estimated spatially. The categories selected for industries were the dyeing, washing, textile, paper mills and tanneries in the area, due to their contribution to water pollution. For modelling then the substances arsenic, cadmium, chlorine, nitrate, sulphate and tannins were investigated. Using the emissions model, the industrial substance load contribution was calculated and mapped. The location was estimated by use of a digital elevation map. The responsible industries could also be seen, showing which industry emits what share of the substance load. Validation was not fully realised in this thesis, however, the next steps for the validation and calibration were highlighted for further use of the emissions model by Deltares, IWM and CEGIS. The scenario analysis showed that connecting industries in the area serviced by the Pagla WWTP had little effect on the arsenic, cadmium, chlorine, nitrate, sulphate and tannin release into the waterways.

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# Appendix

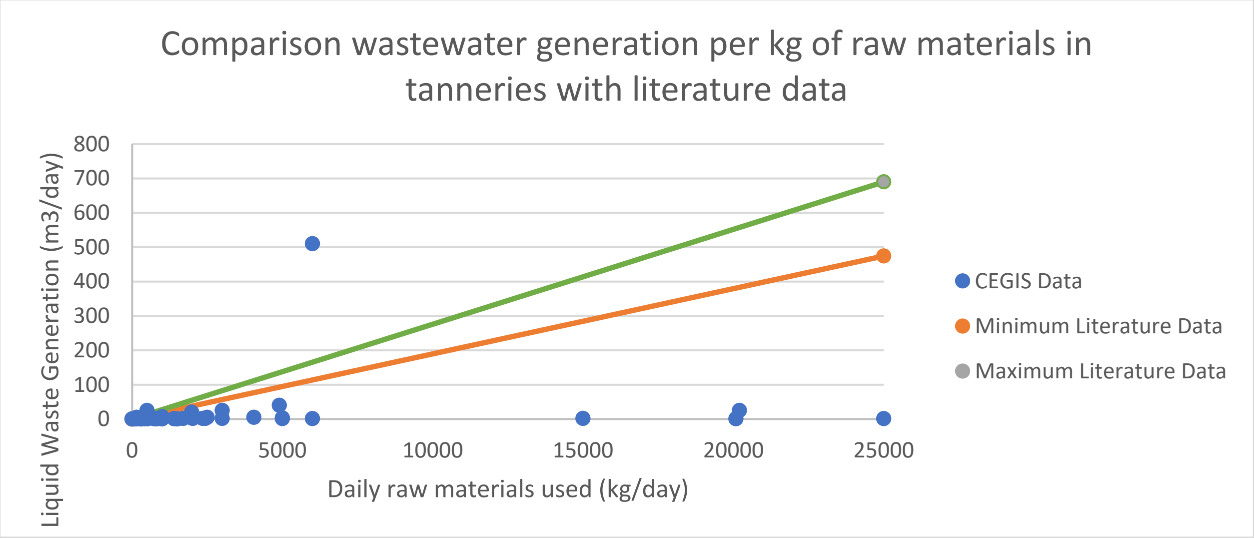


*Figure A-1: Graph showing the correlation between the literature data for the wastewater production by tanneries compared to the data provided by CEGIS. 0 values for wastewater were omitted.*

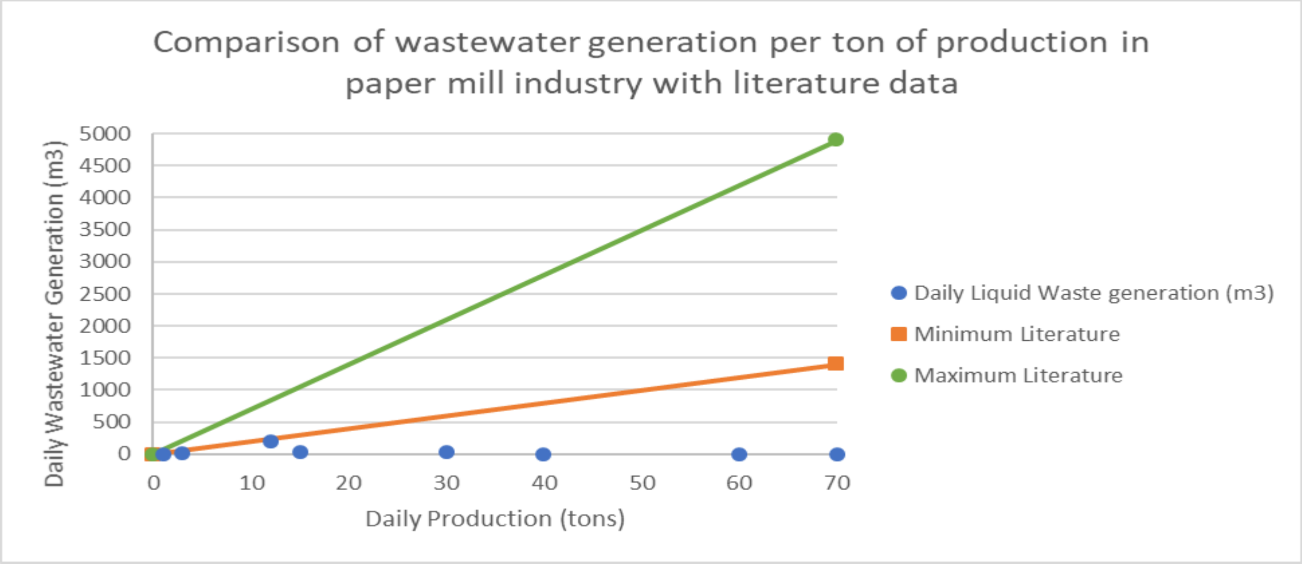


*Figure A-2: Graph showing the correlation between the literature data for the wastewater production by the paper mill industry compared to the data provided by CEGIS. 0 values for wastewater were omitted.*

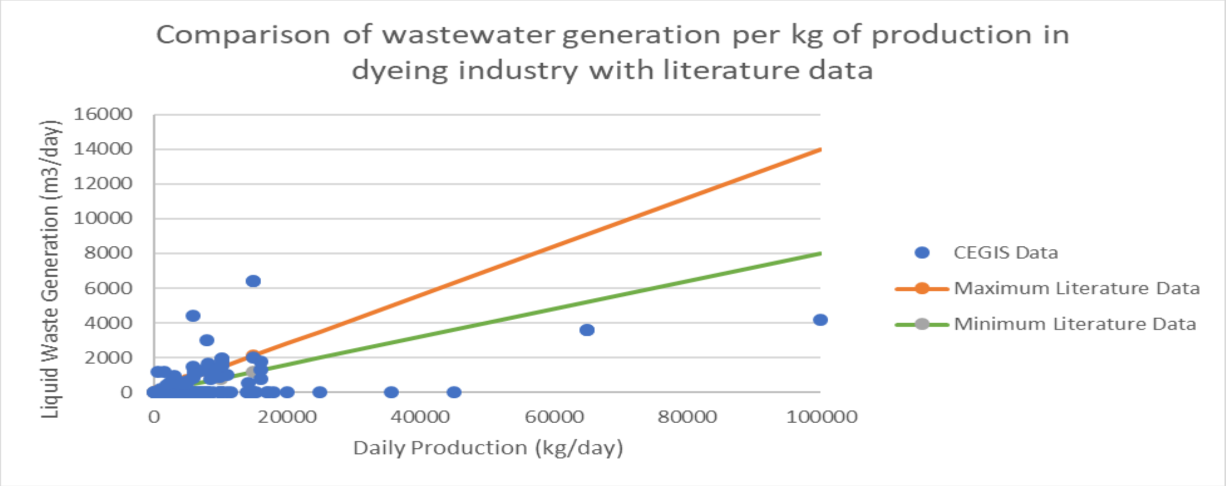


*Figure A-3: Graph showing the correlation between the literature data for the wastewater production by the paper mill industry compared to the data provided by CEGIS. 0 values for wastewater were omitted.*

