

SURFACE WATER QUALITY AND ITS IMPACT ON WATER SUPPLY SCENARIO IN KHULNA CITY OF BANGLADESH

By

Md Kamal Hossain

A thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of
Science in Civil Engineering in the department of Civil Engineering



Khulna University of Engineering & Technology
Khulna 9203, Bangladesh
April 2017

Declaration

This is to certify that the thesis entitled as '*Surface Water Quality And Its Impact On Water Supply Scenario In Khulna City, Bangladesh*' has been carried out by Md. Kamal Hossain in the Department of Civil Engineering, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh. The above thesis work or any part of this work here in described not been submitted anywhere to receive award, degree or diploma.

Signature of Supervisor

Signature of Candidate

Dedication

To
Beloved Parents
&
Family

Acknowledgement

First of all I would like to express all satisfaction and praise to almighty Allah; only by his grace and pity it is possible to complete this thesis work for the fulfillment of the degree. I am grateful and would like to thank to my supervisor Prof. Dr. Md. Shahjahan Ali, Department of Civil Engineering, Khulna University of Engineering & Technology, for his time to time guidance and advise regarding this thesis works.

Md. Kamal Hossain

Author of this Thesis

April, 2017

Approval

This is to certify that the thesis work submitted by Md Kamal Hossain entitled ‘ *Study on Surface Water Quality and Its Impact on Water Supply Scenario in Khulna City, Bangladesh* ’ has been approved by the board of examiners for the partial fulfillment of the requirements for the degree of *Master of Science in Civil Engineering* in the Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh in April 2017.

BOARD OF EXAMINERS

1. _____ Chairman
(Supervisor)
Dr. Md. Shahjahan Ali
Professor, Department of Civil Engineering
Khulna University of Engineering & Technology
2. _____ Member
Dr. Muhammad Harunur Rashid
Head, Department of Civil Engineering
Khulna University of Engineering & Technology
3. _____ Member
Dr. Kh. Md. Shafiu Islam
Professor, Department of Civil Engineering
Khulna University of Engineering & Technology
4. _____ Member
Dr. kh. Mahbub Hassan
Professor, Department of Civil Engineering
Khulna University of Engineering & Technology
5. _____ Member
(External)
Dr. Md. Niamul Bari
Professor, Department of Civil Engineering
Rajshahi University of Engineering & Technology

ABSTRACT

To get potable water is an acute problem now a days which is increasing in an alarming rate in southern region of Bangladesh. Khulna, the third largest city in Bangladesh, is located in the southwest of the country and has a population of 1.5 million. Ground water is the main source of supply water presently used by the Khulna Water Supply Authority, KWASA. Water supply for Citizens in Khulna has been suffering from limited access to water supply services. Out of approximately one and half million of population, only 17% has access to piped water supply, and the rest resorts to alternative sources, such as shared public taps and tube wells built privately. The present water supply in Khulna is mainly from ground water sources drawn from both deep and shallow tube wells. In the long term as demand increases, conjunctive use of ground water and surface water will be required, even though surface water may suffer from salinity intrusion in dry season. Due to increasing water demand in the city, the water supply system is vulnerable to supply required water to the people. Extensive abstraction of ground water from deep aquifer causes depletion of ground water level. Water in ground aquifer is not replenishing at the same rate of abstraction. In future, it may not be possible to yield sufficient quantity of ground water necessary for Khulna city. Therefore, to cope with current insufficient supply and increasing demand of potable and domestic water, it is necessary to allocate alternate source instead of groundwater. Therefore, a comparative study of water quality for different rivers in and around Khulna city is necessary. The main objective of this study is to investigate the usability of surface water to reduce the vulnerability of ground water for the water supply system of Khulna City Corporation (KCC) area.

There are many rivers flow through south western zone into or nearby the Khulna city and meet with Bay of Bengal in southern part of Bangladesh. Those are the Vairab, Rupsha, Kobadak, Pashur, Mayur, Modhumoti etc. In this thesis, firstly the water quality parameters for four stations of Gorai- Modhumoti river system are presented. These stations are Station-1: Haridaspur (Kumar river), Station -2: Modhupur (Gorai-Modhumoti river), Station -3: Chapailghat (Modhumoti river) and Station -4: Mollarhat (Modhumoti river). After that the water quality parameters of Rupsha- Bhairab river system are presented. Among the water quality parameters turbidity, pH, TDS, EC, chloride, salinity etc. are tested in the laboratory. Mayur river has not been considered in this study due to its insufficient water flow and its upstream source is almost moribund. The water flow source of Mayur river is mainly KCC drainage waste water and rain water in rainy season. Recently, KWASA has selected the Mollahat Point of Modhumoti River as the intake point of raw water for the alternate water source to supply after treatment. In this study, the historical flow characteristics of Gorai-

Modhumoti river is also studied to explain the sustainability of the raw water intake site for KWASA.

