A STUDY ON WATER QUALITY PARAMETERS DUE TO WITHDRAWAL AND FLOW AUGMENTATION IN THE DHAKA PERIPHERAL RIVER SYSTEM

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CERTIFICATE OF APPROVAL

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This is hereby declared that this thesis entitled as **"A Study on Water Quality Parameters due to Withdrawal and Flow Augmentation in the Dhaka Peripheral River System"** is the outcome of research carried out by me under the supervision of Dr. Anika Yunus, Professor and Head, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka. I do hereby declare that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma from any other institution.

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ABSTRACT

This study focused on the water quality of Dhaka peripheral river network of 195 km consisted of Turag, Buriganga, Dhaleshwari, Shitalakhya, Balu and Tongi Khal. 1D hydrodynamic and water quality model of Dhaka peripheral river network is developed in HEC-RAS. The hydrodynamic model was calibrated and validated for the year 2014 and 2016 respectively for Manning's n=0.025 in all cross sections along the river network. The water quality model was calibrated and validated for January-June of the year 2014 and July-December for the year 2016 respectively for dispersion coefficient, D = 0.07 m^2/s in all cross sections. The result of performance evaluation for the calibrated-validated hydrodynamic and water quality model has shown good match between the observed data and the simulated data.

To develop the flow scenario, available source of water has been identified by calculating monthly mean flow (MMF) and environmental flow. While calculating the environmental flow, two approaches have been considered, Tennant method and Flow Duration Curve method. MMF has been compared to environmental flow to determine the amount of available water to withdrawal for each month of Turag, Buriganga, Dhaleshwari, Shitalakhya, Balu and Tongi Khal. The analysis of water quality parameters showed that the water quality is satisfactory in high flow season, but unsatisfactory in low flow season, except for Dhaleshwari and Shitalakhya. Based on the output, three withdrawal scenarios and four augmentation scenarios have been developed. The response of the most important water quality parameters DO and BOD to the withdrawal and augmentation scenario have been assessed in this study.

Results show that low flow season in all rivers mostly exhibit the conditions for flow augmentation scenario due to less amount of MMF compared to environmental flow. Only few months of Dhaleshwari and Shitalakhya exhibit the conditions of withdrawal scenario as the MMF was more than environmental flow. In few months of low flow season, Turag, Buriganga, Balu and Tongi Khal exhibit the situation when MMF was more than environmental flow but no available water to be withdrawal due to poor condition of water quality. Results indicate that the withdrawal scenarios decrease the amount of DO and increase the amount of BOD. Conversely, augmentation scenarios increase DO up to

16.43% and decrease BOD up to 8.58% for 100% of available flow augmentation. Highest value of DO and lowest value of BOD for a specific month of a location were observed when 100% of available flow was augmented among the four augmentation scenarios. DO increased in maximum amount in May at Dhaleshwari and BOD decreased in maximum amount in April at Shitalakhya for 100% of available flow augmentation as the amount of available flow is quite high in Dhaleshwari and Shitalakhya compared to other Dhaka peripheral rivers. The effect of flow augmentation is not that much remarkable at Turag, Buriganga, Balu and Tongi Khal due to severely polluted water of Turag, Buriganga and less amount of available flow compared to Dhaleshwari and Shitalakhya. Though increases of DO and decreases of BOD occur in response to the augmentation scenario, the amount of change in DO and BOD is not that much significant even for 100% augmentation of available flow because it does not satisfy the inland river water standard of DO and BOD. It is tough to improve the water quality by implementing only the withdrawal and augmentation scenario without controlling the external source of pollution as the poor condition of water quality and flow availability. This research will greatly contribute and introduce new method for cleansing the heavily polluted river in future.

LIST OF ABBREVIATION

ACRONYM	ELABORATION
ArcGIS	Arc Geographic Information System
BWDB	Bangladesh Water Development Board
HEC-RAS	Hydrologic Engineering Center River Analysis System
MLD	Millions of Liters Per Day
ETP	Effluent Treatment Plant
NSE	Nash- Sutcliffe efficiency
PBIAS	Percent Bias
PCA	Principal Component Analysis
PRA	Participatory Rural Appraisal
RSR	RMSE-Observations standard deviation ratio

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CHAPTER ONE

INTRODUCTION

1.1 Background

Bangladesh is the 95th largest country by area, at the same time 8th most populous country in the world (World population review, 2019). Dhaka, the capital of Bangladesh, is the most populated city situated in central Bangladesh along the Buriganga river. The city lies on the lower reaches of the Ganges Delta and covers a total area of 306.38 square kilometers (Wikipedia contributors, 2019). The Greater Dhaka Area includes Dhaka and the municipalities have a total population of 19.84 million, and the city has shown population growth of about 4.2% annually (Dhaka population, 2019). If this population growth remains steady, in 2020 and 2030 we will have around 21 million and 27 million occupants respectively (Bangladesh Bureau of Statistics, 2019). One of the main reasons behind this uncontrolled population growth is the inward migration from rural areas which is creating unprecedented socio-economic challenges. From the early sixties, industrial revolution started to spring up slowly in Bangladesh and the development of new industries throughout the country, specifically around Dhaka city is continuing. Islam et al. (2009) showed that Dhaka city is expanding unsystematically with an annual rate of 3.5% to accommodate huge population influx of more than seven million people (Islam et al., 2009).

The major export commodity of Bangladesh is garments which made USD 12.3 billion back in 2009 fiscal year (Economy watch content, 2010). 78% of the total export earning in Bangladesh comes from textile and textile related goods which contribute 12% to GDP. But the textile and readymade garments sector generate huge volume of water-based effluent during the wet processing due to use of enormous volume of water either in the actual chemical processing or during reprocessing in preparatory, dying, printing and finishing. Also, the tanneries and factories around Dhaka city, for example, Hazaribagh and Keranigonj regularly discharge huge amounts of waste into the Dhaka peripheral rivers i.e. Buriganga, Shitalakkha, Balu, Turag and Bangshi (Kamal, 2016). The generated waste or effluent is destroying the chemical, physical and biological characteristics of water in respect to suitability for an intended purpose.

According to the study of the World Bank in 2009, the peripheral river system of Dhaka city receives 1.5×10^6 $m^3$of waste effluent every day from 7,000 industrial units in the surrounding areas and another 0.5×10^6 $m^3$from other sources (Ahmed and Bramley, 2015). As a consequence, the water quality of the river system has deteriorated tremendously thus hampering the ecological balance. In the pre-monsoon and post-monsoon season, the flow is far below the requirement. Though the flow is sufficient in the monsoon season, the waste disposal into the river system remains unchanged (Magumdar, 2005). The flow which is required to maintain the health of the river system, i.e. environmental flow or e-flow cannot be maintained throughout the year (Markoff, 2017). As a result, the flow of the rivers becomes stagnant. The Buriganga, which once was considered the life of Dhaka city, today is the dying river and also the most polluted river of Bangladesh (Kibria and Kadir, 2015). This river most specifically polluted by the tannery waste located in Hazaribagh and in dry season the river becomes very toxic as the amount dissolved oxygen becomes very low (Quader, 2015). The daily untreated waste of Tejgaon metropolitan industrial area is around 12000 m^3 which consists of waste from soap industries, dyeing, pharmaceuticals, metal industries etc. (Freeman et al., 2013). These untreated effluents are directly discharged into the Balu river through Begunbari and Narai canal. As the water from Balu river flows into Shitalakhya river and the water from Shitalakhya river is used in Saydabad water treatment plant, the situation poses a threat for the Dhaka city dwellers (Haque, 2018). Beside this, there are also several industries like textiles and dyeing, paper and pulp, jute, pharmaceuticals, fertilizers, etc of moderate to big size and several urban developments along the entire stretch of the river (Alam et al., 2012). These waste flows to Sitalakhya river directly or through Killarpul khal, Kalibazar khal and Tanbazar khal increasing the pollution load.

The water supply in Dhaka is less than the water demand and 25% people of Dhaka city has no direct access to potable water (Nishat et al., 2008). The demand of water is more than 0.73 km^3 per year whereas, the authority can supply only 0.51 km^3 per year and the water quality is on danger level as well (Rahman et al., 2012). The daily water demand of Dhaka city is around 2.50E+09 to 3.00E+09 liter for 17 million residents of which 78% is supplied by extracting groundwater while the remaining 22% is supplied after treating the water of the surrounding rivers (DWASA, 2016). Four surface water treatment plants, i.e.

Saidabad WTP Phase I; Chandnighat Water Works, Godnail and Sonakanda WTPs have a total installed capacity of 1630 MLD and the present production from these plants is around 500 MLD (Haque, 2018). Previously government took several decisions for example, tannery shifting to Savar area and subsidy from the toxic industries for establishing Effluent Treatment Plant (ETP) (Bhowmik, 2008), but none of these decisions have been implemented (Haque, 2018). Therefore, water quality analysis of surface water system is obligatory to maintain the ecological balance.

Dissolved oxygen (DO) and Biochemical Oxygen Demand (BOD) are two of the most important parameters of water quality measurement of any surface water due to their significant impacts on the sustainability of aquatic life. The amount of oxygen dissolved in a water body for example lake, river or stream in known as DO (Web Finance Inc., 2019). DO is the most important indicator of the health of a water body and its capacity to support a balanced aquatic ecosystem of plants and animals. It is necessary for the survival of fish, invertebrates, bacteria, underwater plants and for the decomposition of organic matter (Fondriest staff, 2019). On the other hand, BOD is a measure of the quantity of oxygen used by microorganisms in the oxidation of organic matter (Real Tech Inc., 2019). BOD is an important water quality parameter because it provides an index to assess the effect of discharged wastewater will have on the receiving environment (Ipsaro, 2019). When the BOD is low, there is an abundance of oxygen which leads to good water quality. A study was done by the collaboration of Dhaka WASA and World Bank which found the water of the six rivers surrounding the Dhaka city is unusable for humans, aquatic lives and industry. The water has been polluted to the extent that it is almost impossible to treat and make it usable again for human being. Both DO and BOD of Dhaka peripheral rivers are far away from the acceptable limit. In Bangladesh, the standard level of DO in the water sets by the Department of Environment (DoE) is 6 mg/liter. Study shows that, the amount of DO in Dhaka peripheral river network is far below the standard level reference. In case of BOD, the river network has more than 2 mg/liter, which is the maximum level of BOD in potable water (Khan, 2016).

Previous study showed that the water demand of Dhaka city will rise to a very high extent over the next 20 years which would be a major challenge to meet the water demand in the future using the available sources (Haque, 2018). Although there is enough water in the Dhaka peripheral river network, but the water cannot be considered as a good source due to rapid urbanization, industrialization and excessive population growth. A study found that 50-60% of total waste is from industrial source and the other 40-50% is from domestic source (DoE, 2016).

Several researchers have studied the water quality parameters of different rivers around the world though there are very few studies in Bangladesh (Rahman and Hossain, 2008; Whitehead et al.,2018; Haque, 2018; Biswas et al., 2015; Rahman et al., 2012). Magumdar (2005) showed that the water quality of the upper and lower reaches of the Shitalakhya and the Dhaleswari is least polluted and can be used for water treatment (Magumdar, 2005). Rahman and Hossain (2008) developed a GIS based map of the study area using ArcGIS showing the water quality sampling points and presented information spatially on existing level of water quality parameters (Rahman et al., 2008).

HEC-RAS, a well-known computer program for water resources engineering field is capable to analyze several hydraulic and water quality analysis. Several researchers have used HEC-RAS for hydrodynamic analysis of different rivers in Bangladesh. Mahmud et al. (2017) studied the behavioral and seasonal variation of hydrodynamic parameters of Padma river using HEC-RAS due to the change from meandering river to braided river. The study showed velocity, water level and discharge are maximum during monsoon season which results high sediment transport rate and erosion/deposition of river bed (Mahmud et al., 2017). Masood and Takeuchi (2011) studied the flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model. In that study the inundation simulation was conducted by HEC-RAS for flood of 100-year return period and the result showed that the maximum depth is 7.55 m at the southeastern part of that area and affected area is more than 50% (Masood and Takeuchi, 2011). HEC-RAS is not very common for doing water quality analysis in Bangladesh. The water quality analysis on Dhaka peripheral river network has not been studied yet as well. So, in this study a calibrated and validated 1D hydrodynamic and water quality model of Dhaka peripheral river network have been setup by HEC-RAS. To assess the water quality of every river of Dhaka peripheral river network, mean monthly flow (MMF) and environmental flow have been calculated using the discharge data of 20 years. After that, scenarios for flow withdrawal and augmentation have been developed. The effect of flow withdrawal and augmentation to maintain the water quality standard on every river of the Dhaka peripheral river network have been assessed. This research will greatly contribute and introduce new method for cleansing the heavily polluted river in future.

1.2 Justification of present study

Several studies have been carried out throughout the world using the concept of hydrodynamic analysis, water quality analysis, environmental flow assessment, flow augmentation and the combination of these concepts. Hydrodynamic analysis and water quality analysis have been done separately in Bangladesh for single or multiple rivers. The idea of hydrodynamic analysis and water quality analysis along with developing the flow scenario by doing the environmental flow assessment for Dhaka peripheral river network is novice. The flow scenario has been developed by determining the flow withdrawal at first and then the flow augmentation. Therefore, this study deals with the water quality parameters specially dissolved oxygen (DO) and biochemical oxygen demand (BOD). The two most important water quality parameters required to assess the waste assimilative capacity of the coastal water are BOD and DO (Thomann and Mueller, 1987). DO is depleted by the waste influx, especially the organic particulate matter in the process of organic degradation. As a gross measure of the oxygen demanding potential of the effluent, BOD is employed. Assimilative capacity varies in accordance with variations in hydrodynamic conditions and other ecological processes (Babu et al., 2006). So, these two parameters have been chosen due to their significant impacts on ecological balance. To perform this study, one-dimensional hydrodynamic model and water quality model have been developed using HEC-RAS (Hydrologic Engineering Center's River Analysis System). HEC-RAS is an integrated system of software, designed for interactive use for interactive use in a multi-tasking environment (Brunner, 2010).

1.3 Selection of the Study Area

The study area covers around 195 km length encompassing Dhaka city which has been showen in Figure 1.1. There are six rivers flowing along the periphery of Dhaka city and they are Balu, Shitalakhya, Turag, Dhaleshwari, Buriganga and Tongi Khal. Turag is a narrow and short river generates from Banshi River at Kaliakair, crosses Mirpur Bridge on Dhaka Aricha Highway at Amin Bazar and finally merges into Buriganga at Kholamara of Keranjiganj (Khondkar and Gousia, 2013). Buriganga is the most polluted river among six Dhaka peripheral rivers. It has its main flow only from Turag. Though the lower part of Buriganga is open throughout the year, but the present head near Chaglakandi has silted up and opens only during flood (Haque, 2018). A branch of Turag generating from the Birolia union of Savar Upazilla, flowing eastward side of Tongi and meeting Balu River at Trimohoni of Uttarkhanupazilla is known as Tongikhal. Shitalakhya flows through Monohordi upazilla of Norshingdi district and Narayanganj city until it merges with Dhaleshwari near Kalagachia. Balu River flows through the extensive swamps of Beel Belai located at the east of Dhaka, merging into the Shitalakhya near Demra. It is also connected to Shitalakhya by Suti River near Kapasia and to Turag River by Tongi Khal. During the flood season, Balu carries flood water from Turag and Shitalakhya which is important for local drainage and access to small boats (Quader, 2015). Dhaleshwari starts as a distributary of the Jamuna River near the northwestern tip of Tangail District. This river divides into two parts, Kaliganga which flows to south and Barinda which flows to east, then flows as Bangshi river upto Savar. Dhaleshwari also flows through the southern part of greater Dhaka Zilla finally to merge with Shitalakhya near Narayanganj District.

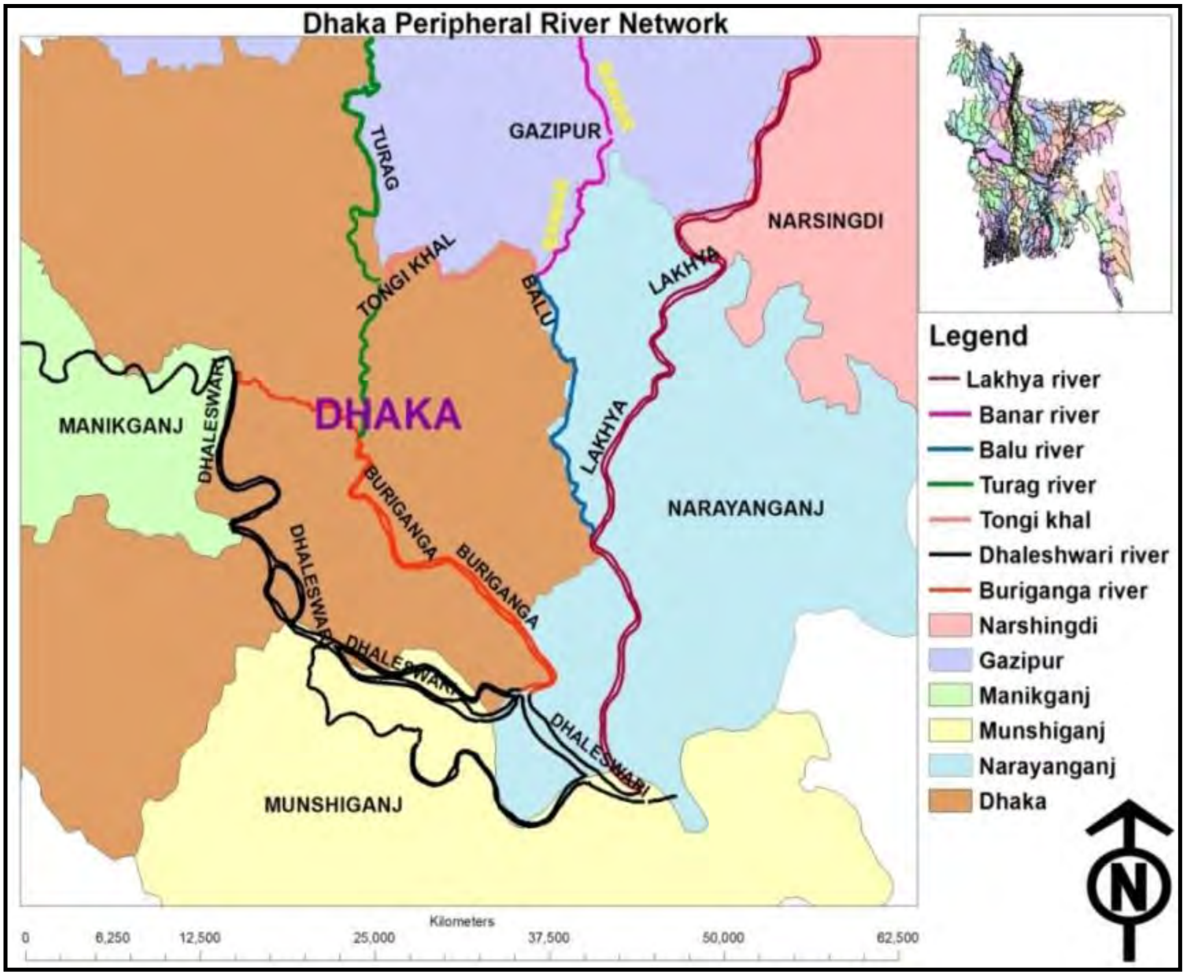

Figure 1.1: Study area showing Dhaka peripheral river network

The mid to lower reach around 25 km of Balu river, 65 km of Shitalakhya river, 35 km of Turag river, 30 km of Dhaleshwari river and full reach around 26 km of Buriganga river and 14 km of Tongi Khal creating the Dhaka peripheral river system have been selected as the study area. Table 1.1 shows the reach lengths and river stations of different rivers of the study area. Station Kalialoir, Mirpur of Turag; Dhaka Mill Barrack, Hariharpara of Buriganga; Jagir, Kalatia, Rekabi Bazaar, Kalagachia of Dhaleshwari,; Ghorashal, Demra, Fatulla of Shitalakhya; Pubali, Demra of Balu and Tongi of Tongi canal have been included in the study area. Figure 1.2 shows the locations of different river stations which have been considered in the study area. A one-dimensional hydrodynamic and water quality model has been developed by HECRAS to develop the flow scenario. This study also analyzes the effect of flow withdrawn and subsequent flow augmentation to maintain the water quality of Dhaka peripheral river network based on two most important water quality parameters namely, dissolved oxygen (DO) and biochemical oxygen demand (BOD).

Table 1.1: Reach lengths and stations of the study area

River	Reach length (km)	Station Name/ ID
Turag	35	Kaliakoir/ SW 301, Mirpur/ SW 302
Buriganga	26	Dhaka mill barrack /SW 42, Hariharpara /SW 43
Dhaleshwari	30	Jagir /SW 68.5, Kalatia /SW 70, Rekabi Bazaar /SW 71A, Kalagachia /SW 71
Shitalakhya	65	Ghorashal /SW 178, Demra /179, Fatulla /SW 180
Balu	25	Pubali /SW 7, Demra /SW 7.5
Tongi canal	14	Tongi /SW 299

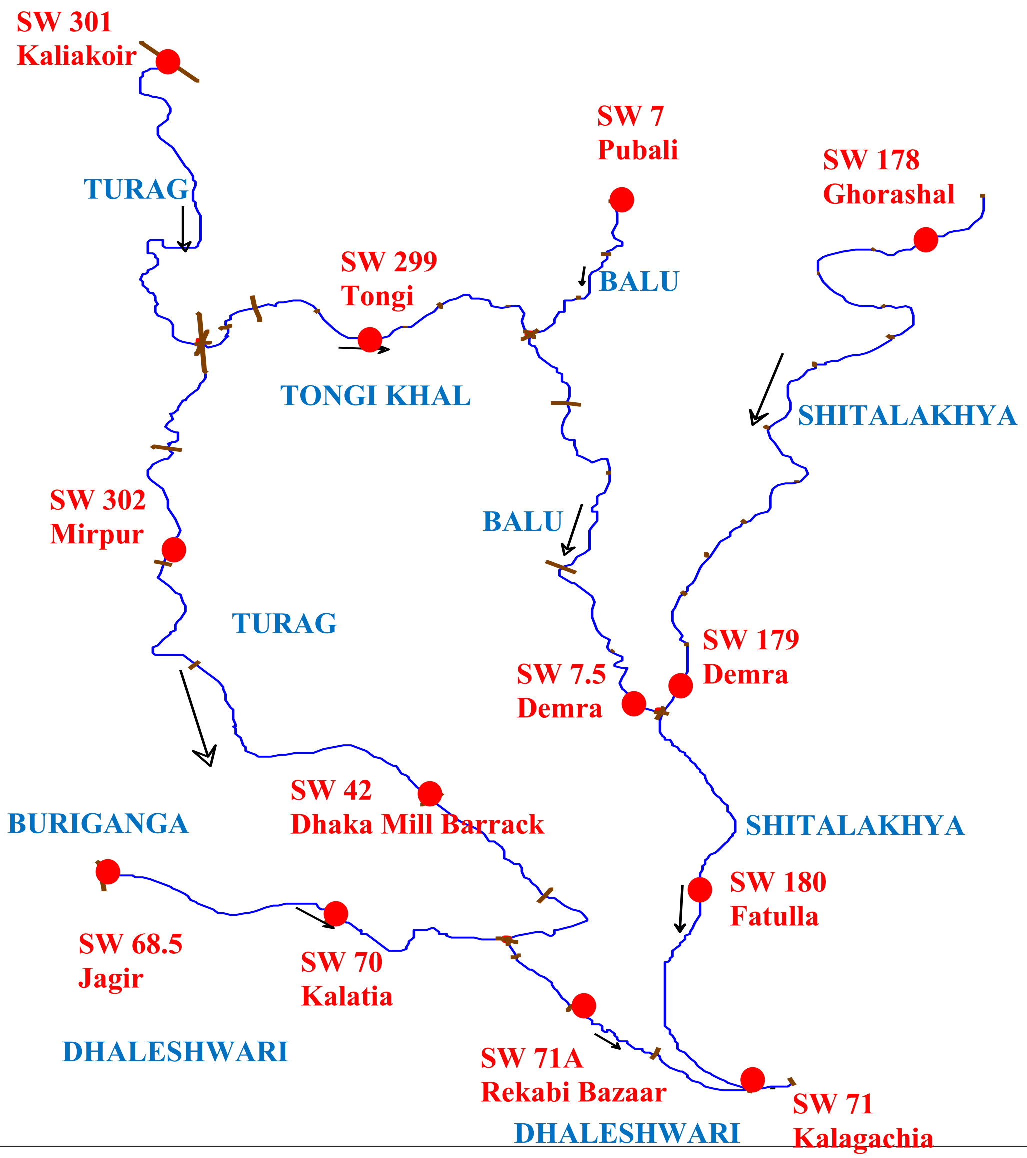

Figure 1.2: Location of different river stations in the study area

1.4 Objectives of the study

The research aims at the following objectives:

- **i.** To setup a hydrodynamic and water quality model for Dhaka peripheral river system.
- **ii.** To determine the flow scenario for the withdrawal and flow augmentation
- **iii.** To assess the effect of withdrawal and flow augmentation to maintain the water quality standard on the basis of DO and BOD.

Therefore, this study would help us to setup a calibrated-validated hydrodynamic and water quality model of Dhaka peripheral river network. Hence detailed assessment of water quality condition based on DO and BOD in response to flow scenarios could be achieved.

1.5 Organization of the thesis

Chapter 1 presents a brief overview of the background and area of the study, objectives and possible outcomes of the thesis.

Chapter 2 starts with the findings from few previous studies on water quality analysis around the world as well as in Bangladesh. This chapter discusses about the salient features of models used in this study including the user interfaces, data storage & management, reporting capability and the theoretical background of simulation using HEC-RAS in hydrodynamic and water quality assessment. The chapter also includes general idea about ArcGIS.

Chapter 3 describes the methodology employed to carry out the research work in detail with the elaboration of different steps required for the hydrodynamic and water quality modeling. It includes collection of required data to set up hydrodynamic and water quality model; procedure to calibration-validation and performance evaluation of hydrodynamic and water quality model, to estimate environmental flow using Tennant method and Flow Duration method, to assess water quality parameters, and to develop flow scenario for flow withdrawal and augmentation.

Chapter 4 includes result and discussion of this study. This chapter present the output of calibration-validation and performance evaluation of the hydrodynamic and water quality model, calculation of environmental flow using Tennant method and Flow Duration method, estimation of available flow in low flow and high flow season, development of flow scenario for flow withdrawal and augmentation based on available flow and the response of DO and BOD to the developed flow scenarios.

Chapter 5 includes the conclusions of the study with a summary of the results obtained and recommendation for advanced study relevant to this study concept.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

This chapter represents the definition of hydrodynamic, water quality, environmental flow, flow augmentation and the literature review on these specific topics around the world as well as in Bangladesh. The chapter includes about the salient features of models used in this study including the user interfaces, data storage & management, reporting capability and the theoretical background of simulation using HEC-RAS in hydrodynamic and water quality assessment. The chapter also discussed general idea about ArcGIS.

2.2 Hydrodynamics

The study of motion of liquids and in particular, water is known as Hydrodynamics, the branch of science that deals with the dynamics of fluids, especially incompressible fluids in motion (Mondal et al., 2016). The motion of fluids is described through the set of equations of computational hydrodynamic models, which are derived from Newton's laws of motion and describe the action of force applied to the fluid; that is, the resulting changes in flow.

2.2.1 Previous studies on Hydrodynamics analysis

Considering the importance of understanding the hydrodynamic characteristics of alluvial rivers, river courses throughout the world and major water courses of South Asia as well as Bangladesh including Ganges, Padma, Meghna, Jamuna, Surma and Gorai have drawn attention of different national and international researchers. Mondal (2016) estimated the hydrodynamic pattern changes and morphological parameter including bed shear stress of Ichamati River using HEC RAS model in West Bengal of India (Mondal et al., 2016). Tang et al. (2016) studied on Modeling and analysis of hydrodynamics and water quality for rivers in the northern cold region of China (Tang et al., 2016). Roy et al. (2016) studied hydro-morphological behavioral change of Padma river using Delft-3D (Roy, 2016). Saha and Navera (2016) studied different hydrodynamic characteristics and features of Surma

River and performed analysis on change in peak flow due to flash flood (Saha and Navera, 2016). Khan et al. (2015) developed a hydrodynamic model of Khowai river using HECRAS which can be used to estimate the tidal volume of water flowing through the river and generation of watershed of Khowai river to estimate the runoff discharge and capacity of the Khowai river basin (Khan et al., 2015). Rahman and Yunus (2016) analyzed the hydrodynamic and morphological parameters of Gorai river using Delft 3D focusing the effect of dredging on the hydro-morphological parameters (Rahman and Yunus, 2016). Several studies have been conducted to understand the hydro-morphodynamic behavior of the rivers of Bangladesh though most of the studies are based on a single river. So, a study on Turag, Buriganga, Dhaleshwari, Shitalakhya, Balu rivers and Tongi Khal encircling the Dhaka metropolitan area creating a river network is of immense importance.

2.3 Water quality

Water quality refers to the chemical, physical, biological, and radiological characteristics of water. These physical, chemical and biological substances of water vary depending on season, the natural setting of the watershed, land use pattern and to a large extent on human activities (Haque, 2018). The most commonly used water quality parameters that can be classified into different categories have been shown in Table 2.1. The water quality is a measure of the condition of water relative to the requirements of one or more biotic species and to any human need or purpose. It is most frequently used by reference to a set of standards against which compliance, generally achieved through treatment of the water, can be assessed. The most common standards used to assess water quality relate to health of ecosystems, safety of human contact, and drinking water (Wikipedia contributors, 2019).

Table 2.1: Commonly used water quality parameters*

Classification	**Water quality parameters**
General, physical and chemical	Temperature, Dissolved Oxygen (DO), pH, Conductivity, Alkalinity, Suspended Solids
Nutrients	NH_4-N_2 NO_2-N, NO_3-N, PO_4^{3-}
Inorganic	Major ions: Na, K, Ca, Mg, Chloride, Sulphate Metals: Fe, Mn, Al, Hg, Cd, Pb, Zn, Cu, Ni, Cr
Organic	BOD, TOC, COD, Pesticides, Phenols, Organic Solvents, Oil & Hydrocarbons
Biological	Chlorophyll-A, Phyto- and Zooplankton, Macrophytes, Macrobenthos, Fish
Microbiological	Total and faecal coliforms, Streptococci, Salmonella

*Source: Haque, (2018)

2.3.1 Previous studies on Water quality analysis

The demand of drinking water in Dhaka is meet up by several deep tube wells which were installed by Dhaka Water Supply Authority (DWASA) of Bangladesh that tap the upper aquifers. Study shows that 78% of water comes from groundwater sources tapping through deep tube wells and the remaining 22% come from the water treatment plant located at Saidabad, Chadnighat and two small units of Narayanganj (DWASA, 2014). In this process the ground water is decreasing in an alarming rate which can cause severe environmental hazards such as land subsidence, prolonged water logging, alteration in vegetation etc. This emphasize the conjunctive use of groundwater and the water from Dhaka peripheral river network as the water supply sources to maintain the balance between anthropogenic demand and water's natural availability. Rahman and Hossain (2008) analyzes the present water quality scenario along the surrounding rivers of Dhaka City and proposed a new intake point by using GIS tools (Rahman and Hossain, 2008). Magumdar (2005) studied the water contamination of Dhaka peripheral river network including the historical trend of the pollution. The study found that the water of the upper and lower reaches of the Shitalakhya river and Dhaleshwari river is least polluted and can be used for the treatment of contaminant water of Dhaka peripheral river network (Magumdar, 2005). Whitehead et al. (2018) studied the Turag-Tongi-Balu river system and found that in dry season dissolved oxygen tends to be almost zero, high organic loading together with extreme levels of Ammonium-N and total coliform in the water (Whitehead et al.,2018).

Water pollution by anthropogenic heavy metal pollution is a critical issue in Bangladesh. Rapid urbanization, industrialization, agricultural development, excessive population growth and upstream withdrawal of water have degraded the river water quality in Bangladesh (Haque, 2018). Table 2.2 represents the important drinking water quality standards of Bangladesh and WHO guidelines.

Table 2.2: Important drinking water quality standards*

Water Quality Parameters	**Unit**	**Bangladesh Standards (ECR 1997)**	**WHO Guideline Values (1996)**
Ammonia (NH_3)	mg/L	0.5	1.5
Arsenic	mg/L	0.05	.01
BOD5 at 20° C	mg/L	0.2	-
Cadmium	mg/L	0.005	0.005
Calcium	mg/L	75	-
Chloride	mg/L	150-600	250
Chlorine	mg/L	0.2	0.5
Chloroform	mg/L	0.09	0.2
Chemical Oxygen Demand	mg/L	4	-
Coliform (Fecal)	No/100 ml	0	0
Coliform (Total)	No/100 ml	0	0
Color	Pt-Co unit	15	15
Dissolved Oxygen	mg/L	6	-
Hardness (as $CaCO_3$)	mg/L	200-500	500
Iron	mg/L	0.3-1.0	0.3
Lead	mg/L	0.05	0.01
Mercury	mg/L	0.001	0.001
Nitrate	mg/L	10	50
Nitrite	mg/L	<1	3
Odor	-	Odorless	Odorless
Oil and Grease	mg/L	0.01	-
pH	-	6.5-8.5	6.5-8.5
Phosphate	mg/L	6	-
Silver	mg/L	0.02	-
Sodium	mg/L	200	200
Suspended solids	mg/L	10	-
Total dissolved solids	mg/L	1000	1000
Tin	mg/L	2	-
Turbidity	NTU	10	5
Zinc	mg/L	5	3

*Source: Ahmed and Rahman (2012)

Saha and Rahman (2018) analyzed the sources of heavy metals contamination in Dhalaibeel and Bangshi River and determined the level of metal concentration by using multivariate statistical approaches and identified the discharge of untreated industrial effluents into the nearby water bodies as the main deterioration reason of the water quality (Saha and Rahman, 2018). Biswas et al. (2015) studied the status of heavy metal including Cd, Cr, Ni, Pb and Zn in the peripheral river network. The study showed that the water from Dhaka peripheral river network can be used for public sewer, inland water and irrigated land based on the concentrations of Cd, Cr, Ni and Zn but based on the concentration of Pb, it is unusable. The water cannot be used for drinking as it does not pass the standards of drinking water. (Biswas et al., 2015). Heavy metals have the tendency to accumulate in various organs of marine organisms, especially fish which in turn may enter the human metabolism through consumption causing serious health hazards. Rahman et al. (2012) studied the concentrations of eight heavy metals i.e. Pb, Cd, Ni, Cr, Cu, Zn, Mn, and As in two different seasons in the muscles of ten species of fish collected from Bangshi River. The study showed that Cd is the least accumulated and Zn is the most accumulated metal in the fish muscles (Rahman et al., 2012).

2.4 Environmental Flow

Freshwater resources are under increasing threat due to anthropogenic activities, both in terms of consumptive and non-consumptive use (Richter et al. 2011). The increasing societal demands for water have led to substantial flow (i.e. discharge) alterations in rivers. Flow alteration can directly affect the physical attributes of rivers and the resulting ecological changes (Clarke et al. 2008). Furthermore, the risk of adverse changes will increase with increasing magnitude of flow alteration (Poff and Zimmerman, 2010). Moreover, the effects of extreme daily fluctuations such as hydropeaking operations have also been shown to lead to potentially deleterious effects on numerous biotic and physical components of riverine ecosystems (Bain, 2007). As a result, concept of Environmental flow was developed.

Environmental flow describes the quantity, quality and timing of water flows required to sustain the freshwater and estuarine eco system and the human livelihood and well-being that depend on the eco-system. An environmental flow assessment (EFA) for a river may be defined simply as an assessment of how much of the original flow regime of a river should continue to flow down it and onto its floodplains to maintain specified, valued features of the ecosystem (Tharme, 2003). Environmental flow depends on multiple factors, such as the size of river bed, flow seasonality at both coarse and fine time scales, flow duration characteristics, surface and subsurface water levels and the downstream ecological value and chemical status of the surface water bodies (Tegos et al., 2017).

2.4.1 Methodologies to assess Environmental flow

Flow management is an ecological imperative which is reflected in a vast array of assessment methodologies internationally (Linnansaari et al., 2012). Tharme (2003) identified over 200 individual environmental flow assessment methodologies and classified these techniques into four general categories: (a) Hydrological method, (b)

Hydraulic method, (c) Habitat simulation and (d) Holistic methodologies. Table 2.3 summarizes the commonly used environmental flow assessment methods.

Table 2.3: Comparison of four general categories of environmental flow assessment*

Category	Method	Source
Hydrological	Tennant (Montana)	Tennant (1976)
	Flow-Duration Curves	Searcy (1959)
	Aquatic Base Flow (ABF)	Caissie and El-Jabi (1995)
	7Q10	Caissie and El-Jabi (1995)
	7Q2	Belzile et al. (1997)
	Median Monthly Flow (Q50)	Caissie and El-Jabi (1995)
	Range of Variability Approach (RVA)	Richter et al. (1997)
	Sustainability Boundary Approach and Presumptive Standard	Richter (2010); Richter et al. (2011)
Hydraulic Rating	Wetted Perimeter Inflection Point Method	Gippel and Stewardson (1998)
	Flowing Perimeter Method	Gippel and Stewardson (1998)
	R-2 Cross	Espegren (1996)
Habitat Simulation	PHABSIM (Physical HABitat SIMulation system)	Bovee (1982)
	RYHABSIM (River hYdraulic and HABitat SIMulation)	Jowett (1989)
	EVHA (EValuation de HAbitat)	Ginot (1995)
	RSS (River System Simulator)	Alfredsen et al. (1995)
	CASIMIR (Computer Aided SIMulation of habitat In Regulated streams)	Jorde (1996)
	River2D	Blackburn and Steffler (2003)
	MesoHABSIM	Parasiewicz (2001)
	MesoCASIMIR	Eisner et al. (2005)
	Generalized Habitat models (e.g. STATHAB)	Lamouroux and Jowett (2005)
Holistic frameworks	Building Block Method (BBM)	Tharme and King (1998)
	DRIFT (Downstream Response to Imposed Flow Transformation)	King et al. (2003)
	Benchmarking	Arthington (1998; et al. 2006)
	ELOHA	Poff and Zimmerman (2010)

*Source: Linnansaari et al., 2012

Though the environmental flow assessment is quite common around the world, but the concept is not that much studied in Bangladesh. In this study, the environmental flow has been estimated for Dhaka peripheral river system to develop the flow scenario. Among the available approaches within the concept of hydrological method of estimating environmental flow, Tennant method and Flow duration curve method have been widely used to quantify the environmental flow (Tharme, 2003) and hence are used in this study.

2.4.1.1 Tennant Method:

According to Tennant method, environmental flow requirement is a percentage of the mean annual flow of a river. For different habitat conditions like flushing, excellent and good flow conditions, the required flow varies from 10% to 200% of the mean annual flow (Tennant, 1976). Tennant method is based on the reasoning that mean annual flow represents flow which has sustained the habitat of the flora, fauna and human activities of the river for several years and hence various percentage of the mean annual flow can be used to determine environmental flow requirement. Table 2.4 represents the Tennant's recommendation for environmental flow to support varying qualities of fish habitat. In the Table "habitat quality" represents the quality of the habitat that the authority desires to achieve and "percentage of mean annual flow" represents the percent of MAF that is needed to achieve that habitat quality. Seven of this classification (optimum to severe degradation) characterizes habitat quality for fish and aquatic wild life and the eighth (flushing or maximum) provides a flushing flow. According to MAF method the required percentage of MAF for habitat quality range from <10% (severe degradation) to 60%-100% (optimum range), the flushing flow requirement being 200% of MAF. The Tennant method requires the MAF can be calculated from a historic and or synthetic flow.

Table 2.4: Percent of MAF according to Tennant Method for Various Habitat Quality*

Habitat Quality	**Percent of Mean Annual Flow (MAF)**	
	Low Flow Season	**High Flow Season**
Flushing or Maximum	200	200
Optimum	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe Degradation	<10	<10

*Source: Tennant, (1976)

2.4.1.2 Flow-Duration curve

The flow-duration curve is a cumulative frequency curve that show the percent of time specified discharges were equaled or exceeded during a given period. It combines in one curve the flow characteristics of a stream throughout the range of discharge, without regard to the sequence of occurrence. The flow duration curve is the integral of the frequency diagram. To prepare a flow-duration curve, the daily, weekly, or monthly flows during a given period are arranged according to magnitude, and the percent of time during which the flow equaled or exceeded the specified values is computed. The curve, drawn to average the plotted points of specified discharges versus the percent of time during which they were equaled or exceeded, thus represents an average for the period considered rather than the distribution of flow within a single year (Searcy, 1959). Figure 2.1 represents a flow-duration curve of daily flow at Bowie Creek, Hattiesburg, Mississippi, USA. The x-axis is representing percent of time indicated discharge was equaled or exceeded and the y-axis is representing discharge in cubic feet per second.

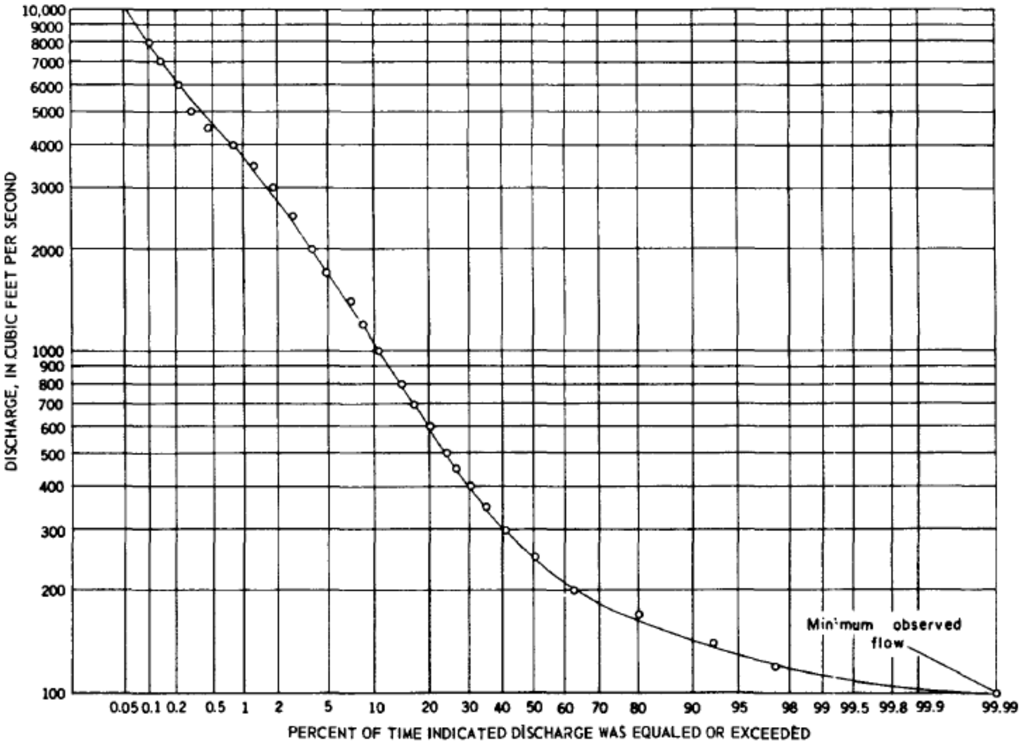

Figure 2.1: Flow-Duration curve of daily flow at Bowie Creek near Hattiesburg*

*Source: Searcy, 1959

2.5 Flow augmentation

According to U.S. Department of the Interior, Bureau of Reclamation, flow augmentation is the release of water stored in a reservoir or other impoundment to increase the natural flow of a stream. During the periods of low natural runoff, water from these reservoirs can be used to sustain certain minimum stream flows, thereby insuring adequate water supplies to downstream users and improving water quality through augmentation effects (Baker and Kramer, 1971).