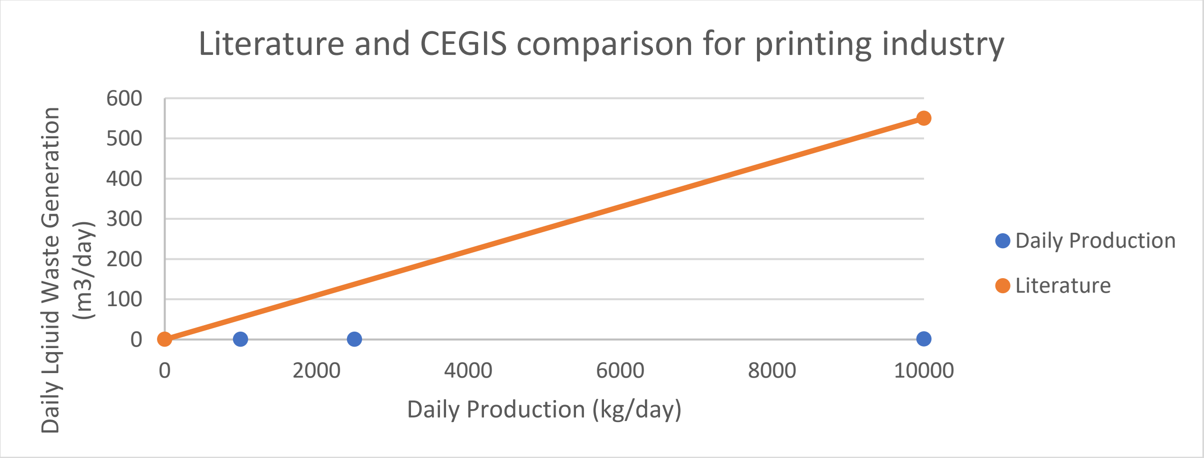


*Figure A-4: Graph showing the correlation between the literature data for the wastewater production by the printing industry compared to the data provided by CEGIS.0 values for wastewater were omitted.*

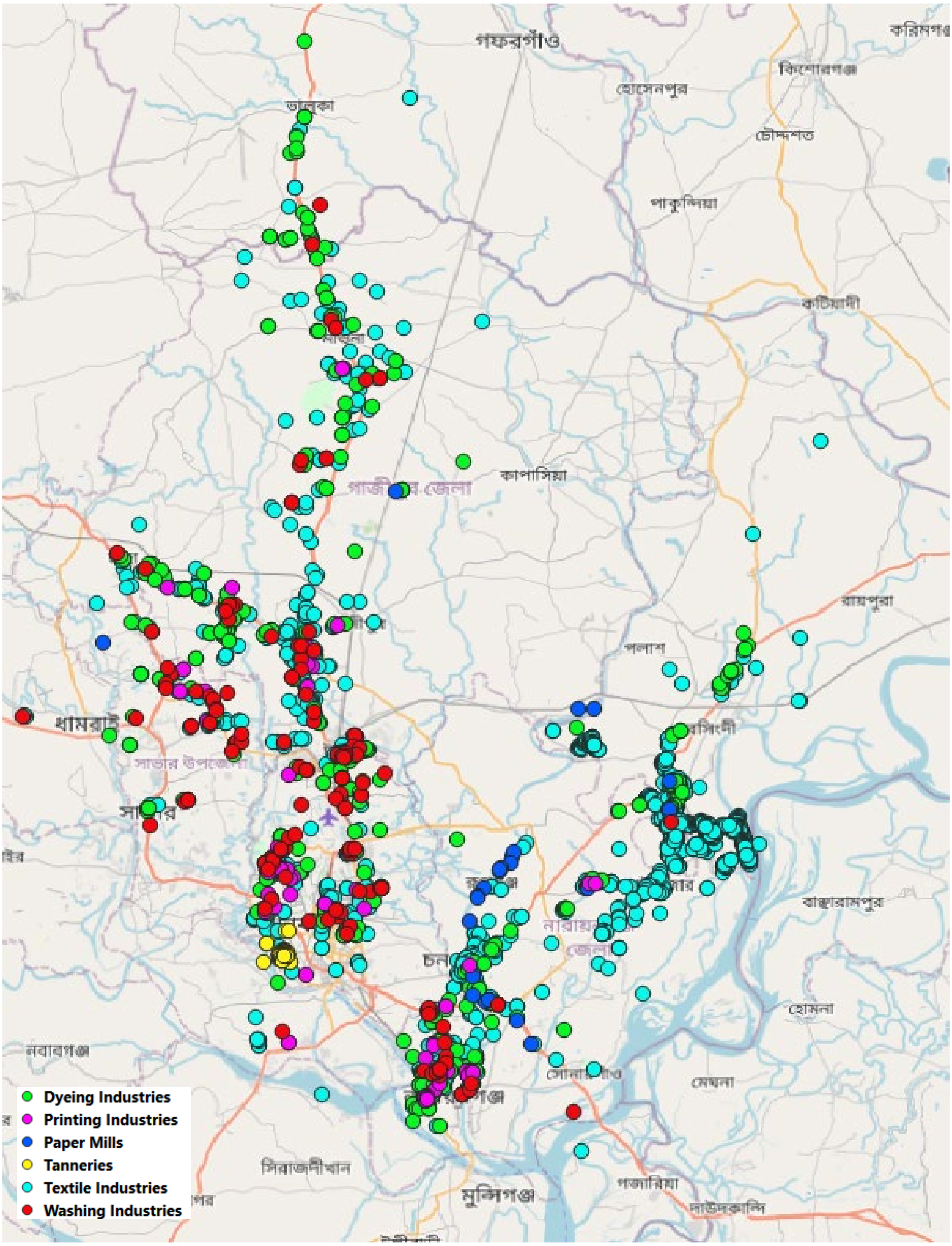


*Figure A-5: The spatial distribution of the industries selected for modelling in this thesis. These are the industries which are functional, temporarily closed or their functionality is unknown. The industries are also all under the Orange A category and the Orange B category as per the ECR.*