From comparison of water quality parameters, it is found that Modhumoti River contains very low amount of chloride concentration and salinity as compare to the other rivers. The salinity is found to be increasing from February and peak in April. Chapailghat, Modhupur and Haridaspur stations are found to have almost same salinity; highest is about 500 mg/l and lowest is 90 mg/l. Mollarhat contained lowest salinity among the four stations. All of stations contain higher salinity in summer due to lower discharge of river. For low discharge the sea water enter the downstream of river easily and contain higher salinity as compare to the upstream of the river. However, the salinity level is found to be increasing with years.

At Mollarhat point of Gorai-Modhumoti river, the discharge is found to be varies nearly zero at winter season to about 4000 cumec in monsoon. The maximum discharge is found to be varied from 1500 to 4000 cumec per year. Annual minimum discharge is varied from zero to 85 cumec for different years. Very low discharges are observed in the years of 2009 to 2011. Like discharge, water level is found to be varied with seasons from nearly 1 m at winter season to about 8 m in monsoon. From the linear trend line it is observed that from an average maximum water level of 8.23 m in 1995, it is decreasing by 0.056 m per year. Annual minimum water level is varied from 1.0 to 3.0 m for different years. Due to the dredging at the mouth of Gorai river in 2011, the water level is increased in 2012, which is again gradually decreased in the following years due to siltation at the mouth of Gorai. In the low water flow season, the average water flow rate in Modhumoti river was $25.5 \text{ m}^3/\text{sec}$ in 2015. The planned water intake volumes for Khulna City by KWASA are $110,000 \text{ m}^3/\text{day}$ ($= 1.273 \text{ m}^3/\text{sec}$) in 2025 and $220,000 \text{ m}^3/\text{day}$ ($= 2.546 \text{ m}^3/\text{sec}$) in 2030. Therefore, in low flow season the water will be drawn by a rate of 5.0% in 2025 and 10.0% in 2030. However, the feasibility study of KWASA assumed that safe amount to intake water from the river is less than 5%.

Modhumoti River is mainly comes through Gorai river from Ganges. A small part comes from Arial khan River through upper Kumar river. In both the source rivers, the discharges are found in decreasing trend both in monsoon and winter. It is evident from the Gorai river discharge and dredging history at Gorai mouth that dredging effectively increases the flow in Gorai river, though huge siltation affect negatively afterwards. Therefore, to increase the discharge of Gorai river, it is necessary to keep dredging on a regular basis of Gorai River, which will maintain potential flow of Modhumoti River. In addition, Kumar river bed dredging to divert flow of Arial Khan river may help further to increase the flow in Modhumoti River. Flow Divider at Gorai Off-take can be installed to divert Ganges flow into Gorai-Modhumoti river.

TABLE OF CONTENTS

CHAPTER NO.	COMPONENTS	PAGE NO.
CHAPTER 1	Introduction	1
1.1	Background	1
1.2	Objectives of the Work	2
1.3	Scope of the Study	3
1.4	Organization of the thesis	3
CHAPTER 2	Literature Review	5
2.1	General	5
2.2	GBM Basin and Ganges Delta	5
2.3	The Active Ganges Floodplain	9
2.4	The High Ganges Floodplain	9
2.5	The Low Ganges River Floodplain	9
2.6	Sediment Carried by Ganga	9
2.7	Gorai river	10
2.8	Restoration of Gorai	12
2.9	Problem of Gorai river	13
2.10	Flow Distribution among the Ganges and the Gorai Rivers	14
2.11	Sediment transport in the Ganges and Gorai Rivers	17
2.12	Causes of Deterioration of the Gorai River Flow	20

2.13	Effects of Farakka Barrage	21
2.14	Clay at Gorai Off-take	22
2.15	Gorai River's Salinity Condition	22
2.16	Geo-morphological and Physiographic Settings of the Modhumoti River	24
2.17	Arial Khan river	24
2.18	Standards for water	27
CHAPTER 3	Approach and Methodology	29
3.1	Introduction	29
3.2	Existing water supply condition and future scenario of KWASA	29
3.3	Behaviour of Gorai-Modhumoti river system	29
3.4	Surface water sampling and laboratory analysis	30
3.4.1	Water samples collection	30
3.4.2	Laboratory tests	33
CHAPTER 4	Water Supply Scenario of KWASA	35
4.1	Introduction	35
4.2	Ground water quality in KWASA area	36
4.3	Existing water supply scenario in KWASA area	40
4.4	Future plan of KWASA	42
CHAPTER 5	Water Quality Parameters	45
5.1	Introduction	45
5.2	Water quality parameters for Gorai- Modhumoti river	46
5.3	Water quality analysis Rupsha- Bhairab river system	53