2.5.1 Flow augmentation to maintain the water quality

There are two principal ways in which flow augmentation can affect water quality. The first of these is through dilution effects accompanying the increased flow. The augmentation water should have a higher DO content, a lower BOD, lower nutrient levels and lower concentrations of toxic chemicals than agricultural, domestic or industrial effluents entering the stream. Consequently, the greater the amount of augmentation water relative to waste effluents, the better the water quality should be.

The second way which flow augmentation can affect water quality is through physical effects accompanying increased flow. These include increases in flow velocity (decreases in time of passage), altered rates of gas exchange and altered rates of gas exchange and altered expanses of riffle conditions in the stream.

2.5.2 Impact of flow augmentation

In highly developed country like USA, Canada, Japan etc., the practice of flow augmentation is quite common, and this method has been using for several years. In San Antonio River and Salado Creek of Texas, USA; recycled water replaces the use of groundwater for instream flow augmentation which improved the water quality and the return of sensitive, pollutant intolerant species. Water quality monitoring and fish surveys were conducted before and after augmentation began and improved water quality was observed (Eckhardt et al., 2003; Eckhardt, 2004; SAWS, 2011). In Bell Creek, Sequim, Washington; flow was augmented using the recycled water to maintain benthic species and improve salmon habitat (Thomas, 2001; Latino and Haggerty, 2007). During the summer and fall, the Grand River Conservation Authority (GRCA) of Ontario, Canada releases water from its seven multipurpose reservoirs to maintain minimum flows in the Grand River system. The minimum flows ensure there is enough water to support the operation of municipal wastewater, drinking water plants and the ecosystem. Table 2.5 summarizes several examples of flow augmentation to improve the water quality and environmental health.

Table 2.5: Examples of water reuse for flow augmentation*

Location	Wastewater treatment	Description	Motivation	References
San Antonio River (San Antonio, Texas)	San Antonio Water System operates three WRCs. Dos Rios and Leon Creek WRCs are conventional activated sludge facilities. Medio Creek WRC employs an extended aeration process. Tertiary treatment includes filtration and disinfection (chlorination and dechlorination, except for Medio Creek WRC, which uses UV disinfection).	Recycled water replaces the use of groundwater for instream flow at the downtown River Walk attraction, which also flows through a city park and zoo, at three new discharge locations. Monitoring shows improved water quality and the return of sensitive, pollutant intolerant species.	By the mid-1950s, headwater reaches near downtown were dry due to groundwater pumping. Reach downstream of WWTP discharge was considered a 40-mile (64-km) "dead zone" due to poor water quality. A City water recycling goal was to improve area streams by maintaining flows.	Eckhardt et al. (2003), Eckhardt (2004), SAWS (2011)
Salado Creek (San Antonio, Texas)		Water quality monitoring and fish surveys were conducted before and after augmentation began, and improved water quality was observed. Creek was removed from the 303(d) List of Impaired and Threatened Waterbodies for DO impairment.	See above. Impaired stream with low DO levels and occasional high fecal coliform. Community desired reliable base flow. Future discharge is under consideration at San Pedro Creek.	
Bell Creek (Sequim, Washington)	Sequim WRF. Includes tertiary treatment with UV disinfection and aeration via cascade structure.	Recycled water is discharged to maintain benthic species and improve salmon habitat (0.06 mgd or 250 m^3/day).	City Council Water Reuse Task Force identified enhancement of Bell Creek as the number one alternative (followed by irrigation). Flow is committed to improve salmon habitat year-round.	Latino and Haggerty (2007), Thomas (2001), WA Ecology (2000); Cupps and Morris (2005)
Hillsborough River, Tampa, Florida (not implemented)	Howard F. Curren Advanced WWTP. Proposed tertiary treatment with aeration and UV disinfection.	Tampa Bay Downstream Augmentation Project was not implemented in part due to public concerns about discharge quality, including PPCPs. Future augmentation (Alafia River) is being considered.	To use recycled water from the City of Tampa to augment river flows and allow upstream potable withdrawal to increase by an equal amount.	Latino and Haggerty (2007), Broome et al. (2006), City of Tampa (2009)
San Luis Obispo Creek (San Luis Obispo, California)	San Luis Obispo WRF. Primary, secondary with nitrification, and tertiary treatment with filtration and chlorination. Dechlorination and cooling tower prior to discharge.	WRF produces 3.6 mgd (14,000 m^3/day) recycled water, of which a minimum of 1.6 mgd (6,000 m^3/day) is released to creek at historical outfall. Creek habitat depends on recycled water discharge, which dominates summer flow.	Not originally intended as environmental enhancement. Observation of improved water quality following recycled water discharge to creek and presence of endangered species led to greater use for stream flow over landscaping and industrial uses.	DiSimone (2006), Asano et al. (2007)
Tossa de Mar Creek (Tossa de Mar, Spain)	Tossa de Mar Water Reclamation Plant (coagulation, flocculation, sedimentation, filtration, UV+chlorine disinfection).	Tertiary-treated recycled water from an artificial pond percolates through soil to the creek, preventing the creek from becoming dry in the summer and providing ecological benefits.	To use recycled water from the WWTP to establish vegetation and create a park using marginal land located between the WWTP and Tossa de Mar Creek.	Sala and de Tejada (2008), Sellarès et al. (2011)
Nobidome Stream (Tokyo, Japan)	Tamagawa-Johryu WWTP includes rapid sand filtration, partial P removal; chemical coagulation and ozonation added in 1989-1991.	Recycled water is viewed as an attractive water supply for stream augmentation in urban areas, as well as for creation of artificial streams.	Once an attractive riverine area of a Tokyo suburb, the stream dried when the headwaters were diverted in 1976.	Yamada et al. (2007), Minamiyama (2009)
Multiple rivers (Tokyo, Japan)	Ochiai WWTP process includes tertiary treatment by rapid sand filtration.		Low flow or dry rivers (Shibuyahawa, Furukawa, Nomikawa, and Megurogawa Rivers) due to rapid urbanization.	

*Source: Plumlee et at., 2012

2.6 Hydrodynamic model

The physical laws governing the flow of water in a stream are the principle of conservation of mass (continuity equation) and the principle of conservation of momentum (momentum equation). Equations 3.1 and 3.2 show the continuity and momentum equation respectively where x = distance measured along the channel, t = time, Q = flow, A_t = total flow area, q_l = lateral inflow per unit length, S_f = friction slope, z= elevation of water surface, $\partial z/\partial x$ = water surface slope and g= acceleration due to gravity (Bruner, 2010).

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \tag{2.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{2.2}$$

HEC-RAS can compute the water surface elevation at all required location for either a given set of flow data (steady flow simulation) or by routing hydrographs through the system (unsteady flow simulation). In this study, unsteady flow simulation is performed for which geometric data and unsteady flow data was required.

2.7 Water quality model

The water quality module uses the QUICKEST-ULTIMATE explicit numerical scheme to solve the one-dimensional advection-dispersion equation. The model simulates fate and transport of water temperature, arbitrary conservative and non-conservative constituents, dissolved nitrogen (NO_3-N, NO_2-N, NH_4-N and Org-N), dissolved phosphorus, algae, CBOD and dissolved oxygen. To run the water quality model, a calibrated HEC-RAS unsteady or steady flow model is necessary.

2.8 Salient Features of the Model used in the Study

The major tools used in this study are one-dimensional numerical model HEC-RAS 4.1.0 to do both the hydrodynamic and water quality analysis and ArcGIS for spatial data processing. General overview on the used software tools are presented below.

2.8.1 HEC-RAS

HEC-RAS is a computer program that models the hydraulics of water flow through Natural River and constructed channels. The program was developed by the US Department of

Defense, Army Corps of Engineers to manage the rivers, harbors and public works under their jurisdiction. Prior to the recent updated version, the program was one dimensional, but release of version 5.0 introduced two-dimensional modeling of flow including hydraulic effect of cross section shape changes, bends as well as sediment transfer in a river or channel network.

2.8.1.1 Capabilities of HEC-RAS

Major capabilities of HEC-RAS include: User Interface, Hydraulic Analysis Components, Data Storage and Management, Graphing and Reporting and RAS Mapper. The following is a description of the major capabilities of HEC-RAS.

User Interface

The user interacts with HEC-RAS through a graphical user interface (GUI) which focuses to make the use of the software easy maintaining a high level of efficiency. The interface provides with functions of File Management, Data Entry and Editing, Hydraulic Analyses, Tabulation and Graphical Displays of Input and Outputs, Inundation mapping and animations of water propagation and so on.

Hydraulic Analysis Components

The HEC-RAS system contains several river analysis components for: (i) steady flow water surface profile computations; (ii) one- and two-dimensional unsteady flow simulation; (iii) movable boundary sediment transport computations; and (iv) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines.

i. Steady Flow Water Surface Profile

This steady flow component is intended for calculating water surface profiles for steady gradually varied flow with handling capability of full channel network or a single river reach. The component is proficient for modeling subcritical, supercritical, and mixed flow regimes water surface profiles. The basic computation bases on the solution of one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation may be used in rapidly varied water surface profiles including mixed flow regime (i.e., hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences.

ii. One- and Two-Dimensional Unsteady Flow Simulation

This component of the HEC-RAS modeling system is capable of simulating one dimensional (1D); two-dimensional(2D); and combined 1D-2D unsteady flow through network of open channels, floodplains, and alluvial fans. The unsteady flow component can be used to perform subcritical, supercritical, and mixed flow regime calculations in unsteady flow. Few of the special features of the unsteady flow component include: Dam break analysis; levee breaching and overtopping; navigation dam operations; automated calibration features; and combined one and two-dimensional unsteady flow modeling.

iii. Sediment Transport/ Movable Boundary Computations

This component of the modeling system is intended for the simulation of 1D sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods. The sediment transport potential is computed by grain size fraction, thereby allowing the simulation of hydraulic sorting. Major features include the ability to model a full network of streams, channel dredging, various levee and encroachment alternatives, and the use of several different equations for the computation of sediment transport. This system can be used to evaluate deposition in reservoirs and predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation in fixed channels.

iv. Water Quality Analysis

This component of the modeling system is intended to allow the user to perform riverine water quality analyses. An advection-dispersion module is included with this version of HEC–RAS, adding the capability to model water temperature. This new module uses the QUICKEST-ULTIMATE explicit numerical scheme to solve the 1D advection-dispersion equation using a control volume approach with a fully implemented heat energy budget. Transport and Fate of a limited set of water quality constituents is now also available in HEC-RAS. The currently available water quality constituents are: Dissolved Nitrogen and Phosphorus; Algae; Dissolved Oxygen (DO); and Carbonaceous Biological Oxygen Demand (CBOD).

Data Storage and Management

Data storage is accomplished using "flat" files (ASCII and binary), the HECDSS (Data Storage System), and HDF5 (Hierarchical Data Format, Version 5). User input data are stored in flat files under separate categories of project, plan, geometry, steady flow, unsteady flow, quasi-steady flow, sediment data, and water quality information. Output data is predominantly stored in separate binary files (HEC and HDF5). Data can be transferred between HEC-RAS and other programs by utilizing the HEC-DSS. Data management is accomplished through the user interface. The user is requested to enter a single filename for the project and once the project filename is entered, all other files are automatically created and named by the interface.

Graphics and Reporting

Graphics include X-Y plots of the river system schematic, cross-sections, profiles, rating curves, hydrographs and inundation mapping. A three-dimensional plot of multiple cross sections is also provided. Inundation mapping is accomplished in the HEC-RAS Mapper portion of the software. Inundation maps can also be animated, and contain multiple background layers (terrain, aerial photography etc.). All graphical and tabular output can be displayed on the screen, sent directly to a printer (or plotter), or passed through the Windows Clipboard to other software, such as a word-processor or spreadsheet. Reporting facilities allow for printed output of input data as well as output data. Reports can be customized as to the amount and type of information desired.

2.8.1.2 Theoretical Basis of 1D Unsteady Flow Routing

For the unsteady flow analysis, the physical laws which govern the flow of water in a stream are the principal of conservation of mass (continuity) and the principal of conservation of momentum.

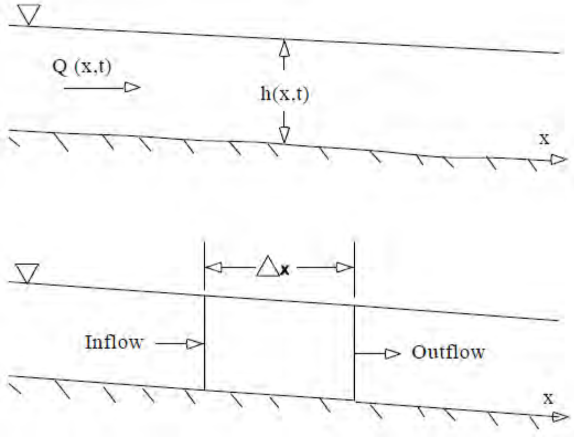

Figure 2.2: Elementary control volume

2.8.1.2.1 Continuity Equation

Conservation of mass for a control volume states that the net rate of flow into the volume be equal to the rate of change of storage inside the volume. Figure 2.2 shows the elementary control volume where x = distance measured along the channel.

Q (x,t) = flow at the midpoint of the control volume

AT= Total flow area= sum of active area A and off-channel storage area S.

The rate of inflow to the control volume can be written as follows:

$$Q - \frac{\partial Q}{\partial x}\frac{\Delta x}{2} \tag{2.3}$$

The rate of outflow as:

$$Q + \frac{\partial Q}{\partial x}\frac{\Delta x}{2} \tag{2.4}$$

And the rate of change in storage as:

$$\frac{\partial A_T}{\partial t}\Delta x \tag{2.5}$$

Assuming that Δx is small, the change in mass in the control volume is as follows:

$$\rho\frac{\partial A_T}{\partial t}\Delta x = \rho\left[\left(Q - \frac{\partial Q}{\partial x}\frac{\Delta x}{2}\right) - \left(Q + \frac{\partial Q}{\partial x}\frac{\Delta x}{2}\right) + Q_l\right] \tag{2.6}$$

Q_l = lateral flow entering the control volume

ρ = fluid density

Simplifying and dividing through by $\rho\Delta$x yields the final form of the continuity equation:

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \tag{2.7}$$

q_l = lateral inflow per unit length

2.8.1.2.2 Momentum Equation

Conservation of momentum is expressed by Newton’s second law as:

$$\sum F_x = \frac{d\vec{M}}{dt} \tag{2.8}$$

Conservation of momentum for a control volume states that the net rate of momentum entering the volume (momentum flux) plus the sum of all external forces acting on the volume be equal to the rate of accumulation of momentum. This is a vector equation applied in the x-direction. The momentum flux (MV) is the fluid mass times the velocity vector in the direction of flow. The considered three forces are pressure, gravity and boundary drag or friction force.

Pressure forces

The pressure distribution is assumed to be hydrostatic (pressure varies linearly with depth) and the total pressure force is the integral of the pressure-area product over the cross section. Figure 2.3 illustrates the general case of an irregular cross section. After Shames (1962), the pressure force at any point may be written as:

$$F_p = \int_0^h \rho g(h-y)T(y)dy \tag{2.9}$$

h = depth

y = distance above the channel invert

T(y) = width function i.e. cross section width to the distance above the channel invert

The force at the upstream end of the control volume can be written as:

$$F_p - \frac{\partial F_p}{\partial x}\frac{\Delta x}{2} \tag{2.10}$$

And at the downstream end:

$$F_p + \frac{\partial F_p}{\partial x}\frac{\Delta x}{2} \tag{2.11}$$

where, F_p = pressure force in the x-direction

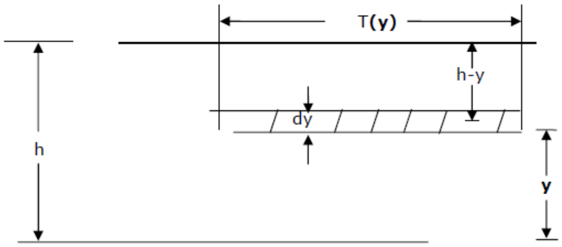

Figure 2.3: Pressure force

The sum of the pressure forces for the control volume can be written as,

$$F_{Pn} = \left|F_p - \frac{\partial F_p}{\partial x}\frac{\Delta x}{2}\right| - \left|F_p + \frac{\partial F_p}{\partial x}\frac{\Delta x}{2}\right| + F_B \tag{2.12}$$

The equation can be simplified as,

$$F_{Pn} = \frac{\partial F_p}{\partial x}\Delta x + F_B \tag{2.13}$$

F_{Pn} = net pressure force for the control volume

F_B = force exerted by the banks in the x-direction on the fluid

Differentiating equation (2.6) using Leibnitz's Rule and then substituting in equation (2.10) results in,

$$F_{Pn} = -\rho g \Delta x \left[\frac{\partial h}{\partial x} \int_0^h T(y) dy + \int_0^h (h-y) \frac{\partial T(y)}{\partial x} dy \right] + F_B \tag{2.14}$$

The net pressure force is:

$$F_{Pn} = -\rho g A \frac{\partial h}{\partial x} \Delta x \tag{2.15}$$

Gravitational force

The force due to gravity on the fluid in the control volume in the x-direction is:

$$F_g = -\rho g A \frac{\partial z_0}{\partial x} \Delta x \tag{2.16}$$

This force will be positive for negative bed slopes.

Boundary drag (Friction force)

Frictional forces between the channel and the fluid can be written as:

$$F_f = -\tau_0 P \Delta x \tag{2.17}$$

τ_0 = average boundary shear stress (force/unit area) acting on the fluid boundaries

P = wetted perimeter

The negative sign indicates that, with flow in the positive x-direction, the force acts in the negative x-direction. From the dimensional analysis, τ_0 may be expressed as:

$$\tau_0 = \rho C_D V^2 \tag{2.18}$$

$$C_D = \frac{g}{C^2} \tag{2.19}$$

C_D = drag coefficient

C = Chezy coefficient

Equation (2.16) can be further written as:

$$V = C\sqrt{RS_f} \tag{2.20}$$

Substituting equations 2.15, 2.16 and 2.17 into 2.14 and simplifying, yields the following expression for the boundary drag force:

$$F_f = -\rho g A S_f \Delta x \tag{2.21}$$

S_f = friction slope (positive for flow in the positive direction)

The friction slope must be related to flow and stage. Traditionally, the Manning and Chezy friction equations have been used. Manning equation can be written as:

$$S_f = \frac{Q|Q|n^2}{2.208 R^{4/3} A^2} \tag{2.22}$$

R = hydraulic radius

n = Manning friction coefficient

Moment flux

With the three force terms defined, only the momentum flux remains. The flux entering the control volume can be written as:

$$\rho\left[QV - \frac{\partial QV}{\partial x}\frac{\Delta x}{2}\right] \tag{2.23}$$

The flux leaving the volume can be written as:

$$\rho\left[QV + \frac{\partial QV}{\partial x}\frac{\Delta x}{2}\right] \tag{2.24}$$

Therefore, the net rate of momentum (momentum flux) entering the control volume is:

$$-\rho\frac{\partial QV}{\partial x}\Delta x \tag{2.25}$$

Since the momentum of the fluid in the control volume is ρQΔx, the rate of accumulation of momentum can be written as:

$$\frac{\partial}{\partial t}(\rho Q\Delta x) = \rho\Delta x\frac{\partial Q}{\partial t} \tag{2.26}$$

So, the conservation of momentum equation is:

$$\rho\Delta x\frac{\partial Q}{\partial t} = -\rho\frac{\partial QV}{\partial x}\Delta x - \rho gA\frac{\partial h}{\partial x}\Delta x - \rho gA\frac{\partial z_0}{\partial x}\Delta x - \rho gAS_f\Delta x \tag{2.27}$$

z = elevation of the water surface = z_0 + h

$$\frac{\partial z}{\partial x} = \frac{\partial h}{\partial x} + \frac{\partial z_0}{\partial x} \tag{2.28}$$

$\partial z/\partial x$ = water surface slope

Substituting equation 2.25 into 2.24, dividing through by ρΔx and moving all terms to the left yields the final form of the momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + GA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{2.29}$$

2.8.2 ArcGIS

GIS is defined as computer systems capable of assembling, storing, manipulating, and displaying geographically referenced information (USGS, 1998). GIS provides a setting in which to overlay data layers and perform spatial queries, and thus create new spatial data. The results can be digitally mapped and tabulated, facilitating efficient analysis and decision-making. Structurally, GIS consists of a computer environment that joins graphical elements (points, lines, polygons) associated with tabular attribute descriptions. In order to provide a conceptual framework, it is necessary first to define some basic GIS constructs.

2.8.2.1 Data Model

Geographic elements in a GIS are typically described by two data models: vector and raster. Each of these is described below:

Vector

Vector objects include three types of elements: points, lines, and polygons. A point is defined by a single set of Cartesian coordinates [easting (x), northing (y)]. A line is defined by a string of points in which the beginning and end points are called nodes, and intermediate points are called vertices (Smith, 1995). A straight line consists of two nodes and no vertices whereas a curved line consists of two nodes and a varying number of vertices. Three or more lines that connect to form an enclosed area define a polygon. Vector feature representation is typically used for linear feature modeling (roads, lakes, etc.) and cartographic base maps.

Raster

The raster data structure consists of a rectangular mesh of points joined with lines, creating a grid of uniformly sized square cells. Each cell is assigned a numerical value that defines the condition of any desired spatially varied quantity (Smith, 1995). Grids are the basis of analysis in raster GIS and are typically used for steady-state spatial modeling and two-dimensional surface representation. A land surface representation in the raster domain is called a digital elevation model (DEM).

2.9 Summary

The definition of hydrodynamic, water quality, environmental flow, flow augmentation and the literature review on these specific topics around the world as well as in Bangladesh have been discussed in this chapter. The salient features of models used in this study, i.e. the user interfaces, data storage and management, reporting capability and the theoretical background of simulation using HEC-RAS in hydrodynamic and water quality assessment have been presented. This chapter concludes with the general idea about ArcGIS.

CHAPTER THREE

METHODOLOGY

3.1 General

This study is about the water quality parameters due to withdrawal and flow augmentation in the Dhaka peripheral river system and this chapter focuses on the methodology to fulfill the objectives of this study. It includes data collections for both hydrodynamic and water quality analysis; set-up, calibration, validation and performance evaluation of the developed hydrodynamic and water quality model by using Coefficient of Determination (R^2), Nash Sutcliffe Efficiency (NSE), Percent BIAS (PBIAS) and RMSE- observations standard deviation ratio (RSR) methods; assessment of environmental flow using Tennant method and flow duration method; assessment of water quality parameters, and finally the development of flow scenario. Figure 3.1 shows the outline of the study methodology at a glance.

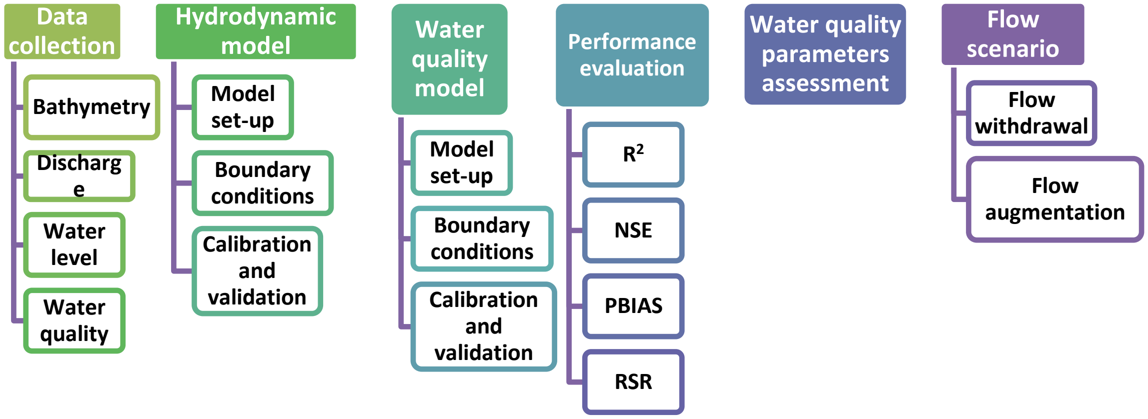

Figure 3.1**:** Outline of methodology of the study

3.2 Data collection

To develop the hydrodynamic and water quality model, as well as the flow scenario for the withdrawal and flow augmentation of the Dhaka peripheral river network of around 195 km; various dataset has been collected and processed. According to the requirement of the hydrodynamic and water quality model, data including cross section, water level, discharge and water quality of the study area have been collected. Table 4.1 includes the data used in this study with the source, location and time period.

Table 3.1: Summary of the Data used in the study

Data Type	**Data Source**	**Location**	**Period**
Bathymetry	IWM	Shitalakhya, Buriganga, Turag, Dhaleshwari, Tongi Khal, Balu	2014
Discharge	BWDB	Kaliakoir, Mirpur, Tongi, Demra, Dhaka Mill Barrack, Jagir	1996-2016
Water Level	BWDB	Kaliakoir, Mirpur, Tongi, Pubali, Demra, Dhaka Mill Barrack, Hariharpara, Jagir, Kalatia, Kalagachia, Rekabi Bazaar, Fatulla	1996-2016
Water quality parameters	Previous studies	Turag, Buriganga, Dhaleshwari, Shiotalakhya, Balu, Tongi Khal	2004-2016

3.2.1 Bathemetry

17 river cross-sections of Shitalakhya, 3 cross-sections of Buriganga, 5 cross-sections of Turag, 35 cross-sections of Dhaleshwari, 9 cross-sections of Tongi Khal and 10 cross-sections of Balu have been collected for the year of 2014 from Institute of Water Modeling (IWM). Collected surveyed bathymetry data from IWM included 97 cross sections with easting, northing and reduced level. In this study, 54 available cross sections covering the rivers encompassing the Dhaka city have been used for the model setup.

3.2.2 Discharge Data

The discharge data of SW 301-Kaliakoir (NTQ) and SW 302-Mirpur (TDQ) for Turag, SW 299-Tongi (TDQ) for Tongi canal, SW 7.5-Demra (TDQ) for Balu, SW 42-Dhaka Mill Barrack (TDQ) for Buriganga, SW 68.5-Jagir Dhaleshwari (NTQ) for Dhaleshwari and SW 179-Demra (TDQ) for Shitalakhya, collected from the Bangladesh Water Development Board (BWDB) for the year 1996-2016 have been used for the boundary condition of 1D river channel of the study area. For the development of hydrodynamic model discharge; hydrograph of daily interval was preferred to use to grasp the incremental change of the flood water depth in main channel and the flood plain. Rating curves were used to generate a continuous daily time series of discharges from daily observed river stages for the years where daily data were not available. The general equation of the rating curves developed by (Kennedy, 1984) is used in this study is shown in equation (3.1),

$$Q = C[h - a]^n \tag{3.1}$$

Where, Q = discharge, C and n = constants, h = river stage and a = river stage at which discharge is zero. Table 3.2 shows the equation of rating curve at four different upstream boundary stations.

Table 3.2 Equation of Rating curve used at four upstream boundary stations

Name of River	Equation of Rating curve
Kaliakoir of Turag	$Q = 21(h - 0.50)^{1.50}$ for h <1.50
	$Q = 22.30(h - 2)^{2}$ for h >1.50
Jagir of Dhaleshwari	$Q = 0.40(h - 0.50)^{2.60}$ for h <8.50
	$Q = 2.70(h - 2.20)^{1.90}$ for h >8.50
Ghorashal of Shitalakhya	$Q = 12(h - 1)^{1.0}$ for h <3
	$Q = 20(h - 2)^{1.80}$ for h >3
Pubali of Balu	$Q = 5.50(h - 0.90)^{2}$ for h <4.30
	$Q = 15(h - 2)^{1.70}$ for h >4.30

3.2.3 Water Level Data

The water level data of SW 301-Kaliakoir (NTWL) and SW 302-Mirpur (TDWL) for Turag, SW 299-Tongi (TDWL) for Tongi canal, SW 7-Pubali (TDWL) and SW 7.5-Demra (TDWL) for Balu, SW 42-Dhaka Mill Barrack (TDWL) and SW 43-Hariharpara (TDWL) for Buriganga, SW 68.5 Jagir Dhaleshwari (NTWL), SW 70-Kalatia (TDWL), SW 71-Kalagachia (TDWL) and SW 71A-Rekabi Bazaar (TDWL) for Dhaleshwari, SW 179-Demra (TDQ) and SW 180-Fatulla (TDQ) for Shitalakhya have been collected from BWDB for the year 1996-2016. These water level data are used for defining the downstream boundary of the hydrodynamic models and calibrating and validating the models as well. The collected water level data were in daily intervals.

3.2.4 Water Quality data

The water quality data of Bangladesh were collected by three different organizations; Department of Environment (DoE), Water Resources Planning Organization (WARPO) and Dhaka Water Supply & Sewage Authority (DWASA). Water quality data at different stations of Turag, Buriganaga, Dhaleshwari, Shitalakhya, Balu and Tongi Khal have been collected for the year 2004-2016 from previous studies.

3.3 Hydrodynamic Model

In this study a network model, where river reaches split apart and then come back together forming loop system was created for Dhaka peripheral river system. According to the first objective of this study, a hydrodynamic and water quality model of Dhaka peripheral river network have been developed using HEC-RAS to perform hydrodynamic and waterquality analysis. Geometric data are required for any of the analysis performed within HEC-RAS. The basic geometric data consist of the river system (River System Schematic), cross-section data, reach length, energy loss coefficients (friction losses, contraction and expansion losses), stream junctions etc. (Anon., 2016).

To perform a simulation in HEC-RAS the schematic diagram is required which is defined as how the various river reaches are connected together, and it is developed by drawing and connecting various hydraulic elements of the system. The Hydrological Station Network map of BWDB was used as the geo-referenced background map to draw the schematic diagram of the Dhaka peripheral river system. Figure 3.2 shows the Hydrological Station Network map and the Dhaka peripheral river network has been showed in the inset. While drawing the schematic diagram, ten reaches were created to define the whole river system. The reaches were named as Turag upper reach, Turag lower reach, Dhaleshwari upper reach, Dhaleshwari lower reach_1, Dhaleshwari lower reach_2, Shitalakhya upper reach, Shitalakhya lower reach, Balu upper reach, Balu lower reach and Tongi Khal reach. Each reach was drawn from upstream to downstream which is the positive flow direction and arrows were automatically created on the schematic diagram in the assumed positive flow direction.

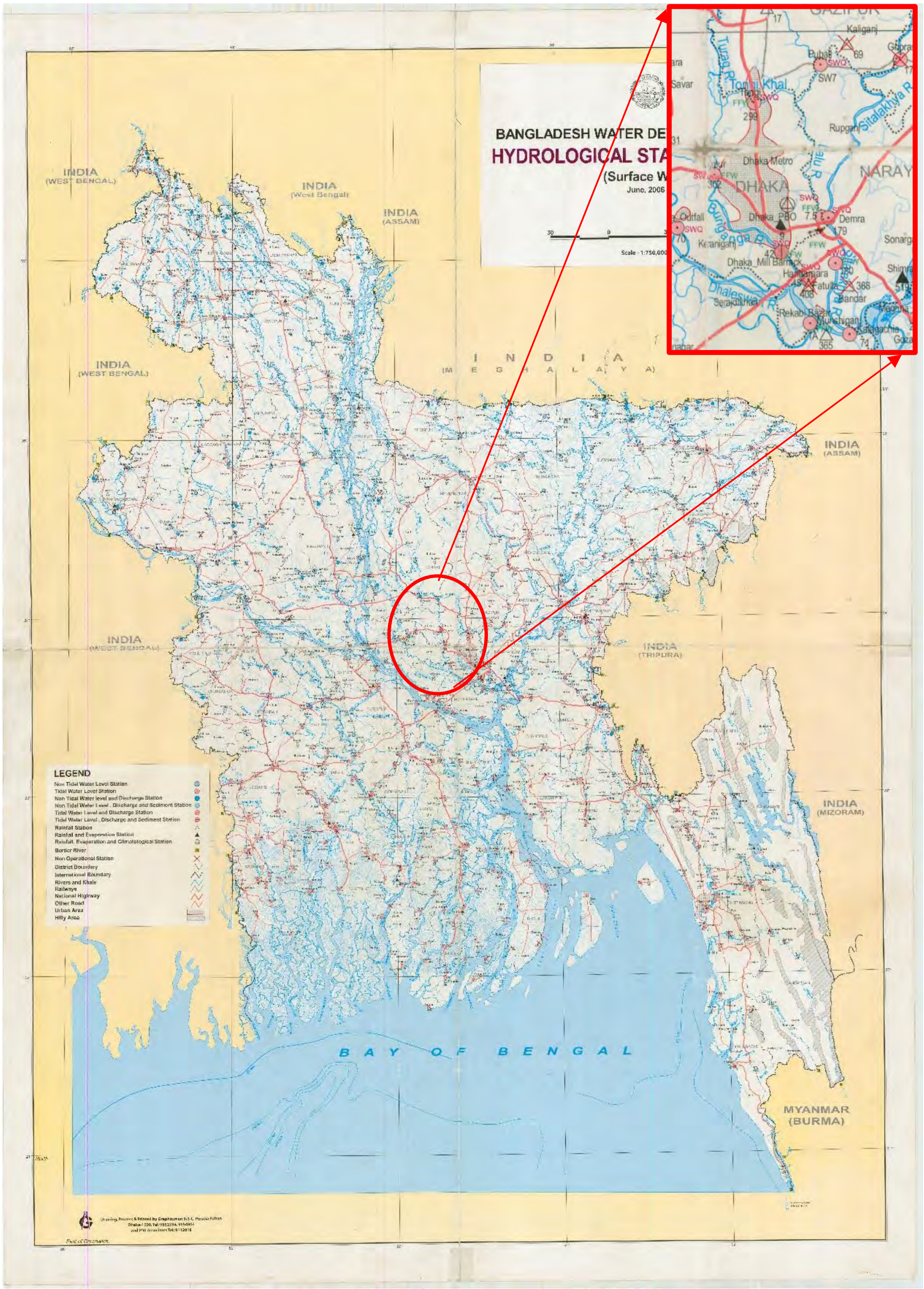

Figure 3.2: Hydrological Station Network Map, Inset: Dhaka peripheral river network

To understand how the computations should proceed from one reach to the next, the connecting points of reaches was defined as junction. In HEC-RAS, junctions are automatically formed as reaches are connected and five junctions were created in the schematic diagram. Table 3.3 shows the junction ID along with the connection reaches.Junction J1 connects Turag upper reach, Turag lower reach and Tongi Khal reach; J3 connects Turag lower reach, Dhaleshwari upper reach and Dhaleshwari lower reach_1; J4 connects Tongi Khal reach, Balu upper reach and Balu lower reach; J5 connects Balu lower reach, Shitalakhya upper reach and Shitalakhya lower reach; J6 connects Shitalakhya lower reach, Dhaleshwari lower reach_1 and Dhaleshwari lower reach_2. Figure 3.3 shows the schematic diagram of Dhaka peripheral river system. This figure shows the rivers, reaches, river station and junctions which are identified by red circle.

Table 3.3: Junction ID and connecting reaches

Junction ID	**Connecting**		
J1	Turag upper reach	Turag lower reach	Tongi Khal Reach
J3	Turag lower reach	Dhaleshwari upper reach	Dhaleshwari lower reach_1
J4	Tongi Khal reach	Balu upper reach	Balu lower reach
J5	Balu lower reach	Shitalakhya upper reach	Shitalakhya lower reach
J6	Shitalakhya lower reach	Dhaleshwari lower reach_1	Dhaleshwari lower reach_2

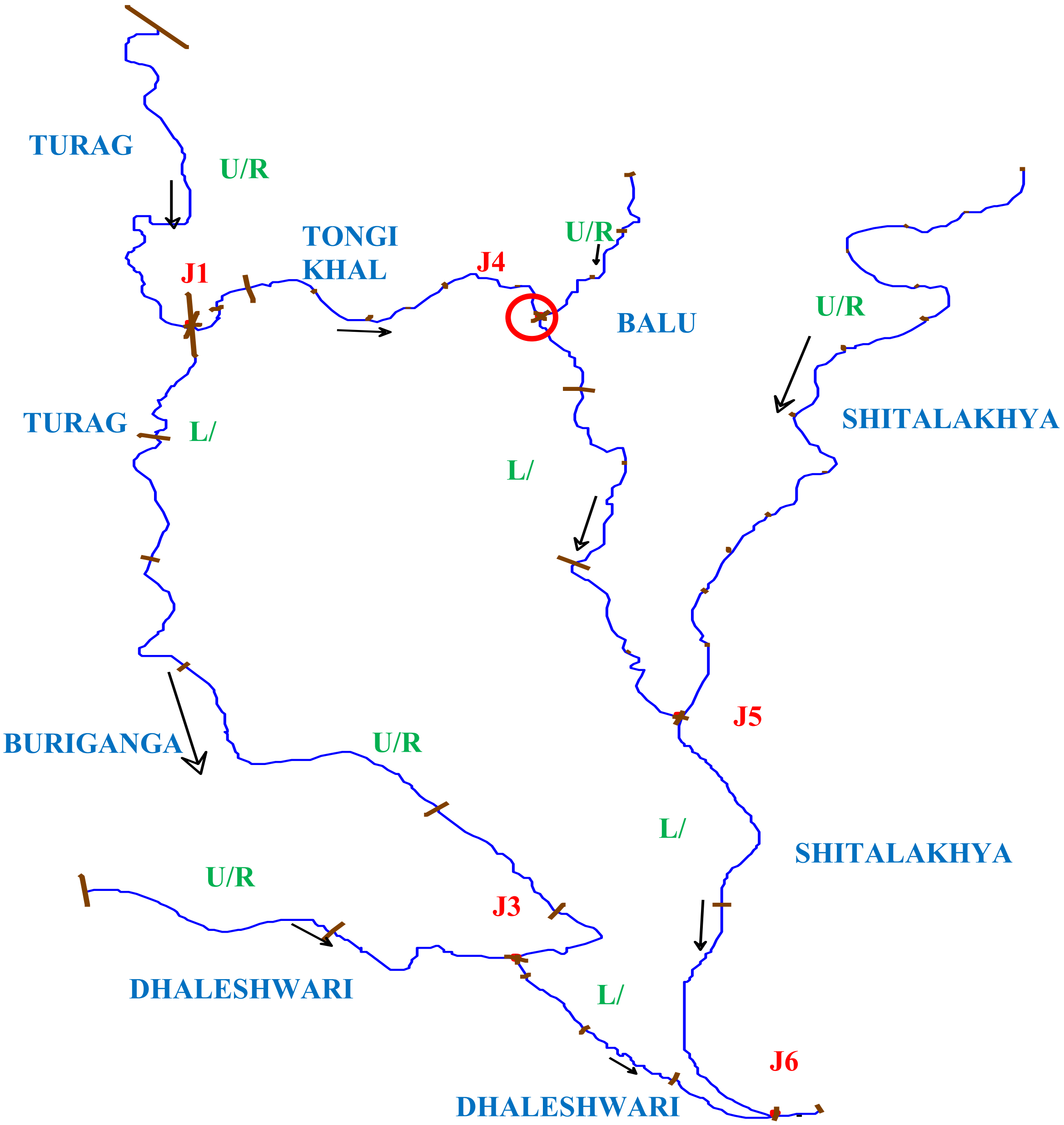

Figure 3.3: Schematic diagram of Dhaka peripheral river network in HEC-RAS

3.3.1 Cross section geometry

To characterize the flow carrying capacity of the stream and its adjacent floodplain, cross sections are located at intervals along a stream and should be perpendicular to the anticipated flow lines. The ‘River’ and ‘Reach’ identifiers define which reach the cross section lives in, while the ‘River station’ identifier defines where that cross section is located within the reach, with respect to the other cross sections of that reach. Bathymetry data were entered as the cross-section coordinates, i.e. station and elevation (X-Y data) from left to right, with respect to looking in the downstream direction.

Other cross section data which are required for each cross section consist of: downstream reach length, roughness coefficient, contraction and expansion coefficient. The measured cross section between cross sections are defined as reach length. The downstream reach lengths for left over bank (LOB), right overbank (ROB) and channel was measured from the bathymetry data which were plotted in ArcGIS. To evaluate the energy losses, two different loss coefficients were used in this study. One is Manning's n values for friction loss and the other one is contraction and expansion coefficients to evaluate transition (shock) losses.

To the accuracy of the computed water surface elevation, selection of an appropriate value for Manning's n plays a significant role. Manning's n is highly variable and depend on several factors such as: surface roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstruction, size and shape of channel, stage and discharge, seasonal changes, temperature, suspended material and bed load etc. Generally, for natural streams, if the main channel is clean, straight, full and does not have any rifts or deep pools, the Manning's n varies from 0.025 to 0.033.

Contraction or expansion of flow due to changes in the cross section is a common cause of energy losses within a reach between two cross sections. When the change in river cross section is gradual and the flow is subcritical, the coefficients of contraction and expansion are typically 0.1 and 0.3 respectively; which have been used while analyzing the hydrodynamic model.

3.3.2 Boundary conditions

Unsteady flow data are required to perform unsteady flow analysis which consist of boundary conditions and initial conditions. Boundary conditions must be established at all open ends of the modeled river system. In upstream ends, stage hydrograph, flow hydrograph, flow and stage hydrograph can be established as boundary condition. On the other hand, for downstream ends, rating curve, normal depth, stage hydrograph, flow hydrograph, flow and stage hydrograph can work as boundary condition. Besides the boundary condition, initial condition consist of flow and stage information is also required to be established at each of cross section of the system at the beginning of the simulation.

Though a flow hydrograph can be used as both upstream and downstream boundary conditions, but it is most commonly used as upstream boundary condition. In this study, four flow hydrographs was introduced at four upstream ends and those were the Pubali in Balu, Jagir in Dhaleshwari, Ghorashal in Shitalakhya and Kaliakoir in Turag. Figure 3.4 presents the locations of the boundary conditions in the study area.