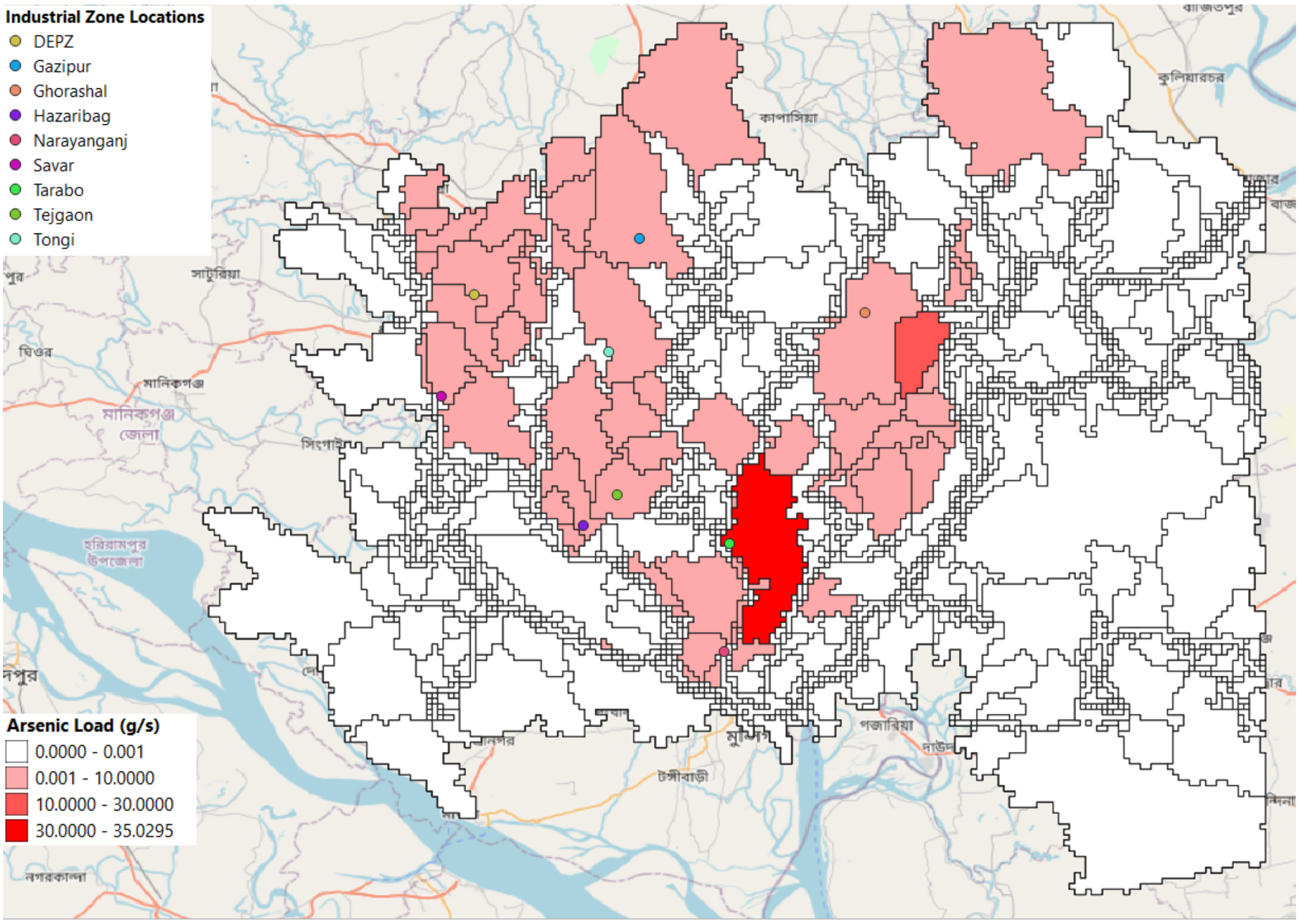


*Figure A-6: Map showing arsenic as an example for highlighting that the industrial clusters (coloured dots) are located in the catchments which have a large pollution load, which is also the case for the other substances apart from tannins.*

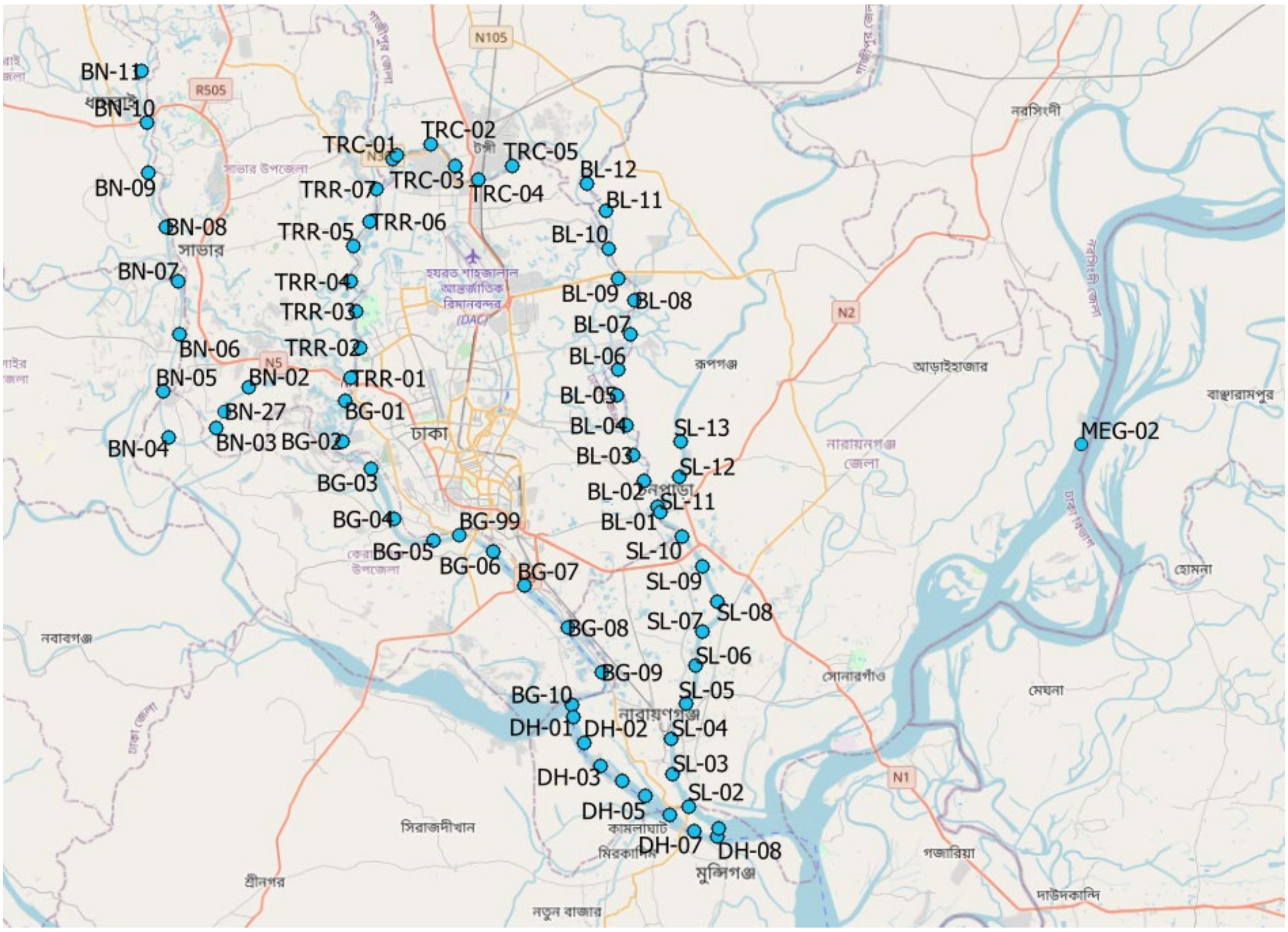
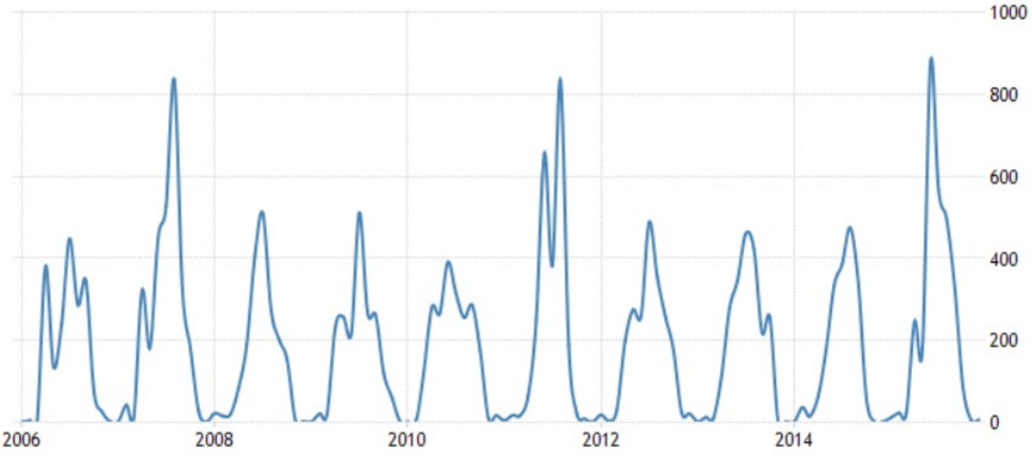


*Figure A-7: Map showing the spatial spread of the nitrate and sulphate measuring locations in the study area. Multiple measurements have been taken from each of these points.*



SOURCE: TRADINGECONOMICS.COM | WORLDBANK

*Figure A-8: historical rainfall taken from tradingeconomics.com for Bangladesh, showing the similarities between rainfall patterns hydrological year 2007-2008 and 2015. The similarities between these years was used as a justification to use the discharge for the hydrological year 2007 to 2008 and the concentration measurements for 2015 to calculate substance loads.*