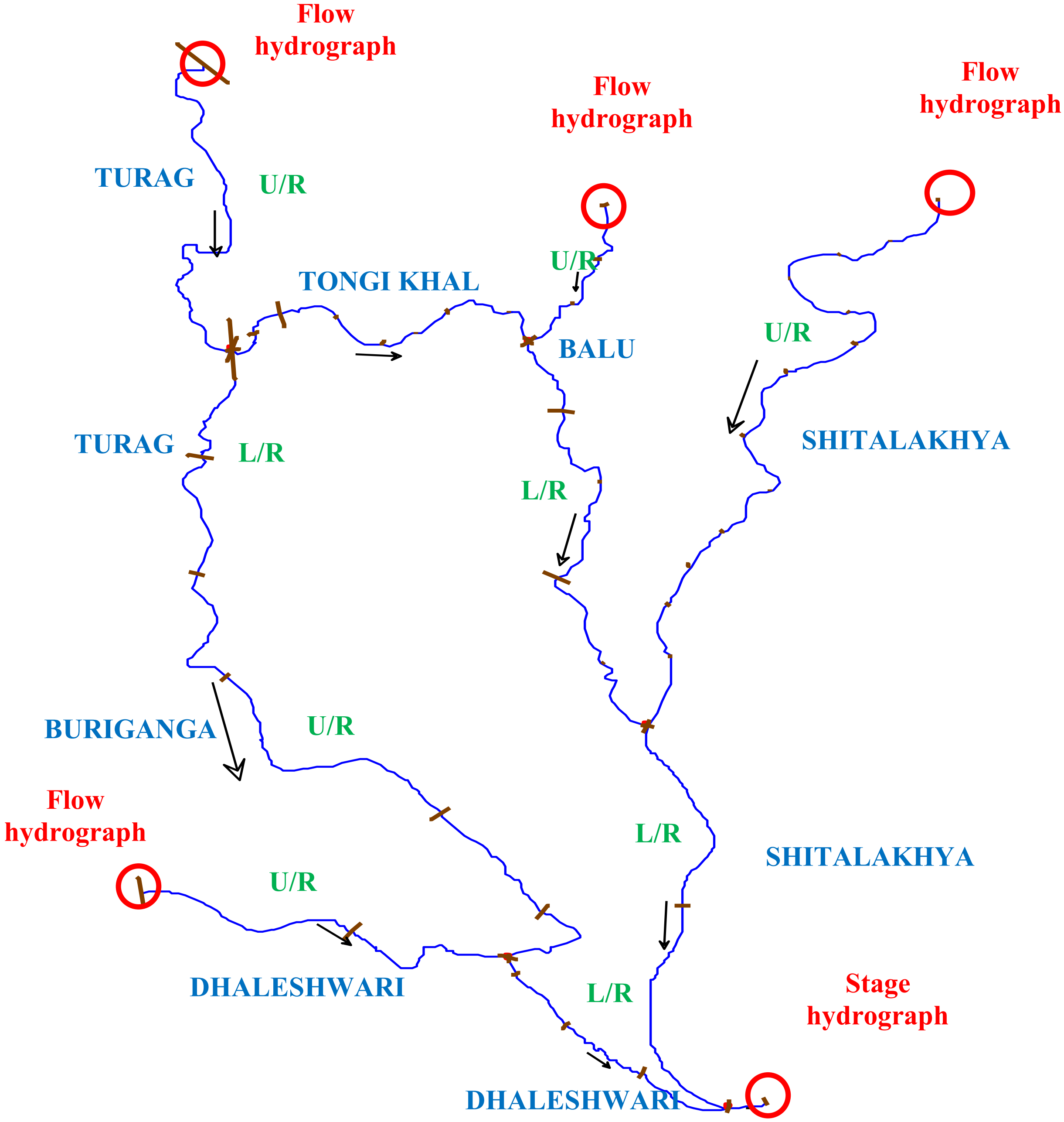

Figure 3.4: Location of boundary condition in the studied area

Figure 3.5 present the flow hydrograph at Pubali, Jagir, Ghorashal and Kaliakoir. Stage hydrograph can also be used as upstream or downstream boundary condition and in this study, one stage hydrograph was used as the downstream boundary condition at Kalagachia in Dhaleshwari which shown in Figure 3.6.

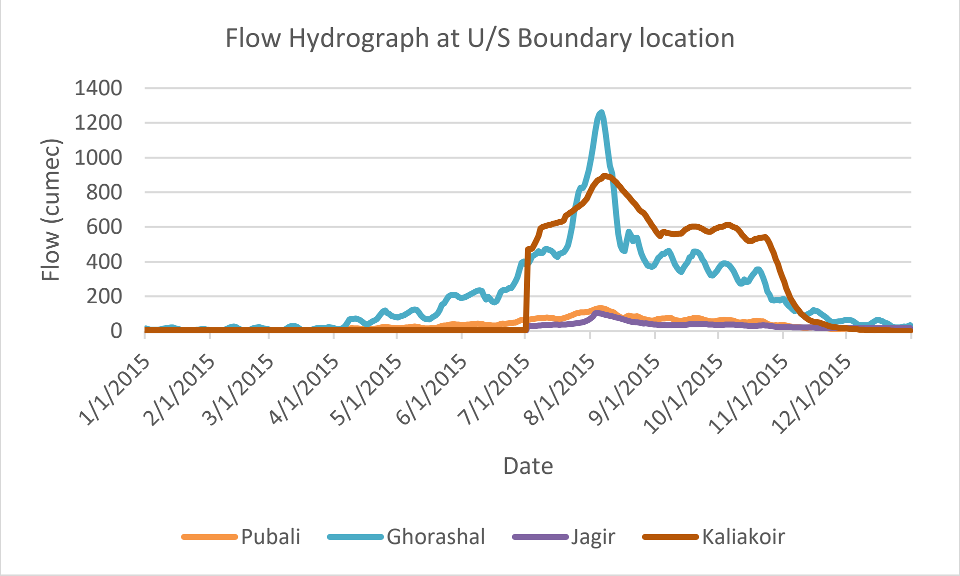

Figure 3.5: Flow Hydrograph at Pubali, Jagir, Ghorashal and Kaliakoir.

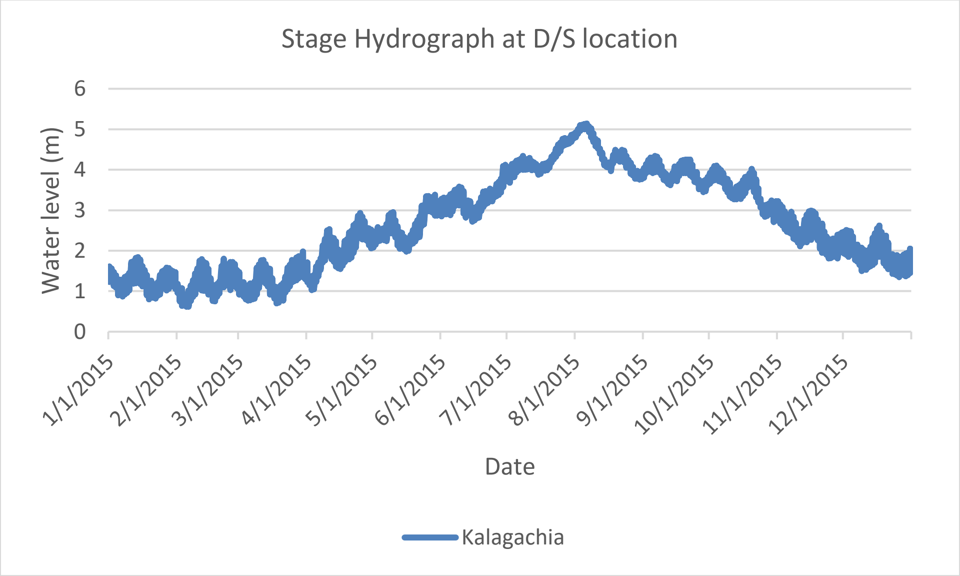

Figure 3.6: Stage hydrograph at Kalagachia

3.3.3 Performing Unsteady Flow simulation

After entering all geometry and unsteady flow data, unsteady flow simulation was performed. The analysis has been done for geometry preprocessor, unsteady flow simulation and post processor. The starting date and time were on December 31, 2015 at 24:00 and the ending date and time was on December 31, 2016 at 24:00. The computational interval, hydrograph output level and detailed output level have been set as 1 day.

3.3.4 Calibration and validation

Calibration is the process whereby selected parameters and variables of the model are adjusted to make the model output match observations. In this study, simulated water level obtained from the model has been compared with the observed water level at the intermediate location between the boundaries to calibrate and validate the developed model. To simulate the model with base and different flow conditions, it is necessary to test the model's capability to replicate the real-life flow dynamics. The calibration of hydrodynamic model generally includes the finding of an appropriate value of roughness coefficient (Manning's 'n') such that simulated values from the model should be close to the observed values in the river (Timbadiya, et al., 2011). Validation provides an assessment of the model's ability to accurately reproduce known results.Thus manning's roughness, n has been used as the calibration parameter of the 1D channel. In this study, the simulated water level was compared with the observed water level to calibrate and validate the model.

After completing the model simulation, simulated results show water level data for different observation points and in this case six observation stations of six Dhaka peripheral rivers have been selected as calibration-validation point which have been shown in Figure 3.7. The calibration has been done for the year 2014 and the validation has been done for the year 2016 at Mirpur of Turag, Dhaka Mil barrack of Buriganga, Kalatia of Dhaleshwari, Fatulla of Shitalakhya, Demra of Balu and Tongi of Tongi Khal.

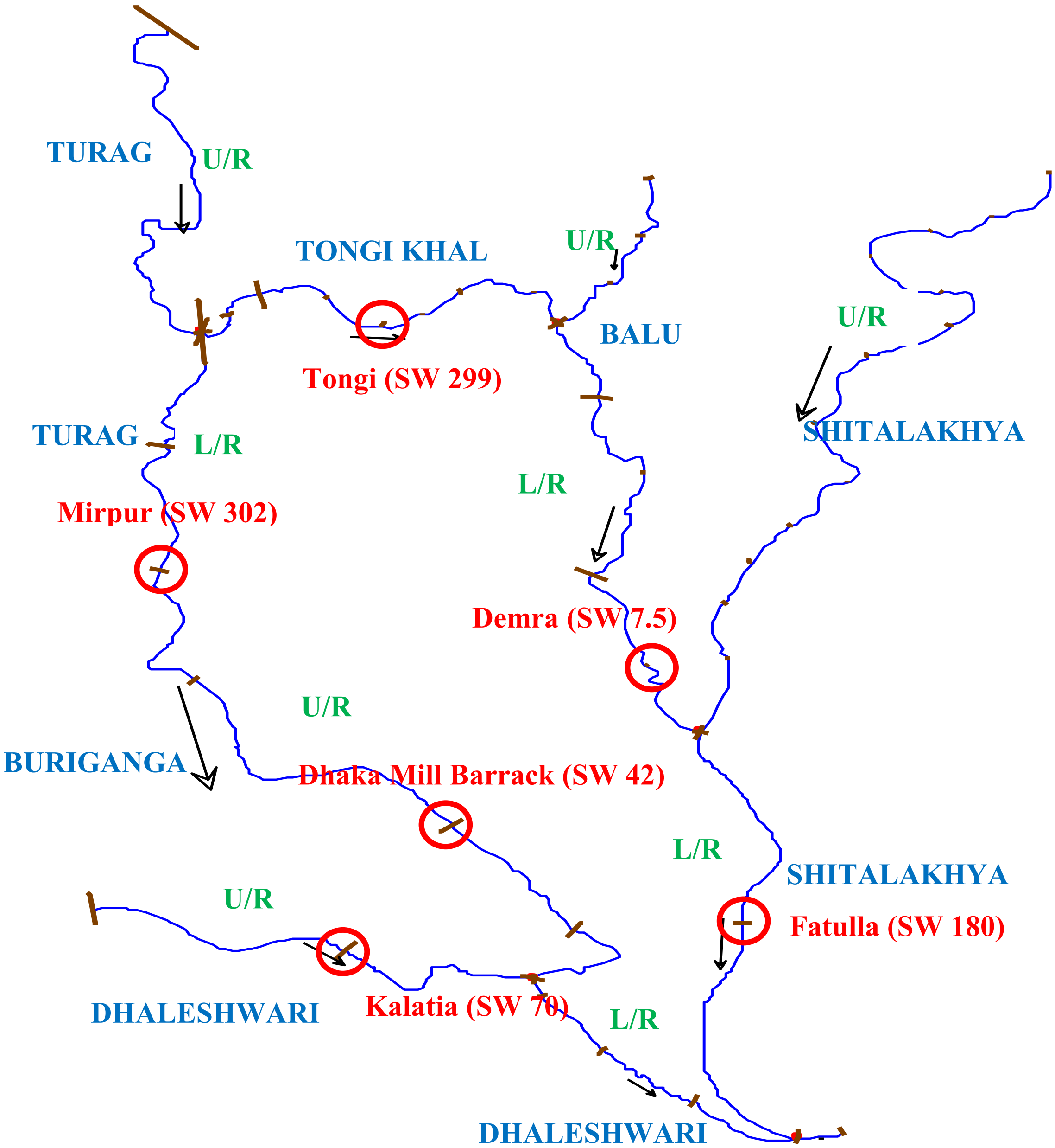

Figure 3.7: Calibration and validation locations of hydrodynamic model

3.4 Water Quality Model

A calibrated and validated HEC-RAS unsteady or steady flow model is necessary to run the water quality model. In this study the unsteady flow model of Dhaka peripheral river system has been used for the water quality simulation.

3.4.1 Water quality constituents

The temperature and nutrient modeling have been selected as water quality constituents for the water quality analysis. Among the water quality parameters, dissolved oxygen (DO) and biochemical oxygen demand (BOD) have been chosen due to their significant impacts on the sustainability of aquatic life and their effect on withdrawal and flow augmentation in the Dhaka peripheral river system. Water quality data i.e. water temperature, algae, DO, BOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorus, orthophosphate were introduced as boundary conditions and initial conditions at different locations of the river network mentioned.

3.4.2 Boundary condition

Locations of required boundary conditions are determined from hydrodynamic model output. Two different boundary conditions have been used in the water quality model. One is upstream boundary which can be defined as the positive flow across the boundary and the other one is downstream boundary which is the negative flow across boundary. In this model, upstream boundary was used at Pubali in Balu, Jagir in Dhaleshwari, Ghorashal in Shitalakhya and Kaliakoir in Turag which has been shown in a tabular form in Table 3.4. Figure 3.8 shows the upstream boundary condition at Pubali, Jagir, Ghorashal and Kaliakoir. One downstream boundary was used at Kalagachia in Dhaleshwari which have been shown in Figure 3.9.

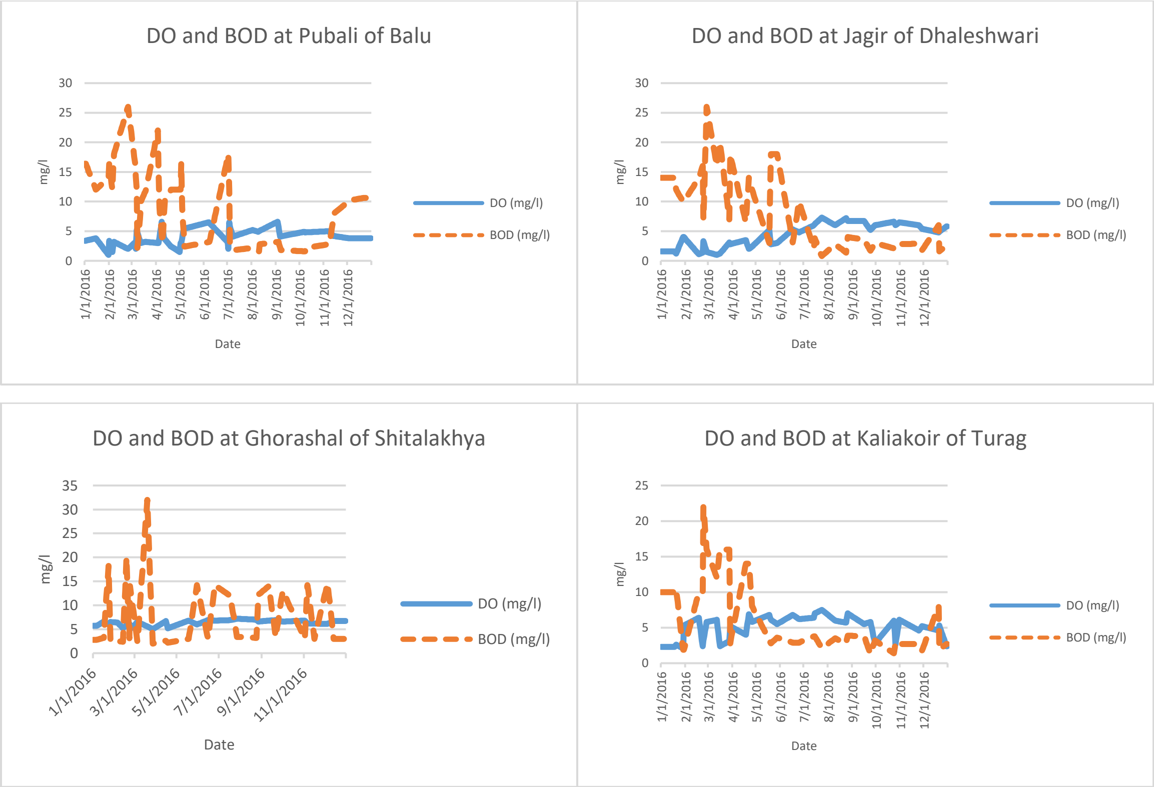

Figure 3.8: Upstream boundary condition at Pubali, Jagir, Ghorashal and Kaliakoir

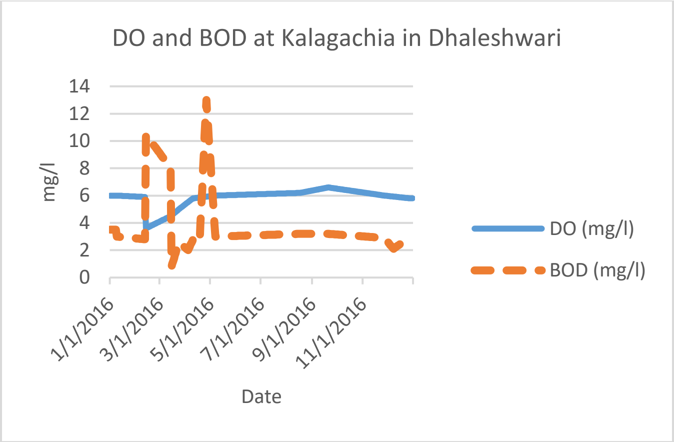

Figure 3.9: Downstream boundary condition at Kalagachia

3.4.3 Performing Water quality analysis

A calibrated steady or unsteady hydrodynamic model is necessary to perform water quality simulation. In this study, the result from unsteady flow simulation was used and the start and end of the simulation period was defined. Like the hydrodynamic model, the starting date and time was on December 31, 2015 at 24:00 and the ending date and time was on December 31, 2016 at 24:00. The output time interval has been set as 1 day.

3.4.4 Calibration and validation of water quality model

As previously mentioned, calibration is the process where selected parameters and variables of the model are adjusted to make the model output match observations. To simulate the model with observed water quality parameters, it is necessary to test the model's capability to replicate the real-life water quality parameters. The calibration of water quality model generally includes the finding of an appropriate value of dispersion coefficient such that simulated values from the model should be close to the observed values in the river. Validation provides an assessment of the model's ability to accurately reproduce known results. Thus, dispersion coefficient has been used as the calibration parameter of the 1D channel. Dispersion coefficient is a measure of the spreading of a flowing substance due to the nature of the porous medium, with its interconnected channels distributed at random in all directions. The dispersion coefficient is dependent on time as well as coordinates, and this is a result of the effect of heterogeneity, variability, and uncertainty of the geological formation within which the chemical concentration is being dispersed (AbdonAtangana, 2018). In this study, simulated DO and BOD obtained from the model has been compared with the observed DO and BOD at the intermediate location between the boundaries to calibrate and validate the developed model.

After completing the model simulation, simulated results show DO and BOD for different observation points and in this case four observation stations have been selected as calibration-validation point which have been shown in Figure 3.10. The calibration has been done from January- June for the year 2014 and the validation have been done from July- December for the year 2016 at Demra of Balu, Rekabi Bazaar of Dhaleshwari, Fatulla of Shitalakhya and Dhaka Mill Barrack of Buriganaga.

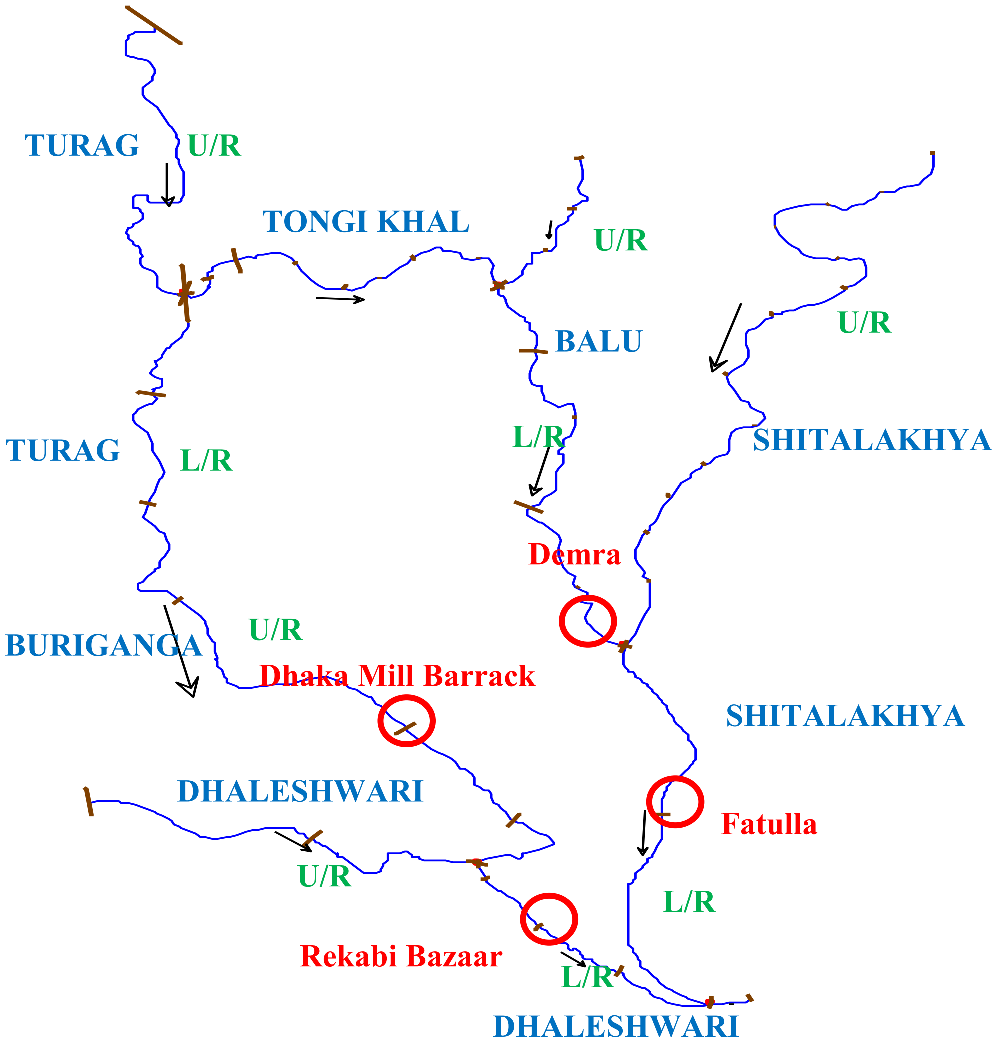

Figure 3.10: Calibration and validation locations of water quality model

3.5 Performance Evaluation of the developed Hydrodynamic and Water Quality Model of Dhaka Peripheral River Network:

Some of the model performance evaluation technique includes Coefficient of Determination (R^2), RMSE, MAE, MSE, NSE, RSR and PBIAS etc. In this study, to evaluate the performance of the developed 1D-2D coupled hydrodynamic model of Dhaka peripheral river network, widely used quantitative statistical performance indicators named Coefficient of Determination (R2), Coefficient of Nash-Sutcliffe Efficiency (NSE), PBIAS and RSR have been used for comparison of simulated output graph with the observed data.

3.5.1 Coefficient of Determination (R^2)

The coefficient of determination is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). It provides a measure of how well-observed outcomes are replicated by the model, based on the proportion of total variation of outcomes explained by the model. It is denoted as R^2. For a simple linear regression r^2 is used instead of R^2 where r^2 is simply the square of the sample correlation coefficient (i.e., r) between the observed outcomes and the observed predictor values and can be obtained from Equation 3.2.

$$r = \frac{n(\Sigma xy)-(\Sigma x)\Sigma y}{[n\Sigma y^2-(\Sigma y)^2]\sqrt{[n\,\Sigma x^2-(\Sigma x)^2]}} \tag{3.2}$$

3.5.2 Nash Sutcliffe Efficiency (NSE)

The Nash- Sutcliffe Efficiency (NSE) determines the relative magnitude of the residual variance compared with the measured data variance (Nash and Sutcliffe, 1970) as a normalized statistic.

$$\text{NSE}=1-[\frac{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}-y_{\text{i}}^{sim}\right)^2}{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}-y_{\text{i}}^{mean}\right)^2}] \tag{3.3}$$

Where, y_{i}^{sim} is the simulated value and y_{i}^{obs} is the observed value, y_{i}^{mean} is the mean value of the data set and n is the total number of observations.

3.5.3 Percent BIAS (PBIAS)

Percent bias measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0 with low magnitude values indicating accurate model simulation. Positive value indicates model underestimation bias and negative value indicates model overestimation bias (Gupta et.al., 1999).

$$\text{PBIAS}=[\frac{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}-y_{\text{i}}^{sim}\right)*100}{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}\right)}] \tag{3.4}$$

3.5.4 RMSE- observations standard deviation ratio (RSR)

RSR is one of the commonly used error statistics that is calculated as the ratio of the root mean square error (RMSE) and standard deviation of the measured data.

$$\text{RSR}=\frac{RMSE}{STDEV_{obs}}=\frac{\left[\sqrt{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}-y_{\text{i}}^{sim}\right)^2}\right]}{\left[\sqrt{\Sigma_{i=1}^{n}\left(y_{\text{i}}^{obs}-y_{\text{i}}^{sim}\right)^2}\right]} \tag{3.5}$$

Table 3.4 shows the general reported rating of R, NSE, PBIAS and RSR.

Table 3.4: General reported rating of model performance evaluation technique*

Performance Rating	**R**	**NSE**	**RSR**	**PBIAS**
Very Good	$R^2>0.70$	$0.75<NSE\le1.00$	$0.00\le RSR\le0.50$	PBIAS< ±10
Good	$0.5< R^2\le0.70$	$0.65<NSE\le0.75$	0. 50< RSR ≤0.60	±10≤PBIAS< ±15
Satisfactory	0. 50< $R^2\le0.3$	0. 50<NSE≤0.65	0. 60< RSR ≤0.70	±15≤PBIAS< ±25
Unsatisfactory	$R^2\le0.30$	$NSE\le0.50$	RSR >0.70	PBIAS≥±25

*Source: Haque et al, 2018

3.6 Assessment of Environmental Flow

Environmental flow describes the quantity, quality and timing of water flows required to sustain the freshwater and estuarine eco system and the human livelihood and well-being that depend on the eco-system. In this study environmental flow requirement for the rivers of Dhaka peripheral river system has been assessed by following the concept of hydrological method which requires historical data on flow only and demands least amount of fieldwork. Among the available approaches within the concept of hydrological method of estimating environmental flow, Tennant method and Flow duration curve method have been widely used to quantify the environmental flow (Tharme, 2003) and hence are used in this study.

To estimate the environmental flow of the Dhaka peripheral river system, discharge data for historical time ranging from 1996-2016 have been collected from Bangladesh Water Development Board (BWDB) for the stations SW 301 of Turag, SW 7.5 of Balu, SW 179 of Shitalakhya, SW 68.5 of Dhaleshwari, SW 42 of Buriganga, SW 299 of Tongi Khal, SW 302 of Turag.

3.6.1 Environmental Flow Assessment by Tennant Method:

To estimate the environmental flow of the Dhaka peripheral river network, first, the mean monthly flow for each of the months of the year ranging from 1996 to 2016 has been calculated for each of the locations of measured discharge data around the Dhaka peripheral river network. Using the mean monthly flow values, annual mean flow has been obtained for each of the years considered for all the locations. Then the Mean Annual Flow (MAF) has been calculated averaging all the annual mean flow values. The values of the mean annual flow have then been used to determine the environmental flow requirement using percentage values proposed by Tennant in Tennant method. In this study, flow for "Good" habitat quality has been selected, which is 20% of MAF for low flow season and 40% of MAF for high flow season. In another study on the surface water availability for Dhaka city, environmental flow was assessed and 10% MAF was selected for both low flow and high flow seasons as the environmental flow by Tennant method which exhibit "Poor" habitat quality (Haque, 2018). In comparison of that, the habitat quality "Good" is a safer option to assess the environmental flow to estimate available water for withdrawal.

3.6.2 Environmental Flow Assessment by Flow-duration Method

In the Flow duration curve method environmental flow requirement is determined by observing the discharge and the percentage of time it is exceeded. In this study, to assess the environmental flow value in flow duration curve method, flow exceedance percentage is computed for each month for 1996 to 2016. For months of high flow season, flow greater or equal to 50th percentile flow (Q_{50}) is recommended as environmental flow value. For low flow season the recommendation on the environmental flow is set at 90th percentile flow (Q_{90}). Then the flow duration curve for each month has been produced using mean monthly discharge data of the years ranging from 1996 to 2016 of seven specified stations through the Dhaka peripheral river network. From there the 90th percentile flow is recommended for low flow season extending from the months of November, December, January, February, March and April. For high flow months including May, June, July, August, September and October, 50th percentile flow is set as recommended discharge.

3.6.3 Selection of Environmental flow

The environmental flow was estimated by two methods in this study. One is by Tennant method for "Good" habitat quality which is 20% of MAF for low flow season and 40% of MAF for high flow season. Another process was calculating Q_{50} for high flow season and Q_{90} for low flow season by Flow duration curve method. The environmental flow has been compared for each month and the higher value has been selected as the environmental flow for each month.

3.7 Assessment of Water Quality Parameters

The water quality parameters can be classified into several categories which has been shown in Table 2.1 of Chapter Two. The pollutant concentration data i.e. pH, chloride, ammonia (NH4), DO, BOD, Total Dissolved Solid (TDS), Lead (Pb), Cadmium (Cd), Chromium (Cr), Zinc (Zn), Mercury (Hg), Phosphate (PO_4) has been collected from previous study on Turag, Buriganga, Dhaleshwari, Shitalakhya, Balu and Tongi Khal from previous study for year 2004-2016. The descriptive statistics on the water quality parameters has been used to describe the basic features of the data by determining mean and median for central tendency and variance and standard deviation for dispersion. Table A.1(a) and Table A.1(b) show the descriptive statistics for low-flow and high-flow season respectively for six peripheral rivers in Appndix A.

Water quality has been analyzed by Haque (2018) based on these observed data to judge whether the water is suitable for withdrawal (Haque, 2018). If a maximum of three water quality parameters fail to satisfy the standard, the water is not considered as a good source for water withdrawal. Table 3.5 and Table 3.6 show the status of water quality parameters of Dhaka peripheral rivers based on the observed water quality parameters compared to standard limit for low-flow and high-flow season respectively.

Table 3.5: Status of water quality parameters compared to standard limit for low flow season*

Rivers		**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Turag	Ok	pH,, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4
	Not Ok	Pb, Cd, DO, Cr, BOD	Pb, Cd, DO, BOD	Pb, Cd, DO, BOD	Pb,Cd, DO, BOD	Pb, Cd, DO, BOD	Pb,Cd, DO, BOD
Buriganga	Ok	pH, Turbidity, Cl, PO_4	pH, Turbidity, Cl, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4
	Not Ok	Cd, DO, BOD,NH_4	Cd, DO, BOD,NH_4	Cd, DO, BOD,NH_4	Cd, DO, BOD,NH_4	Cd, DO, BOD,NH_4	Cd, DO, BOD,NH_4
Dhaleshwari	Ok	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH4, PO4	pH, Tubidity, Cl, NH4, PO4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Shitalakhya	Ok	pH, Tubidity, Cl, NH_4, PO4	pH, Tubidity, Cl, NH_4, PO4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Balu	Ok	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, DO, Tubidity, Cl, NH_4, PO_4	pH, DO, Tubidity, Cl, NH_4, PO_4	pH, DO, Tubidity, Cl, NH_4, PO_4
	Not Ok	Pb, Cd Cr, DO, BOD	Pb, Cd Cr, DO, BOD	Pb, Cd Cr, DO, BOD	Pb, Cd Cr, DO, BOD	Pb, Cd Cr, DO, BOD	Pb, Cd Cr, DO, BOD
Tongi Khal	Ok	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4
	Not Ok	Pb, Cd, Cr, DO, BOD	Pb, Cd, Cr, DO, BOD	Pb, Cd, BOD, DO	Pb, Cd, BOD, DO	Pb, Cd, BOD, DO	Pb, Cd, BOD, DO

Source: Haque, 2018

Table 3.6: Status of water quality parameters compared to standard limit for high flow season*

Rivers	Water Quality Parameter	May	Jun	Jul	Aug	Sep	Oct
Turag	Ok	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Buriganga	Ok	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Dhaleshwari	Ok	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4	pH, Turbidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Shitalakhya	Ok	pH, Tubidity, Cl, PO_4	pH, Tubidity, Cl, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Balu	Ok	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO
Tongi Khal	Ok	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4	pH, Tubidity, Cl, NH_4, PO_4
	Not Ok	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO	BOD, DO

Source: Haque, 2018

Table 3.7 and 3.8 present the summary of water suitability for flow withdrawal based on water quality on each month of Dhaka peripheral rivers for low flow and high flow season respectively.

Table 3.7: Suitability of water based on water quality for flow withdrawal in low flow season

	Suitability of water					
River	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Turag	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
Buriganga	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
Dhaleshwari	Ok	Ok	Ok	Ok	Ok	Ok
Shitalakhya	Ok	Ok	Ok	Ok	Ok	Ok
Balu	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
Tongi Khal	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok

Table 3.8: Suitability of water based on water quality for flow withdrawal in high flow season

	Suitability of water					
River	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Turag	Ok	Ok	Ok	Ok	Ok	Ok
Buriganga	Ok	Ok	Ok	Ok	Ok	Ok
Dhaleshwari	Ok	Ok	Ok	Ok	Ok	Ok
Shitalakhya	Ok	Ok	Ok	Ok	Ok	Ok
Balu	Ok	Ok	Ok	Ok	Ok	Ok
Tongi Khal	Ok	Ok	Ok	Ok	Ok	Ok

From Table 3.7 and Table 3.8 it can be summarized that in low flow season, the water quality of Balu, Buriganga, Turag and Tongi Khal is not suitable for flow withdrawal; whereas in high flow season the water quality is suitable for flow withdrawal. The water quality of Sitalakhya and Dhaleshwari is suitable for withdrawal throughout the year.

3.8 Development of flow scenario

Determination of the flow scenario for withdrawal and flow augmentation based on DO and BOD is one of the major concerns of this study. DO and BOD are two of the most important parameters of water quality measurement of any surface water due to their significant impacts on the sustainability of aquatic life. To develop the flow scenario, the amount of total available water per month for withdrawal in six peripheral rivers has been estimated. Three things have been considered while developing flow scenario; i.e. mean monthly flow (MMF or Q_{avg}), environmental flow (Q_{env}) and water quality. Flow scenario for Dhaka peripheral river network has been developed in this study under four different cases. To develop the flow scenario, several notations have been used which are explained in Table 3.9.

Table 3.9: Explanation of notations used to develop flow scenario

Flow Scenario	**Notation**	**Explanation**
	Q_{avg}	Mean Monthly Flow (MMF)
	Q_{env}	Environmental flow
	Q_{wd}	Flow to be withdrawal
	Q_{aug}	Flow to be augmented
Withdrawal scenario	Q_{env} +75%Q_{wd}	Summation of Environmental flow and 75% of available flow
	Q_{env} +50%Q_{wd}	Summation of Environmental flow and 50% of available flow
	Q_{env} +25%Q_{wd}	Summation of Environmental flow and 25% of available flow
Augmentation scenario	Q_{avg} +25%Q_{aug}	Summation of mean monthly flow and 25% of available flow
	Q_{avg} +50%Q_{aug}	Summation of mean monthly flow and 50% of available flow
	Q_{avg} +75%Q_{aug}	Summation of mean monthly flow and 75% of available flow
	Q_{avg} +100%Q_{aug}	Summation of mean monthly flow and 100% of available flow

Case 1:

This case is valid when mean monthly flow is greater than environmental flow for a month and the water quality satisfies the standard limit of water quality parameters for the same month. When these two conditions satisfy for an observed station, the water is okay to be withdrawal and can be calculated using the following equation:

$$Q_{avg} - Q_{env} = Q_{wd} \tag{3.6}$$

Case 2:

This case is valid when mean monthly flow is less than environmental flow for a month and the water quality satisfies the standard limit of water quality parameters for the same month. When these two conditions satisfy for an observed station, flow augmentation is needed for that month and can be calculated using the following equation:

$$Q_{env} - Q_{avg} = Q_{aug} \tag{3.7}$$

Case 3:

This case is valid when mean monthly flow is greater than environmental flow for a month and the water quality does not satisfy the standard limit of water quality parameters for the same month. In this condition, though mean monthly flow is greater than environmental flow, flow could not be withdrawal due to the poor condition of water quality parameters. To improve the water quality parameters external sources of pollution, need to be controlled which is not the focus of this study.

Case 4:

This case is valid when mean monthly flow is less than environmental flow for a month and the water quality does not satisfy the standard limit of water quality parameters for the same month. When these two conditions satisfy for an observed station, flow augmentation is needed for that month and can be calculated using the following equation:

$$Q_{env} - Q_{avg} = Q_{aug} \tag{3.8}$$

By using different percentages of available flow, seven different flow scenarios for withdrawal and augmentation have been developed in this study. Three flow withdrawal scenarios, i.e. Q_{env}+75%Q_{wd}, Q_{env}+50%Q_{wd}, Q_{env}+75%Q_{wd} and four flow augmentation scenarios, i.e. Q_{avg}+25%Q_{aug}, Q_{avg}+50%Q_{aug}, Q_{avg}+75%Q_{aug} and Q_{avg}+100%Q_{aug} have been developed mentioned in Table 3.10. Q_{avg} is the mean monthly flow calculated for the year ranging from 1996 to 2016 for each of the locations of measured discharge data around the Dhaka peripheral river network. Q_{env} is the environmental flow calculated by using Tennant method and Flow Duration method. Q_{env}+75%Q_{wd} is the summation of environmental flow and 75% of available flow, where 25% of available flow has been withdrawal. Q_{env} +50%Q_{wd} shows the summation of environmental flow and 50% of available flow where 50% of available flow has been withdrawal. Q_{env}+25%Q_{wd} shows the summation of environmental flow and 25% of available flow where 75% of available flow has been withdrawal. Q_{avg}+25%Q_{aug} is the summation of mean monthly flow and 25% of available flow, where 25% of available flow has been augmented additional to mean monthly flow. Q_{avg}+50%Q_{aug} is the summation of mean monthly flow and 50% of available flow where 50% of available flow has been augmented. Q_{avg}+75%Q_{aug} is the summation of mean monthly flow and 75% of available flow where 75% of available flow has been augmented. Q_{avg}+100%Q_{aug} is the summation of mean monthly flow and 100% of available flow where 100% of available flow has been augmented. This scenario reflects the maximum amount of water available to sustain the freshwater and estuarine which is environmental flow.

3.9 Summary

This chapter describes data collections locations for both hydrodynamic and water quality analysis; methodology to set-up, calibration, validation and performance evaluation of the developed hydrodynamic and water quality model; assessment of environmental flow and water quality parameters; and finally, the procedure to develop seven different flow scenarios in withdrawal and augmentation category. The applications and results of these methods have been shown in the next chapter.

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CHAPTER FOUR

RESULT AND DISCUSSION

4.1 General

This chapter includes the result and discussion of this study. It contains calibration and validation of developed hydrodynamic and water quality model, development of the flow scenario for the flow withdrawal and augmentation, assessment of the effect of developed flow scenario to maintain the water quality standard based on DO and BOD. In this study all calculations have been done for six peripheral rivers of Dhaka city in two categories, i.e. low flow season and high flow season. To calculate the environmental flow, two most commonly used methods, i.e. Tennant method and flow duration method have been used.

4.2 Calibration and validation of HEC-RAS 1D Model of Dhaka Peripheral River Network

Calibration and Validation of HEC-RAS 1D model of Dhaka peripheral river network include two phases, one is the calibration and validation of 1D hydrodynamic model and another one is calibration and validation of water quality model.

4.2.1 Calibration and validation of Hydrodynamic model

In this study, the 1D hydrodynamic model of Dhaka peripheral river network has been calibrated and validated for the year 2014 and 2016 respectively. Flow hydrograph and stage hydrograph have been used as the upstream and downstream boundary condition respectively (shown in Figure 3.5 and Figure 3.6). Mean daily water level data of six intermediate location for six peripheral rivers named as Mirpur (SW 302) of Turag, Dhaka Mil barrack (SW 42) of Buriganga, Kalatia (SW70) of Dhaleshwari, Fatulla (SW 180) of Shitalakhya, Demra (SW 7.5) of Balu and Tongi (SW 299) of Tongi Khal (shown in Figure 3.7) have been compared with the model simulated daily water level at the same location. The developed 1D hydrodynamic model of Dhaka peripheral river network has been simulated using the mean daily discharge and water level data from 1st January to 31st December of 2014 as the boundary conditions using the value of Manning's roughness n as tuning parameter. Several trial simulations with variable Manning's n ranging from n = 0.010-0.025 along the different cross sections were conducted. Initial simulation with the

Manning's roughness, n=0.010 fixed for all the cross sections underestimated the water level at the calibration location compared with the observed values of the water levels. As we know water surface elevation gets increased by higher value of Manning's roughness coefficient which retards the flow velocity, for the subsequent trials higher values of Manning's roughness from 0.015-0.025 have been used. After several trials, Manning's roughness value of 0.025 for all cross sections has been found to produce closer approximation of simulated water level with observed water levels. Using the calibrated Manning's roughness coefficient (n) value, validation for the model has been performed from 1st January to 31st December of the year 2016. The validation result shows good agreement of the simulated water level with the observed water level for the time span. Figure 4.1 to Figure 4.6 show the graphical representation of observed and simulated water level for both the calibration and validation period at six different location along Dhaka peripheral river network.

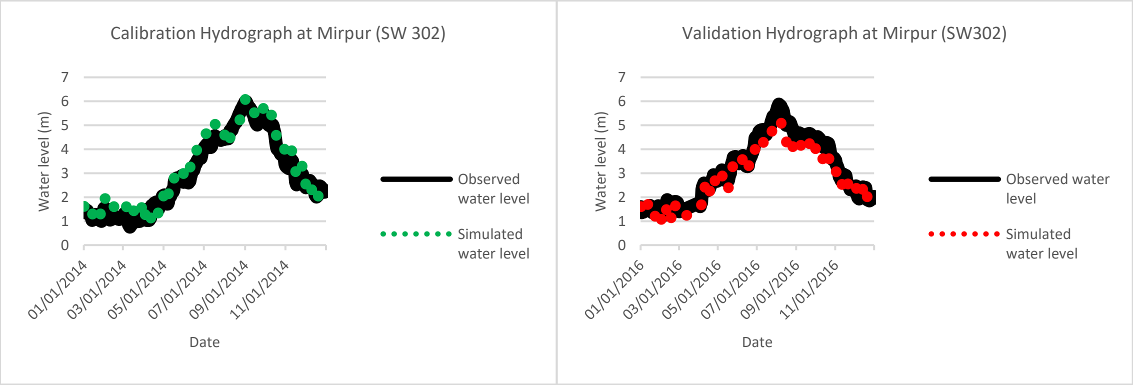


Figure 4.3: Calibration and validation at Mirpur of Turag

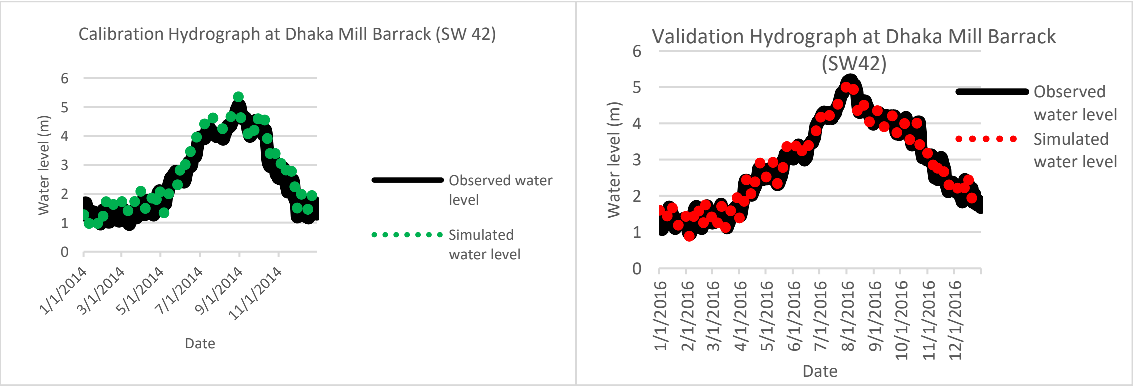
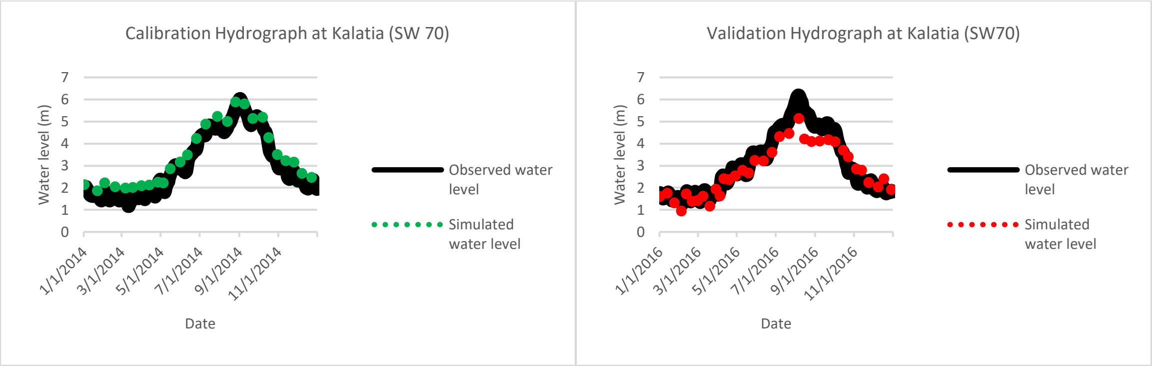
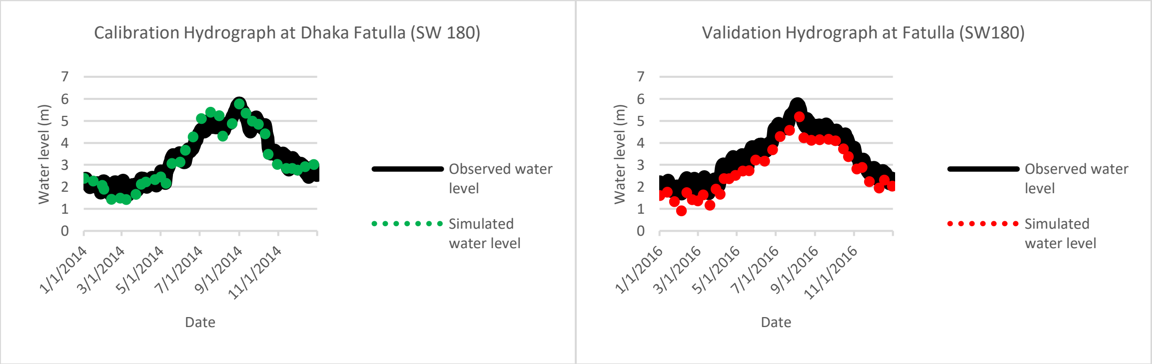


Figure 4.24: Calibration and validation at Dhaka Mill Barrack of Buriganga


Calibration Hydrograph at Kalatia (SW 70)

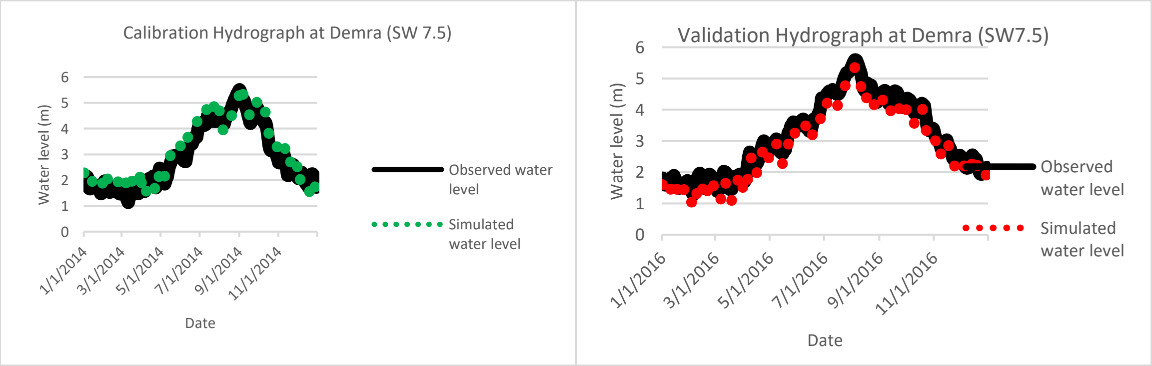
Validation Hydrograph at Kalatia (SW70)

Figure 4.3: Calibration and validation at Kalatia of Dhaleshwari


Calibration Hydrograph at Dhaka Fatulla (SW 180)

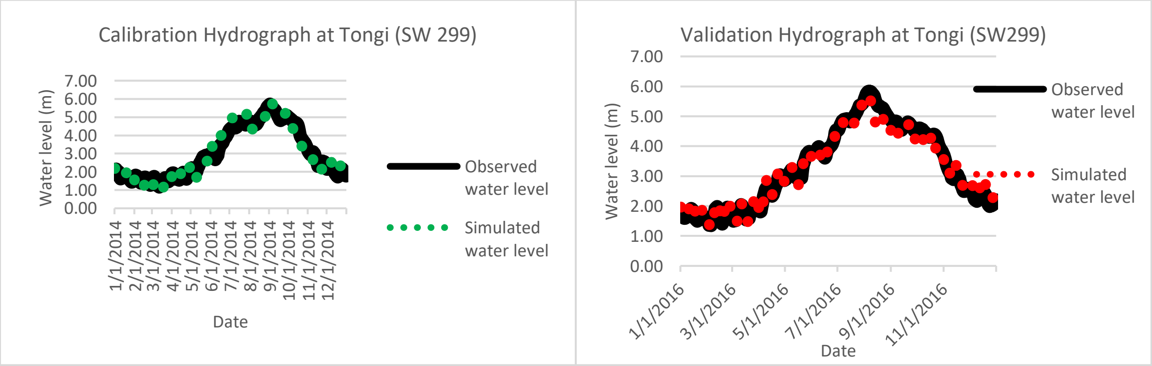
Validation Hydrograph at Fatulla (SW180)

Figure 4.4: Calibration and validation at Fatulla of Shitalakhya


Calibration Hydrograph at Demra (SW 7.5)

Validation Hydrograph at Demra (SW7.5)

Figure 4.5: Calibration and validation at Demra of Balu


Calibration Hydrograph at Tongi (SW 299)

Validation Hydrograph at Tongi (SW299)

Figure 4.6: Calibration and validation at Tongi of Tongi Khal

4.2.2 Calibration and validation of Water Quality model

In this study, the water quality model of Dhaka peripheral river network has been calibrated and validated for January to June of the year 2014 and July to December of the year 2016 respectively. The variation of DO and BOD with time have been used as the upstream and downstream boundary condition (shown in Figure 3.8 and Figure 3.9). The daily observed DO data of two intermediate location of two peripheral rivers named as Demra of Balu and Fatulla of Shitalakhya have been compared with the model simulated daily DO at the same location (shown in Figure 3.10). Also, the daily observed BOD data of two intermediate location of two peripheral rivers named as Rekabi Bazaar of Dhaleshwari and Dhaka Mill Barrack of Buriganga have been compared with the model simulated daily BOD at the same location. The developed water quality model of Dhaka peripheral river network has been simulated using water temperature, algae, DO, BOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorus, orthophosphate data from 1st January to 30th June of 2014 as the boundary conditions using the value of Dispersion coefficient, D as the tuning parameter. Several trial simulations with variable Dispersion coefficient ranging from 0.010 to 2.5 m^2/s along the different cross sections were conducted. Initial simulation with the Dispersion coefficient, $D = 0.010\ m^2/s$ for all the cross sections overestimated DO and BOD at the calibration location compared with the observed values of DO and BOD. According to Szomorova et al. (2015) the value of the simulated water quality parameters decreased with increasing value of D (Szomorova et al., 2015). For the subsequent trials, higher values of D from 0.05- 0.10 m^2/s have been used. After several trials, Dispersion coefficient value of 0.07 m^2/s fixed for all cross sections has been found to produce closer approximation of simulated DO and BOD level with observed DO and BOD. Using the calibrated Dispersion coefficient (D) value, validation for the model has been performed from 1st July to 31st December of the year 2016. The validation result shows good agreement of the simulated water level with the observed water level for the time span. Figure 4.7 Figure 4.8 show the graphical representation of observed and simulated DO for both the calibration and validation period at Demra and Fatulla. Figure 4.9 Figure 4.10 show the graphical representation of observed and simulated BOD for both the calibration and validation period at Rekabi Bazaar and Dhaka Mill Barrack.

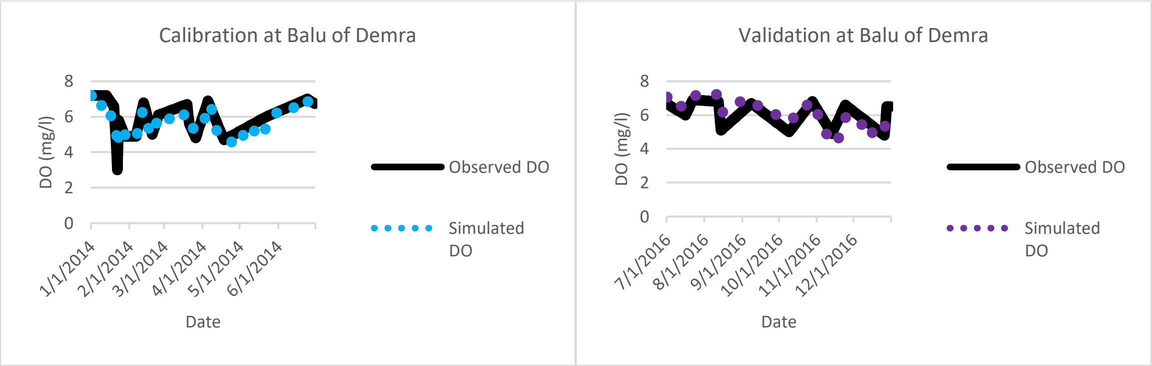


Figure 4.7: Calibration and validation with respect to DO at Demra of Balu

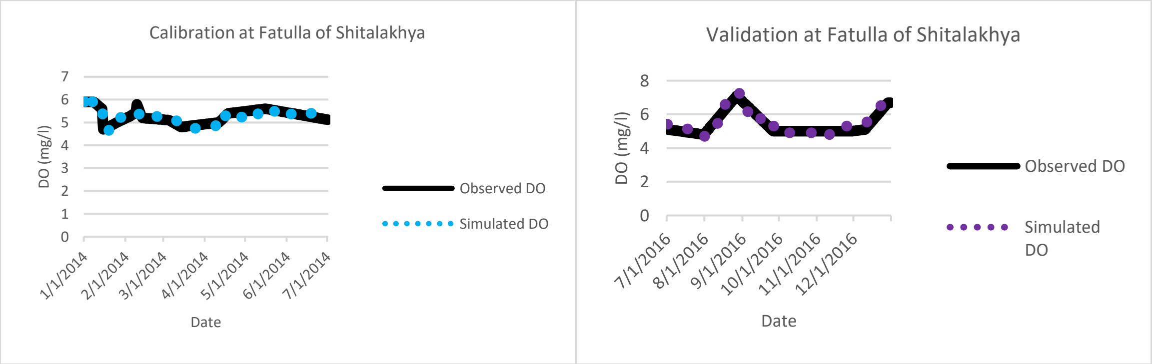


Figure 4.8: Calibration and validation with respect to DO at Fatulla of Shitalakhya

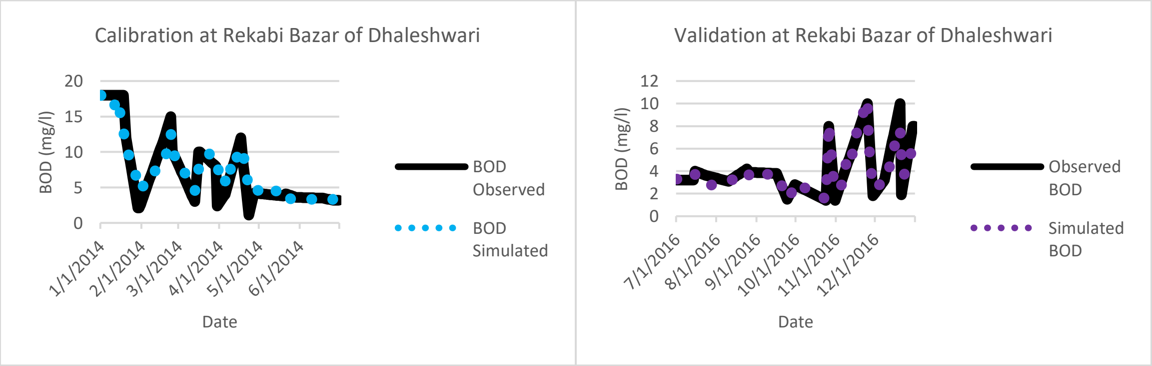


Figure 4.9: Calibration and validation with respect to BOD at Rekabi Bazaar of Dhaleshwari

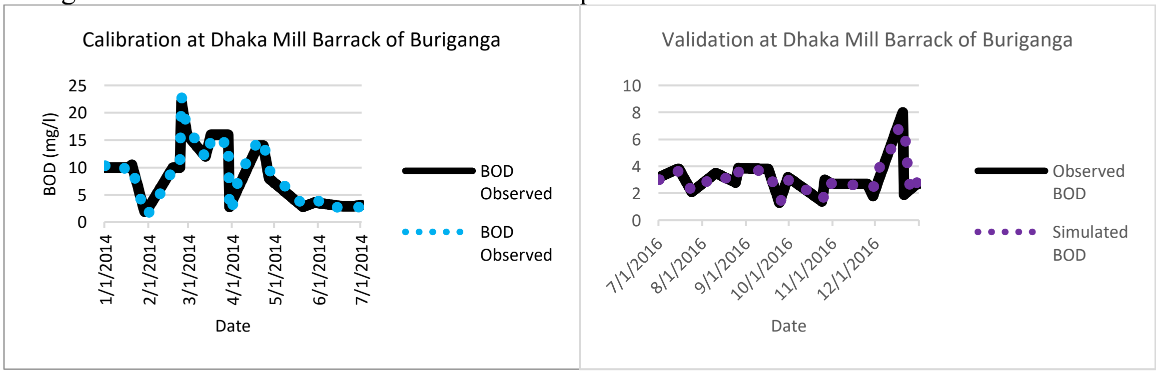


Figure 4.10: Calibration and validation with respect to BOD at Dhaka Mill Barrack of Buriganga

4.3 Performance Evaluation of the developed Hydrodynamic and Water Quality Model of Dhaka Peripheral River Network:

The values of the model performance evaluation techniques of R^2, NSE, PBIAS and RSR have been obtained for the hydrodynamic and water quality simulation of the Dhaka peripheral river system and the obtained results are presented in the following Table 4.1 through 4.4 to evaluate the level of matching of the observed and simulated water levels after simulation for the year 2014 and 2016 respectively. The remarks on the obtained results depict very good matching of the water levels.

Results on performance evaluation of the water quality model of Dhaka peripheral river network are shown in Table 4.1 through 4.4. For the calibration of water quality model of Dhaka Peripheral river network dissolved oxygen (DO) at Demra of Balu river and Fatulla of Shitalakhya River have been considered and the Biochemical oxygen demand (BOD) at Rekabibazar of Dhaleswari and Kaliakair of Turag were considered. The results depict that for both the calibration and validation the observed data were in good match with the simulated data.

Table 4.1: Performance Evaluation for the calibration of the Hydrodynamic model of Dhaka Peripheral River Network

Component	**Calibration**											
	SW 299		SW 42		SW7.5		SW 302		SW 70		SW 180	
	Value	Remark	Value	Remark	Value	Remark	Value	Remark	Value	Remark	Value	Remark
R^2	0.94	very good	0.95	very good	0.95	very good	0.96	very good	0.99	very good	0.92	very good
NSE	0.93	very good	0.92	very good	0.91	very good	0.94	very good	0.93	very good	0.91	very good
PBIAS	1.05	very good	-8.37	very good	-7.34	very good	-7.27	very good	-10.91	good	0.95	very good
RSR	0.25	very good	0.28	very good	0.29	very good	0.22	very good	0.25	very good	0.29	very good

Table 4.2: Performance Evaluation for the validation of the Hydrodynamic model of Dhaka Peripheral River Network

Component	**Validation**											
	SW 299		SW 42		SW 7.5		SW 302		SW 70		SW 180	
	Value	Remark	Value	Remark	Value	Remark	Value	Remark	Value	Remark	Value	Remark
R^2	0.98	Very Good	0.98	very good	0.99	very good	0.98	very good	0.93	very good	0.98	very good
NSE	0.97	Good	0.98	very good	0.94	very good	0.87	very good	0.88	very good	0.76	very good
PBIAS	0.81	Very Good	-0.95	very good	8.11	very good	4.74	very good	7.29	very good	15.59	Satisfactory
RSR	0.17	Good	0.12	very good	0.23	very good	0.35	very good	0.34	very good	0.48	very good

Table 4.3: Performance Evaluation of the Water quality model of Dhaka Peripheral River Network for Dissolved Oxygen (DO)

Component	**Dissolved Oxygen (DO)**							
	Calibration				**Validation**			
	Demra(Balu)		Fatulla(Shitalakhya)		Demra(Balu)		Fatulla(Shitalakhya)	
	Value	Remark	Value	Remark	Value	Remark	Value	Remark
R^2	0.846	very good	0.751	very good	0.601	Good	0.870	Very Good
NSE	0.765	very good	0.999	very good	0.317	Unsatisfactory	0.998	Very Good
PBIAS	3.663	very good	-0.037	very good	-1.783	very good	-1.563	Very Good
RSR	0.485	very good	0.029	very good	0.826	Unsatisfactory	0.049	Very Good

Table 4.4: Performance Evaluation of the Water quality model of Dhaka Peripheral River Network for Biochemical Oxygen Demand (BOD)

Component	**Biochemical Oxygen Demand (BOD)**							
	Calibration				**Validation**			
	Rekabibazar (Dhaleswari)		Kaliakair (Turag)		Rekabibazar (Dhaleswari)		Kaliakair (Turag)	
	Value	Remark	Value	Remark	Value	Remark	Value	Remark
R^2	0.897	very good	0.971	very good	0.908	very good	0.746	very good
NSE	0.884	very good	0.992	very good	0.981	very good	0.971	very good
PBIAS	-1.978	very good	-2.234	very good	3.342	very good	-0.617	very good
RSR	0.340	very good	0.091	very good	0.138	very good	0.171	very good

4.4 Environmental flow

To estimate the environmental flow of the Dhaka peripheral river system, discharge data for historical time ranging from 1996-2016 have been collected from Bangladesh Water Development Board (BWDB) for the stations SW 301 of Turag River, SW 7.5 of Balu river, SW 178 of Shitalakhya river, SW 178 of Dhaleshwari river, SW 42 of Buriganga river, SW 299 of Tongi Khal, SW 302 of Turag River. Environmental flow has been calculated by two methods in this study, Tennant method and Flow duration method.

4.4.1 Monthly Mean Flow

For the assessment of available water sources, historical time-series discharge data of 20 years from 1996 to 2016 has been analyzed. The total six rivers Balu, Turag, Tongi, Sitalakhya, Dhaleswari and Buriganga were taken into consideration. For the assessment of the water availability of the Dhaka peripheral river system, discharge data for historical time ranging from 1996-2016 have been collected from Bangladesh Water Development Board (BWDB) for the stations Kaliakoir (SW 301) and Mirpur (SW 302) of Turag River, Demra (SW 7.5) of Balu river, Demra (SW 179) of Shitalakhya river, Jagir (SW 68.5) of Dhaleshwari river, Dhaka Mill Barrack (SW 42) of Buriganga river and Tongi (SW 299) of Tongi Khal. To calculate the monthly mean flow, flow data has been averaged for a specific month for 20 years period. For Bangladesh, low flow season and high flow season is considered from November to April and May to October respectively. Table 4.5 shows the monthly mean flow for low flow season and Table 4.6 shows the monthly mean flow for high flow season for the locations along the Dhaka peripheral river network.

Table 4.5: Monthly mean flow for low flow season

		Monthly mean flow (cumec)					
River	**Station ID/Name**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Turag	SW 301/Kaliakoir	39.56	24.93	18.33	15.87	17.11	33.86
Turag	SW 302/Mirpur	39.46	26.70	18.38	15.95	17.38	32.95
Buriganga	SW 42/Dhaka Mill Barrack	69.12	30.88	18.41	19.39	26.12	26.55
Dhaleshwari	SW 68.5/Jagir	449.10	116.14	98.62	116.01	128.71	142.37
Shitalakhya	SW 179/ Demra	362.09	32.99	29.99	33.24	38.86	49.03
Balu	SW 7.5/ Demra	46.46	18.84	17.54	16.40	15.89	17.75
Tongi Khal	SW 299/ Tongi	11.78	5.51	1.10	1.67	2.59	2.86

Table 4.6: Monthly mean flow for high flow season

River	Station ID/Name	Monthly mean flow (cumec)					
		May	Jun	Jul	Aug	Sep	Oct
Turag	SW 301/Kaliakoir	65.04	74.80	204.27	393.57	353.85	201.36
Turag	SW 302/Mirpur	63.12	74.65	208.93	391.74	353.48	201.36
Buriganga	SW 42/Dhaka Mill Barrack	33.69	188.39	398.41	462.31	439.84	367.80
Dhaleshwari	SW 68.5/Jagir	198.99	604.38	1223.34	1631.02	1567.28	1178.21
Shitalakhya	SW 179/ Demra	72.22	269.48	290.32	503.67	575.45	696.21
Balu	SW 7.5/ Demra	30.08	133.05	392.36	354.87	292.70	286.78
Tongi Khal	SW 299/ Tongi	4.39	11.08	16.38	21.15	27.60	43.14

From the Table 4.5 and 4.6, it can be seen that the discharge in low flow season is reduced significantly in Turag, Bugiganga, Balu and Tongi Khal. Shitalakhya and Dhaleshwari have higher discharge compared to other peripheral rivers in low flow season. In the following sections, environmental flow has been estimated for the Dhaka peripheral network to develop the flow scenario.

4.4.2 Mean annual flow

To estimate the annual mean flow of SW 301, SW 302, SW 7.5, SW 179, SW 68.5, SW 42 and SW 299 of the Dhaka peripheral river network, the annual total flow (i.e. summation of monthly mean flow) is averaged for twelve months for each station. Table 4.7 shows annual total flow and annual mean flow for the locations along the Dhaka peripheral river network.

Table 4.7: Mean annual flow calculation

River	Station ID/Name	Annual total flow (cumec)	Mean Annual flow (cumec)
Turag	SW 301/Kaliakoir	1442.57	120.21
Turag	SW 302/Mirpur	1444.09	120.34
Buriganga	SW 42/Dhaka Mill Barrack	2080.90	173.41
Dhaleshwari	SW 68.5/Jagir	7454.18	621.18
Shitalakhya	SW 179/ Demra	2953.55	246.13
Balu	SW 7.5/ Demra	1622.73	135.23
Tongi Khal	SW 299/ Tongi	149.26	12.44

4.4.3 Environmental Flow Assessment by Tennant Method

The Mean Annual Flow (MAF) at Kaliakair of Turag River, Mirpur of Turag River, Dhaka Mill Barrack of Buriganga River, Jagir of Dhaleshwari River, Demra of Shitalakhya River, Demra of Balu River and at Tongi of Tongi Khal have been obtained as 120 cumec, 120 cumec, 173 cumec, 621 cumec, 246 cumec, 135 cumec and 12 cumec respectively. The values of the mean annual flow have then been used to determine the environmental flow requirement using percentage values proposed by Tennant in Tennant method (Tennant, 1976). Table 4.8 presents the calculations of environmental flow using the mean annual flow at Kaliakoir or Turag by Tennant method.

Table 4.8: Environmental Flow Requirement (EFR) by Tennant method at Kaliakoir of Turag River (SW 301)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	120.21	200.00	240.43	200.00	240.43
Optimum		60-100	72.13-120.21	60-100	72.13-120.21
Outstanding		40.00	48.09	60.00	72.13
Excellent		30.00	36.06	50.00	60.11
Good		20.00	24.04	40.00	48.09
Fair		10.00	12.02	30.00	36.06
Poor		10.00	12.02	10.00	12.02
Severe Degradation		<10	<12	<10	<12

The calculations of environmental flow by Tennant method at Mirpur of Turag, Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal have been shown in Appendix B from Table B.1(a) through Table B.1(f).

4.4.4 Environmental Flow Assessment by Flow Duration Curve Method

In the Flow duration curve method environmental flow requirement is determined by observing the discharge and the percentage of time it is exceeded. In this study, to assess the environmental flow value in flow duration curve method, flow exceedance percentage is computed for each month for 1996 to 2016. For months of high flow season, flow greater or equal to 50th percentile flow is recommended as environmental flow value. For low flow season the recommendation on the environmental flow is set at 90th percentile flow. Then the flow duration curve for each month has been produced using mean monthly discharge data of the years ranging from 1996 to 2016 of seven specified stations through the Dhaka peripheral river network. From there the 90th percentile flow is recommended for low flow season extending from the months of November, December, January, February, March and April. For high flow months including May, June, July, August, September and October, 50th percentile flow is set as recommended discharge (Searcy, 1959). Following sub-sections represents the detailed assessment of the environmental flow of the Dhaka peripheral river network.

4.4.4.1 Environmental flow at Kaliakoir location of Turag River

Figure 4.11 shows the flow duration curve for each of the months at Kaliakair of Turag River (SW 301). Table 4.9 shows the required environmental flow using flow duration curve method at the station. It has been seen that flow requirement for low flow season at the Kaliakair of Turag river within the Dhaka peripheral river network varies from 15-39 cumec and for high flow season it ranges from 54-400 cumec.

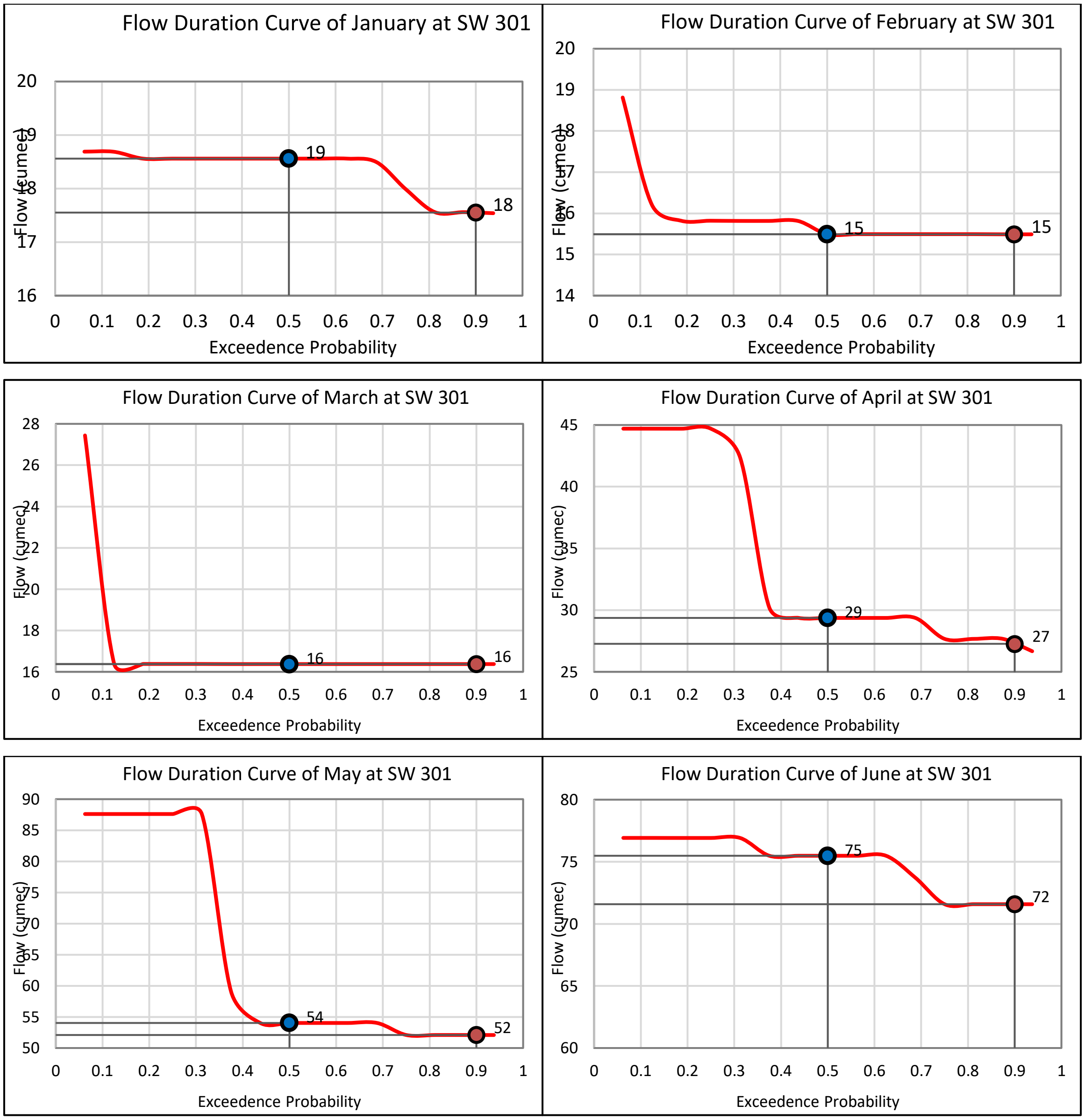
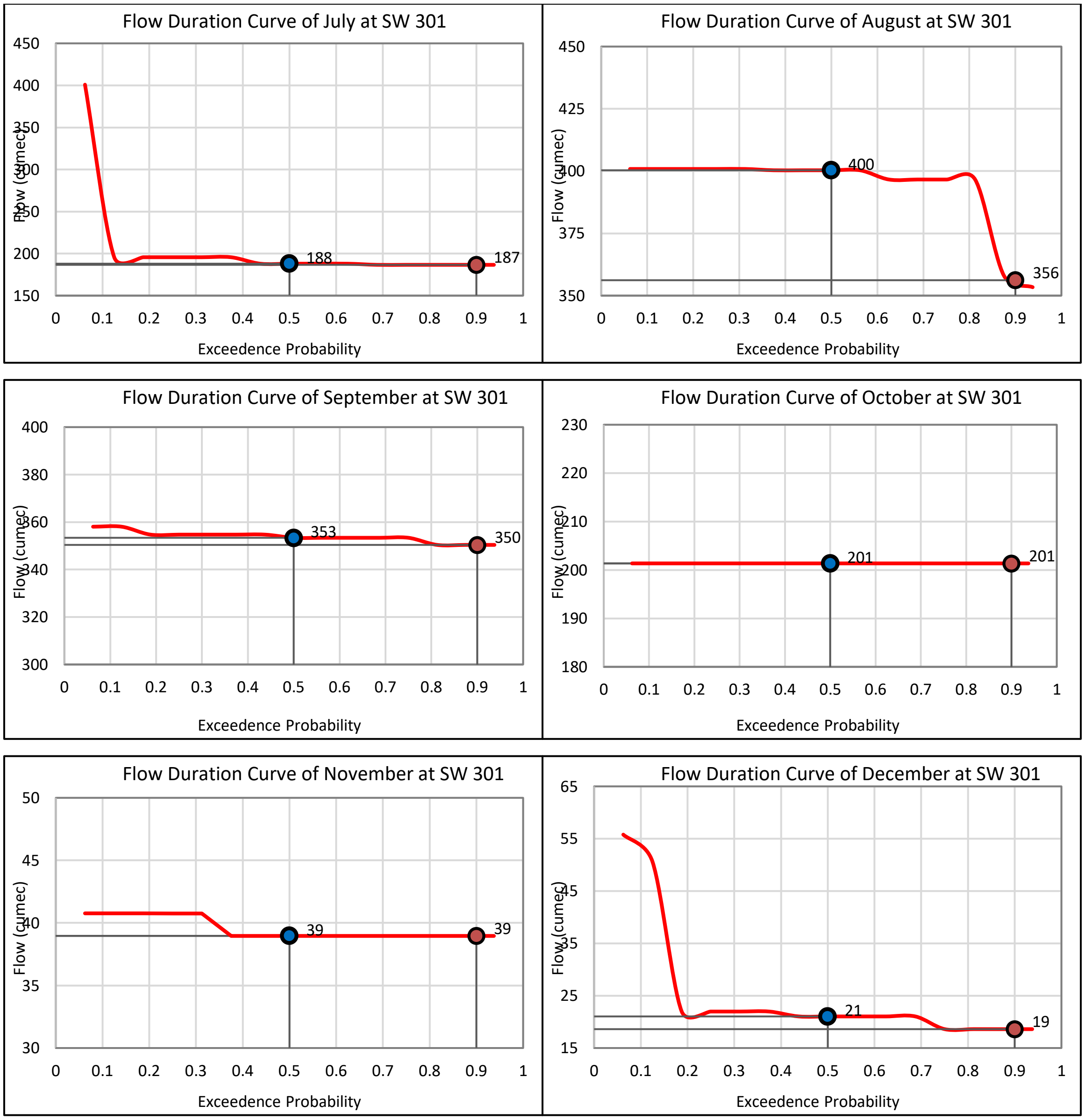


Figure 4.11: Flow duration curve at Kaliakoir of Turag from January to June



Flow Duration Curve of July at SW 301

Flow Duration Curve of August at SW 301

Flow Duration Curve of September at SW 301

Flow Duration Curve of October at SW 301

Flow Duration Curve of November at SW 301

Flow Duration Curve of December at SW 301

Figure 4.11 (continued): Flow duration curve at Kaliakair of Turag from July to December

Table 4.9: Environmental flow requirement (EFR) using Flow duration curve method at Kaliakair of Turag River (SW 301)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	19	15	16	29	54	75	188	400	353	201	39	21
90th Percentile Flow (cumec)	18	15	16	27	52	72	187	356	350	201	39	19
EFR (Cuemc)	18	15	16	27	54	75	188	400	353	201	39	19

The calculations of environmental flow by Flow duration method at Mirpur of Turag, Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal have been shown in Appendix B. Figure B.2(a) to A.2(f) shows the flow duration curve for each month for the mentioned stations. Table B.2(a) to Table B.2(f) shows the required environmental flow using flow duration curve method at the six observed stations.

4.4.5 Selection of Environmental flow

For Tennant method, flow for “Outstanding”, “Excellent” or “Good” habitat quality can be selected to assess the environmental flow. In this study, habitat quality “Good” has been selected as it is a safer option to assess the environmental flow to estimate available water for withdrawal. Habitat quality “Outstanding” or “Excellent” results in very high value of environmental flow which will eventually decrease the available water for withdrawal from a station. In “Good” habitat quality 20% of MAF has been estimated for low flow season and 40% of MAF has been estimated for high flow season. Table 4.10 and Table 4.11 show the environmental flow estimated by Tennant method for low flow season and high flow season respectively.

Table 4.10: Environmental flow estimated by Tennant method for low flow season

		Environmental flow requirement (cumec)					
River	**Station ID/Name**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Turag	SW 301/Kaliakoir	24.04	24.04	24.04	24.04	24.04	24.04
Turag	SW 302/Mirpur	24.07	24.07	24.07	24.07	24.07	24.07
Buriganga	SW 42/Dhaka Mill Barrack	34.68	34.68	34.68	34.68	34.68	34.68
Dhaleshwari	SW 68.5/Jagir	124.24	124.24	124.24	124.24	124.24	124.24
Shitalakhya	SW 179/ Demra	49.23	49.23	49.23	49.23	49.23	49.23
Balu	SW 7.5/ Demra	27.05	27.05	27.05	27.05	27.05	27.05
Tongi Khal	SW 299/ Tongi	2.49	2.49	2.49	2.49	2.49	2.49

Table 4.11: Environmental flow estimated by Tennant method for high flow season

		Environmental flow requirement (cumec)					
River	**Station ID/Name**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Turag	SW 301/Kaliakoir	48.09	48.09	48.09	48.09	48.09	48.09
Turag	SW 302/Mirpur	48.14	48.14	48.14	48.14	48.14	48.14
Buriganga	SW 42/Dhaka Mill Barrack	69.36	69.36	69.36	69.36	69.36	69.36
Dhaleshwari	SW 68.5/Jagir	248.47	248.47	248.47	248.47	248.47	248.47
Shitalakhya	SW 179/ Demra	98.45	98.45	98.45	98.45	98.45	98.45
Balu	SW 7.5/ Demra	54.09	54.09	54.09	54.09	54.09	54.09
Tongi Khal	SW 299/ Tongi	4.98	4.98	4.98	4.98	4.98	4.98

In Flow Duration method Q_{50} and Q_{90} have been selected for high flow season and low flow season respectively. Table 4.12 and Table 4.13 show the summary of environmental flow estimated by Flow Duration method for low flow season and high flow season respectively measured along the stations of Dhaka peripheral river network.

Table 4.12: Environmental flow estimated by Flow Duration method for low flow season

		Environmental flow (cumec)					
River	**Station ID/Name**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Turag	SW 301/Kaliakoir	39	19	18	15	16	27
Turag	SW 302/Mirpur	39	19	18	15	16	28
Buriganga	SW 42/Dhaka Mill Barrack	55	28	18	17	22	21
Dhaleshwari	SW 68.5/Jagir	336	76	63	102	116	110
Shitalakhya	SW 179/ Demra	284	30	15	25	32	44
Balu	SW 7.5/ Demra	39	18	16	15	15	16
Tongi Khal	SW 299/ Tongi	19	5	1	1	2	3

Table 4.13: Environmental flow estimated by Flow Duration method for high flow season

		Environmental flow (cumec)					
River	**Station ID/Name**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Turag	SW 301/Kaliakoir	54	75	188	400	353	201
Turag	SW 302/Mirpur	54	75	188	400	353	201
Buriganga	SW 42/Dhaka Mill Barrack	34	189	410	459	353	201
Dhaleshwari	SW 68.5/Jagir	190	549	742	1219	1243	714
Shitalakhya	SW 179/ Demra	71	268	296	372	557	282
Balu	SW 7.5/ Demra	28	119	407	372	282	282
Tongi Khal	SW 299/ Tongi	4	11	17	20	28	42

In this study, environmental flow has been calculated using two methods, i.e. Tennant method and Flow Duration method. The maximum value of environmental flow calculated by these two methods has been selected for further analysis for a specific month of a station. Table 4.14 and 4.15 shows the selection procedure of environmental flow for low flow and high flow season respectively.

Table 4.14: Selection of Environmental flow for low flow season

			Environmental flow requirement (cumec)					
River	Station ID/Name	Method	Nov	Dec	Jan	Feb	Mar	Apr
Turag	SW 301/Kaliakoir	Tennant	24	24	24	24	24	24
		Flow duration	39	19	18	15	16	27
		Environmental flow	39	24	24	24	24	27
Turag	SW 302/Mirpur	Tennant	24	24	24	24	24	24
		Flow duration	39	19	18	15	16	28
		Environmental flow	39	24	24	24	24	28
Buriganga	SW 42/Dhaka Mill Barrack	Tennant	35	35	35	35	35	35
		Flow duration	55	28	18	17	22	21
		Environmental flow	55	35	35	35	35	35
Dhaleshwari	SW 68.5/Jagir	Tennant	124	124	124	124	124	124
		Flow duration	336	76	63	102	116	110
		Environmental flow	336	124	124	124	124	124
Shitalakhya	SW 179/ Demra	Tennant	49	49	49	49	49	49
		Flow duration	284	30	15	25	32	44
		Environmental flow	284	49	49	49	49	49
Balu	SW 7.5/ Demra	Tennant	27	27	27	27	27	27
		Flow duration	39	18	16	15	15	16
		Environmental flow	39	27	27	27	27	27
Tongi Khal	SW 299/ Tongi	Tennant	2	2	2	2	2	2
		Flow duration	19	5	1	1	2	3
		Environmental flow	19	5	2	2	2	3

Table 4.15: Selection of Environmental flow for high flow season

			Environmental flow requirement (cumec)					
River	Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Turag	SW 301/Kaliakoir	Tennant	48	48	48	48	48	48
		Flow duration	54	75	188	400	353	201
		Environmental flow	54	75	188	400	353	201
Turag	SW 302/Mirpur	Tennant	48	48	48	48	48	48
		Flow duration	54	75	188	400	353	201
		Environmental flow	54	75	188	400	353	201
Buriganga	SW 42/Dhaka Mill Barrack	Tennant	69	69	69	69	69	69
		Flow duration	34	189	410	459	353	201
		Environmental flow	69	189	410	459	353	201
Dhaleshwari	SW 68.5/Jagir	Tennant	248	248	248	248	248	248
		Flow duration	190	549	742	1219	1243	714
		Environmental flow	248	549	742	1219	1243	714
Shitalakhya	SW 179/ Demra	Tennant	98	98	98	98	98	98
		Flow duration	71	268	296	372	557	282
		284	98	268	296	372	557	282
Balu	SW 7.5/ Demra	Tennant	54	54	54	54	54	54
		Flow duration	28	119	407	372	282	282
		Environmental flow	54	119	407	372	282	282
Tongi Khal	SW 299/ Tongi	Tennant	5	5	5	5	5	5
		Flow duration	4	11	17	20	28	42
		Environmental flow	5	11	17	20	28	42

4.5 Assessment of Water Quality Parameters

Data of water quality parameters have been collected from the year 2004 to 2016 and the status of water quality parameters have been shown based on the standard limit in Tables 3.5 and 3.6 in section 3.7 of chapter 3. If a maximum of three water quality parameters fail to satisfy the standard, the water is not considered as a good source for flow withdrawal (Haque, 2018). Tables 3.7 and 3.8 present the summary of water suitability for the development of flow scenario based on the monthly observed water quality parameters of Dhaka peripheral rivers for low flow and high flow season.