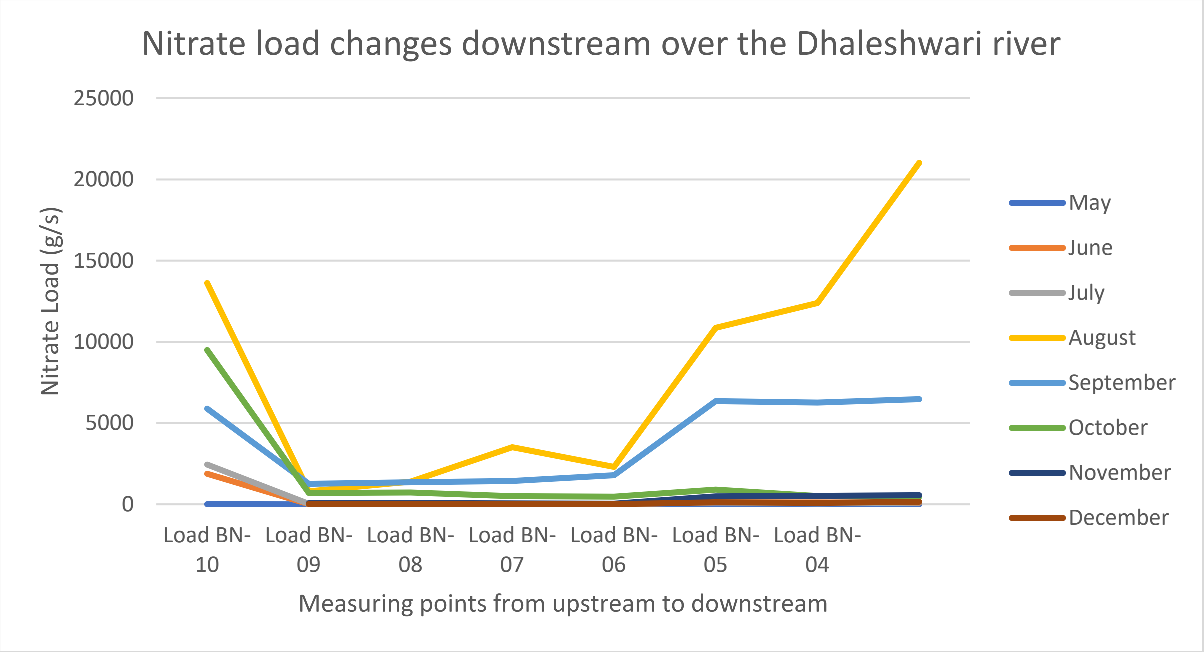


*Figure A-9: Graph showing the load changes for nitrate downstream the Dhaleshwari river. The different colours indicate the different months in 2015 when the measurements were taken.*

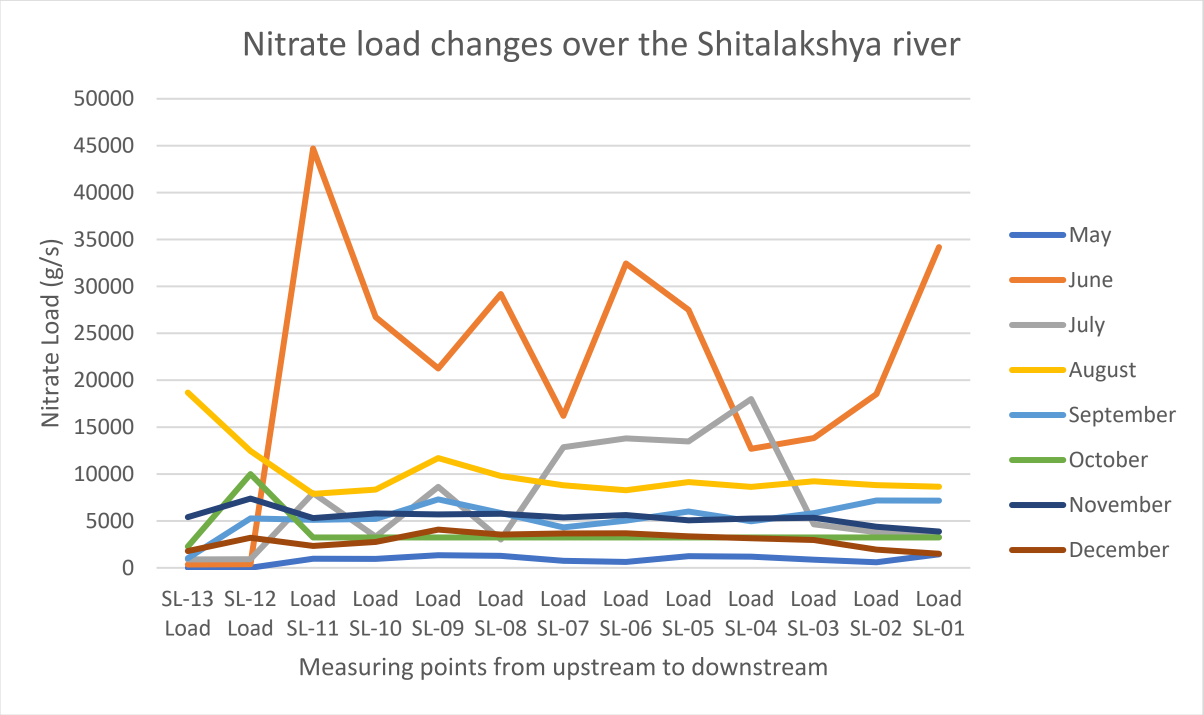


*Figure A-10: Graph showing the load changes for nitrate downstream the Shitalakshya river. The different colours indicate the different months in 2015 when the measurements were taken.*

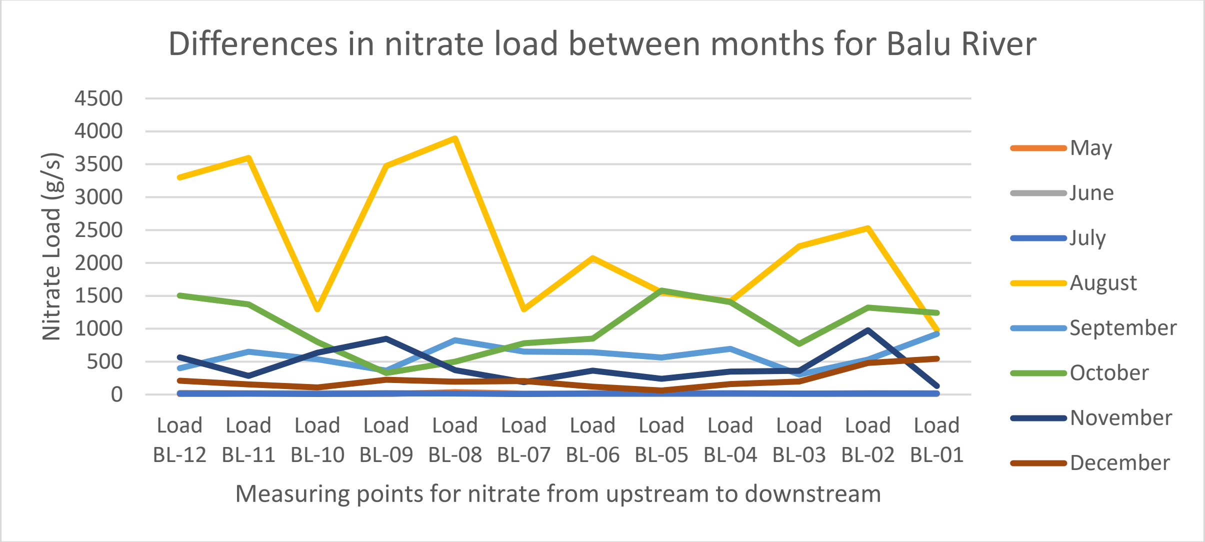


*Figure A-11: Graph showing the load changes for nitrate downstream the Balu river. The different colours indicate the different months in 2015 when the measurements were taken.*