4.6 Development of Flow Scenario

Three conditions have been considered while developing flow scenario; i.e. mean monthly flow (MMF or Q_{avg}), environmental flow (Q_{env}) and water quality. The procedure of developing the flow scenario for Dhaka peripheral river network has been discussed in the previous chapter in section 3.8. Several abbreviations have been used while developing the flow scenario which were described in Table 3.9 of chapter 3. Figure 4.12 shows the summary of the conditions to develop the flow scenario in four categories.

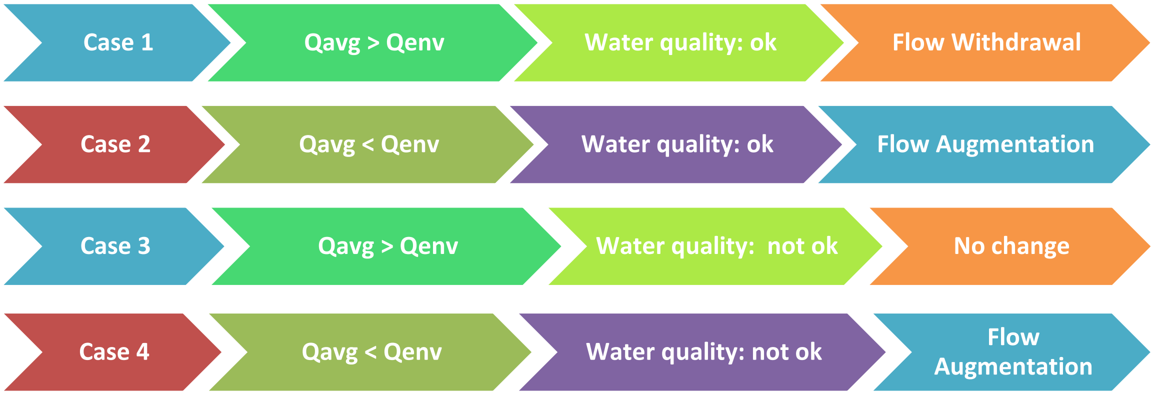


Figure 4.12: Conditions to develop the flow scenario for Dhaka peripheral river network

4.6.1 Determination of flow scenario for the withdrawal and flow augmentation

Flow needs to be withdrawal when Q_{avg} is greater than Q_{env} and the water quality satisfies the standard limit of water quality parameters for the same month. The calculation of available flow to be withdrawal and need to be augmented are presented in Table 4.16 and Table 4.17 for low flow and high flow season respectively. It has been depicted from the Tables that flow is available for withdrawal at Kaliakoir in the month of May, July, September and October; at Mirpur in the month of May, July, September and October; at Dhaka Mill Barrack in the month of August, September and October; at Jagir in the month of March, April, June, July, August, September, October and November; at Demra (Shitalakhya) in the month of June, August, September, October and November; at Demra (Balu) in the month of June, September and October; at Tongi in the month of June, August and October. Considering these seven river stations in Dhaka peripheral river network, the total available flow for withdrawal in March, April, May, June July, August, September, October and November are 4.47, 18.14, 20.16, 70.98, 518.54, 508.72, 441.59, 1007.59 and 191.19 cumec respectively. There is no flow available for withdrawal in the month of December, January and February of low flow season. The maximum total flow for withdrawal 1007.59 cumec is available in October of high flow season. The calculation of available flow to be withdrawal and to be augmented for low flow season is presented in Table 4.16.

Table 4.16: Calculation of available flow to be withdrawal and to be augmented in low flow season

River	Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Turag	SW 301/Kaliakoir	Qavg	39.6	24.9	18.3	15.9	17.1	33.9
		Qenv	39.0	24.0	24.0	24.0	24.0	27.0
		WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
		Qwd	NA	NA	NA	NA	NA	NA
		Qaug	0.0	0.0	5.7	8.2	6.9	0.0
Turag	SW 302/Mirpur	Qavg	39.5	26.7	18.4	15.9	17.4	33.0
		Qenv	39.0	24.1	24.1	24.1	24.1	28.0
		WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
		Qwd	NA	NA	NA	NA	NA	NA
		Qaug	0.0	0.0	5.7	8.1	6.7	0.0
Buriganga	SW 42/Dhaka Mill Barrack	Qavg	69.1	30.9	18.4	19.4	26.1	26.5
		Qenv	55.0	34.7	34.7	34.7	34.7	34.7
		WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
		Qwd	NA	NA	NA	NA	NA	NA
		Qaug	0.0	3.8	16.3	15.3	8.6	8.1
Dhaleshwari	SW 68.5/Jagir	Qavg	449.1	116.1	98.6	116.0	128.7	142.4
		Qenv	336.0	124.2	124.2	124.2	124.2	124.2
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	113.1	0.0	0.0	0.0	4.5	18.1
		Qaug	0.0	8.1	25.6	8.2	0.0	0.0
Shitalakhya	SW 179/Demra	Qavg	362.1	33.0	30.0	33.2	38.9	49.0
		Qenv	284.0	49.2	49.2	49.2	49.2	49.2
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	78.1	0.0	0.0	0.0	0.0	0.0
		Qaug	0.0	16.2	19.2	16.0	10.4	0.2
Balu	SW 7.5/Demra	Qavg	46.5	18.8	17.5	16.4	15.9	17.8
		Qenv	39.0	27.0	27.0	27.0	27.0	27.0
		WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
		Qwd	NA	NA	NA	NA	NA	NA
		Qaug	0.0	8.2	9.5	10.6	11.2	9.3
Tongi Khal	SW 299/Tongi	Qavg	11.8	5.5	1.1	1.7	2.6	2.9
		Qenv	19.0	5.0	2.5	2.5	2.5	3.0
		WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
		Qwd	NA	NA	NA	NA	NA	NA
		Qaug	7.2	NA	1.4	0.8	NA	0.1
Total available flow to be withdrawal			191.2	0.0	0.0	0.0	4.5	18.1
Total flow needs to be augmented			7.2	36.3	83.4	67.3	43.7	17.8

Flow needs to be augmented when Q_{avg} is less than Q_{env} and the water quality satisfy or do not satisfy the standard limit of water quality parameters for the same month as discussed in Figure 4.12. From the calculations of Table 4.16 and Table 4.17, it is depicted that the flow needs to be augmented at Kaliakoir in the month of January, February, March, June and August; at Mirpur in the month of January, February, March, June and August; at Dhaka Mill Barrack in the month of January, February, March, April, May, June, July and December; at Jagir in the month of January, February, May and December; at Demra (Shitalakhya) in the month of January, February, March, April, May, July and December; at Demra (Balu) in the month of January, February, March, April, May, July, August and December; at Tongi in the month of January, February, April, May, July, September and November. Few months from high-flow season also exhibit the condition of flow augmentation due to very high Q_{env} compared to Q_{avg}. The total available flow needs to be augmented in these seven river stations in January, February, March, April, May, June July, August, September, October, November and December are 83.41, 67.27, 43.69, 17.76, 135.98, 1.16, 32.53, 30.68, 0.40, 1.14, 7.22 and 36.33 cumec respectively. The maximum flow augmentation of 135.98 cumec is needed in the month of May of high flow season due to high value of environmental flow of that month in different stations. The minimum flow augmentation of 0.40 cumec is needed in the month of September of high flow season. Table 4.17 shows the calculation of available flow to be withdrawal and to be augmented for high flow season respectively.

Table 4.17: Calculation of available flow to be withdrawal and flow need to be augmented in high flow season

River	Station ID/Name	Flow scenario (cumec)	May	Jun	Jul	Aug	Sep	Oct
Turag	SW 301/ Kaliakoir	Qavg	65.04	74.80	204.27	393.57	353.85	201.36
		Qenv	54.00	75.00	188.00	400.00	353.00	201.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	11.04	0.00	16.27	0.00	0.85	0.36
		Qaug	0.00	0.20	0.00	6.43	0.00	0.00
Turag	SW 302/Mirpur	Qavg	63.12	74.65	208.93	391.74	353.48	201.36
		Qenv	54.00	75.00	188.00	400.00	353.00	201.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	9.12	0.00	20.93	0.00	0.48	0.36
		Qaug	0.00	0.35	0.00	8.26	0.00	0.00
Buriganga	SW 42/Dhaka Mill Barrack	Qavg	33.69	188.39	398.41	462.31	439.84	367.80
		Qenv	69.36	189.00	410.00	459.00	353.00	201.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	0.00	0.00	0.00	3.31	86.84	166.80
		Qaug	35.68	0.61	11.59	0.00	0.00	0.00
Dhaleshwari	SW 68.5/Jagir	Qavg	198.99	604.38	1223.34	1631.02	1567.28	1178.21
		Qenv	248.47	549.00	742.00	1219.00	1243.00	714.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	0.00	55.38	481.34	412.02	324.28	464.21
		Qaug	49.48	0.00	0.00	0.00	0.00	0.00
Shitalakhya	SW 179/Demra	Qavg	72.22	269.48	290.32	503.67	575.45	696.21
		Qenv	98.45	268.00	296.00	372.00	557.00	282.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	0.00	1.48	0.00	131.67	18.45	414.21
		Qaug	26.23	0.00	5.68	0.00	0.00	0.00
Balu	SW 7.5/Demra	Qavg	30.08	133.05	392.36	354.87	292.70	286.78
		Qenv	54.09	119.00	407.00	372.00	282.00	282.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	0.00	14.05	0.00	0.00	10.70	4.78
		Qaug	24.01	0.00	14.64	17.13	0.00	0.00
Tongi Khal	SW 299/Tongi	Qavg	4.39	11.08	16.38	21.15	27.60	43.14
		Qenv	4.98	11.00	17.00	20.00	28.00	42.00
		WQ	Ok	Ok	Ok	Ok	Ok	Ok
		Qwd	0.00	0.08	0.00	38.28	0.00	43.14
		Qaug	0.58	0.00	0.62	1.15	0.40	1.14
Total available flow to be withdrawal			20.16	70.98	518.54	508.72	441.59	1007.59
Total flow needs to be augmented			135.98	1.16	32.53	30.68	0.40	1.14

From the calculation of Table 4.16 and Table 4.17, it can be determined whether a station is capable of flow withdrawal or augmentation. Table 4.18 shows the months where flow withdrawal and augmentation have been performed in different stations. In some specific case, flow could not be withdrawal as Q_{avg} is greater than Q_{env} and the water quality do not satisfy the standard limit of water quality parameters for that specific month as shown in Table 4.18. April, November and December of Kaliakoir and Mirpur; November of Dhaka Mill barrack and Demra (Balu); March and December of Tongi reflect this condition.

Table 4.18: Summary of flow withdrawal and augmentation in different months of the stations

River	**Station ID/ Name**	**Method**	**Months with flow scenario**	**Months without flow scenario**
Turag	SW 301/ Kaliakoir	Withdrawal	May, July, September, October	April, November, December
		Augmentation	January, February, March, June, August	
	SW 302/ Mirpur	Withdrawal	May, July, September, October	April, November, December
		Augmentation	January, February, March, June, August	
Buriganga	SW 42 / Dhaka Mill Barrack	Withdrawal	August, September, October	November
		Augmentation	January, February, March, April, May, June, July, December	
Dhaleshwari	SW 68.5/ Jagir	Withdrawal	March, April, June, July, August, September, October, November	November
		Augmentation	January, February, May, December	
Shitalakhya	SW 179 / Demra	Withdrawal	June, August, September, October, November	NA
		Augmentation	January, February, March, April, May, July, December	
Balu	SW 7.5/ Demra	Withdrawal	June, September, October	NA
		Augmentation	January, February, March, April, May, July, August, December	
Tongi Khal	SW 299/ Tongi	Withdrawal	June, August, October	March, December
		Augmentation	January, February, April, May, July, September, November	

Table 4.19 through Table 4.25 show the calculation to flow for withdrawal and augmentation in low flow season and Table 4.26 through Table 4.32 show the calculation to flow for withdrawal and augmentation in high flow season for Kaliakoir of Turag, Mirpur of Turag Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal for low flow and high flow season. Three withdrawal scenarios, i.e. (Q_{env}+75%Q_{wd}), (Q_{env}+50%Q_{wd}), (Q_{env}+25%Q_{wd}) and four

augmentation scenarios, i.e. (Q_{avg}+25%Q_{aug}), (Q_{avg}+50%Q_{aug}), (Q_{avg}+75%Q_{aug}), (Q_{avg}+100%Q_{aug}) have been considered in this study. The months where flow scenarios of flow augmentation and withdrawal have been performed in the months mentioned in Table 4.18. Among the three withdrawal scenarios, (Q_{env}+75%Q_{wd}) is the minimum amount of flow withdrawal scenario where 25% of available flow has been taken away and (Q_{env}+75%Q_{wd}) is the maximum amount of flow withdrawal scenario where 75% of available flow has been taken away. On the other hand, (Q_{avg}+25%Q_{aug}) is the minimum amount of flow augmentation scenario where 25% of Q_{aug} has been increased and (Q_{avg}+100%Q_{aug}) is the maximum amount of flow augmentation scenario where 100% of Q_{aug} has been increased, which is actually Q_{env} .

Table 4.19: Development of flow scenario for withdrawal and augmentation in low flow season at Kaliakoir (SW 301) of Turag

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Turag/SW 301/Kaliakoir	Q_{avg}	39.56	24.93	18.33	15.87	17.11	33.86
	Q_{env}	39.00	24.04	24.04	24.04	24.04	27.00
	WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
	Q_{wd}	NA	NA	NA	NA	NA	NA
	Q_{aug}	0.00	0.00	5.71	8.17	6.93	0.00
Withdrawal	Q_{env}+75%Q_{wd}	39.56	24.93	18.33	15.87	17.11	33.86
	Q_{env}+50%Q_{wd}	39.56	24.93	18.33	15.87	17.11	33.86
	Q_{env}+25%Q_{wd}	39.56	24.93	18.33	15.87	17.11	33.86
Augmentation	Q_{avg}+25% Q_{aug}	39.56	24.93	19.76	17.91	18.85	33.86
	Q_{avg}+50%Q_{aug}	39.56	24.93	21.19	19.96	20.58	33.86
	Q_{avg}+75%Q_{aug}	39.56	24.93	22.62	22.00	22.31	33.86
	Q_{avg}+100%Q_{aug}	39.56	24.93	24.04	24.04	24.04	33.86

Table 4.20: Development of flow scenario for withdrawal and augmentation in low flow season at Mirpur (SW 302) of Turag

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Turag/SW 302/Mirpur	Q_{avg}	39.46	26.70	18.38	15.95	17.38	32.95
	Q_{env}	39.00	24.07	24.07	24.07	24.07	28.00
	WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
	Q_{wd}	NA	NA	NA	NA	NA	NA
	Q_{aug}	0.00	0.00	5.68	8.12	6.69	0.00
Withdrawal	Q_{env}+75%Q_{wd}	39.46	26.70	18.38	15.95	17.38	32.95
	Q_{env}+50%Q_{wd}	39.46	26.70	18.38	15.95	17.38	32.95
	Q_{env}+25%Q_{wd}	39.46	26.70	18.38	15.95	17.38	32.95
Augmentation	Q_{avg}+25% Q_{aug}	39.46	26.70	19.80	17.98	19.05	32.95
	Q_{avg}+50%Q_{aug}	39.46	26.70	21.23	20.01	20.72	32.95
	Q_{avg}+75%Q_{aug}	39.46	26.70	22.65	22.04	22.40	32.95
	Q_{avg}+100%Q_{aug}	39.46	26.70	24.07	24.07	24.07	32.95

Table 4.21: Development of flow scenario for withdrawal and augmentation in low flow season at Dhaka Mill Barrack (SW 42) of Buriganga

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Buriganga/SW 42/Dhaka Mill Barrack	Q_{avg}	69.12	30.88	18.41	19.39	26.12	26.55
	Q_{env}	55.00	34.68	34.68	34.68	34.68	34.68
	WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
	Q_{wd}	NA	NA	NA	NA	NA	NA
	Q_{aug}	0.00	3.80	16.27	15.29	8.56	8.13
Withdrawal	Q_{env}+75%Q_{wd}	69.12	30.88	18.41	19.39	26.12	26.55
	Q_{env}+50%Q_{wd}	69.12	30.88	18.41	19.39	26.12	26.55
	Q_{env}+25%Q_{wd}	69.12	30.88	18.41	19.39	26.12	26.55
Augmentation	Q_{avg}+25% Q_{aug}	69.12	31.83	22.48	23.21	28.26	28.58
	Q_{avg}+50%Q_{aug}	69.12	32.78	26.55	27.03	30.40	30.62
	Q_{avg}+75%Q_{aug}	69.12	33.73	30.61	30.86	32.54	32.65
	Q_{avg}+100%Q_{aug}	69.12	34.68	34.68	34.68	34.68	34.68

Table 4.22: Development of flow scenario for withdrawal and augmentation in low flow season at Jagir (SW 68.5) of Dhaleshwari

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
DhaleshwariSW 68.5/Jagir	Q_{avg}	449.10	116.14	98.62	116.01	128.71	142.37
	Q_{env}	336.00	124.24	124.24	124.24	124.24	124.24
	WQ	Ok	Ok	Ok	Ok	Ok	Ok
	Q_{wd}	113.10	0.00	0.00	0.00	4.47	18.14
	Q_{aug}	0.00	8.09	25.62	8.23	0.00	0.00
Withdrawal	Q_{env}+75%Q_{wd}	420.83	116.14	98.62	116.01	127.59	137.84
	Q_{env}+50%Q_{wd}	392.55	116.14	98.62	116.01	126.47	133.30
	Q_{env}+25%Q_{wd}	364.28	116.14	98.62	116.01	125.35	128.77
Augmentation	Q_{avg}+25% Q_{aug}	336.00	118.17	105.02	118.06	124.24	124.24
	Q_{avg}+50%Q_{aug}	336.00	120.19	111.43	120.12	124.24	124.24
	Q_{avg}+75%Q_{aug}	336.00	122.21	117.83	122.18	124.24	124.24
	Q_{avg}+100%Q_{aug}	336.00	124.24	124.24	124.24	124.24	124.24

Table 4.23: Development of flow scenario for withdrawal and augmentation in low flow season at Demra (SW 179) of Shitalakhya

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Shitalakhya/SW 179/Demra	Q_{avg}	362.09	32.99	29.99	33.24	38.86	49.03
	Q_{env}	284.00	49.23	49.23	49.23	49.23	49.23
	WQ	Ok	Ok	Ok	Ok	Ok	Ok
	Q_{wd}	78.09	0.00	0.00	0.00	0.00	0.00
	Q_{aug}	0.00	16.23	19.23	15.99	10.37	0.19
Withdrawal	Q_{env}+75%Q_{wd}	342.56	32.99	29.99	33.24	38.86	49.03
	Q_{env}+50%Q_{wd}	323.04	32.99	29.99	33.24	38.86	49.03
	Q_{env}+25%Q_{wd}	303.52	32.99	29.99	33.24	38.86	49.03
Augmentation	Q_{avg}+25% Q_{aug}	284.00	37.05	34.80	37.23	41.45	49.08
	Q_{avg}+50%Q_{aug}	284.00	41.11	39.61	41.23	44.04	49.13
	Q_{avg}+75%Q_{aug}	284.00	45.17	44.42	45.23	46.63	49.18
	Q_{avg}+100%Q_{aug}	284.00	49.23	49.23	49.23	49.23	49.23

Table 4.24: Development of flow scenario for withdrawal and augmentation in low flow season at Demra (SW 7.5) of Balu

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Balu/SW 7.5/Demra	Q_{avg}	46.46	18.84	17.54	16.40	15.89	17.75
	Q_{env}	39.00	27.05	27.05	27.05	27.05	27.05
	WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
	Q_{wd}	NA	NA	NA	NA	NA	NA
	Q_{aug}	0.00	8.21	9.50	10.64	11.15	9.30
Withdrawal	Q_{env}+75%Q_{wd}	46.46	18.84	17.54	16.40	15.89	17.75
	Q_{env}+50%Q_{wd}	46.46	18.84	17.54	16.40	15.89	17.75
	Q_{env}+25%Q_{wd}	46.46	18.84	17.54	16.40	15.89	17.75
Augmentation	Q_{avg}+25% Q_{aug}	46.46	20.89	19.92	19.06	18.68	20.07
	Q_{avg}+50%Q_{aug}	46.46	22.94	22.29	21.73	21.47	22.40
	Q_{avg}+75%Q_{aug}	46.46	24.58	24.67	23.85	24.26	24.72
	Q_{avg}+100%Q_{aug}	46.46	27.05	27.05	27.05	27.05	27.05

Table 4.25: Development of flow scenario for withdrawal and augmentation in low flow season at Tongi (SW 299) of Tongi Khal

River/Station ID/Name	Flow scenario (cumec)	Nov	Dec	Jan	Feb	Mar	Apr
Tongi Khal/SW 299/Tongi	Q_{avg}	11.78	5.51	1.10	1.67	2.59	2.86
	Q_{env}	19.00	5.00	2.49	2.49	2.49	3.00
	WQ	Not ok	Not ok	Not ok	Not ok	Not ok	Not ok
	Q_{wd}	NA	NA	NA	NA	NA	NA
	Q_{aug}	7.22	0.00	1.39	0.82	0.00	0.14
Withdrawal	Q_{env}+75%Q_{wd}	11.78	5.51	1.10	1.67	2.59	2.86
	Q_{env}+50%Q_{wd}	11.78	5.51	1.10	1.67	2.59	2.86
	Q_{env}+25%Q_{wd}	11.78	5.51	1.10	1.67	2.59	2.86
Augmentation	Q_{avg}+25% Q_{aug}	13.59	5.51	1.44	1.87	2.59	2.90
	Q_{avg}+50%Q_{aug}	15.39	5.51	1.79	2.08	2.59	2.93
	Q_{avg}+75%Q_{aug}	17.20	5.51	2.14	2.28	2.59	2.97
	Q_{avg}+100%Q_{aug}	19.00	5.51	2.49	2.49	2.59	3.00

Table 4.26: Development of flow scenario for withdrawal and augmentation in high flow season at Kaliakoir (SW 301) of Turag

River/Station ID/Name	Flow scenario (cumec)	May	Jun	Jul	Aug	Sep	Oct
Turag/SW 301/Kaliakoir	Q_{avg}	65.04	74.80	204.27	393.57	353.85	201.36
	Q_{env}	54.00	75.00	188.00	400.00	353.00	201.00
	WQ	Ok	Ok	Ok	Ok	Ok	Ok
	Q_{wd}	11.04	0.00	16.27	0.00	0.85	0.36
	Q_{aug}	0.00	0.20	0.00	6.43	0.00	0.00
Withdrawal	Q_{env}+75%Q_{wd}	62.28	74.80	200.20	393.57	353.64	201.27
	Q_{env}+50%Q_{wd}	59.52	74.80	196.14	393.57	353.43	201.18
	Q_{env}+25%Q_{wd}	56.76	74.80	192.07	393.57	353.21	201.09
Augmentation	Q_{avg}+25% Q_{aug}	54.00	74.85	188.00	395.18	353.00	201.00
	Q_{avg}+50%Q_{aug}	54.00	74.90	188.00	396.78	353.00	201.00
	Q_{avg}+75%Q_{aug}	54.00	74.95	188.00	398.39	353.00	201.00
	Q_{avg}+100%Q_{aug}	54.00	75.00	188.00	400.00	353.00	201.00

Table 4.27: Development of flow scenario for withdrawal and augmentation in high flow season at Mirpur (SW 302) of Turag

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Turag/SW 302/Mirpur	Q_{avg}	63.12	74.65	208.93	391.74	353.48	201.36
	Q_{env}	54.00	75.00	188.00	400.00	353.00	201.00
	WQ	Ok	Ok	Ok	Ok	Ok	Ok
	Q_{wd}	9.12	0.00	20.93	0.00	0.48	0.36
	Q_{aug}	0.00	0.35	0.00	8.26	0.00	0.00
Withdrawal	Q_{env}+75%Q_{wd}	60.84	74.65	203.70	391.74	353.36	201.27
	Q_{env}+50%Q_{wd}	58.56	74.65	198.46	391.74	353.24	201.18
	Q_{env}+25%Q_{wd}	56.28	74.65	193.23	391.74	353.12	201.09
Augmentation	Q_{avg}+25% Q_{aug}	54.00	74.74	188.00	393.80	353.00	201.00
	Q_{avg}+50%Q_{aug}	54.00	74.82	188.00	395.87	353.00	201.00
	Q_{avg}+75%Q_{aug}	54.00	74.91	188.00	397.93	353.00	201.00
	Q_{avg}+100%Q_{aug}	54.00	75.00	188.00	400.00	353.00	201.00

Table 4.28: Development of flow scenario for withdrawal and augmentation in high flow season at Dhaka Mill Barrack (SW 42) of Buriganga

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Buriganga/SW 42/Dhaka Mill Barrack	Q_{avg}	33.69	188.39	398.41	462.31	439.84	367.80
	Q_{avg}	69.36	189.00	410.00	459.00	353.00	201.00
	Q_{env}	Ok	Ok	Ok	Ok	Ok	Ok
	WQ	0.00	0.00	0.00	3.31	86.84	166.80
	Q_{wd}	35.68	0.61	11.59	0.00	0.00	0.00
Withdrawal	Q_{aug}	33.69	188.39	398.41	461.48	418.13	326.10
	Q_{env}+75%Q_{wd}	33.69	188.39	398.41	460.65	396.42	284.40
	Q_{env}+50%Q_{wd}	33.69	188.39	398.41	459.83	374.71	242.70
Augmentation	Q_{env}+25%Q_{wd}	42.61	188.54	401.30	459.00	353.00	201.00
	Q_{avg}+25% Q_{aug}	51.52	188.70	404.20	459.00	353.00	201.00
	Q_{avg}+50%Q_{aug}	60.44	188.85	407.10	459.00	353.00	201.00
	Q_{avg}+75%Q_{aug}	69.36	189.00	410.00	459.00	353.00	201.00

Table 4.29: Development of flow scenario for withdrawal and augmentation in high flow season at Jagir (SW 68.5) of Dhaleshwari

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
DhaleshwariS W 68.5/Jagir	Q_{avg}	198.99	604.38	1223.34	1631.02	1567.28	1178.21
	Q_{avg}	248.47	549.00	742.00	1219.00	1243.00	714.00
	Q_{env}	Ok	Ok	Ok	Ok	Ok	Ok
	WQ	0.00	55.38	481.34	412.02	324.28	464.21
	Q_{wd}	49.48	0.00	0.00	0.00	0.00	0.00
Withdrawal	Q_{aug}	198.99	590.53	1103.01	1528.01	1486.21	1062.16
	Q_{env}+75%Q_{wd}	198.99	576.69	982.67	1425.01	1405.14	946.10
	Q_{env}+50%Q_{wd}	198.99	562.84	862.34	1322.00	1324.07	830.05
Augmentation	Q_{env}+25%Q_{wd}	211.36	549.00	742.00	1219.00	1243.00	714.00
	Q_{avg}+25% Q_{aug}	223.73	549.00	742.00	1219.00	1243.00	714.00
	Q_{avg}+50%Q_{aug}	236.10	549.00	742.00	1219.00	1243.00	714.00
	Q_{avg}+75%Q_{aug}	248.47	549.00	742.00	1219.00	1243.00	714.00

Table 4.30: Development of flow scenario for withdrawal and augmentation in high flow season at Demra (SW 179) of Shitalakhya

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Shitalakhya/ SW 179/Demra	Q_{avg}	72.22	269.48	290.32	503.67	575.45	696.21
	Q_{avg}	98.45	268.00	296.00	372.00	557.00	282.00
	Q_{env}	Ok	Ok	Ok	Ok	Ok	Ok
	WQ	0.00	1.48	0.00	131.67	18.45	414.21
	Q_{wd}	26.23	0.00	5.68	0.00	0.00	0.00
Withdrawal	Q_{aug}	72.22	269.11	290.32	470.75	570.84	592.66
	Q_{env}+75%Q_{wd}	72.22	268.74	290.32	437.84	566.22	489.10
	Q_{env}+50%Q_{wd}	72.22	268.37	290.32	404.92	561.61	385.55
Augmentation	Q_{env}+25%Q_{wd}	78.78	268.00	291.74	372.00	557.00	282.00
	Q_{avg}+25% Q_{aug}	85.34	268.00	293.16	372.00	557.00	282.00
	Q_{avg}+50%Q_{aug}	91.89	268.00	294.58	372.00	557.00	282.00
	Q_{avg}+75%Q_{aug}	98.45	268.00	296.00	372.00	557.00	282.00

Table 4.31: Development of flow scenario for withdrawal and augmentation in high flow season at Demra (SW 7.5) of Balu

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Balu/SW 7.5/Demra	Q_{avg}	30.08	133.05	392.36	354.87	292.70	286.78
	Q_{avg}	54.09	119.00	407.00	372.00	282.00	282.00
	Q_{env}	Ok	Ok	Ok	Ok	Ok	Ok
	WQ	0.00	14.05	0.00	0.00	10.70	4.78
	Q_{wd}	24.01	0.00	14.64	17.13	0.00	0.00
Withdrawal	Q_{aug}	30.08	129.53	392.36	354.87	290.02	285.59
	$Q_{env}+75\%Q_{wd}$	30.08	126.02	392.36	354.87	287.35	284.39
	$Q_{env}+50\%Q_{wd}$	30.08	122.51	392.36	354.87	284.67	283.20
Augmentation	$Q_{env}+25\%Q_{wd}$	36.09	119.00	396.02	359.15	282.00	282.00
	$Q_{avg}+25\%\ Q_{aug}$	42.09	119.00	399.68	363.44	282.00	282.00
	$Q_{avg}+50\%Q_{aug}$	48.09	119.00	403.34	367.72	282.00	282.00
	$Q_{avg}+75\%Q_{aug}$	54.09	119.00	407.00	372.00	282.00	282.00

Table 4.32: Development of flow scenario for withdrawal and augmentation in high flow season at Tongi (SW 299) of Tongi Khal

River/Station ID/Name	Method	May	Jun	Jul	Aug	Sep	Oct
Tongi Khal/SW 299/Tongi	Q_{avg}	4.39	11.08	16.38	21.15	27.60	43.14
	Q_{avg}	4.98	11.00	17.00	20.00	28.00	42.00
	Q_{env}	Ok	Ok	Ok	Ok	Ok	Ok
	WQ	0.00	0.08	0.00	1.15	0.00	1.14
	Q_{wd}	0.58	0.00	0.62	0.00	0.40	0.00
Withdrawal	Q_{aug}	4.39	11.06	16.38	20.86	27.60	42.86
	$Q_{env}+75\%Q_{wd}$	4.39	11.04	16.38	20.57	27.60	42.57
	$Q_{env}+50\%Q_{wd}$	4.39	11.02	16.38	20.29	27.60	42.29
Augmentation	$Q_{env}+25\%Q_{wd}$	4.54	11.00	16.54	20.00	27.70	42.00
	$Q_{avg}+25\%\ Q_{aug}$	4.68	11.00	16.69	20.00	27.80	42.00
	$Q_{avg}+50\%Q_{aug}$	4.83	11.00	16.85	20.00	27.90	42.00
	$Q_{avg}+75\%Q_{aug}$	4.98	11.00	17.00	20.00	28.00	42.00

4.6.2 Assessment of the effect of flow withdrawal based on DO and BOD

For the withdrawal scenario, the available flow of a station for a specific month decreased as water is taken away. Three withdrawal scenarios, i.e. (Q_{env}+75%Q_{wd}), (Q_{env}+50%Q_{wd}) and (Q_{env}+25%Q_{wd}) have been considered in this study where 25%, 50% and 75% of available flow have been withdrawal from a station. Decrement of available flow decrease the amount of dissolved oxygen (DO) and increase the amount of biochemical oxygen demand (BOD) for a specific month of a station. Table 4.33 through Table 4.39 present the response of DO and BOD for three different withdrawal scenarios at Kaliakoir of Turag, Mirpur of Turag Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal. Haque (2018) reported that the inland river water standard of DO is 6 mg/l and BOD is 2 mg/l. From the Table, it is found that DO decreased when 25% of available flow is withdrawal compared to the observed value of DO for Q_{avg}. Further decrement of DO occur when 50% of available flow is withdrawal. It is also found that DO is minimum for (Q_{env}+25%Q_{wd}) scenario among three different withdrawal scenarios where 75% of available flow has been withdrawal. On the other hand, BOD increased when 25% of available flow is withdrawal compared to the observed value of BOD for Q_{avg}. BOD again increased when 50% of available flow is withdrawal. BOD is maximum for (Q_{env}+25%Q_{wd}) scenario among three different withdrawal scenarios where 75% of available flow has been withdrawal.

Table 4.33 shows that for Kaliakoir of Turag, the amount of DO decreased from 5.39 mg/l to 5.12 mg/l, 6.25 mg/l to 6.06 mg/l, 5.27 mg/l to 5.11 mg/l and 4.12 mg/l to 3.19 mg/l for May, July, September and October respectively due to three withdrawal scenarios. The amount BOD increased from 4.32 mg/l to 4.63 mg/l, 3.07 mg/l to 3.30 mg/l, 3.16 mg/l to 3.40 mg/l, 2.37 mg/l 2.56 mg/l for May, July, September and October respectively in response of three withdrawal scenarios.

Table 4.33: Response of DO and BOD for different withdrawal scenarios at Kaliakoir of Turag

River/Station ID/Name	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l							
		Q_{avg}		Q_{env}+75%Q_{wd}		Q_{env}+50%Q_{wd}		Q_{env}+25%Q_{wd}	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Turag/SW 301/ Kaliakoir	May	5.39	4.32	5.32	4.42	5.25	4.53	5.12	4.63
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	6.25	3.07	6.20	3.14	6.15	3.22	6.06	3.30
		Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK
	Sep	5.27	3.16	5.23	3.23	5.19	3.31	5.11	3.40
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	4.12	2.37	4.07	2.43	4.01	2.49	3.91	2.56
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.34 present the response of DO and BOD for different withdrawal scenario at Mirpur of Turag. It is seen that for Mirpur of Turag, the amount of DO decreased from 1.27 mg/l to 1.22 mg/l, 2.88 mg/l to 2.81 mg/l, 3.23 mg/l to 3.16 mg/l and 2.24 mg/l to 2.16 mg/l for May, July, September and October respectively due to three withdrawal scenarios. It is also seen that the amount BOD increased from 4.83 mg/l to 5.11 mg/l, 3.44 mg/l to 3.64 mg/l, 2.85 mg/l to 3.02 mg/l and 2.39 mg/l 2.54 mg/l for May, July, September and October respectively in response of three withdrawal scenarios.

Table 4.34: Response of DO and BOD for different withdrawal scenarios at Mirpur of Turag

River/Station ID/Name	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l							
		Q_{avg}		Q_{env}+75%Q_{wd}		Q_{env}+50%Q_{wd}		Q_{env}+25%Q_{wd}	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Turag/SW 302/ Mirpur	May	1.27	4.83	1.25	4.94	1.25	4.99	1.22	5.11
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	2.88	3.44	2.85	3.52	2.85	3.55	2.81	3.64
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Sep	3.23	2.85	3.20	2.92	3.20	2.95	3.16	3.02
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	2.24	2.39	2.21	2.45	2.21	2.47	2.16	2.54
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.35 present the response of DO and BOD for different withdrawal scenario at Dhaka Mill Barrack of Buriganga. It is observed that for Dhaka Mill Barrack of Buriganga, the amount of DO decreased from 3.11 mg/l to 3.00 mg/l, 2.78 mg/l to 2.70 mg/l and 1.79 mg/l to 1.72 mg/l for August, September and October respectively due to three withdrawal scenarios. It is also observed that the amount BOD increased from 3.07 mg/l to 3.28 mg/l, 2.87 mg/l to 3.06 mg/l and 2.39 mg/l to 2.54 mg/l1 for August, September and October respectively in response of three withdrawal scenarios.

Table 4.35: Response of DO and BOD for different withdrawal scenarios at Dhaka Mill Barrack of Buriganga

River/Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**							
		Q_{avg}		**Q_{env}+75%Q_{wd}**		**Q_{env}+50%Q_{wd}**		**Q_{env}+25%Q_{wd}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Buriganga/SW 42/Dhaka Mill Barrack	Aug	3.11	3.07	3.07	3.16	3.05	3.19	3.00	3.28
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Sep	2.78	2.87	2.75	2.95	2.73	2.97	2.70	3.06
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	1.79	2.39	1.76	2.45	1.75	2.47	1.72	2.54
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.36 present the response of DO and BOD for different withdrawal scenario at Jagir of Dhaleshwari. It is found that for Jagir of Dhaleshwari, the amount of DO decreased from 0.87 mg/l to 0.83 mg/l, 1.52 mg/l to 1.45 mg/l, 3.56 mg/l to 3.43 mg/l, 5.28 mg/l to 5.09 mg/l, 5.76 mg/l to 5.55 mg/l, 5.52 mg/l to 5.35 mg/l, 5.38 mg/l to 5.17 mg/l and 4.75 mg/l to 4.56 mg/l for March, April, June, July, August, September, October and November due to three withdrawal scenarios. It is also found that the amount of BOD increased from 16.76 mg/l to 18.43 mg/l, 11.49 mg/l to 12.66 mg/l, 8.42 mg/l to 9.37 mg/l, 3.21 mg/l to 3.55 mg/l, 2.51 mg/l to 2.80 mg/l, 3.15 mg/l to 3.52 mg/l, 2.57 mg/l to 2.87 mg/l and 2.75 mg/l to 3.03 mg/l for March, April, June, July, August, September, October and November in response of three withdrawal scenarios.

Table 4.36: Response of DO and BOD for different withdrawal scenarios at Jagir of Dhaleshwari

River/Station ID/Name	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l							
		Q_{avg}		Q_{env}+75%Q_{wd}		Q_{env}+50%Q_{wd}		Q_{env}+25%Q_{wd}	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Dhaleshwari/SW 68.5/ Jagir	Mar	0.87	16.76	0.85	17.29	0.85	17.53	0.83	18.43
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Apr	1.52	11.49	1.50	11.86	1.48	12.03	1.45	12.66
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jun	3.56	8.42	3.51	8.74	3.48	8.86	3.43	9.37
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	5.28	3.21	5.21	3.32	5.17	3.36	5.09	3.55
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Aug	5.76	2.51	5.68	2.61	5.63	2.64	5.55	2.80
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Sep	5.52	3.15	5.46	3.28	5.42	3.32	5.35	3.52
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	5.38	2.57	5.30	2.67	5.26	2.71	5.17	2.87
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Nov	4.75	2.75	4.68	2.84	4.64	2.88	4.56	3.03
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.37 present the response of DO and BOD for different withdrawal scenario at Demra of Shitalakhya. It is seen that for Demra of Shitalakhya, the amount of DO decreased from 6.03 mg/l to 5.71 mg/l, 6.54 mg/l to 6.26 mg/l, 6.40 mg/l to 6.17 mg/l, 6.37 mg/l to 6.00 mg/l and 5.83 mg/l to 5.48 mg/l for June, August, September, October and November due to three withdrawal scenarios. It is also seen that the amount BOD increased from 5.35 mg/l to 5.77 mg/l, 4.51 mg/l to 4.89 mg/l, 5.05 mg/l to 5.46 mg/l, 5.22 mg/l to 5.70 mg/l and 5.23 mg/l to 5.59 mg/l for June, August, September, October and November due to three withdrawal scenarios.

Table 4.37: Response of DO and BOD for different withdrawal scenarios at Demra of Shitalakhya

River/Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**							
		Q_{avg}		**Q_{env}+75%Q_{wd}**		**Q_{env}+50%Q_{wd}**		**Q_{env}+25%Q_{wd}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Shitalakhya/SW 179/Demra	Jun	6.03	5.35	5.91	5.50	5.85	5.58	5.71	5.77
		Ok	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Aug	6.54	4.51	6.45	4.65	6.38	4.72	6.26	4.89
		Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK
	Sep	6.40	5.05	6.33	5.20	6.27	5.27	6.17	5.46
		Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK
	Oct	6.37	5.22	6.23	5.40	6.17	5.47	6.00	5.70
		Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK
	Nov	5.83	5.23	5.69	5.35	5.64	5.42	5.48	5.59
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.38 present the response of DO and BOD for different withdrawal scenario at Demra of Balu. It is seen that for Demra of Balu, the amount of DO decreased from 4.85 mg/l to 4.59 mg/l, 4.78 mg/l to 4.61 mg/l and 4.58 mg/l to 4.31 mg/l for June, September and October due to three withdrawal scenarios. It is also observed that the amount BOD increased from 3.68 mg/l to 3.89 mg/l, 2.73 mg/l to 2.89 mg/l and 2.78 mg/l 2.98 mg/l for June, September and October due to three withdrawal scenarios.

Table 4.38: Response of DO and BOD for different withdrawal scenarios at Demra of Balu

River/Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**							
		Q_{avg}		**Q_{env}+75%Q_{wd}**		**Q_{env}+50%Q_{wd}**		**Q_{env}+25%Q_{wd}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Balu/SW 7.5/ Demra	Jun	4.85	3.68	4.75	3.78	4.71	3.78	4.59	3.89
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Sep	4.78	2.73	4.73	2.81	4.69	2.81	4.61	2.89
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	4.58	2.78	4.48	2.88	4.44	2.88	4.31	2.98
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.39 present the response of DO and BOD for different withdrawal scenario at Tongi of Tongi Khal. It is found that for Tongi of Tongi Khal, the amount of DO decreased from 2.86 mg/l to 2.74 mg/l, 3.94 mg/l to 3.80 mg/l and 3.89 mg/l to 3.72 mg/l for June, August and October due to three withdrawal scenarios. The Table Blso shows that the amount BOD increased from 7.44 mg/l 7.86 mg/l, 2.72 mg/l to 2.89 mg/l and 2.48 mg/l to 2.66 mg/l for June, August and October due to three withdrawal scenarios.

Table 4.39: Response of DO and BOD for different withdrawal scenarios at Tongi of Tongi Khal

River/Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**							
		Q_{avg}		**Q_{env}+75%Q_{wd}**		**Q_{env}+50%Q_{wd}**		**Q_{env}+25%Q_{wd}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Tongi Khal/SW 299/ Tongi	Jun	2.86	7.44	2.82	7.64	2.79	7.65	2.74	7.86
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Aug	3.94	2.72	3.89	2.80	3.85	2.80	3.80	2.89
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Oct	3.89	2.48	3.83	2.57	3.79	2.57	3.72	2.66
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

4.6.3 Assessment of the effect of flow augmentation based on DO and BOD

For the augmentation scenario, the available flow of a station for a specific month increased as water is augmented. As previously mentioned, four augmentation scenarios, i.e. (Q_{avg}+25%Q_{aug}), (Q_{avg}+50%Q_{aug}), (Q_{avg}+75%Q_{aug}), (Q_{avg}+100%Q_{aug}) where 25%, 50%, 75% and 100% of available flow have been increased for a station. Increment of available flow increase the amount of DO and decrease the amount of BOD for a specific month of a station. Table 4.40 through Table 4.46 present the response of DO and BOD for four different augmentation scenarios at Kaliakoir of Turag, Mirpur of Turag, Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal. DO increased when 25% of available flow is augmented compared to the observed value of DO for Q_{avg}. Further increment of DO occur when 50% and 75% of available flow is increased. DO is maximum for (Q_{avg}+100%Q_{aug}) scenario among four different augmentation scenarios where 100% of available flow has been augmented. On the other hand, BOD decreased when 25% of available flow is augmented compared to the observed value of BOD for Q_{avg}. BOD again decreased when 50% and 75% of available flow is augmented. BOD is least for (Q_{avg}+100%Q_{aug}) scenario among four different augmentation scenarios where 100% of available flow has been augmented.

Table 4.40 present the response of DO and BOD for different augmentation scenario at Kaliakoir of Turag. Table 4.40 shows that for Kaliakoir of Turag, the amount of DO increased from 1.95 mg/l to 2.04 mg/l, 3.87 mg/l to 4.08 mg/l, 3.22 mg/l to 3.46 mg/l, 5.50 mg/l to 6.04 mg/l and 5.90 mg/l to 6.50 mg/l for January, February, March, June and August respectively due to four augmentation scenarios. The Table Blso shows that the amount of BOD decreased from 4.10 mg/l to 4.00 mg/l, 9.26 mg/l 8.71 mg/l 13.87 mg/l to 13.00 mg/l, 3.08 mg/l to 2.91 mg/l and 3.27 mg/l to 3.15 mg/l for January, February, March, June and August respectively in response of four augmentation scenarios.

Table 4.40: Response of DO and BOD for different augmentation scenarios at Kaliakoir of Turag

River/ Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**									
		Q_{avg}		**Q_{avg}+25%Q_{aug}**		**Q_{avg}+50%Q_{aug}**		**Q_{avg}+75%Q_{aug}**		**Q_{avg}+100%Q_{aug}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Turag/ SW 301/ Kaliakoir	Jan	1.95	4.10	1.98	4.06	2.00	4.05	2.02	4.00	2.04	4.00
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	3.87	9.26	3.93	9.15	3.98	9.03	4.03	8.81	4.08	8.71
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	3.22	13.87	3.27	13.69	3.33	13.52	3.39	13.17	3.46	13.00
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jun	5.50	3.08	5.63	3.04	5.76	3.01	5.90	2.94	6.04	2.91
		Not Ok	Not OK	Not Ok	Not OK	Not Ok	Not OK	Not Ok	Not OK	Ok	Not OK
	Aug	5.90	3.27	6.05	3.24	6.19	3.22	6.34	3.17	6.50	3.15
		Not Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK

Table 4.41 present the response of DO and BOD for different augmentation scenario at Mirpur of Turag. It is seen from the Table that For Mirpur of Turag, the amount of DO increased drom 0.25 mg/l to 0.26 mg/l, 0.35 mg/l to 0.36 mg/l, 0.25 mg/l to 0.26 mg/l, 1.45 mg/l to 1.55 mg/l and 3.61 mg/l to 3.85 mg/l for January, February, March, June and August respectively due to four augmentation scenarios. It is also seen that the amount of BOD decreased from 5.49 mg/l to 5.16 mg/l, 8.41 mg/l to 7.84 mg/l, 13.25 mg/l to 12.39 mg/l, 4.43 mg/l to 4.16 mg/l, 3.08 mg/l to 2.93 mg/l for January, February, March, June and August respectively in response of four augmentation scenarios.

Table 4.41: Response of DO and BOD for different augmentation scenarios at Mirpur of Turag

River/ Station ID/Name |	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l									
		Q_{avg}		Q_{avg}+25%Q_{aug}		Q_{avg}+50%Q_{aug}		Q_{avg}+75%Q_{aug}		Q_{avg}+100%Q_{aug}	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Turag/ SW 302/ Mirpur	Jan	0.25	5.49	0.25	5.42	0.25	5.42	0.26	5.33	0.26	5.16
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	0.35	8.41	0.35	8.29	0.36	8.28	0.36	8.12	0.36	7.84
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	0.25	13.25	0.25	13.07	0.25	13.05	0.26	12.82	0.26	12.39
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jun	1.45	4.43	1.49	4.38	1.50	4.37	1.54	4.30	1.55	4.16
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Aug	3.61	3.08	3.70	3.06	3.73	3.05	3.82	3.01	3.85	2.93
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.42 present the response of DO and BOD for different augmentation scenario at Dhaka Mill Barrack of Buriganga. From the Table it is found that for Dhaka Mill Barrack of Buriganga, the amount of DO increased from 0.127 mg/l to 0.133 mg/l, 0.80 mg/l to 0.85 mg/l, 2.29 mg/l to 2.46 mg/l in January, June and July respectively. Though augmentation scenarios have been implemented in February, March, April, May and December as well, but the increment of DO is less significant as the existing amount of DO in Burianga is very low due to the severity of pollution. The amount of BOD decreased from 4.85 mg/l to 4.63 mg/l, 6.99 mg/l to 6.58 mg/l, 13.17 mg/l to 12.48 mg/l, 9.73 mg/l to 9.13 mg/l, 5.05 mg/l to 4.74 mg/l, 4.11 mg/l to 3.93 mg/l, 3.42 mg/l to 3.26 mg/l and 4.93 mg/l to 4.63 mg/l for January, February, March, April, May, June, July and December respectively due to four augmentation scenarios.

Table 4.42: Response of DO and BOD for different augmentation scenarios at Dhaka Mill Barrack of Buriganga

River/ Station ID/Name	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l									
		Q_{avg}		$Q_{avg}+25\%Q_{aug}$		$Q_{avg}+50\%Q_{aug}$		$Q_{avg}+75\%Q_{aug}$		$Q_{avg}+100\%Q_{aug}$	
		DO (mg/l)	BOD (mg/l)	DO (mg/l)	BOD (mg/l)	DO (mg/l)	BOD (mg/l)	DO (mg/l)	BOD (mg/l)	DO (mg/l)	BOD (mg/l)
Buriganga / SW 42/ Dhaka Mill Barrack	Jan	0.127	4.85	0.128	4.79	0.129	4.76	0.131	4.69	0.133	4.63
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	0.0002	6.99	0.0002	6.87	0.0002	6.83	0.0003	6.70	0.0003	6.58
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	0.002	13.17	0.00	12.98	0.00	12.90	0.00	12.69	0.0021	12.48
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Apr	0.04	9.73	0.04	9.56	0.04	9.50	0.04	9.31	0.04	9.13
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	May	0.49	5.05	0.50	4.96	0.50	4.93	0.52	4.83	0.52	4.74
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jun	0.80	4.11	0.82	4.07	0.83	4.04	0.85	3.99	0.85	3.93
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	2.29	3.42	2.37	3.38	2.39	3.36	2.47	3.31	2.46	3.26
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Dec	0.067	4.93	0.068	4.84	0.069	4.81	0.070	4.72	0.071	4.63
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.43 presents the response of DO and BOD for different augmentation scenario at Jagir of Dhaleshwari. For Jagir of Dhaleshwari, the amount of DO increased from 0.94 mg/l to 1.06 mg/l, 1.12 mg/l to 1.28 mg/l, 2.10 mg/l to 2.44 mg/l and 2.68 mg/l to 3.05 mg/l for January, February, May and December respectively due to four augmentation scenarios. Table 4.43 also shows that the amount of BOD decreased from 3.72 mg/l to 3.52 mg/l, 12.83 mg/l to 12.00 mg/l, 10.62 mg/l to 9.94 mg/l and 3.44 mg/l to 3.22 mg/l for January, February, May and December respectively due to four augmentation scenarios.

Table 4.43: Response of DO and BOD for different augmentation scenarios at Jagir of Dhaleshwari

River/Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**									
		Q_{avg}		**Q_{avg}+25%Q_{aug}**		**Q_{avg}+50% Q_{aug}**		**Q_{avg}+75% Q_{aug}**		**Q_{avg}+100% Q_{aug}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Dhaleshwari/ SW 68.5/ Jagir	Jan	0.94	3.72	0.97	3.67	0.98	3.64	1.02	3.58	1.06	3.52
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	1.13	12.83	1.16	12.61	1.17	12.50	1.23	12.25	1.28	12.00
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	May	2.10	10.62	2.17	10.43	2.20	10.34	2.33	10.14	2.44	9.94
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Dec	2.68	3.44	2.75	3.38	2.79	3.35	2.93	3.28	3.05	3.22
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.44 presents the response of DO and BOD for different augmentation scenario at Demra of Shitalakhya. It is observed that for Demra of Shitalakhya, the amount of DO increased from 4.16 mg/l to 4.47 mg/l, 3.98 mg/l to 4.31 mg/l, 4.13 mg/l to 4.54 mg/l, 4.30 mg/l to 4.73 mg/l, 5.04 mg/l to 5.61 mg/l, 6.32 mg/l to 7.07 mg/l and 4.38 mg/l to 4.86 mg/l for January, February, March, April, May, July and December respectively due to four augmentation scenarios. It is also observed that the amount of BOD decreased from 5.32 mg/l to 4.97 mg/l, 7.09 mg/l to 6.52 mg/l, 13.20 mg/l to 12.20 mg/l, 11.35 mg/l to 10.38 mg/l, 8.39 mg/l to 7.75 mg/l, 4.83 mg/l to 4.57 mg/l and 5.36 mg/l to 4.91 mg/l for January, February, March, April, May, July and December respectively due to four augmentation scenarios.

Table 4.44: Response of DO and BOD for different augmentation scenarios at Demra of Shitalakhya

River/ Station ID/Name	Month	Inland river water standard of DO=6 mg/l and BOD=2 mg/l									
		Q_{avg}		Q_{avg}+25%Q_{aug}		Q_{avg}+50% Q_{aug}		Q_{avg}+75% Q_{aug}		Q_{avg}+100% Q_{aug}	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Shitalakhya / SW 179/ Demra	Jan	4.16	5.32	4.21	5.23	4.27	5.18	4.37	5.07	4.47	4.97
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	3.98	7.09	4.05	6.94	4.10	6.87	4.20	6.68	4.31	6.52
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	4.13	13.20	4.22	12.93	4.28	12.81	4.40	12.48	4.54	12.20
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Apr	4.30	11.35	4.39	11.08	4.45	10.98	4.59	10.66	4.73	10.38
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	May	5.04	8.39	5.17	8.21	5.24	8.14	5.42	7.93	5.61	7.75
		Not Ok	Not OK	Not Ok	Not OK	Not Ok	Not OK	Not Ok	Not OK	Not Ok	Not OK
	Jul	6.32	4.83	6.50	4.77	6.59	4.72	6.82	4.64	7.07	4.57
		Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK
	Dec	4.38	5.36	4.49	5.24	4.55	5.19	4.70	5.04	4.86	4.91
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.45 presents the response of DO and BOD for different augmentation scenario at Demra of Balu. For Demra of Balu, it is found that the amount of DO increased from 4.17 mg/l to 4.33 mg/l, 3.57 mg/l to 3.72 mg/l, 3.77 mg/l to 3.99 mg/l, 3.09 mg/l to 3.31 mg/l, 3.27 mg/l to 3.53 mg/l, 5.09 mg/l to 5.53 mg/l, 4.84 mg/l to 5.29 mg/l and 3.30 mg/l to 3.55 mg/l for January, February, March, April, May, July, August and December respectively due to four augmentation scenarios. It is also found that the amount of BOD decreased from 5.02 mg/l to 4.66 mg/l, 7.61 mg/l to 6.96 mg/l, 6.13 mg/l to 5.66 mg/l, 5.33 mg/l to 4.87 mg/l, 3.87 mg/l to 3.54 mg/l, 3.47 mg/l to 3.30 mg/l, 3.27 mg/l to 3.09 mg/l and 5.05 mg/l to 4.62 mg/l for January, February, March, April, May, July, August and December respectively due to four augmentation scenarios.

Table 4.45: Response of DO and BOD for different augmentation scenarios at Demra of Balu

River/ Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**									
		Q_{avg}		**Q_{avg}+25%Q_{aug}**		**Q_{avg}+50% Q_{aug}**		**Q_{avg}+75% Q_{aug}**		**Q_{avg}+100% Q_{aug}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Balu/SW 7.5/ Demra	Jan	4.17	5.02	4.22	4.92	4.22	4.88	4.28	4.76	4.33	4.66
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	3.57	7.61	3.62	7.43	3.62	7.36	3.67	7.15	3.72	6.96
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	3.77	6.13	3.84	6.00	3.84	5.95	3.92	5.79	3.99	5.66
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Apr	3.09	5.33	3.16	5.20	3.16	5.15	3.23	5.01	3.31	4.87
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	May	3.27	3.87	3.35	3.78	3.36	3.74	3.45	3.64	3.53	3.54
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	5.09	3.47	5.23	3.43	5.24	3.40	5.38	3.35	5.53	3.30
		Not Ok	Not OK	Not Ok	Not Ok	Not Ok	Not Ok	Not Ok	Not Ok	Not Ok	Not OK
	Aug	4.84	3.27	4.98	3.23	4.99	3.20	5.14	3.14	5.29	3.09
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not Ok	Not Ok	Not Ok	Not OK
	Dec	3.30	5.05	3.38	4.93	3.38	4.88	3.46	4.74	3.55	4.62
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

Table 4.46 present the response of DO and BOD for different augmentation scenario at Tongi of Tongi Khal. For Tongi of Tongi Khal, it is seen that the amount of DO increased from 1.16 mg/l to 1.20 mg/l, 0.92 mg/l to 0.95 mg/l, 1.21 mg/l to 1.26 mg/l, 1.15 mg/l to 1.21 mg/l, 1.36 mg/l to 1.43 mg/l, 3.30 mg/l to 3.49 mg/l, 3.51 mg/l to 3.72 mg/l and 2.81 mg/l to 2.94 mg/l for January, February, March, April, May, July, September and November respectively due to four augmentation scenarios. The Table Blso shows that the amount of BOD decreased from12.53 mg/l to 11.65 mg/l, 17.89 mg/l to 16.36 mg/l, 11.48 mg/l to 10.58 mg/l, 10.29 mg/l to 9.41 mg/l, 4.20 mg/l to 3.85 mg/l, 3.52 mg/l to 3.35 mg/l, 1.93 mg/l to 1.84 mg/l and 5.26 mg/l to 4.82 mg/l for January, February, March, April, May, July, September and November respectively due to four augmentation scenarios.

Table 4.46: Response of DO and BOD for different augmentation scenarios at Tongi of Tongi Khal

River/ Station ID/Name	**Month**	**Inland river water standard of DO=6 mg/l and BOD=2 mg/l**									
		Q_{avg}		**Q_{avg}+25%Q_{aug}**		**Q_{avg}+50% Q_{aug}**		**Q_{avg}+75% Q_{aug}**		**Q_{avg}+100% Q_{aug}**	
		DO (mg/l)	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**	**DO (mg/l)**	**BOD (mg/l)**
Tongi Khal/SW 299/ Tongi	Jan	1.16	12.53	1.17	12.30	1.18	12.19	1.18	11.90	1.20	11.65
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Feb	0.92	17.89	0.93	17.46	0.94	17.31	0.94	16.80	0.95	16.36
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Mar	1.21	11.48	1.23	11.23	1.23	11.13	1.24	10.84	1.26	10.58
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Apr	1.15	10.29	1.17	10.05	1.18	9.96	1.18	9.67	1.21	9.41
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	May	1.36	4.20	1.39	4.10	1.39	4.06	1.40	3.95	1.43	3.85
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Jul	3.30	3.52	3.38	3.48	3.39	3.45	3.41	3.40	3.49	3.35
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK
	Sep	3.51	1.93	3.60	1.91	3.62	1.89	3.63	1.86	3.72	1.84
		Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok	Not OK	Ok
	Nov	2.81	5.26	2.86	5.14	2.88	5.09	2.89	4.95	2.94	4.82
		Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK	Not OK

From the above Tables on response of DO and BOD for different augmentation scenario at Kaliakoir of Turag, Mirpur of Turag Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal; it is depicted that, though flow augmentation scenarios increase the amount of DO and decrease the amount of BOD in Dhaka peripheral rivers, this change is not that much significant so that it satisfy the standard limit of DO and BOD.

4.6.4 Percentage change of DO and BOD based on flow withdrawal scenario

Due to the three withdrawal scenarios, i.e. (Q_{env}+75%Q_{wd}), (Q_{env}+50%Q_{wd}) and (Q_{env}+25%Q_{wd}) where 25%, 50% and 75% of available flow have been withdrawal, the amount of DO and BOD have been changed compared to the observed value of DO and BOD for Q_{avg}. The percentage change of DO and BOD in response of the withdrawal scenario has been presented in graphical format in this chapter from Figure 4.13 through Figure 4.19 and in tabular format in Appendix B.3, Table B.3 (a).

Figure 4.13 presents the percentage change of DO and BOD in response of withdrawal scenarios at Kaliakoir of Turag. For Kaliakoir of Turag, the amount of DO decreased by 1.24% to 4.86%, 0.78% to 3.10%, 0.73% to 2.90% and 1.29% to 5.05% for May, July, September and October respectively due to three withdrawal scenarios. It is found from the Figure 4.13 that the amount of BOD increased by 2.33% to 7.16%, 2.30% to 7.38%, 2.47% to 7.61% and 2.49% to 5.05% for May, July, September and October respectively in response of three withdrawal scenarios. The percentage change of DO and BOD is minimum in September and maximum in October.

Figure 4.14 presents the percentage change of DO and BOD in response of withdrawal scenarios at Mirpur of Turag. In case of Mirpur of Turag from the Figure 4.14, it is observed that the amount of DO decreased by 1.35% to 3.29%, 0.90% to 2.39%, 0.85% to 2.30% and 1.40% to 3.38% for May, July, September and October respectively due to three withdrawal scenarios. The amount of BOD increased by 2.42% to 5.84%, 2.49% to 5.98%, 2.56% to 6.13% and 2.58% to 6.17% for May, July, September and October respectively in response of three withdrawal scenarios. The percentage change of DO is minimum in September and maximum in October. For BOD, the minimum change occurred in May and maximum change in October.

Figure 4.15 presents the percentage change of DO and BOD in response of withdrawal scenarios at Dhaka Mill Barrack of Buriganga. For Dhaka Mill Barrack of Buriganga, the Figure 4.15 presents that the amount of DO decreased by 1.35% to 3.29%, 0.90% to 2.39%, 0.85% to 2.30% and 1.40% to 3.38% for May, July, September and October respectively due to three withdrawal scenarios. The amount of BOD therefore increased by 1.42% to 3.65%, 1.05% to 2.93% and 1.49% to 3.78% for August, September and October respectively in response of three withdrawal scenarios. The percentage change of DO is minimum in September and maximum in October. For BOD, the minimum change occurred in October and maximum in August.

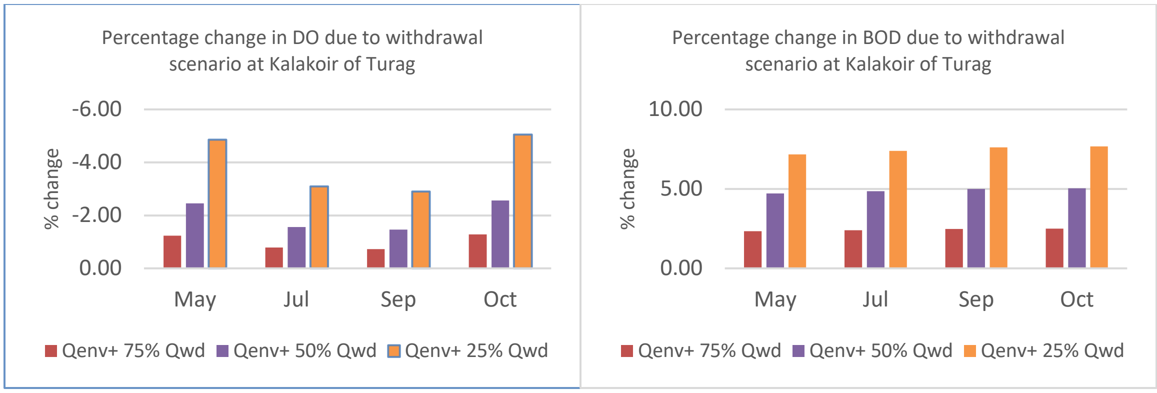


Figure 4.13: Percentage change of DO and BOD in response of withdrawal scenarios at Kaliakoir of Turag

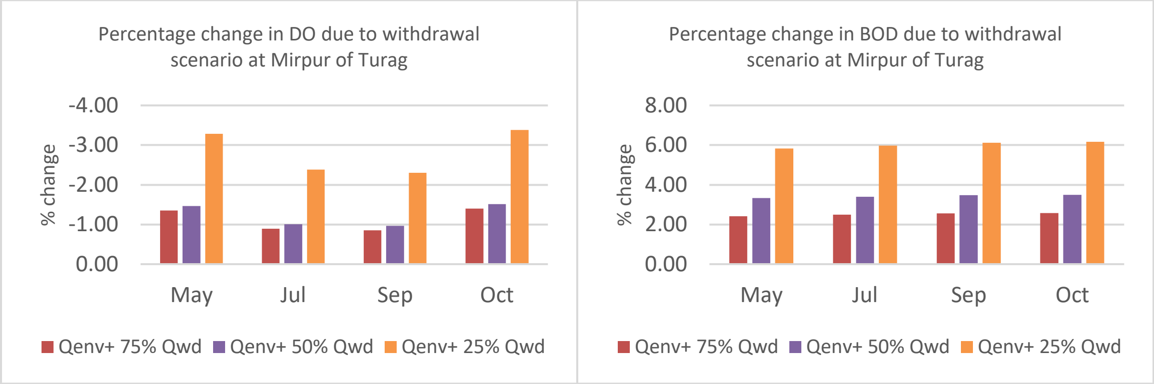


Figure 4.14: Percentage change of DO and BOD in response of withdrawal scenarios at Mirpur of Turag

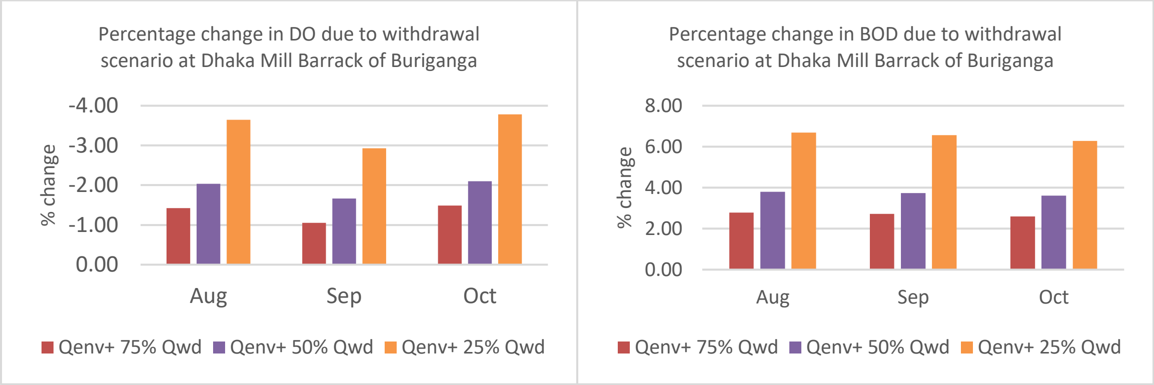


Figure 4.15: Percentage change of DO and BOD in response of withdrawal scenarios at Dhaka Mill Barrack of Buriganga

Figure 4.16 shows the percentage change of DO and BOD in response of withdrawal scenarios at Jagir of Dhaleshwari. The Figure shows that for Jagir of Dhaleshwari, the amount of DO decreased by 1.55% to 4.11%, 1.80% to 4.60%, 1.20% to 3.43%, 1.22% to

3.46%, 1.32% to 3.67%, 1.03% to 3.10%, 1.51% to 4.03% and 1.49% to 3.99% for March, April, June, July, August, September, October and November due to three withdrawal scenarios. Also, the amount of BOD increased by 3.14% to 9.92%, 3.27% to 10.20%, 3.80% to 11.33%, 3.52% to 10.72%, 4.05% to 11.86%, 3.90% to 11.55%, 3.84% to 11.42% and 3.33% to 10.31% for March, April, June, July, August, September, October and November in response of three withdrawal scenarios. The percentage change of DO is minimum in September and maximum in April. For BOD, the minimum change occurred in March and maximum in August.

Figure 4.17 shows the percentage change of DO and BOD in response of withdrawal scenarios at Demra of Shitalakhya. From the Figure, it is observed that for Demra of Shitalakhya, the amount of DO decreased by 1.99% to 5.36%, 1.39% to 4.19%, 1.11% to 3.65%, 2.20% to 5.75% and 2.28% to 5.90% for June, August, September, October and November due to three withdrawal scenarios. It is also observed that the amount of BOD increased by 2.78% to 7.86%, 3.02% to 8.38%, 2.88% to 8.07%, 3.45% to 9.26% and 2.31% to 6.87% for June, August, September, October and November due to three withdrawal scenarios. The percentage change of DO is minimum in September and maximum in November. For BOD, the minimum change occurred in November and maximum in October.

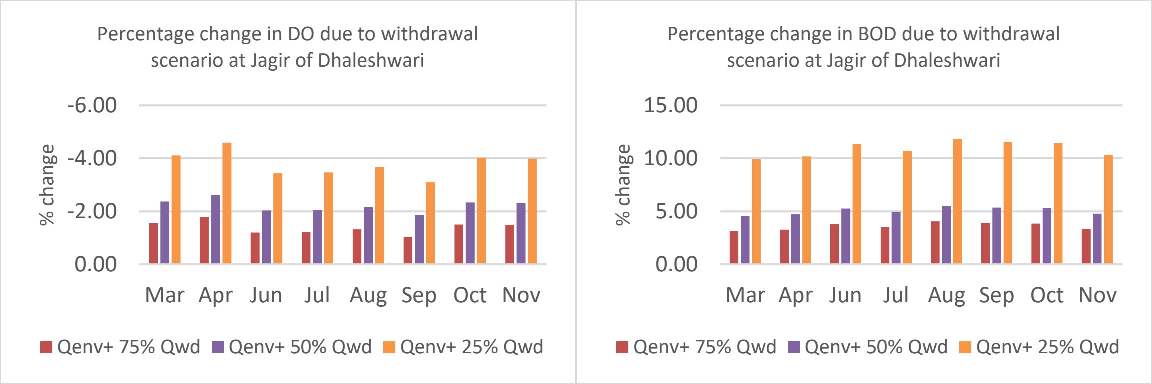


Figure 4.16: Percentage change of DO and BOD in response of withdrawal scenarios at Jagir of Dhaleshwari

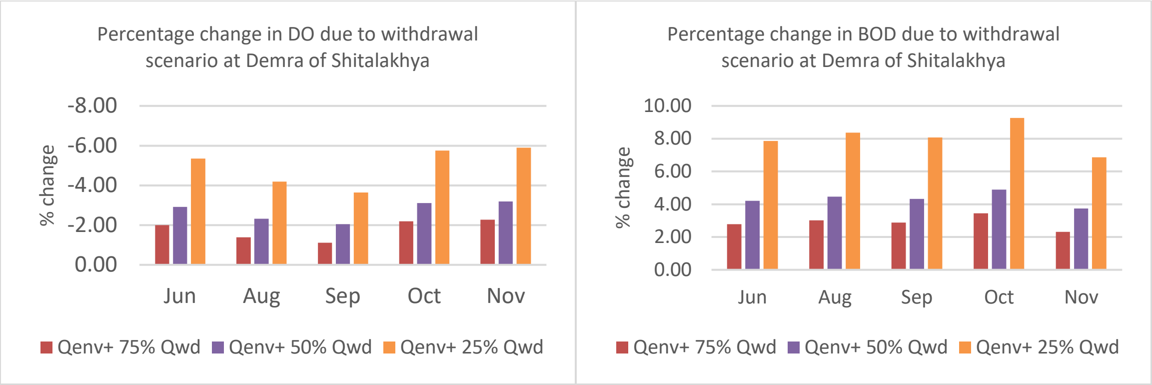


Figure 4.17: Percentage change of DO and BOD in response of withdrawal scenarios at Demra of Shitalakhya

Figure 4.18 shows the percentage change of DO and BOD in response of withdrawal scenarios at Demra of Balu. It is found that for Demra of Balu, the amount of DO decreased by 1.98% to 5.28%, 1.05% to 3.48% and 2.27% to 5.85% for June, September and October due to three withdrawal scenarios. And the amount of BOD increased by 2.69% to 5.63%, 2.80% to 5.86% and 3.42% to 7.15% for June, September and October due to three withdrawal scenarios. The percentage change of DO is minimum in September and maximum in October, whereas for BOD, the minimum change occurred in June and maximum in October.

Figure 4.19 shows the percentage change of DO and BOD in response of withdrawal scenarios at Tongi of Tongi Khal. For Tongi of Tongi Khal, the amount of DO decreased by 1.62% to 4.17%, 1.22% to 3.40% and 1.78% to 4.49% for June, August and October due to three withdrawal scenarios. The amount of BOD increased by 2.69% to 5.63%, 2.92% to 6.11% and 3.42% to 7.15% for June, August and October due to three withdrawal scenarios. The percentage change of DO is minimum in August and maximum in October, whereas for BOD, the minimum change occurred in June and maximum in October.

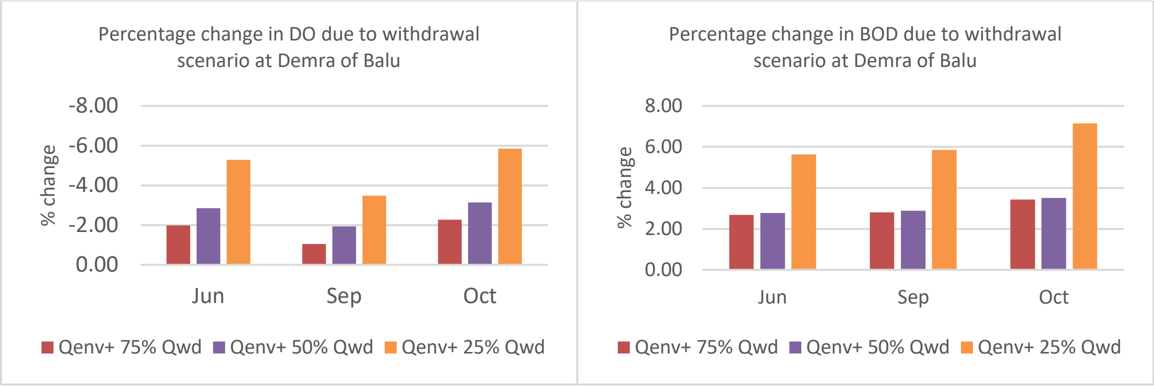


Figure 4.18: Percentage change of DO and BOD in response of withdrawal scenarios at Demra of Balu

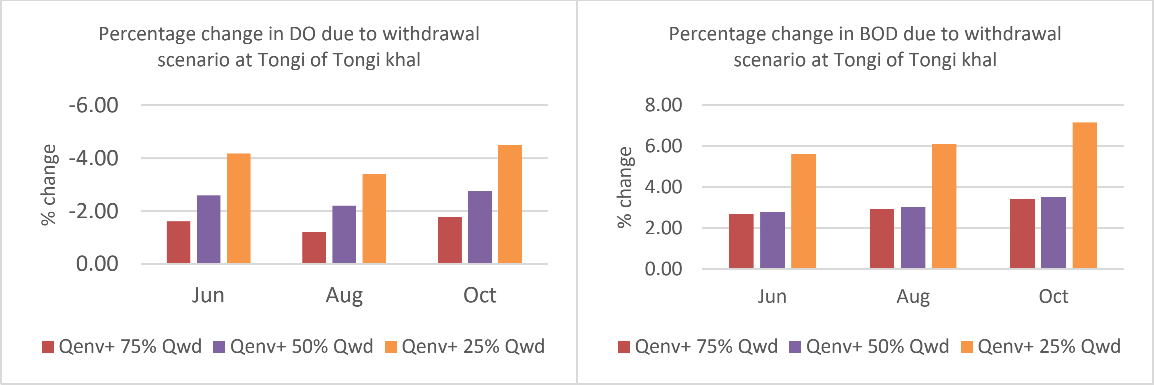


Figure 4.19: Percentage change of DO and BOD in response of withdrawal scenarios at Tongi of Tongi Khal

From the above results of percent change in DO and BOD at Kaliakoir of Turag, Mirpur of Turag Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal; it is depicted that, DO decreased in maximum amount on October at Kaliakoir of Turag by 5.05% for Q_{env}+25%Q_{wd} withdrawal scenario where 75% of available flow has been taken away. On the other hand, BOD increased in maximum amount on August at Jagir of Dhaleshwari by 11.86% for Q_{env}+25%Q_{wd} withdrawal scenario where 75% of available flow has been taken away.

4.6.5 Percentage change of DO and BOD based on flow augmentation scenario

Due to the four augmentation scenarios, i.e. (Q_{avg}+25%Q_{aug}), (Q_{avg}+50%Q_{aug}), (Q_{avg}+75%Q_{aug}), (Q_{avg}+100%Q_{aug}) where 25%, 50%, 75% and 100% of available flow have been augmented, the amount of DO and BOD have been changed compared to the observed value of DO and BOD for Q_{avg}. The percentage change of DO and BOD in response of the augmentation scenario has been presented in graphical format in this chapter from Figure 4.20 through Figure 4.26 and in tabular format in Appendix B.3, Table B.3(b).

Figure 4.20 presents the percentage change of DO and BOD in response of augmentation scenarios at Kaliakoir of Turag. For Kaliakoir of Turag, the amount of DO increased by 1.10% to 4.48%, 1.30% to 5.31%, 1.80% to 7.41%, 2.39% to 9.92% and 2.43% to 10.09% for January, February, March, June and August respectively due to four augmentation scenarios. The amount of BOD decreased by 1.19% to 2.65%, 1.22% to 5.96%, 1.29% to 6.27%, 1.12% to 5.48% and 0.72% to 3.57% for January, February, March, June and August respectively in response of four augmentation scenarios. The percentage increase of DO is minimum in January and maximum in August. For BOD, the minimum percentage decrease occurred in January and maximum in March.

Figure 4.21 presents the percentage change of DO and BOD in response of augmentation scenarios at Mirpur of Turag. For Mirpur of Turag, the amount of DO increased by 1.19% to 4.23%, 1.39% to 4.33%, 1.89% to 5.37%, 2.48% to 6.80% and 2.52% to 6.88% for January, February, March, June and August respectively due to four augmentation scenarios. The amount BOD decreased by 1.21% to 6.10%, 1.43% to 6.73%, 1.34% to 6.47%, 1.25% to 6.21% and 0.82% to 4.99% for January, February, March, June and August respectively in response of four augmentation scenarios. The percentage increase of DO is minimum in February and maximum in August. For BOD, the minimum percentage decrease occurred in August and maximum in February.

Figure 4.22 shows the percentage change of DO and BOD in response of augmentation scenarios at Dhaka Mill Barrack of Buriganga. For Dhaka Mill Barrack of Buriganga, the amount of DO increased by 1.20% to 5.14%, 1.42% to 5.37%, 2.15% to 6.12%, 2.32% to 6.30%, 2.53% to 6.51%, 2.68% to 6.68%, 3.41% to 7.43% and 1.60% to 5.55% for January, February, March, April, May, June, July and December respectively due to four augmentation scenarios. The amount BOD decreased by 1.20% to 4.58%, 1.63% to 5.83%, 1.42% to 5.22%, 1.73% to 6.11%, 1.77% to 6.23%, 1.14% to 4.43%, 1.23% to 4.67% and 1.69% to 6.02% for January, February, March, April, May, June, July and December respectively due to four augmentation scenarios. The percentage increase of DO is minimum in January and February and maximum in July. For BOD, the minimum percentage decrease occurred in June and maximum in May.

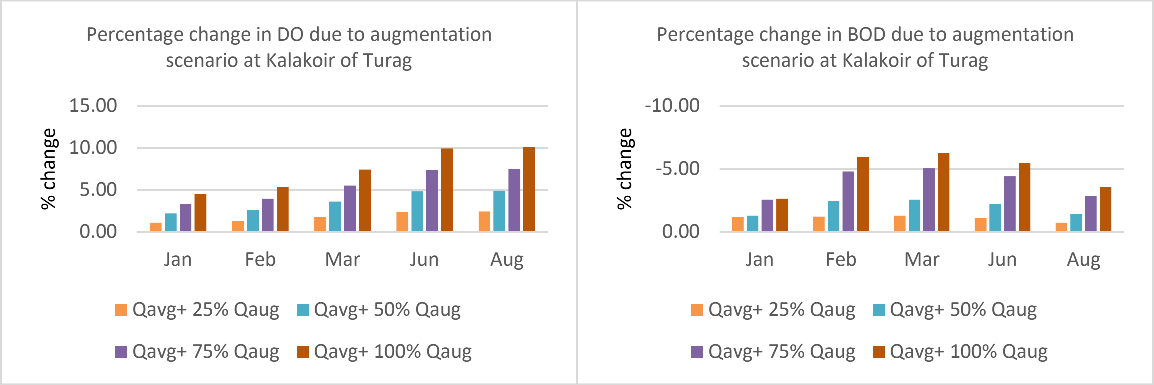


Figure 4.20: Percentage change of DO and BOD in response of augmentation scenarios at Kaliakoir of Turag

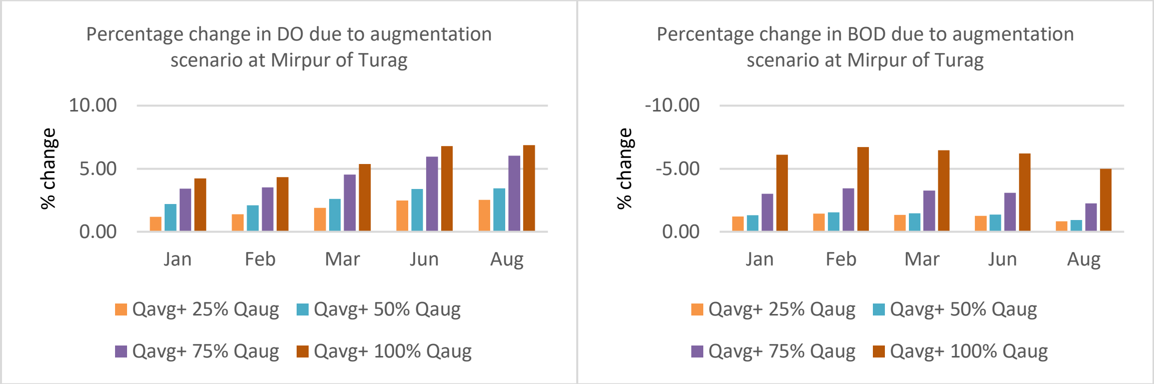


Figure 4.21: Percentage change of DO and BOD in response of augmentation scenarios at Mirpur of Turag

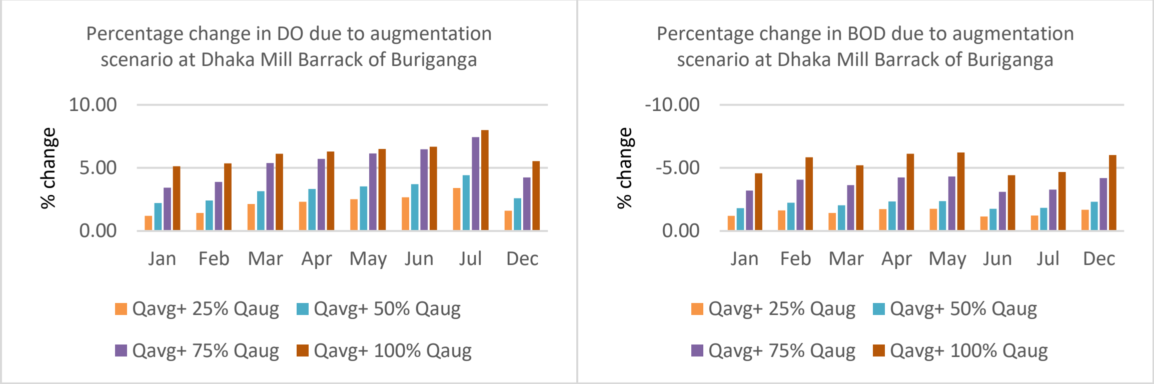


Figure 4.22: Percentage change of DO and BOD in response of augmentation scenarios at Dhaka Mill Barrack of Buriganga

Figure 4.23 shows the percentage change of DO and BOD in response of augmentation scenarios at Jagir of Dhaleshwari. For Jagir of Dhaleshwari, the amount of DO increased by 2.45% to 12.43%, 2.64% to 13.06%, 3.65% to 16.43% and 2.91% to 13.95% for January, February, May and December respectively due to four augmentation scenarios.

The amount BOD decreased by 1.41% to 5.39%, 1.79% to 6.49%, 1.76% to 6.41% and 1.74% to 6.37% for January, February, May and December respectively due to four augmentation scenarios. The percentage increase of DO is minimum in January and maximum in May. For BOD, the minimum percentage decrease occurred in January and maximum in February.

Figure 4.24 presents the percentage change of DO and BOD in response of augmentation scenarios at Demra of Shitalakhya. For Demra of Shitalakhya, the amount of DO increased by 1.44% to 7.54%, 1.63% to 8.14%, 2.13% to 9.74%, 2.25% to 10.15%, 2.63% to 11.63%, 2.80% to 11.92% and 2.50% to 10.96% for January, February, March, April, May, July and December respectively due to four augmentation scenarios. The amount BOD decreased by 1.70% to 6.62%, 2.24% to 8.14%, 2.04% to 7.58%, 2.25% to 8.57%, 2.63% to 7.64%, 2.80% to 5.35% and 2.50% to 8.42% for January, February, March, April, May, July and December respectively due to four augmentation scenarios. The percentage increase of DO is minimum in January and maximum in July. For BOD, the minimum percentage decrease occurred in July and maximum in April.