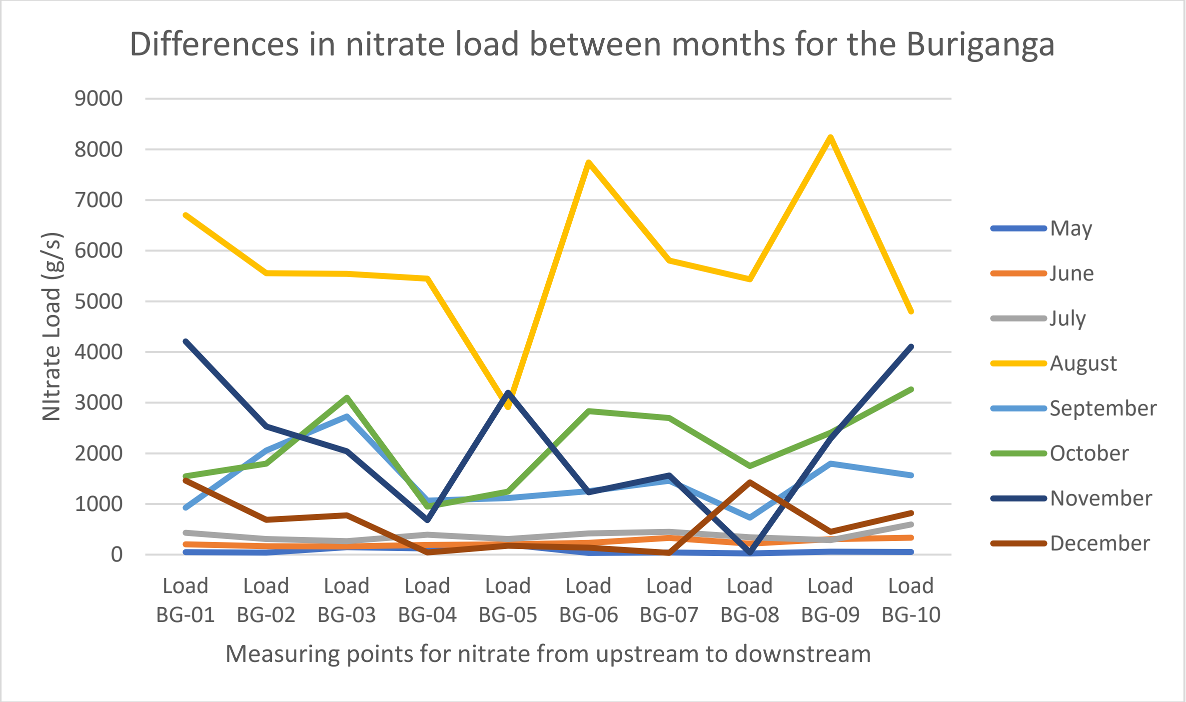


*Figure A-12: Graph showing the load changes for nitrate downstream the Buriganga river. The different colours indicate the different months in 2015 when the measurements were taken.*

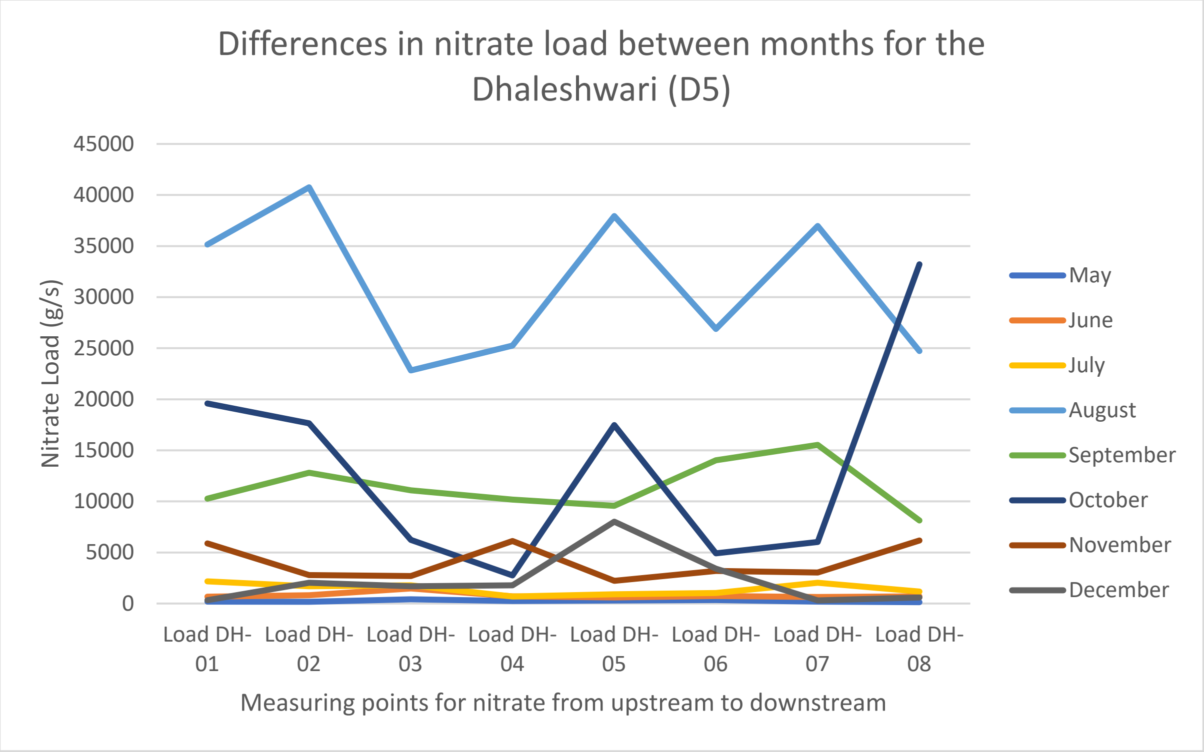


*Figure A-13: Graph showing the load changes for nitrate downstream the Dhaleshwari (D5) river. The different colours indicate the different months in 2015 when the measurements were taken.*

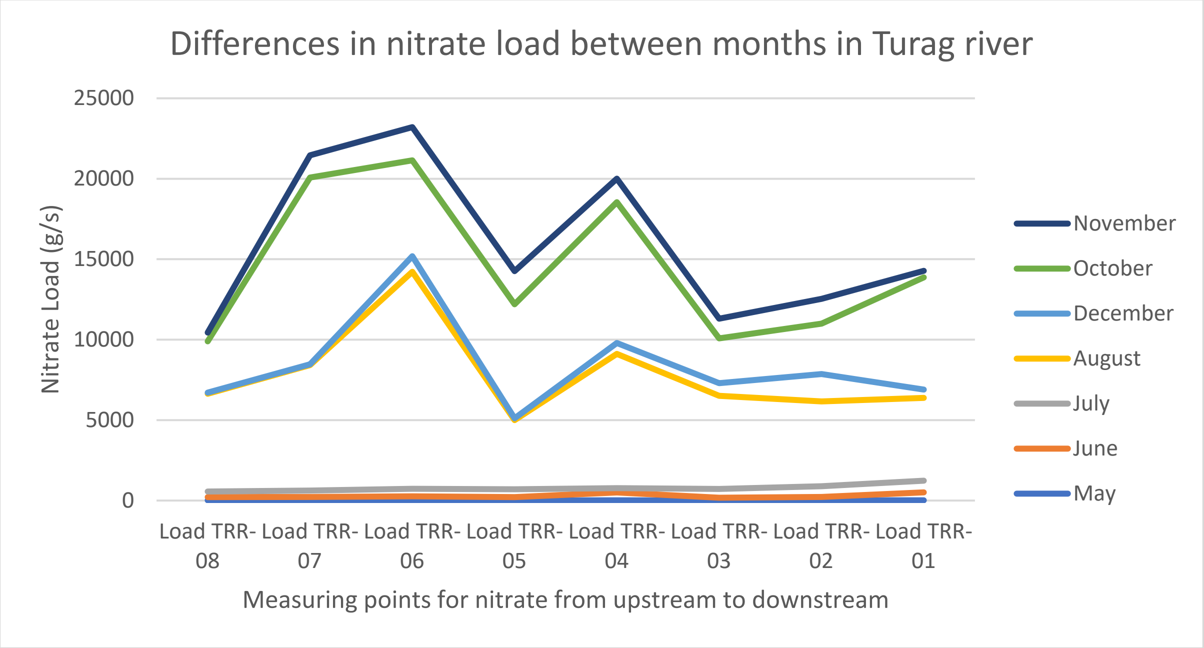


*Figure A-14: Graph showing the load changes for nitrate downstream the Turag river. The different colours indicate the different months in 2015 when the measurements were taken.*