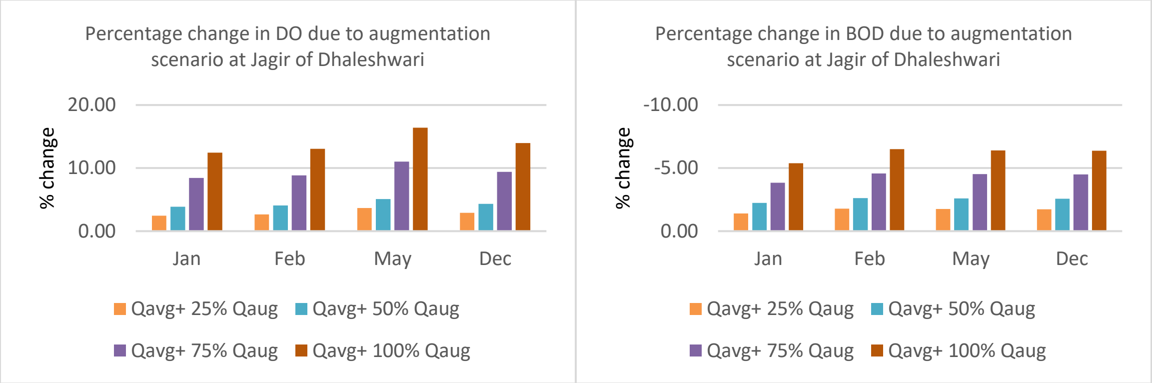


Figure 4.23: Percentage change of DO and BOD in response of augmentation scenarios at Jagir of Dhaleshwari

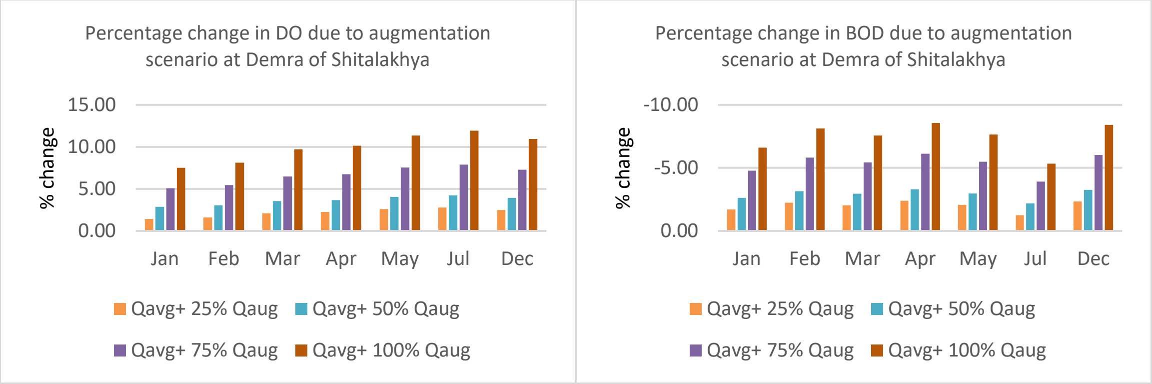


Figure 4.24: Percentage change of DO and BOD in response of augmentation scenarios at Demra of Shitalakhya

Figure 4.25 shows the percentage change of DO and BOD in response of augmentation scenarios at Demra of Balu. For Demra of Balu, the amount of DO increased by 1.20% to 3.83%, 1.39% to 4.42%, 1.90% to 6.01%, 2.21% to 6.98%, 2.55% to 8.03%, 2.73% to 8.60%, 2.92% to 9.22% and 2.41% to 7.61% for January, February, March, April, May, July, August and December respectively due to four augmentation scenarios. The amount BOD decreased by 1.88% to 7.09%, 2.40% to 8.55%, 2.12% to 7.77%, 2.39% to 8.53%, 2.31% to 8.31%, 1.09% to 4.84%, 1.26% to 5.33% and 2.41% to 8.58% for January, February, March, April, May, July, August and December respectively due to four augmentation scenarios. The percentage increase of DO is minimum in January and maximum in August. For BOD, the minimum percentage decrease occurred in July and maximum in December.

Figure 4.26 presents the percentage change of DO and BOD in response of augmentation scenarios at Tongi of Tongi Khal. For Tongi of Tongi Khal, the amount of DO increased by 1.09% to 3.11%, 1.29% to 3.52%, 1.98% to 4.94%, 2.32% to 5.64%, 2.39% to 5.78%, 2.39% to 5.78%, 2.46% to 5.93% and 1.89% to 4.75% for January, February, March, April, May, July, September and November respectively due to four augmentation scenarios. The amount BOD decreased by 1.88% to 7.09%, 2.40% to 8.55%, 2.12% to 7.77%, 2.39% to 8.53%, 2.31% to 8.31%, 1.09% to 4.84%, 1.05% to 4.70% and 2.30% to 8.27% for January, February, March, April, May, July, September and November respectively due to four augmentation scenarios. The percentage increase of DO is minimum in January and maximum in September. For BOD, the minimum percentage decrease occurred in September and maximum in February.

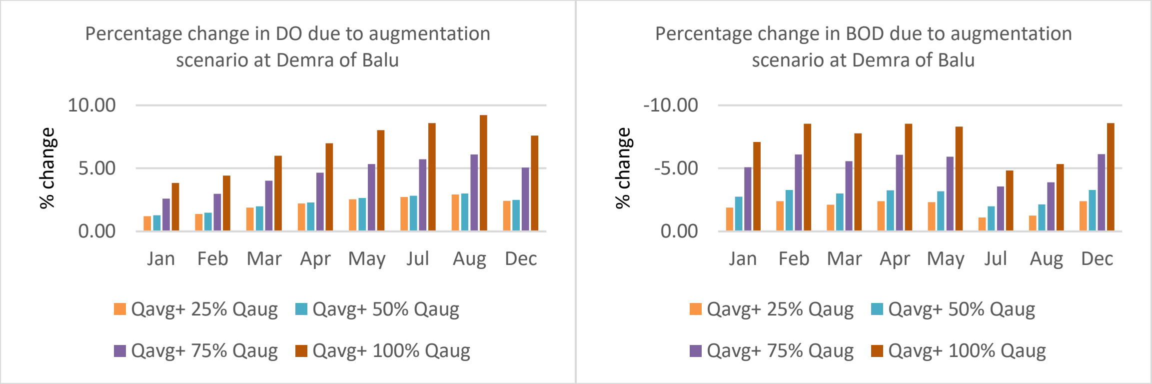


Figure 4.25: Percentage change of DO and BOD in response of augmentation scenarios at Demra of Balu

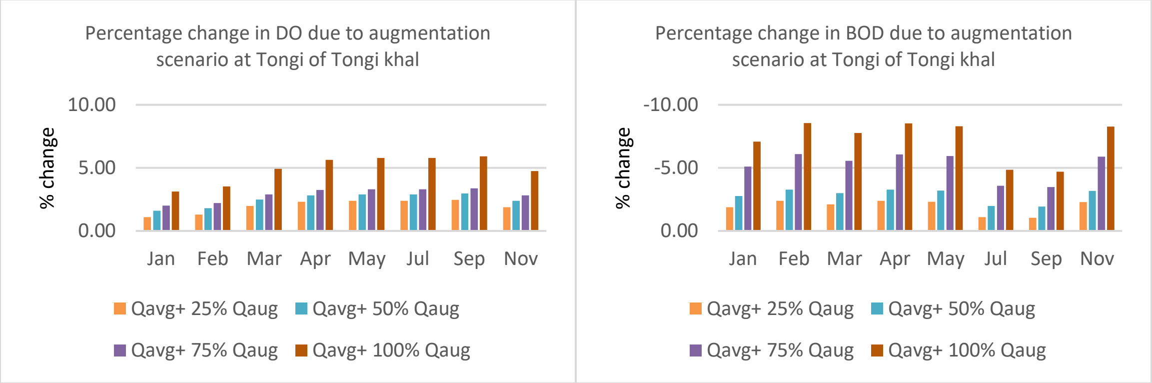


Figure 4.5: Percentage change of DO and BOD in response of augmentation scenarios at Tongi of Tongi Khal

From the above results of percent change in DO and BOD at Kaliakoir of Turag, Mirpur of Turag Dhaka Mill Barrack of Buriganga, Jagir of Dhaleshwari, Demra of Shitalakhya, Demra of Balu and Tongi of Tongi Khal; it is depicted that, DO increased in maximum amount on May of Dhaleshwari by 12.78% for Q_{avg}+100%Q_{aug} augmentation scenario where 100% of available flow has been increased. On the other hand, BOD decreased in maximum amount on April at Demra of Shitalakhya by 6.18% for Q_{avg}+100%Q_{aug} withdrawal scenario where 100% of available flow has been taken away. The effect of flow augmentation is not that much significant at Turag, Buriganga, Balu and Tongi Khal due to less amont of available flow compared to Dhaleshwari and Shitalakhya.

4.7 Summary

Low flow season in all stations mostly exhibit the conditions for flow augmentation scenario due to less amount of MMF compared to environmental flow. Only few months of the station of Dhaleshwari and Shitalakhya exhibit the conditions of withdrawal scenario as the MMF was more than environmental flow. Turag, Buriganga, Balu and Tongi Khal exhibit the situation when MMF was more than environmental flow but no available water to be withdrawal due to poor condition of water quality in few months of low flow season. The withdrawal scenarios decrease the amount of DO and increase the amount of BOD. Conversely, augmentation scenarios increase the amount of DO and decrease the amount of BOD. DO increased up to 3.65%, 5.10%, 11.00% and 16.43% for 25%, 50%, 75% and 100% of available flow augmentation respectively. BOD decreased up to 2.41%, 3.31%, 6.12% and 8.58% for 25%, 50%, 75% and 100% of available flow augmentation respectively. Highest value of DO and lowest value of BOD for a specific month of a location has been obtained when 100% of available flow was augmented among the four augmentation scenarios. DO has been increased in maximum amount in May at Dhaleshwari by 16.43% and BOD has been decreased in maximum amount in April at Shitalakhya by 8.58% for 100% of available flow augmentation as the amount of available flow is quite high in Dhaleshwari and Shitalakhya compared to other Dhaka peripheral rivers. The effect of flow augmentation is not that much remarkable at Turag, Buriganga, Balu and Tongi Khal due to severely polluted water of Turag, Buriganga and less amount of available flow compared to Dhaleshwari and Shitalakhya. Though DO increase and BOD decrease in response to the augmentation scenario, but the amount of change in DO and BOD is not that much significant even for 100% augmentation of available flow so that it satisfies the inland river water standard of DO and BOD.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion of the study

Dhaka city is situated in central Bangladesh along the river Buriganga. Turag, Buriganga, Dhaleshwari, Shitalakhya, Balu and Tongi Khal create a peripheral river network of about 195 km encompassing the Dhaka city. The water quality in this river network is deteriorating gradually by domestic and industrial activities leading the contamination to such a devastating level that is hampering the ecological balance. Textile industries, tanneries and factories situated around Dhaka city, generate huge volume of waste and water-based effluents are continuously destroying the physical, chemical and biological quality of the river water. Hence, this study focuses on the water quality analysis of Dhaka peripheral river network. Dissolved oxygen (DO) and Biochemical Oxygen Demand (BOD) are the two most important water quality parameters for the sustainability of the aquatic life. The water of Dhaka peripheral river network has been polluted to such extent that DO and BOD are far away from the standard limit. Therefore, several flow scenarios for flow withdrawal and augmentation in six peripheral rivers surrounding Dhaka city have been developed and the response of DO and BOD for flow scenarios have been analyzed in this study.

To perform this study, a 1D hydrodynamic and water quality model of Dhaka peripheral river network was developed in HEC-RAS. The hydrodynamic model was calibrated for the year 2014 and validated for the year 2016 at Mirpur, Dhaka Mill Barrack, Kalatia, Fatulla, Demra and Tongi for Manning's n=0.025 in all cross sections along the river network. The water quality model was calibrated for January-June of the year 2014 and validated for July-December for the year 2016 at Dhaka Mill Barrack, Rekabi Bazaar, Fatulla and Demra for dispersion coefficient, $D = 0.07 \text{ m}^2/\text{s}$ in all cross sections along the river network.

For the assessment of available water sources, Monthly Mean Flow (MMF) and Mean Annual Flow (MAF) was calculated by analyzing historical time-series discharge data of 20 years from 1996 to 2016. The calculation of Environmental flow in each month was done by Tennant method and Flow Duration method and the maximum value of environmental flow was selected. To assess

the water quality parameters, when a maximum of three parameters fail to satisfy the standard, the water was not considered as a good source for flow withdrawal.
Flow withdrawal scenario was developed when MMF is greater than environmental flow and water quality is satisfactory. Flow augmentation scenario was developed when environmental flow is greater than MMF and water quality is satisfactory or unsatisfactory. When environmental flow is greater than MMF and water quality is unsatisfactory, flow augmentation scenario was not implemented as this category needs the control of external pollution source which was not the focus of this study. November to April and May to October were considered as low flow and high flow seasons respectively. Three withdrawal scenarios where 25%, 50% and 75% of available flow were withdrawal and four augmentation scenarios where 25%, 50%, 75% and 100% of available flow was augmented for a station in a month. The response of DO and BOD to the withdrawal and augmentation scenario was assessed in this study.

The following conclusion can be made from the study given below:

- According to the assessment of water quality parameters, in low flow season, water quality is not satisfactory in all Dhaka peripheral rivers except Dhaleshwari and Shotalakhya. But for high flow season water quality of the peripheral rivers is satisfactory.
- The months of low flow season in all stations mostly exhibit the conditions for flow augmentation scenario. Only few months of the station of Dhaleshwari and Shitalakhya exhibit the conditions of withdrawal scenario as MMF was more than environmental flow. In few months of low flow season in Turag, Buriganga, Balu and Tongi Khal exhibit the situation when MMF was more than environmental flow but no available water to be withdrawal due to poor condition of water quality.
- In all stations, withdrawal scenario was implemented on October and augmentation scenario was implemented in January and February.
- Withdrawal scenarios decrease DO and increase BOD as a specific percentage of available flow was withdrawal for a specific month of a station. DO decreased up to 2.28%, 3.20% and 5.90% for 25%, 50% and 75% of available flow withdrawal respectively. BOD increased up to 4.05%, 5.50% and 11.86% for 25%, 50% and 75% of available flow withdrawal respectively. Lowest value of DO and highest value of BOD for a specific

month of a location were obtained when 75% of available flow was withdrawal among the three withdrawal scenarios.

- DO increase and BOD decrease for augmentation scenarios as a specific percentage of available flow was augmented for a specific month of a station. DO increased up to 3.65%, 5.10%, 11.00% and 16.43% for 25%, 50%, 75% and 100% of available flow augmentation respectively. BOD decreased up to 2.41%, 3.31%, 6.12% and 8.58% for 25%, 50%, 75% and 100% of available flow augmentation respectively. Highest value of DO and lowest value of BOD for a specific month of a location were obtained when 100% of available flow was augmented among the four augmentation scenarios.
- DO increased in maximum amount in May at Dhaleshwari by 16.43% and BOD decreased in maximum amount on April at Shitalakhya by 8.58% for 100% of available flow augmentation as the amount of available flow is quite high in Dhaleshwari and Shitalakhya compared to other Dhaka peripheral rivers.
- The effect of flow augmentation is not that much significant at Turag, Buriganga, Balu and Tongi Khal due to severely polluted water of Turag, Buriganga and less amount of available flow compared to Dhaleshwari and Shitalakhya.
- Though DO increase and BOD decrease in response to the augmentation scenario, but the amount of change in DO and BOD is not that much significant even for 100% augmentation of available flow so that it satisfies the inland river water standard of DO and BOD.
- It is too complicated to improve the water quality by implementing only the withdrawal and augmentation scenario without controlling the external source of pollution due to the poor condition of water quality and flow availability.

5.2 Recommendation for future study

This study focuses on the water quality of Dhaka peripheral river network. A 1D hydrodynamic and water quality model was simulated and flow scenario was developed based on available flow. The response of DO and BOD with respect to the flow withdrawal and augmentation scenarios was analyzed. Based on the results and the experience gained during the study, some actions can be recommended for the improvement of this study as stated below:

- Daily time series data of water quality parameters improve the water quality model by doing better prediction of the scenario. So, it is recommended to use daily time series data of water quality parameters instead of using water quality parameters data with large interval.
- To replicate real-life water quality condition of Dhaka peripheral river network, it is recommended to incorporate pollutant from industrial inflow as source of pollution. As HEC-RAS is not capable to consider this factor, future studies can be done using advanced software so that pollutant from industrial inflow can be considered while doing the analysis.
- The result and analysis of this study is focused on the response of two water quality parameters, i.e. DO and BOD due to their importance on the survival of the aquatic life. It is recommended to consider other water quality parameters as well to check their response to the flow scenarios.
- This study showed the improvement of water quality of rivers for the sustainability of aquatic life by augmenting the flow. Therefore, one of approaches of flow augmentation could be achieved by feeding Buriganga from the water of Jamuna through Dhaleshwari river. Similar kind of approach could introduce a new method for cleansing the heavily polluted rivers in Bangladesh. And this also could help to the Regulatory body to take the necessary steps to improve the water quality of Dhaka peripheral river network.

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APPENDIX A

Appendix A.1: Descriptive statistics of water quality parameters for Dhaka peripheral river network

Table A.1(a): Descriptive statistics of water quality parameters for Dhaka peripheral river network at low flow season

Water quality parameters	**Unit**	**Turag**				**Buriganga**				**Dhaleshwari**			
		Central tendency		**Dispersion**		**Central tendency**		**Dispersion**		**Central tendency**		**Dispersion**	
		Mean	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**
pH	-	7.22	7.25	0.02	0.16	7.62	7.55	0.03	0.18	5.45	5.00	0.41	0.64
Turbidity	NTU	6.67	7.00	0.22	0.47	7.45	6.85	1.60	1.26	7.03	7.10	0.05	0.21
Chloride	mg/l	13.83	16.50	23.81	4.88	162.50	162.50	156.25	12.50	11.50	12.50	22.92	4.79
Ammonia	mg/l	0.34	0.34	0.01	0.11	0.24	0.23	0.00	0.02	0.24	0.23	0.00	0.03
DO	mg/l	5.90	5.45	0.76	0.87	3.75	3.75	0.06	0.25	4.37	4.40	0.17	0.41
BOD	mg/l	6.17	6.00	0.10	0.32	10.95	6.35	61.95	7.87	0.77	0.75	0.01	0.07
TDS	mg/l	313.33	370.00	11255.56	106.09	754.17	555.00	188086.81	433.69	141.67	167.50	2155.56	46.43
Lead	mg/l	0.07	0.07	0.00	0.02	0.08	0.08	0.00	0.01	0.03	0.03	0.00	0.00
Cadmium	mg/l	0.04	0.04	0.00	0.03	0.04	0.03	0.00	0.02	0.02	0.02	0.00	0.00
Chromium	mg/l	0.05	0.01	0.00	0.06	0.03	0.03	0.00	0.00	0.04	0.05	0.00	0.01
Zinc	mg/l	2.42	2.20	0.17	0.42	4.47	4.50	0.02	0.15	0.02	0.02	0.00	0.00
Mercury	mg/l	0.07	0.08	0.00	0.01	0.04	0.04	0.00	0.01	0.04	0.04	0.00	0.01
Phosphate	mg/l	0.06	0.05	0.00	0.04	0.08	0.05	0.00	0.06	0.08	0.07	0.00	0.03

Table A.1(a) (continued): Descriptive statistics of water quality parameters for Dhaka peripheral river network at low flow season

Water quality parameters	**Unit**	**Shitalakhya**				**Balu**				**Tongi Khal**			
		Central tendency		**Dispersion**		**Central tendency**		**Dispersion**		**Central tendency**		**Dispersion**	
		Mean	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**
pH	-	7.07	7.05	0.03	0.16	6.66	6.68	0.06	0.24	7.43	7.50	0.03	0.18
Turbidity	NTU	8.00	8.00	0.33	0.58	7.33	6.60	1.74	1.32	7.62	7.70	0.17	0.41
Chloride	mg/l	13.67	16.50	30.22	5.50	169.00	170.50	20.67	4.55	8.00	8.00	1.00	1.00
Ammonia	mg/l	0.47	0.49	0.02	0.13	1.72	1.62	0.41	0.64	0.30	0.27	0.01	0.09
DO	mg/l	3.00	3.00	0.67	0.82	5.67	5.25	1.45	1.21	5.52	5.10	1.85	1.36
BOD	mg/l	12.50	12.00	3.92	1.98	16.00	13.95	40.18	6.34	2.95	3.00	1.23	1.11
TDS	mg/l	321.67	390.00	11880.56	109.00	663.67	672.50	2678.89	51.76	145.00	130.00	2625.00	51.23
Lead	mg/l	0.06	0.07	0.00	0.01	0.05	0.06	0.00	0.02	0.08	0.08	0.00	0.01
Cadmium	mg/l	0.08	0.08	0.00	0.00	0.07	0.08	0.00	0.01	0.00	0.00	0.00	0.00
Chromium	mg/l	0.04	0.04	0.00	0.01	0.07	0.08	0.00	0.01	0.02	0.02	0.00	0.00
Zinc	mg/l	3.72	3.80	0.13	0.36	3.53	3.50	0.17	0.41	2.63	2.55	0.10	0.32
Mercury	mg/l	0.07	0.07	0.00	0.02	0.04	0.04	0.00	0.02	0.00	0.00	0.00	0.00
Phosphate	mg/l	0.07	0.05	0.00	0.06	0.07	0.05	0.00	0.05	0.07	0.05	0.00	0.06

Table A.1(b): Descriptive statistics of water quality parameters for Dhaka peripheral river network at high flow season

Water quality parameters	**Unit**	**Turag**				**Buriganga**				**Dhaleshwari**			
		Central tendency		**Dispersion**		**Central tendency**		**Dispersion**		**Central tendency**		**Dispersion**	
		Mean	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**
pH	-	6.97	6.90	0.04	0.21	7.05	7.00	0.16	0.40	6.25	6.50	0.44	0.66
Turbidity	NTU	6.33	6.00	0.22	0.47	6.60	6.50	0.02	0.15	6.73	6.70	0.00	0.05
Chloride	mg/l	9.83	9.50	6.47	2.54	162.50	162.50	156.25	12.50	7.83	7.50	3.14	1.77
Ammonia	mg/l	0.30	0.28	0.00	0.07	0.27	0.25	0.00	0.04	0.27	0.25	0.00	0.04
DO	mg/l	5.83	5.85	0.01	0.11	4.17	4.25	0.14	0.37	4.17	4.00	0.24	0.49
BOD	mg/l	5.81	5.94	0.16	0.40	15.08	11.25	40.53	6.37	0.78	0.85	0.02	0.13
TDS	mg/l	143.33	110.00	4688.89	68.48	437.33	355.00	47108.89	217.05	108.33	95.00	780.56	27.94
Lead	mg/l	0.04	0.04	0.00	0.02	0.05	0.05	0.00	0.00	0.02	0.02	0.00	0.00
Cadmium	mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00
Chromium	mg/l	0.05	0.01	0.00	0.06	0.03	0.03	0.00	0.00	0.02	0.02	0.00	0.00
Zinc	mg/l	2.53	2.40	0.16	0.39	4.62	4.65	0.08	0.29	0.02	0.02	0.00	0.00
Mercury	mg/l	0.06	0.05	0.00	0.02	0.05	0.05	0.00	0.01	0.05	0.06	0.00	0.02
Phosphate	mg/l	0.09	0.07	0.00	0.02	0.10	0.09	0.00	0.04	0.09	0.07	0.00	0.02

Table A.1(b) (continued): Descriptive statistics of water quality parameters for Dhaka peripheral river network at high flow season

Water quality parameters	**Unit**	**Shitalakhya**				**Balu**				**Tongi Khal**			
		Central tendency		**Dispersion**		**Central tendency**		**Dispersion**		**Central tendency**		**Dispersion**	
		Mean	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**	**Mean**	**Median**	**Variance**	**SD**
pH	-	7.08	7.05	0.02	0.13	6.81	6.80	0.04	0.21	7.43	7.50	0.05	0.21
Turbidity	NTU	9.50	9.50	0.25	0.50	6.40	6.50	0.03	0.18	7.42	7.30	0.19	0.44
Chloride	mg/l	11.00	10.00	14.67	3.83	168.83	169.50	12.47	3.53	8.67	8.50	2.89	1.70
Ammonia	mg/l	0.27	0.28	0.00	0.02	0.42	0.46	0.02	0.12	0.29	0.27	0.00	0.06
DO	mg/l	3.33	3.00	0.89	0.94	5.35	5.50	0.92	0.96	5.72	6.35	1.98	1.41
BOD	mg/l	5.08	3.15	10.92	3.30	14.83	14.00	8.14	2.85	2.80	3.00	1.42	1.19
TDS	mg/l	163.33	140.00	4988.89	70.63	643.17	639.00	979.81	31.30	96.67	95.00	55.56	7.45
Lead	mg/l	0.04	0.02	0.00	0.02	0.04	0.04	0.00	0.01	0.02	0.02	0.00	0.01
Cadmium	mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	mg/l	0.04	0.04	0.00	0.01	0.05	0.05	0.00	0.02	0.02	0.02	0.00	0.00
Zinc	mg/l	3.90	3.95	0.03	0.16	3.62	3.55	0.13	0.36	2.98	3.00	0.01	0.11
Mercury	mg/l	0.05	0.05	0.00	0.02	0.07	0.07	0.00	0.02	0.00	0.00	0.00	0.00
Phosphate	mg/l	0.09	0.07	0.00	0.03	0.09	0.09	0.00	0.04	0.09	0.07	0.00	0.03

APPEXDIX B

Appendix B.1: Environmental Flow Calculation by Tennant method

Table B.1(a): Environmental Flow Requirement (EFR) by Tennant method at Mirpur of Turag (SW 302)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	120.34	200	240.68	200	240.68
Optimum		60-100	72.20	60-100	72.20
Outstanding		40	48.14	60	72.20
Excellent		30	36.10	50	60.17
Good		20	24.07	40	48.14
Fair		10	12.03	30	36.10
Poor		10	12.03	10	12.03
Severe Degradation		<10	12.03	<10	12.03

Table B.1(b): Environmental Flow Requirement (EFR) by Tennant method at Dhaka Mill Barrack of Buriganga (SW 42)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	173.41	200	346.82	200	346.82
Optimum		60-100	104.04-173.41	60-100	104.04-173.41
Outstanding		40	69.36	60	104.04
Excellent		30	52.02	50	86.70
Good		20	34.68	40	69.36
Fair		10	17.34	30	52.02
Poor		10	17.34	10	17.34
Severe Degradation		<10	17.34	<10	17.34

Table B.1(c): Environmental Flow Requirement (EFR) by Tennant method at Jagir of Dhaleshwari (SW 68.5)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	621.18	200.00	1242.36	200.00	1242.36
Optimum		60-100	372.71	60-100	372.71
Outstanding		40.00	248.47	60.00	372.71
Excellent		30.00	186.35	50.00	310.59
Good		20.00	124.24	40.00	248.47
Fair		10.00	62.12	30.00	186.35
Poor		10.00	62.12	10.00	62.12
Severe Degradation		<10	62.12	<10	62.12

Table B.1(d): Environmental Flow Requirement (EFR) by Tennant method at Demra of Shitalakhya (SW 179)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	246.13	200.00	492.26	200.00	492.26
Optimum		60-100	147.68	60-100	147.68
Outstanding		40.00	98.45	60.00	147.68
Excellent		30.00	73.84	50.00	123.06
Good		20.00	49.23	40.00	98.45
Fair		10.00	24.61	30.00	73.84
Poor		10.00	24.61	10.00	24.61
Severe Degradation		<10	24.61	<10	24.61

Table B.1(e): Environmental Flow Requirement (EFR) by Tennant method at Demra of Balu River (SW 7.5)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	135.23	200.00	270.45	200.00	270.45
Optimum		60-100	81.14-135.23	60-100	81.14-135.23
Outstanding		40.00	54.09	60.00	81.14
Excellent		30.00	40.57	50.00	67.61
Good		20.00	27.05	40.00	54.09
Fair		10.00	13.52	30.00	40.57
Poor		10.00	13.52	10.00	13.52
Severe Degradation		<10	13.52	<10	13.52

Table 4.10: Environmental Flow Requirement (EFR) by Tennant method at Tongi of Tongi Khal (SW 299)

Habitat Quality	Mean Annual Flow (Cumec)	Low Flow Season		High Flow Season	
		% of MAF	EFR (Cumec)	% of MAF	EFR (Cumec)
Flushing	12.44	200.00	24.88	200.00	24.88
Optimum		60-100	7.46	60-100	7.46
Outstanding		40.00	4.98	60.00	7.46
Excellent		30.00	3.73	50.00	6.22
Good		20.00	2.49	40.00	4.98
Fair		10.00	1.24	30.00	3.73
Poor		10.00	1.24	10.00	1.24
Severe Degradation		<10	1.24	<10	1.24

Appendix B.2: Environmental Flow Calculation by Flow Duration Curve method

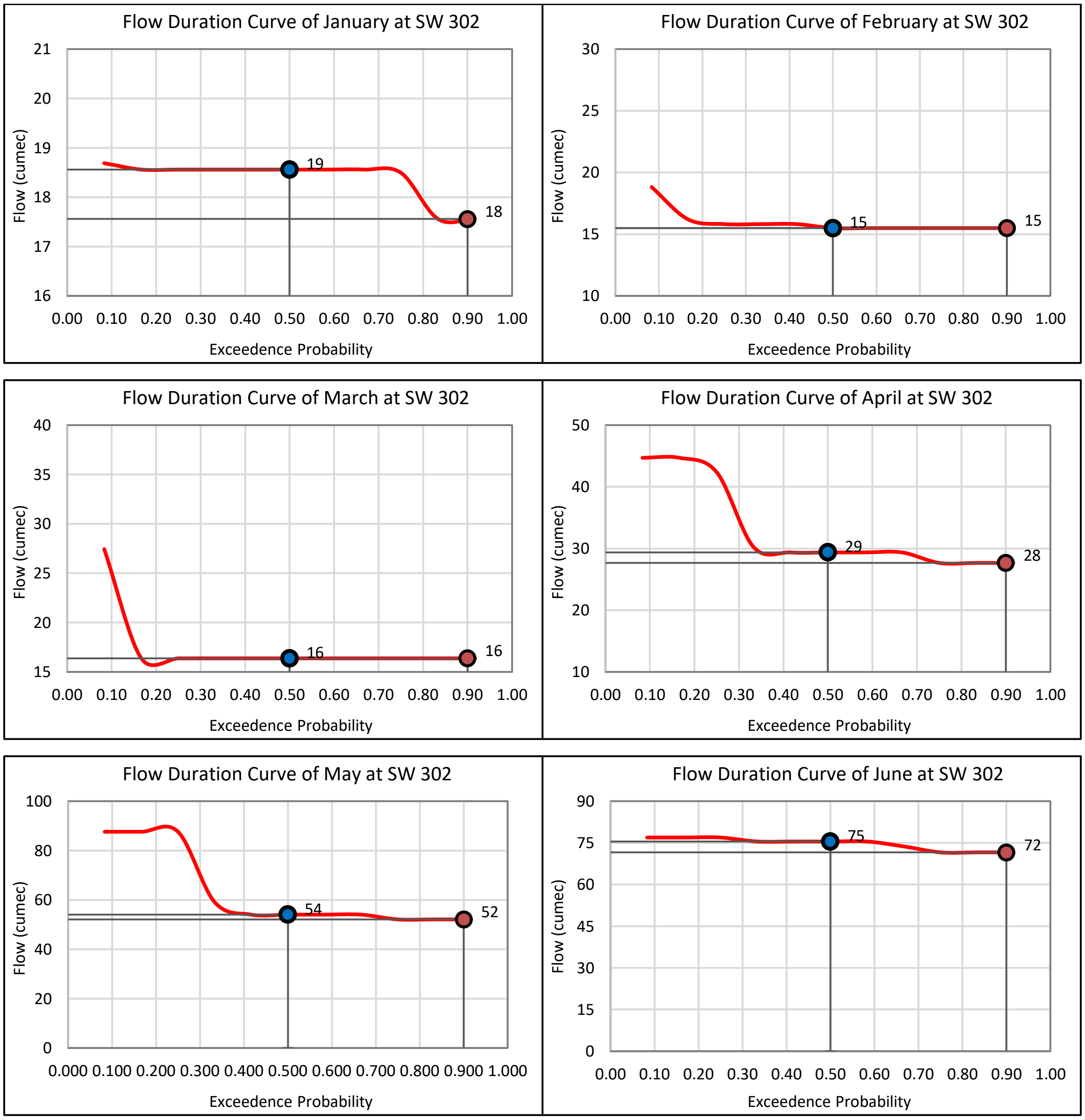


Figure B.2(a): Flow duration curve at Mirpur of Turag (SW 302) from January to June

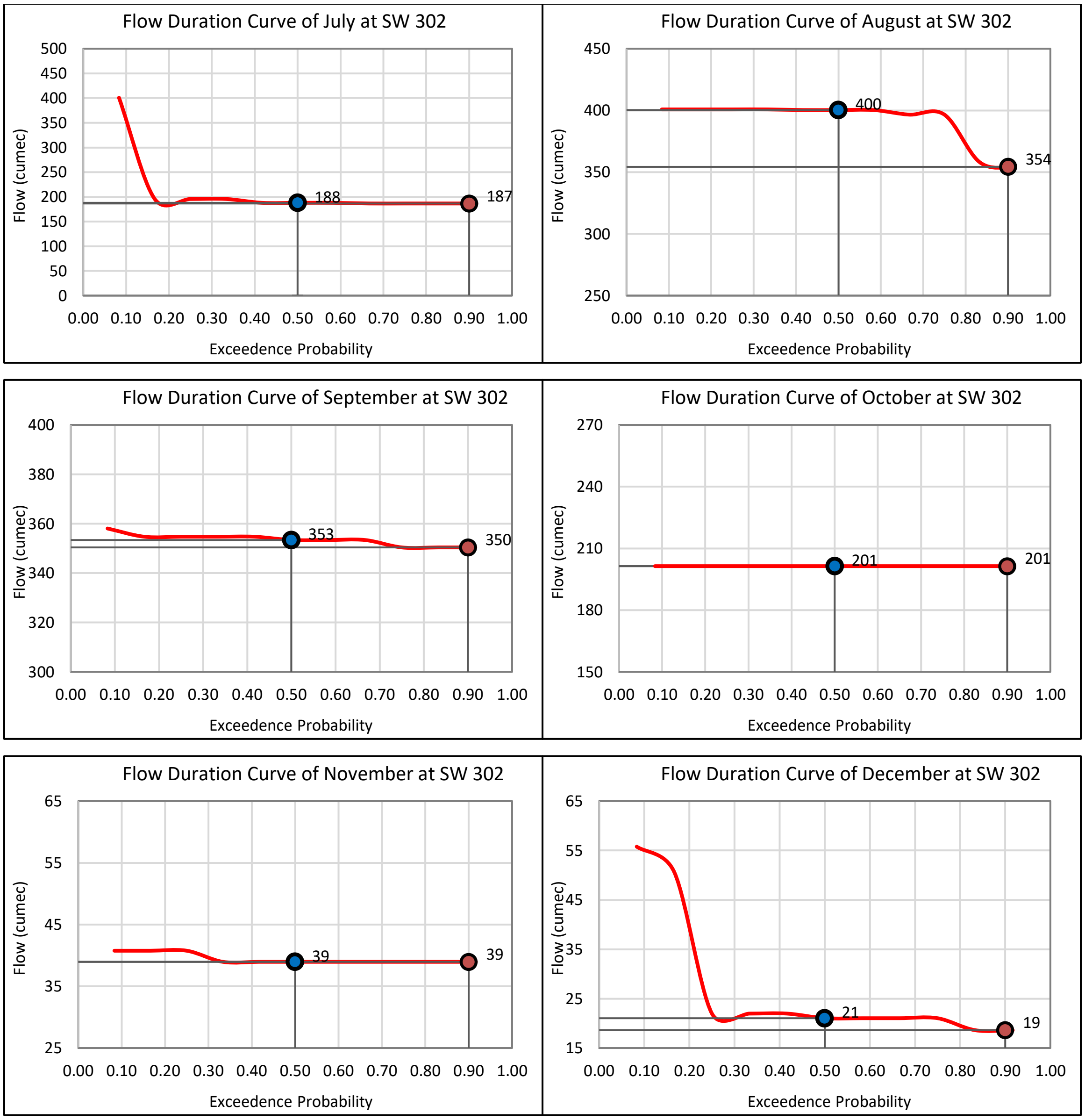


Figure B.2(a) (continued): Flow duration curve at Mirpur of Turag (SW 302) from July to December

Table B.2(a): Environmental flow requirement (EFR) using Flow duration curve method at Mirpur of Turag River (SW 302)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	19	15	16	29	54	75	188	400	353	201	39	21
90th Percentile Flow (cumec)	18	15	16	28	52	72	187	354	350	201	39	19
EFR (Cuemc)	18	15	16	28	54	75	188	400	353	201	39	19

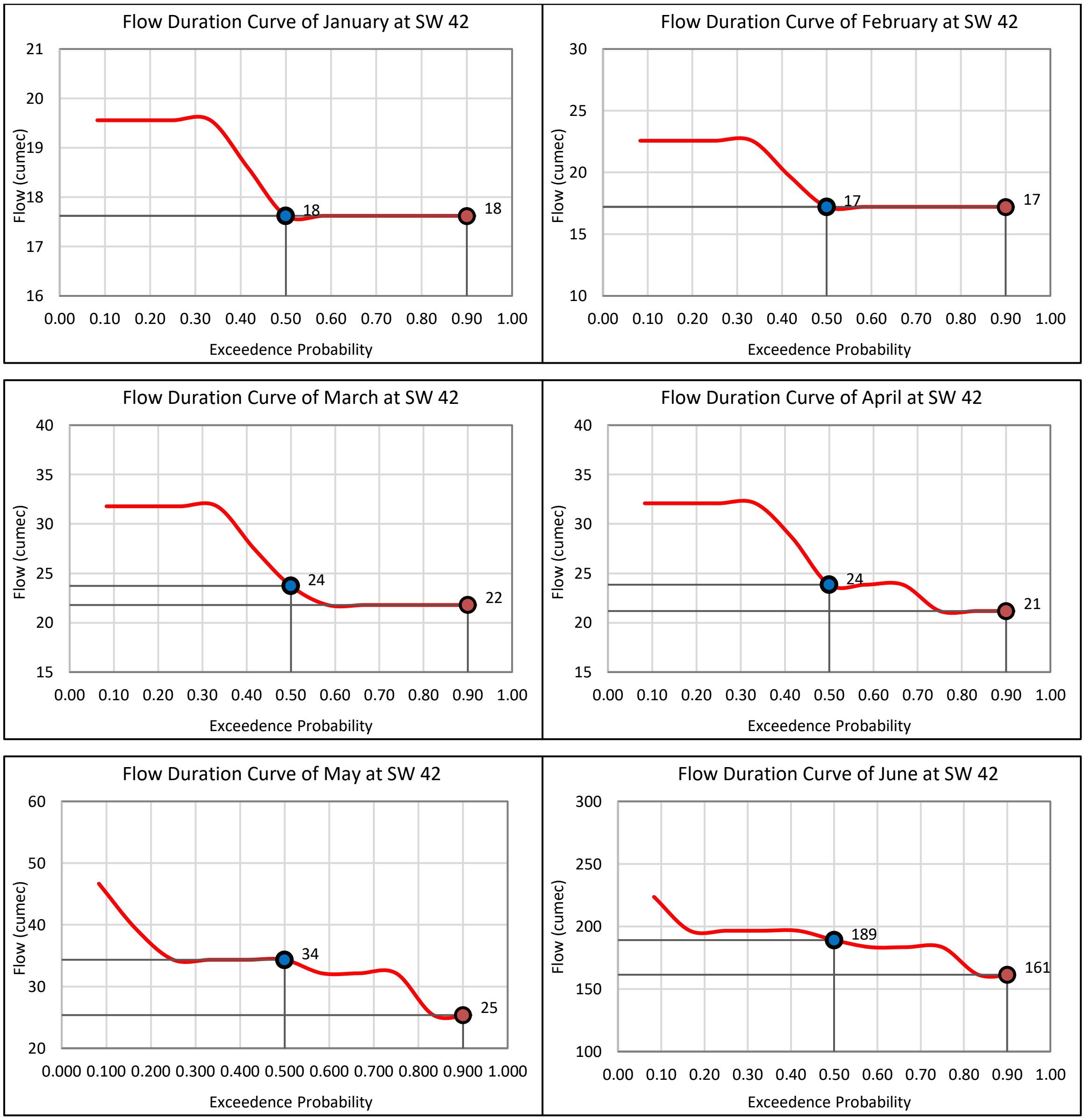


Figure B.2(b): Flow duration curve at Dhaka Mill Barrack of Buriganga (SW 42) from January to June

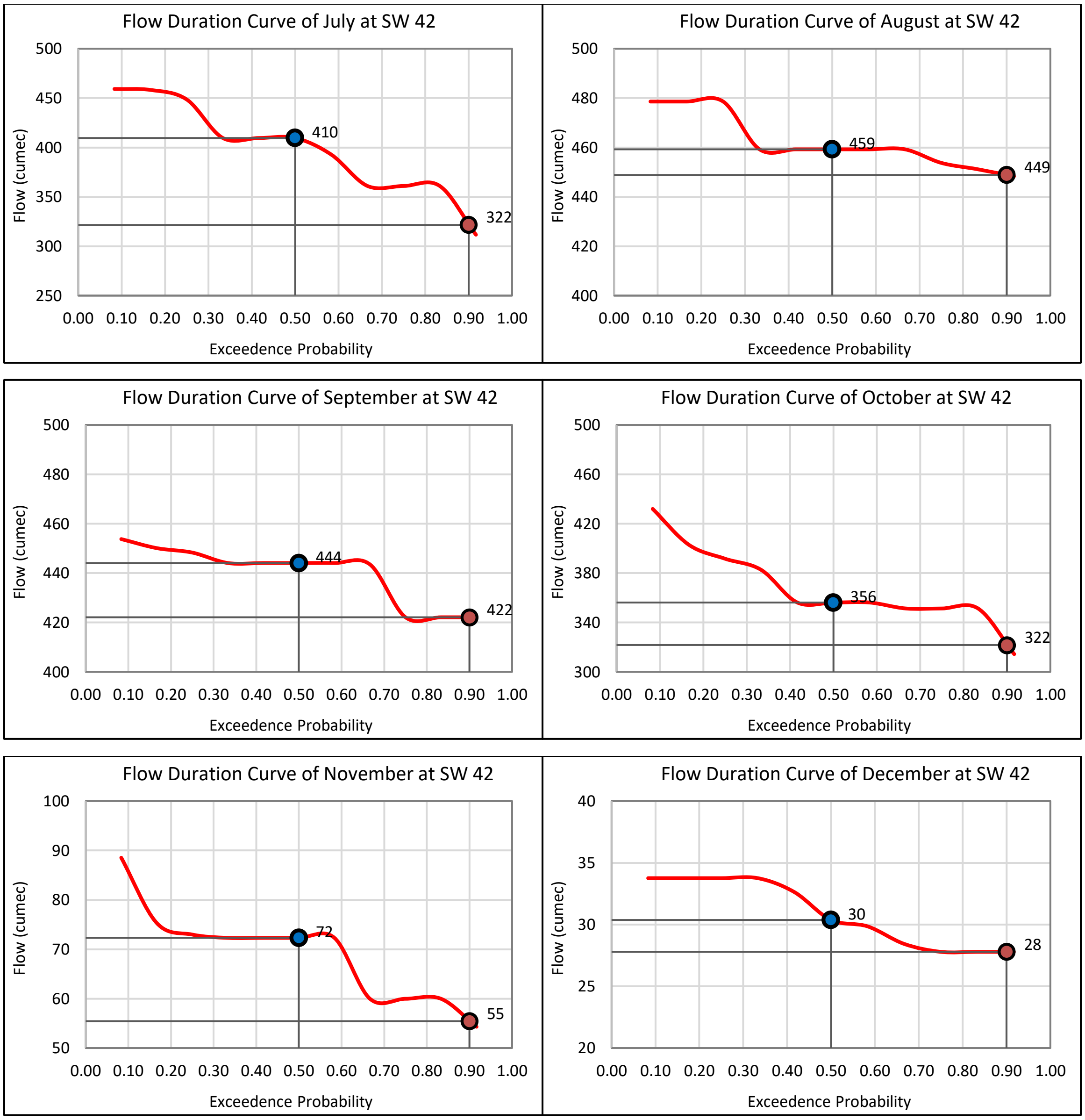


Figure B.2(b) (continued): Flow duration curve at Dhaka Mill Barrack of Buriganga (SW 42) from July to December