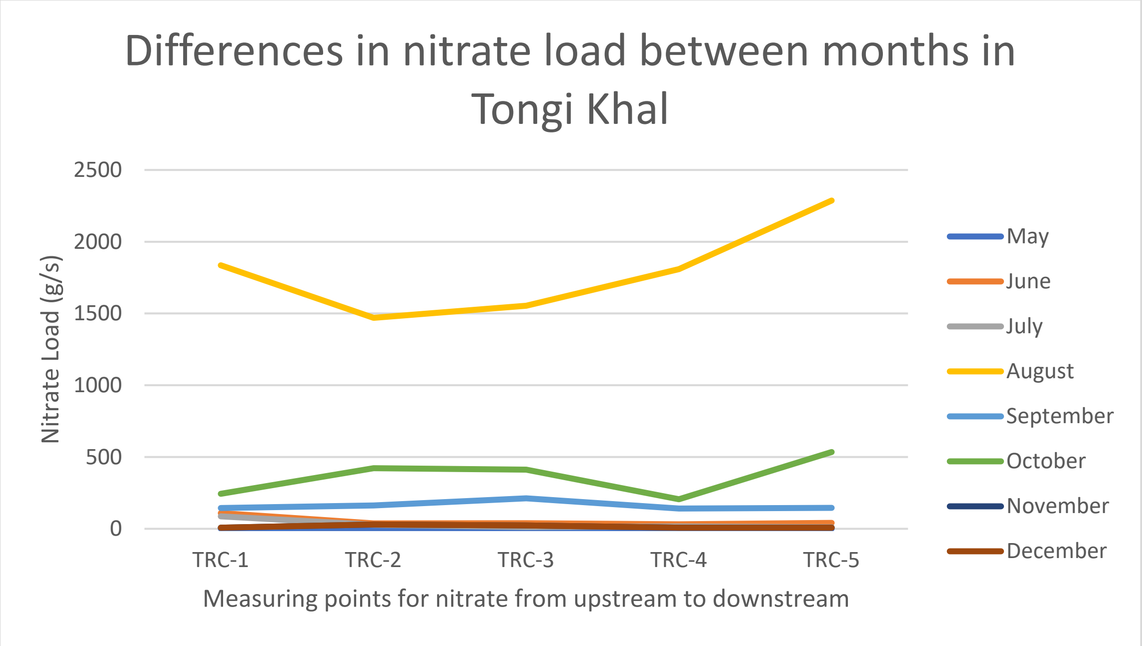


*Figure A-15: Graph showing the load changes for nitrate downstream the Tongi Khal. The different colours indicate the different months in 2015 when the measurements were taken.*

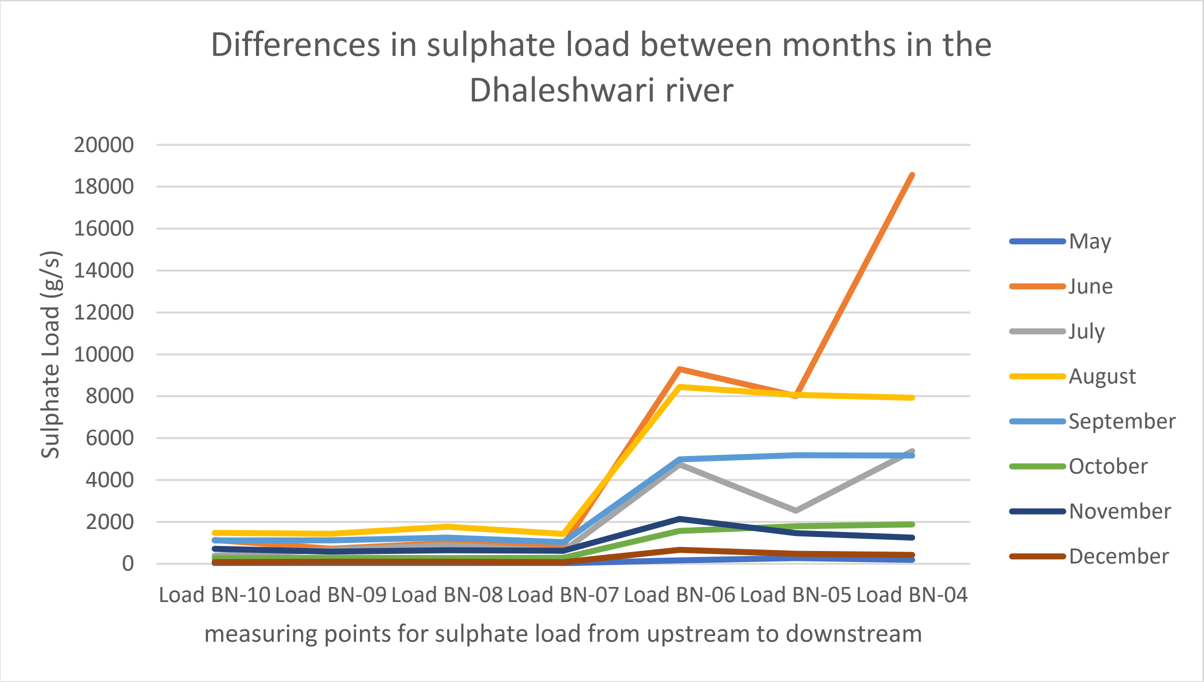


*Figure A-16: Graph showing the load changes for sulphate downstream the Dhaleshwari river. The different colours indicate the different months in 2015 when the measurements were taken.*

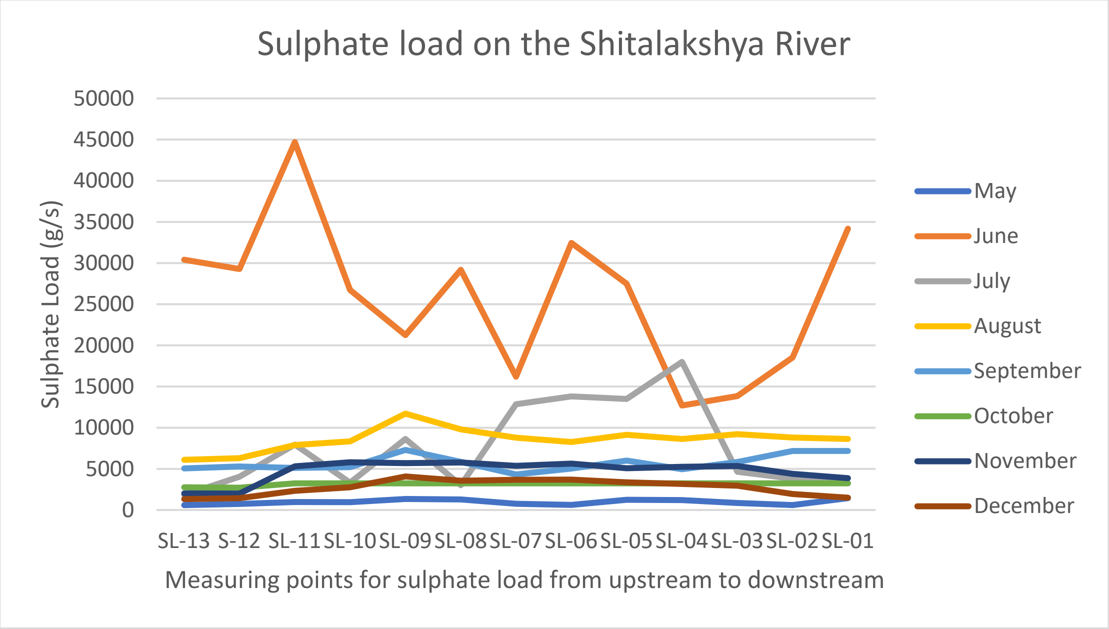


*Figure A-17: Graph showing the load changes for sulphate downstream the Dhaleshwari river. The different colours indicate the different months in 2015 when the measurements were taken.*

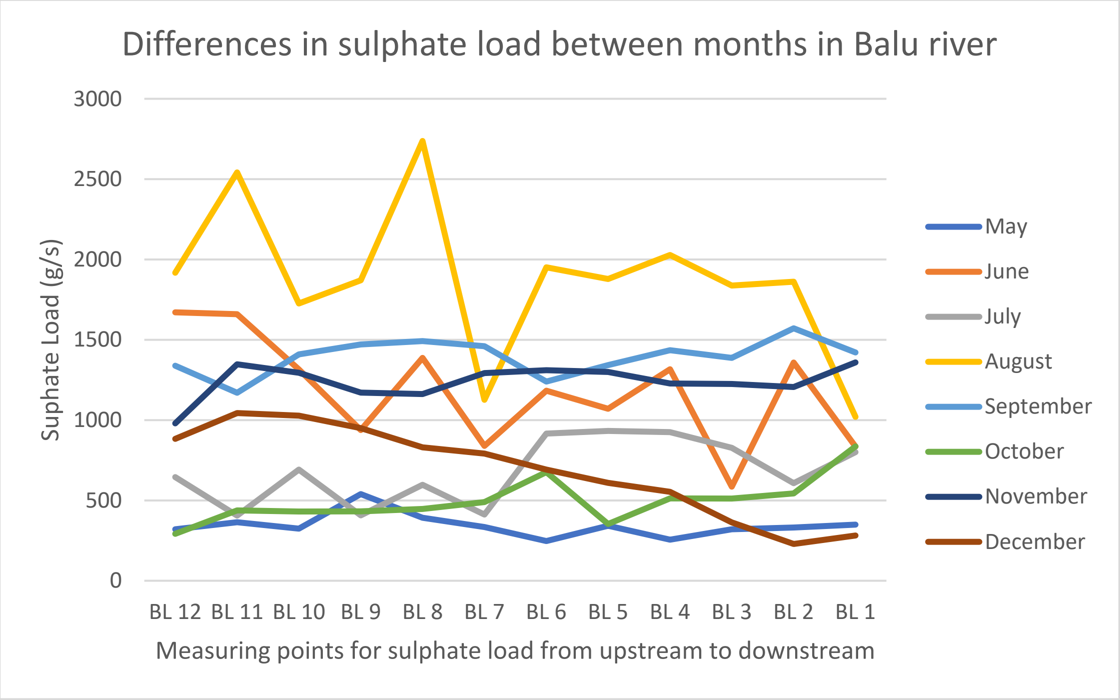


*Figure A-18: Graph showing the load changes for sulphate downstream the Balu river. The different colours indicate the different months in 2015 when the measurements were taken.*

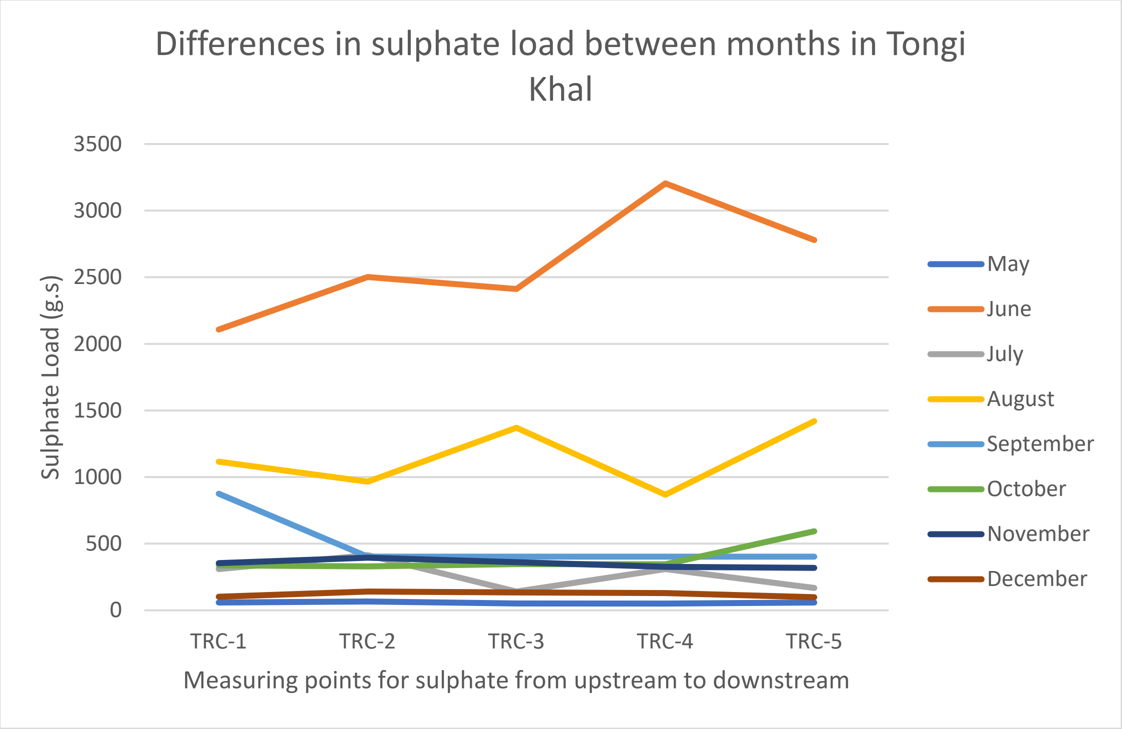


*Figure A-19: Graph showing the load changes for sulphate downstream the Tongi Khal. The different colours indicate the different months in 2015 when the measurements were taken.*

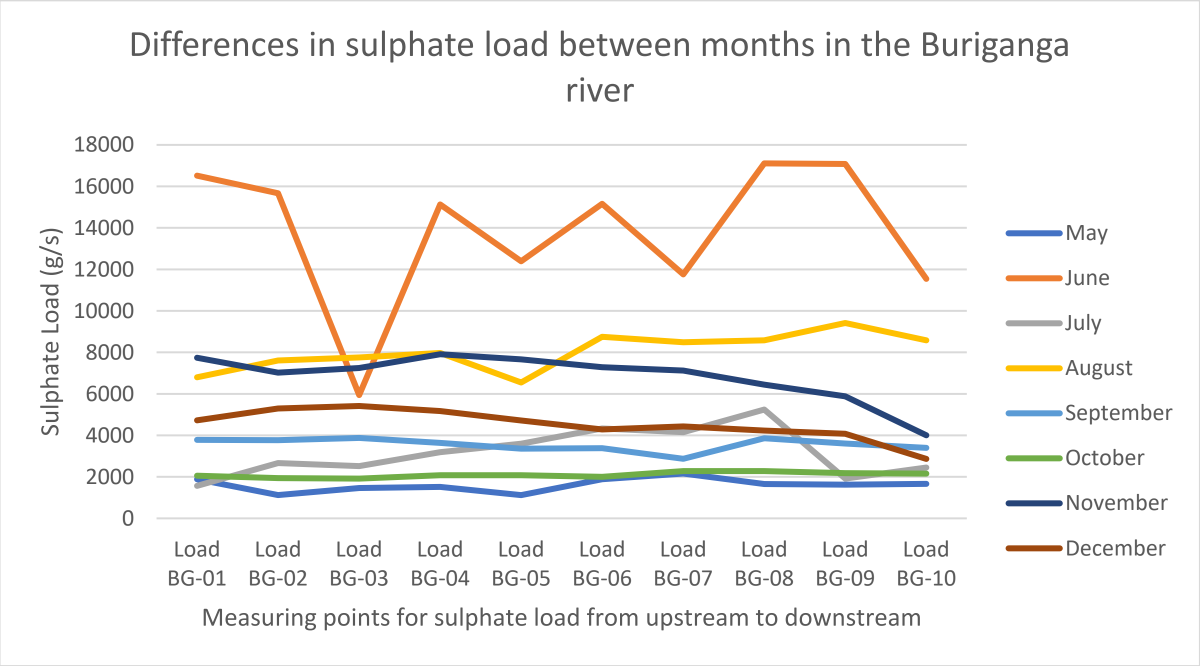


*Figure A-20: Graph showing the load changes for sulphate downstream the Buriganga river. The different colours indicate the different months in 2015 when the measurements were taken.*