Table B.2(b): Environmental flow requirement (EFR) using Flow duration curve method at Dhaka Mill Barack of Buriganga River (SW 42)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	18	17	24	24	34	189	410	459	444	356	72	30
90th Percentile Flow (cumec)	18	17	22	21	25	161	322	449	422	322	55	28
EFR (Cuemc)	18	17	22	21	34	189	410	459	353	201	55	28

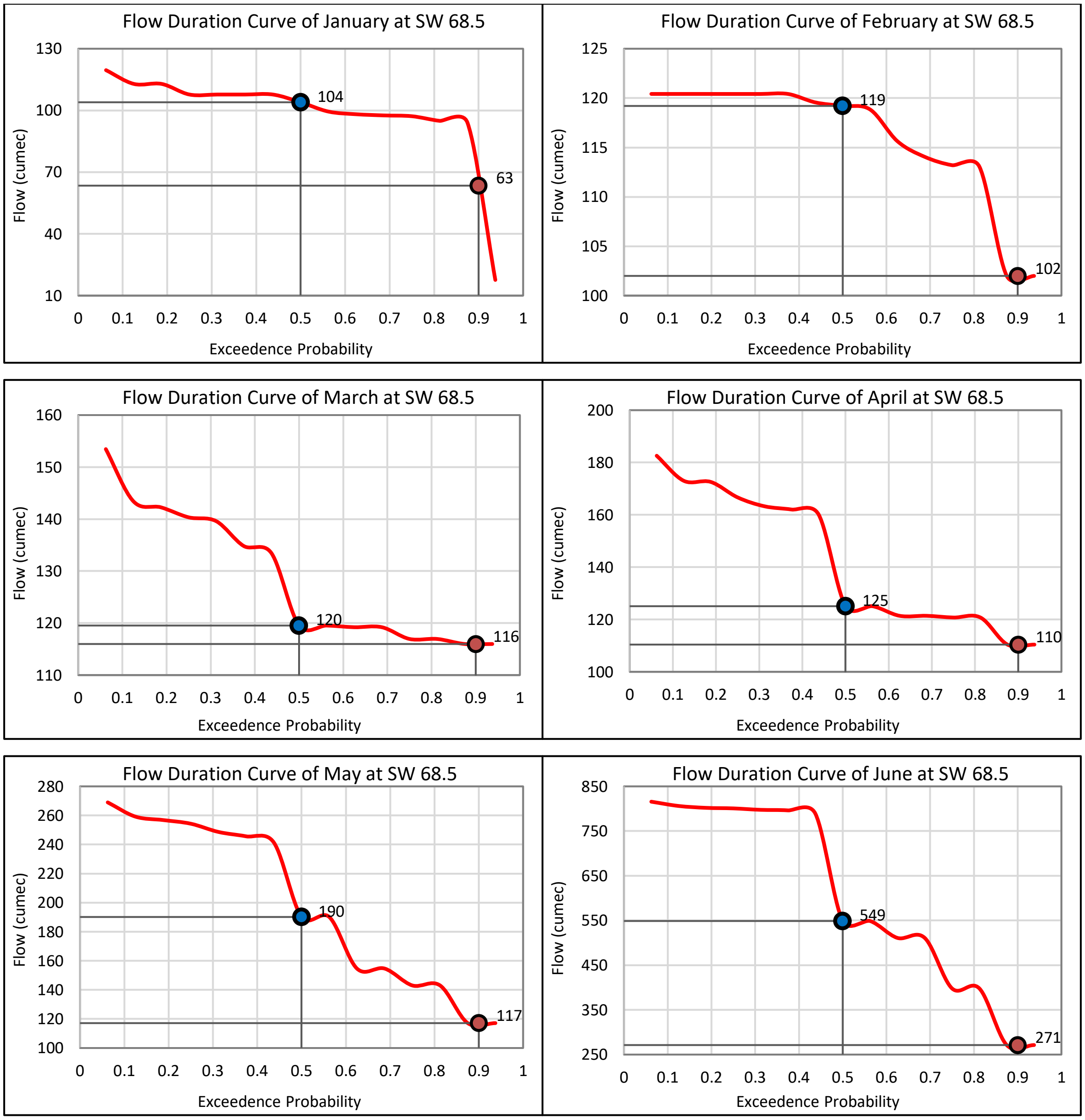


Figure B.2(c): Flow duration curve at Jagir of Dhaleshwari (SW 68.5) from January to June

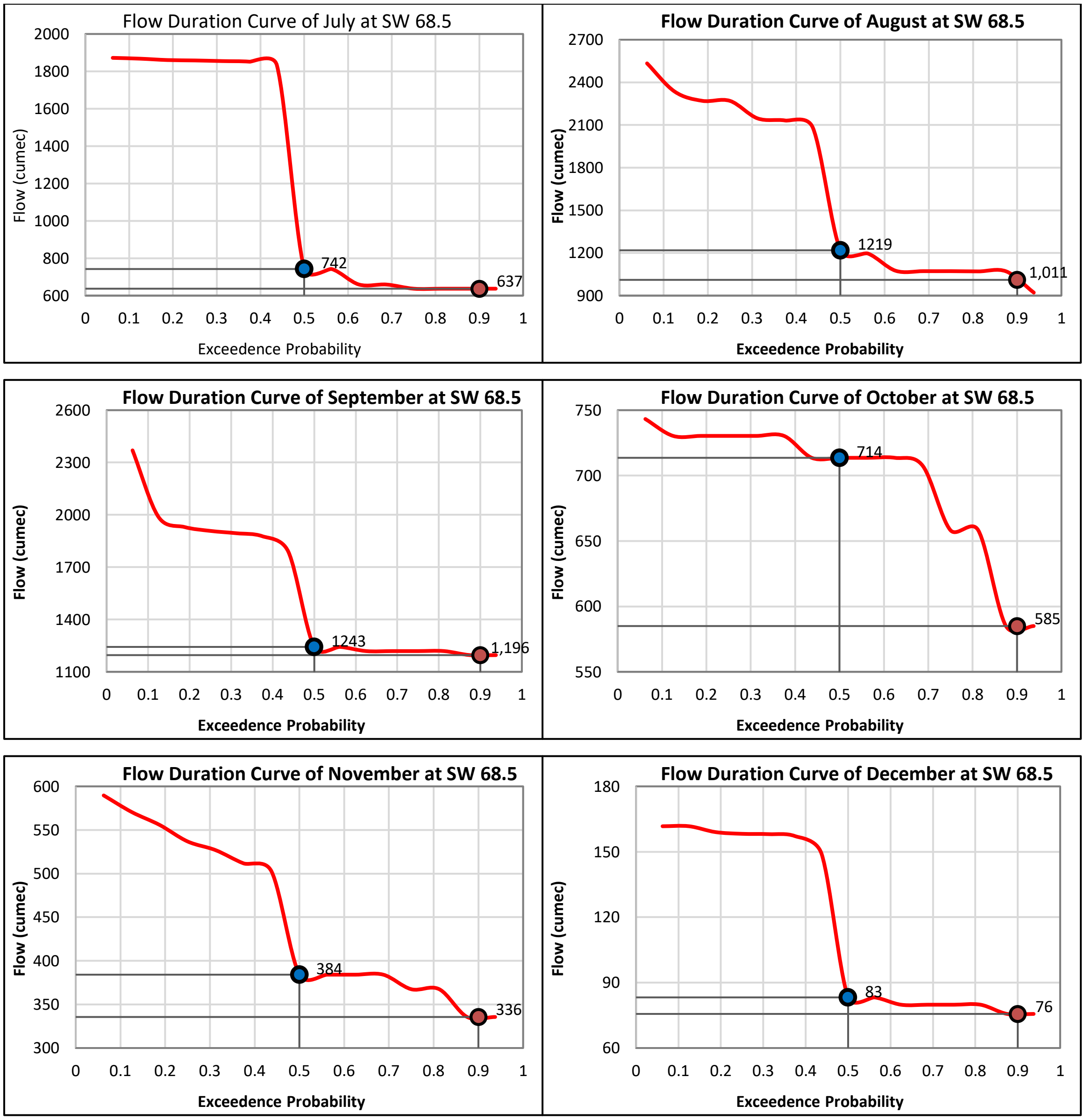


Figure B.2(c) (continued): Flow duration curve at Jagir of Dhaleshwari (SW 68.5) from July to December

Table B.2(c): Environmental flow requirement (EFR) using Flow duration curve method at Jagir of Dhaleshwari River (SW 68.5)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	104	119	120	125	190	549	742	1219	1243	714	384	83
90th Percentile Flow (cumec)	63	102	116	110	117	271	637	1011	1196	585	336	76
EFR (Cuemc)	63	102	116	110	190	549	742	1219	1243	714	336	76

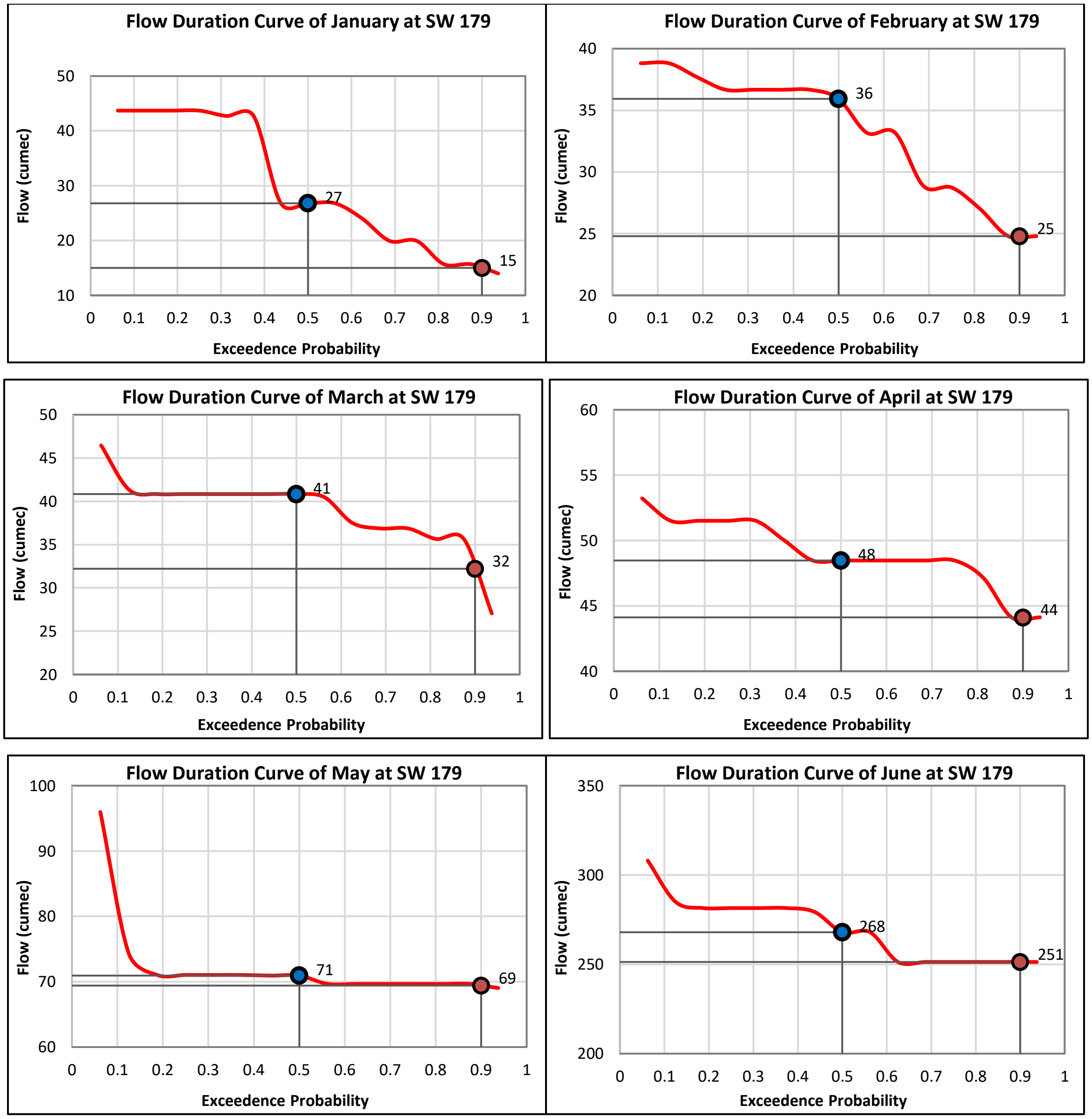


Figure B.2(d): Flow duration curve at Jagir of Demra of Shitalakhya (SW 179) from January to June

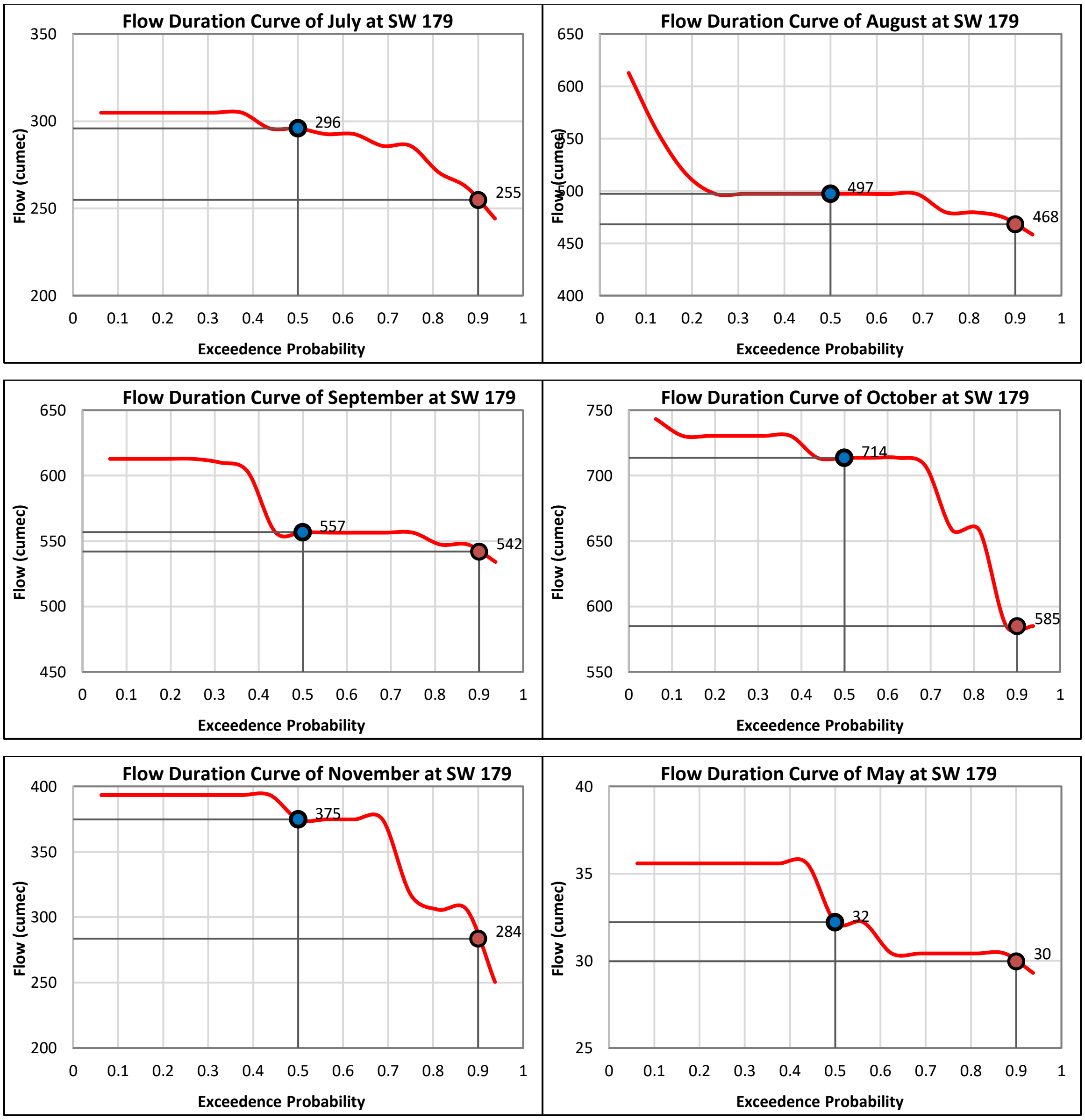


Figure B.2(d) (continued): Flow duration curve at Demra of Shitalakhya (SW 179) from July to December

Table B.2(d): Environmental flow requirement (EFR) using Flow duration curve method at Demra of Shitalakhya River (SW 179)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	27	36	41	48	71	268	296	497	557	714	375	32
90th Percentile Flow (cumec)	15	25	32	44	69	251	255	468	542	585	284	30
EFR (Cuemc)	15	25	32	44	71	268	296	372	557	282	284	30

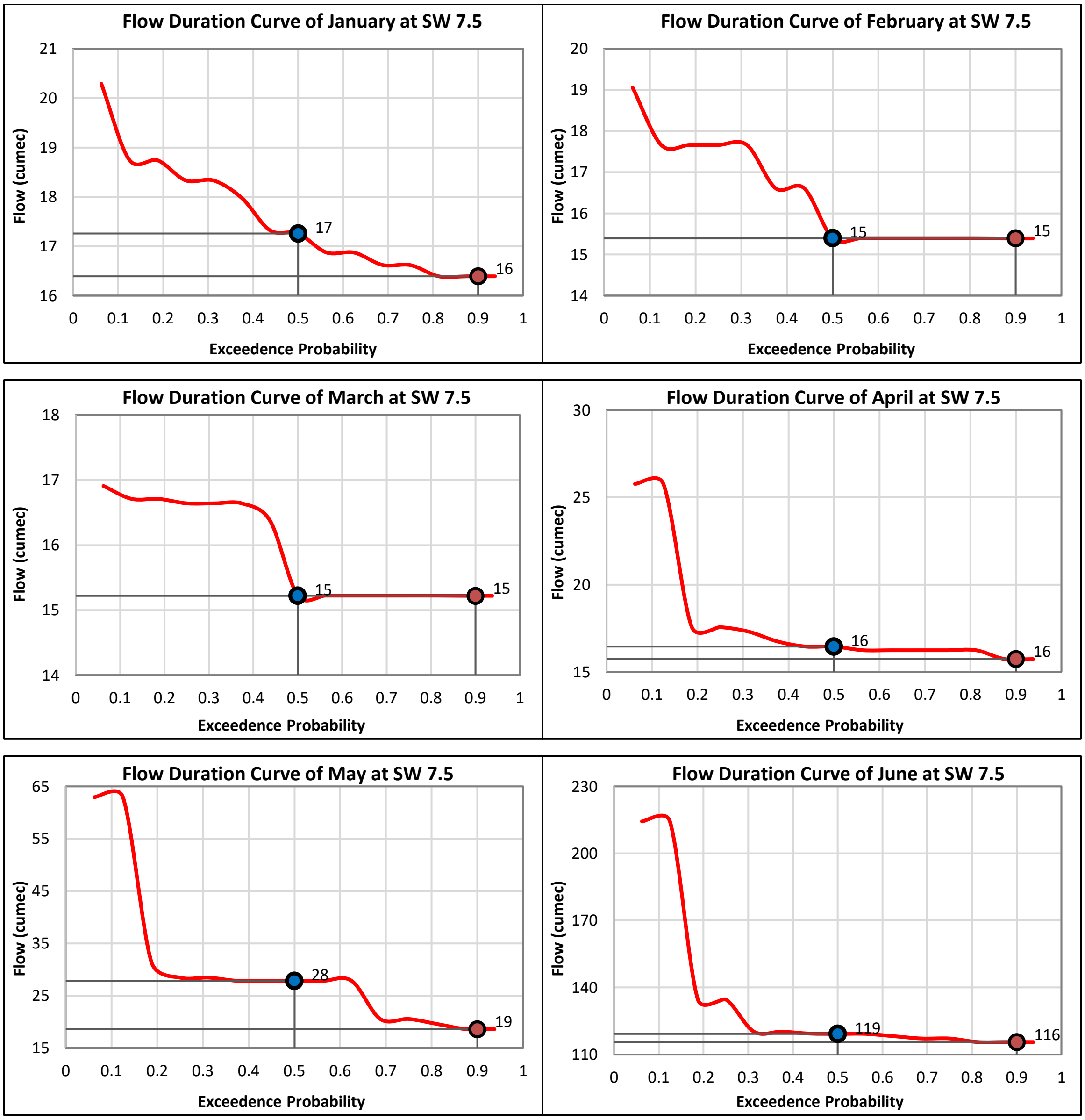
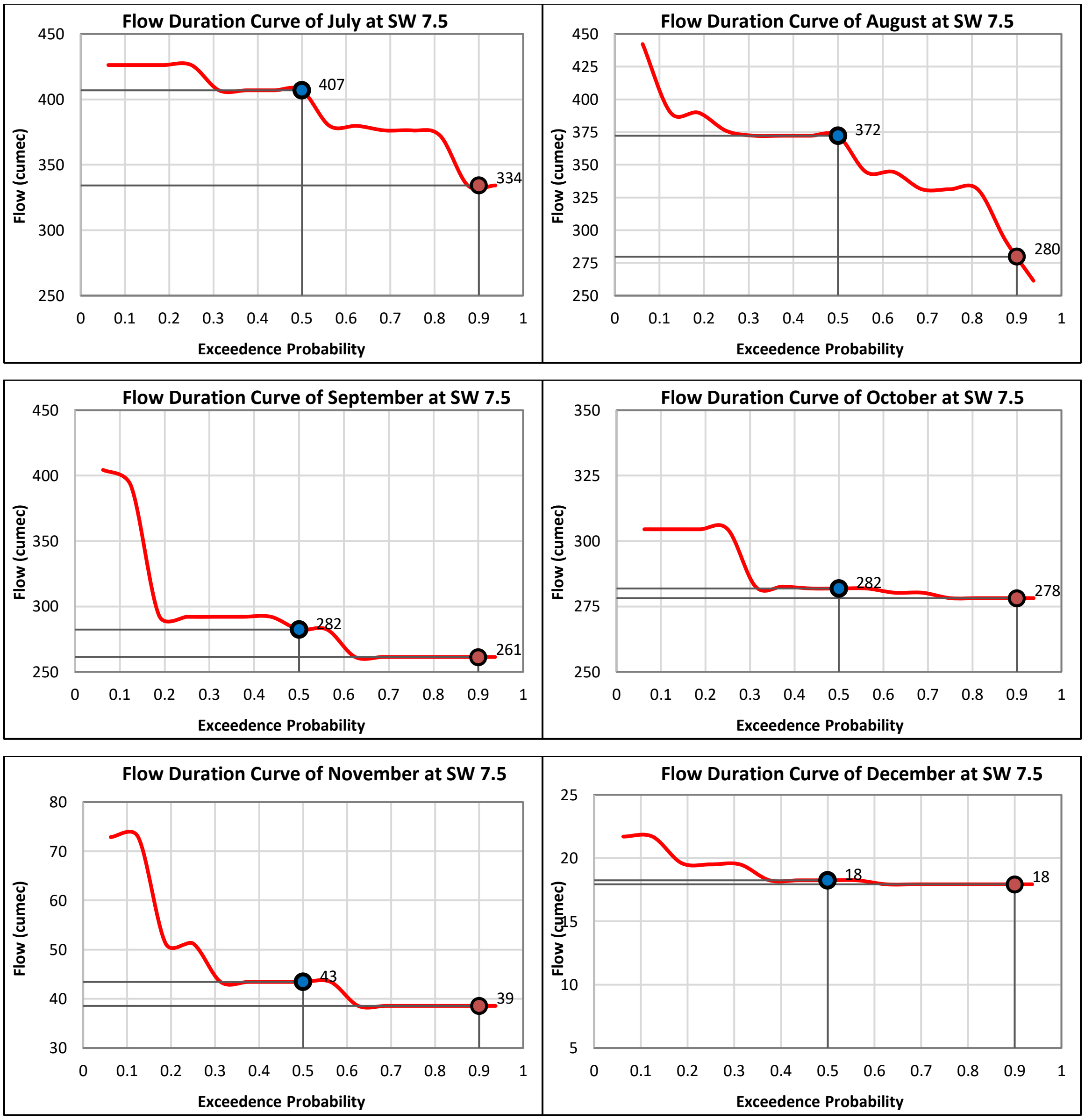


Figure B.2(e): Flow duration curve at Demra of Balu (SW 7.5) from January to June



Flow Duration Curve of July at SW 7.5

Flow Duration Curve of August at SW 7.5

Flow Duration Curve of September at SW 7.5

Flow Duration Curve of October at SW 7.5

Flow Duration Curve of November at SW 7.5

Flow Duration Curve of December at SW 7.5

Figure B.2(e) (continued): Flow duration curve at Demra of Balu (SW 7.5) from July to December

Table B.2(e): Environmental flow requirement (EFR) using Flow duration curve method at Demra of Balu River (SW 7.5)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	17	15	15	16	28	119	407	372	282	282	43	18
90th Percentile Flow (cumec)	16	15	15	16	19	116	334	280	261	278	39	18
EFR (Cuemc)	16	15	15	16	28	119	407	372	282	282	39	18

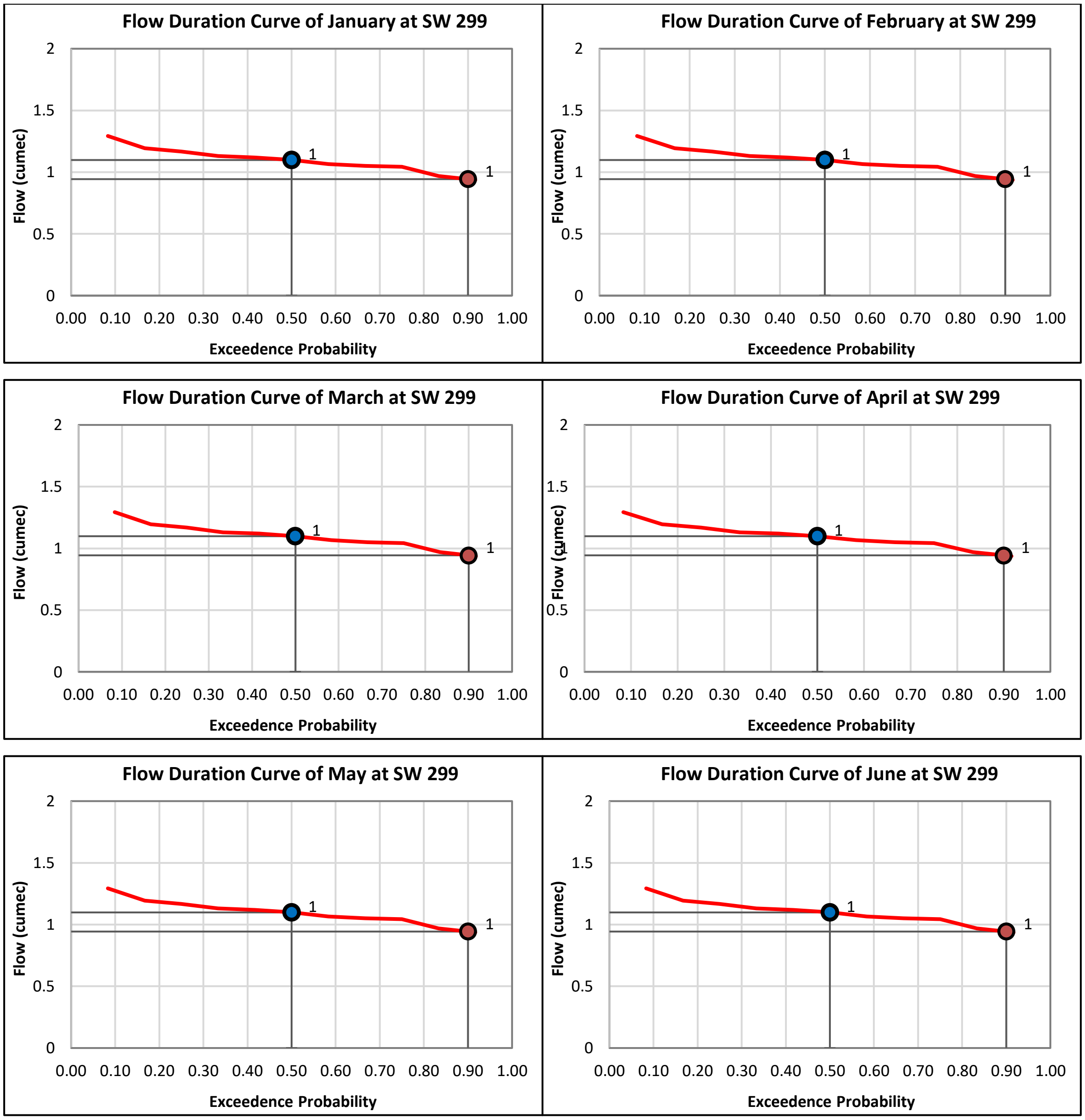


Figure B.2(f): Flow duration curve at Tongi of Tongi Khal (SW 299) from January to June

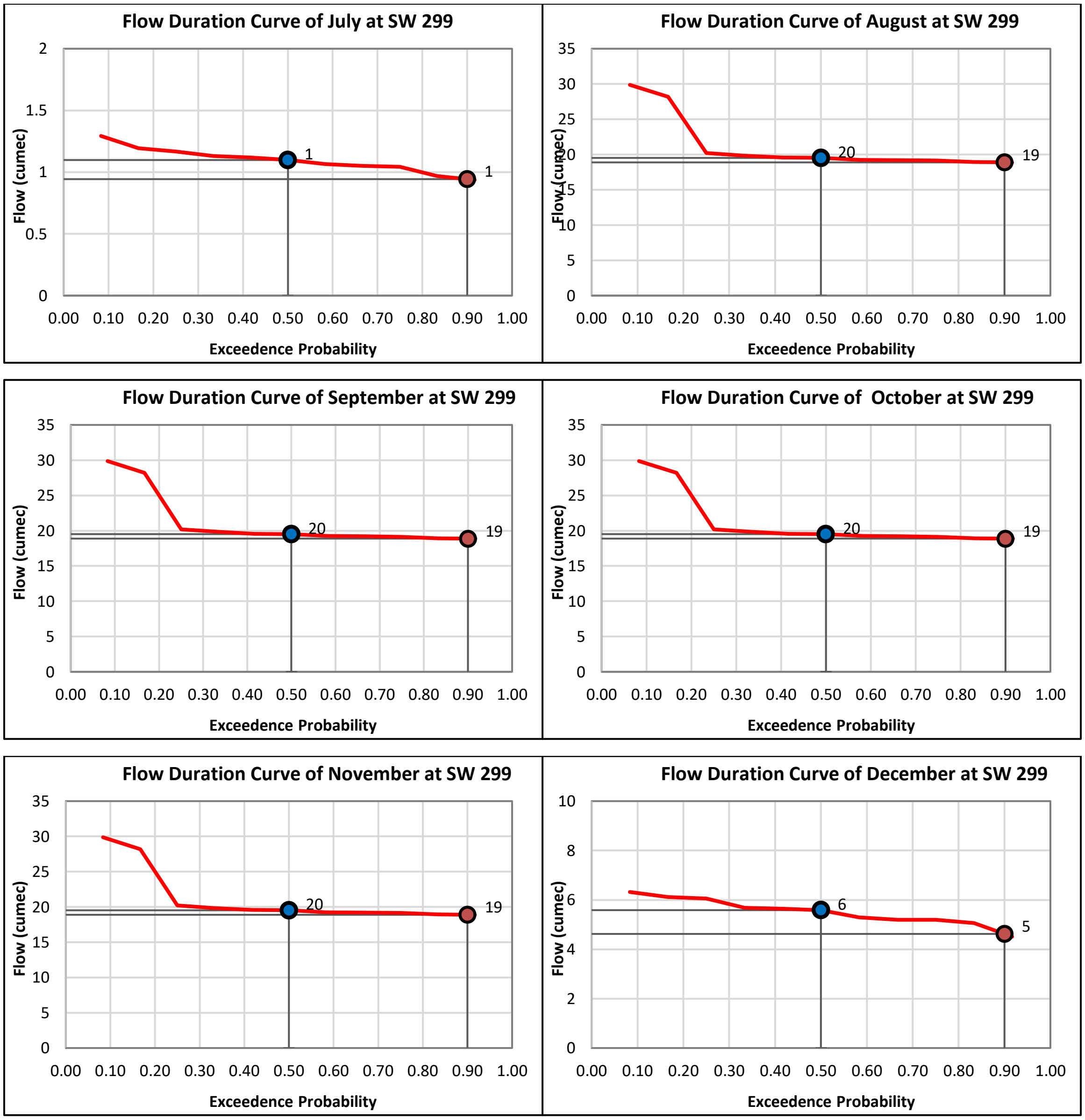


Figure B.2(f) (continued): Flow duration curve at Tongi of Tongi Khal (SW 299) from July to December

Table B.2(f): Environmental flow requirement (EFR) using Flow duration curve method at Tongi of Tongi Khal (SW 299)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow Season	Low	Low	Low	Low	High	High	High	High	High	High	Low	Low
50th Percentile Flow (cuemc)	1	2	3	3	4	11	17	20	28	42	20	6
90th Percentile Flow (cumec)	1	1	2	3	4	10	14	19	19	27	19	5
EFR (Cuemc)	1	1	2	3	4	11	17	20	28	42	19	5

Appendix B.3: Response of Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD) to Flow Scenario

Table B.3(a): Percentage change of DO and BOD for flow withdrawal scenarios

Station ID/Name	Month	Percentage change for Withdrawal scenario (%)					
		$Q_{env}+75\%Q_{wd}$		$Q_{env}+50\%Q_{wd}$		$Q_{env}+25\%\ Q_{wd}$	
		DO	**BOD**	**DO**	**BOD**	**DO**	**BOD**
Turag/SW 301/ Kaliakoir	May	-1.24	2.33	-2.46	4.71	-4.86	7.16
	Jul	-0.78	2.40	-1.56	4.86	-3.10	7.38
	Sep	-0.73	2.47	-1.46	5.00	-2.90	7.61
	Oct	-1.29	2.49	-2.56	5.04	-5.05	7.67
Turag/SW 302/ Mirpur	May	-1.35	2.42	-1.47	3.33	-3.29	5.84
	Jul	-0.90	2.49	-1.01	3.40	-2.39	5.98
	Sep	-0.85	2.56	-0.96	3.47	-2.30	6.13
	Oct	-1.40	2.58	-1.51	3.49	-3.38	6.17
Buriganga/SW 42/Dhaka Mill Barrack	Aug	-1.42	2.78	-2.03	3.80	-3.65	6.69
	Sep	-1.05	2.72	-1.67	3.74	-2.93	6.56
	Oct	-1.49	2.59	-2.10	3.61	-3.78	6.29
Dhaleshwari/SW 68.5/ Jagir	Mar	-1.55	3.14	-2.37	4.58	-4.11	9.92
	Apr	-1.80	3.27	-2.62	4.72	-4.60	10.20
	Jun	-1.20	3.80	-2.03	5.25	-3.43	11.33
	Jul	-1.22	3.52	-2.05	4.96	-3.46	10.72
	Aug	-1.32	4.05	-2.15	5.50	-3.67	11.86
	Sep	-1.03	3.90	-1.86	5.36	-3.10	11.55
	Oct	-1.51	3.84	-2.33	5.29	-4.03	11.42
	Nov	-1.49	3.33	-2.32	4.77	-3.99	10.31
Shitalakhya/SW 179/Demra	Jun	-1.99	2.78	-2.92	4.22	-5.36	7.86
	Aug	-1.39	3.02	-2.32	4.46	-4.19	8.38
	Sep	-1.11	2.88	-2.04	4.32	-3.65	8.07
	Oct	-2.20	3.45	-3.12	4.89	-5.75	9.26
	Nov	-2.28	2.31	-3.20	3.74	-5.90	6.87
Balu/SW 7.5/ Demra	Jun	-1.98	2.69	-2.86	2.78	-5.28	5.63
	Sep	-1.05	2.80	-1.94	2.89	-3.48	5.86
	Oct	-2.27	3.42	-3.15	3.52	-5.85	7.15
Tongi Khal/SW 299/ Tongi	Jun	-1.62	2.69	-2.60	2.78	-4.17	5.63
	Aug	-1.22	2.92	-2.21	3.01	-3.40	6.11
	Oct	-1.78	3.42	-2.76	3.52	-4.49	7.15

Table B.3(b): Percentage change of DO and BOD for flow augmentation scenarios

Station ID/Name	Month	Percentage change for Augmentation scenario (%)							
		Q_{avg}+ 25% Q_{aug}	Q_{avg}+ 25% Q_{aug}	Q_{avg}+ 50% Q_{aug}	Q_{avg}+ 50% Q_{aug}	Q_{avg}+ 75% Q_{aug}	Q_{avg}+ 75% Q_{aug}	Q_{avg}+ 100% Q_{aug}	Q_{avg}+ 100% Q_{aug}
		DO	BOD	DO	BOD	DO	BOD	DO	BOD
Turag/SW 301/ Kaliakoir	Jan	1.10	-1.19	2.21	-1.29	3.35	-2.56	4.48	-2.65
	Feb	1.30	-1.22	2.62	-2.43	3.96	-4.80	5.31	-5.96
	Mar	1.80	-1.29	3.63	-2.56	5.51	-5.05	7.41	-6.27
	Jun	2.39	-1.12	4.84	-2.23	7.35	-4.41	9.92	-5.48
	Aug	2.43	-0.72	4.92	-1.44	7.48	-2.87	10.09	-3.57
Turag/SW 302/ Mirpur	Jan	1.19	-1.21	2.20	-1.32	3.42	-3.00	4.23	-6.10
	Feb	1.39	-1.43	2.09	-1.54	3.51	-3.44	4.33	-6.73
	Mar	1.89	-1.34	2.60	-1.45	4.54	-3.26	5.37	-6.47
	Jun	2.48	-1.25	3.39	-1.36	5.96	-3.09	6.80	-6.21
	Aug	2.52	-0.82	3.43	-0.94	6.04	-2.24	6.88	-4.99
Buriganga/SW 42/ Dhaka Mill Barrack	Jan	1.20	-1.20	2.20	-1.81	3.43	-3.21	5.14	-4.58
	Feb	1.42	-1.63	2.43	-2.24	3.88	-4.06	5.37	-5.83
	Mar	2.15	-1.42	3.16	-2.03	5.38	-3.64	6.12	-5.22
	Apr	2.32	-1.73	3.33	-2.34	5.72	-4.25	6.30	-6.11
	May	2.53	-1.77	3.54	-2.38	6.15	-4.33	6.51	-6.23
	Jun	2.68	-1.14	3.70	-1.76	6.48	-3.10	6.68	-4.43
	Jul	3.41	-1.23	4.43	-1.84	7.43	-3.27	8.00	-4.67
	Dec	1.60	-1.69	2.60	-2.31	4.25	-4.18	5.55	-6.02
Dhaleshwari/SW 68.5/ Jagir	Jan	2.45	-1.41	3.88	-2.23	8.45	-3.83	12.43	-5.39
	Feb	2.64	-1.79	4.08	-2.61	8.85	-4.58	13.06	-6.49
	May	3.65	-1.76	5.10	-2.59	11.00	-4.52	16.43	-6.41
	Dec	2.91	-1.74	4.35	-2.57	9.42	-4.49	13.95	-6.37
Shitalakhya/SW 179/ Demra	Jan	1.44	-1.70	2.86	-2.63	5.07	-4.79	7.54	-6.62
	Feb	1.63	-2.24	3.05	-3.16	5.46	-5.83	8.14	-8.14
	Mar	2.13	-2.04	3.55	-2.96	6.49	-5.45	9.74	-7.58
	Apr	2.25	-2.39	3.68	-3.31	6.76	-6.12	10.15	-8.57
	May	2.63	-2.06	4.06	-2.98	7.54	-5.49	11.36	-7.64
	Jul	2.80	-1.26	4.24	-2.19	7.90	-3.93	11.92	-5.35
	Dec	2.50	-2.34	3.94	-3.25	7.28	-6.02	10.96	-8.42
Balu/SW 7.5/ Demra	Jan	1.20	-1.88	1.29	-2.76	2.60	-5.10	3.83	-7.09
	Feb	1.39	-2.40	1.48	-3.27	2.98	-6.09	4.42	-8.55
	Mar	1.90	-2.12	1.99	-3.00	4.02	-5.56	6.01	-7.77
	Apr	2.21	-2.39	2.31	-3.27	4.66	-6.08	6.98	-8.53
	May	2.55	-2.31	2.64	-3.19	5.34	-5.93	8.03	-8.31
	Jul	2.73	-1.09	2.82	-1.98	5.71	-3.57	8.60	-4.84
	Aug	2.92	-1.26	3.01	-2.15	6.11	-3.90	9.22	-5.33
	Dec	2.41	-2.41	2.51	-3.29	5.07	-6.12	7.61	-8.58
Tongi Khal/SW 299/ Tongi	Jan	1.09	-1.88	1.60	-2.76	2.00	-5.10	3.11	-7.09
	Feb	1.29	-2.40	1.80	-3.27	2.20	-6.09	3.52	-8.55
	Mar	1.98	-2.12	2.49	-3.00	2.90	-5.56	4.94	-7.77
	Apr	2.32	-2.39	2.83	-3.27	3.24	-6.08	5.64	-8.53
	May	2.39	-2.31	2.90	-3.19	3.31	-5.93	5.78	-8.31
	Jul	2.39	-1.09	2.90	-1.98	3.31	-3.57	5.78	-4.84
	Sep	2.46	-1.05	2.97	-1.94	3.38	-3.48	5.93	-4.70
	Nov	1.89	-2.30	2.40	-3.18	2.81	-5.90	4.75	-8.27