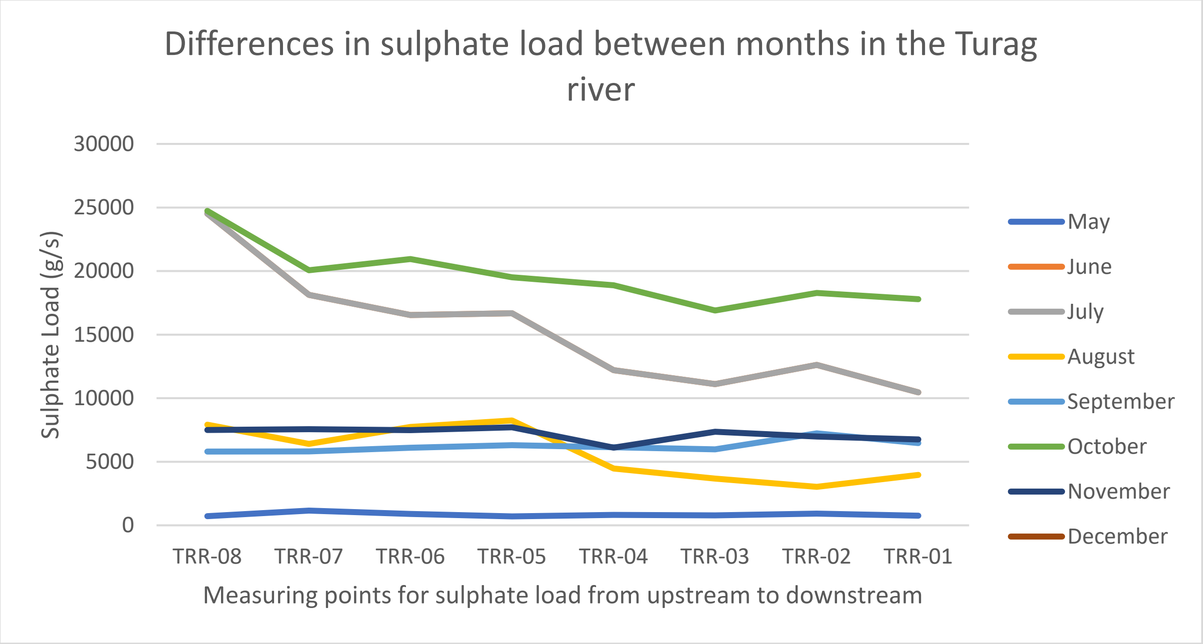


*Figure A-21: Graph showing the load changes for sulphate downstream the Turag river. The different colours indicate the different months in 2015 when the measurements were taken.*

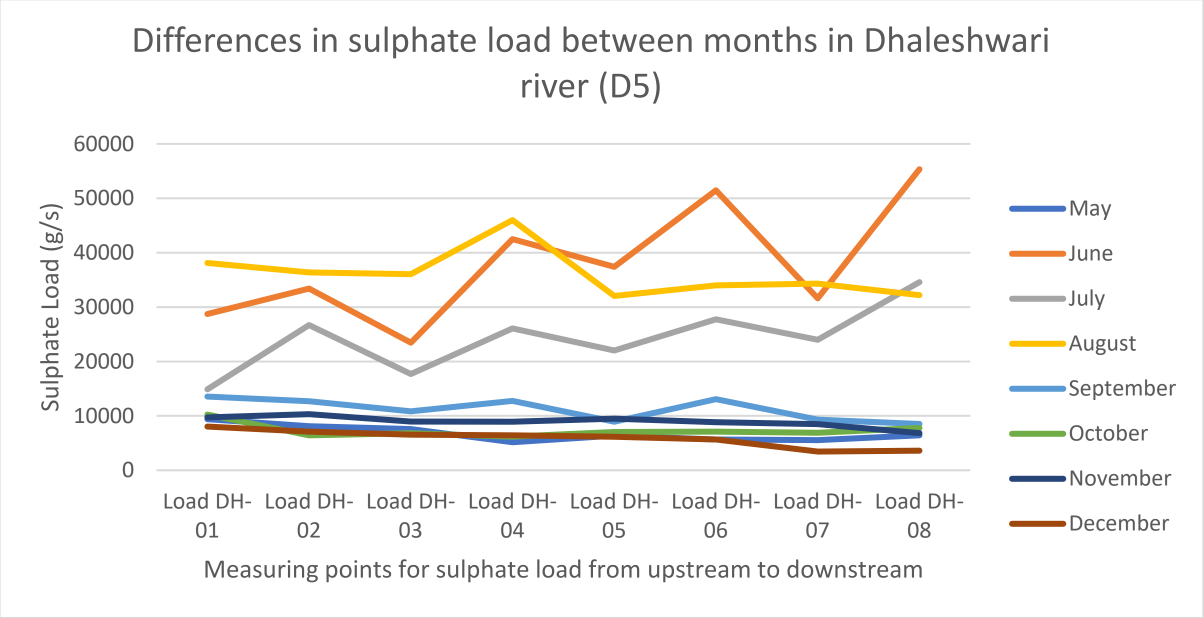


*Figure A-22: Graph showing the load changes for sulphate downstream the Dhaleshwari (D5) river. The different colours indicate the different months in 2015 when the measurements were taken.*

*Table A-1: Table showing the modelled nitrate load added to each of the rivers considered, compared to the minimum and maximum difference in nitrate load. The factor difference is also shown, which was achiever by dividing the minimum measured load by the modelled load.*

| | **Shitalakshya** | **Dhaleshwari** | **Dhaleshwari (D5)** | **Balu** | **Buriganga** | **Turag** | **Tongi Khal** |
|---|---|---|---|---|---|---|---|
| **Modelled load input (g/s)** | 9.26 | 0.54 | 0.08 | 0.05 | 4.98 | 2.27 | - |
| **Minimum measured difference nitrate load in and out of river (g/s)** | 969 | 144.28 | 28.59 | 2.39 | 2.47 | 298.04 | 0.08 |
| **Month minimum** | October | December | June | May | May | July | Decembe |
| **Maximum measured difference nitrate load in and out of river (g/s)** | 33828 | 1671.82 | 13628.51 | 521 | 1716.00 | 3779.16 | 451.58 |
| **Month maximum** | June | July | November | September | October | October | August |
| **Factor difference (minimum measured difference/modelled load)** | 72.3 | 267.19 | 357.38 | 47.8 | 0.50 | 131.28 | - |

*Table A-2: Table showing the modelled sulphate load added to each of the rivers considered, compared to the minimum and maximum difference in nitrate load. The factor difference is also shown, which was achiever by dividing the minimum measured load by the modelled load.*

| | **Shitalakshya** | **Dhaleshwari** | **Dhaleshwari (D5)** | **Balu** | **Buriganga** | **Turag** | **Tongi Khal** |
|---|---|---|---|---|---|---|---|
| **Modelled load input (g/s)** | 162.94 | 6.68 | 0.99 | 0.62 | 50.97 | 24.27 | - |
| **Minimum measured difference load in and out of river (g/s)** | 175.37 | 162.64 | 19702.85 | 29.7 | 101.26 | 43.17 | 256.61 |
| **Month minimum** | December | May | July | May | October | May | October |
| **Maximum measured difference nitrate load in and out of river (g/s)** | 3782.64 | 17430.63 | 26617.85 | 544 | 884.62 | 665.89 | 671.50 |
| **Month maximum** | June | June | June | October | July | September | June |
| **Factor difference (minimum measured difference/modelled load)** | 1.08 | 24.35 | 1922.07 | 47.9 | 1.99 | 1.78 | - |

*Table A-3: Table showing the results from the scenario analysis based on adding the industries in the reach of the WWTP Pagla at a load reduction rate of 40%. Tannins were not removed at all as they originate from paper mills in this model, and these are not within this area. The amount of chlorine load removed was smaller than a 1000th of a percent and therefore is listed as 0.00% in this table.*

| **Substance** | **Load removed by WWTP (g/day)** | **Percentage of total load removed (%)** |
|---|---|---|
| **Arsenic** | 17297.34 | 0.19 |
| **Cadmium** | 9024.31 | 0.48 |
| **Chlorine** | 13491.34 | 0.00 |
| **Nitrate** | 30187.73 | 0.43 |
| **Sulphate** | 375151.54 | 0.13 |
| **Tannins** | 0.00 | 0 |