5.4	Water quality analysis of Arial Khan river	58
5.5	Comparison of water quality among different rivers	59
CHAPTER 6	River Flow Behaviour	63
6.1	General	63
6.2	Gorai railway bridge point	65
6.3	Gorai -Kamarkhali point	69
6.4	Arial Khan Off Take point	72
6.5	Modhumoti Mollar Hat point	76
6.6	Availability of discharge at raw water intake point	79
CHAPTER 7	Conclusion and Recommendation	80
	REFERENCES	84

LIST OF TABLES

TABLE NO.	DESCRIPTION	PAGE
2.1	Standards for drinking water for Bangladesh	27
2.2	Standard for inland surface water for Bangladesh	28
3.1	Global position of five sampling station of Bhairab- Rupsha river, khulna	34
3.2	Measurement of parameters and analytical method	33
4.1	The summary of the results for ground water quality of KWASA area for the year of 2015	37
4.2	Water demand projection of KWASA	39

LIST OF FIGURES

FIGURE NO.	DESCRIPTION	PAGE
2.1	Route Map of Ganges river	6
2.2	Limit of Ganges Delta	7
2.3	Ground Level elevation of SW zone of Bangladesh	8
2.4	Water discharge of Gorai River(1969-2008)	13
2.5	Ratio of annual flow volume between Gorai and the Ganges rivers	15
2.6	Peak discharge of Gorai River compared to the Ganges river	15
2.7	Changes in the ratio between the Ganges and Gorai flow during 1988-99	15
2.8	Changes in the ratio between the Ganges and the Gorai during 2000-2010	16
2.9	Velocity measurement of Ganges and Gorai river	16
2.10	Float tracking along the Ganges and the Gorai during 03-04 January 2012	17
2.11	Image of Gorai off-take	18
2.12	Total suspended sediment concentration of Ganges and Gorai river(1996)	19
2.13	Sediment concentration measurement by FAP 24	19
2.14	Sediment concentration at Hardinge Bridge and Gorai Off-Take(1996)	20
2.15	Sediment concentration at Hardinge Bridge and Gorai Railway Bridge (IWM, 2011)	20
2.16	Monthly salinity variation at Khulna on the Rupsha river with upstream fresh water flow(IWM, 2014)	24
2.17	Arial Khan River Off Take	25
2.18	Annual maximum flow of the Arial Khan and Upper Kumar rivers(2012)	26
3.1	Water sample collection stations in Gorai-Modhumoti river system	30
3.2	Pictorial view of water sample collection station in Gorai- Modhumoti river system	32

4.1	Map of KCC area	36
4.2	Options of raw water intake points (KWASA, 2010)	41
4.3	Selected site of raw water intake for KWASA water supply project (KWASA, 2010)	44
5.1	Monthly variation of Rainfall and Temperature in Khulna region (KCC, 2014)	45
5.2	Variation of turbidity at different locations for Modhumoti river (2014-2015)	46
5.3	Variation of P^H at different locations for Modhumoti river (2014-2015)	47
5.4	Variation of COD at different locations for Modhumoti river (2014-2015).	48
5.5	Variation of BOD at different locations for Modhumoti river(2014-2015).	48
5.6	Variation of Total dissolve solid at different locations for Modhumoti river(2014-2015).	49
5.7	Variation of hardness at different locations for Modhumoti river (2014-2015).	50
5.8	Variation of Electrical Conductivity (EC) at different locations for Modhumoti river (Sep 2014-May 2015).	51
5.9	Variation of salinity at different locations for Modhumoti river (Nov 2014-Mar 2016)	51
5.10	Variation of chloride concentration at different four (4) locations for Modhumoti rivers (Sep2014- May-2016)	52
5.11	Monthly variation of salinity at RupshaGhat of Gorai-Bhairab river system (Year 2015)	53
5.12	Temporal variations of pH at Fultala station of Bhairab/Rupsha river (2015)	54
5.13	Temporal variations of turbidity of Bhairab/Rupsha river (Year 2015)	54
5.14	Temporal variations of conductivity of Bhairab/Rupsha river (Year 2015)	55
5.15	Temporal variations of Hardness of Bhairab/Rupsha river(Year 2015)	55
5.16	Temporal variations of TDS of Bhairab river (Year 2015)	56

5.17	Temporal variations of Chloride of Bhairab river(Year 2015)	57
5.18	Temporal variations BOD of Bhairab river(Year 2015)	58
5.19	Temporal variations of COD of Bhairab river (Year 2015)	58
5.20	Temporal variations of salinity at Arial Khan river off take	59
5.21	Variation of chloride concentration of different rivers in 2015	60
5.22	Chloride concentration of different rivers for 2014. (Source: KWASA, 2014)	60
5.23	Electrical conductivity of different rivers (Year 2015)	61
5.24	Spatial Variation of chloride Concentration of different river (Year 2009 and 2015).	61
5.25	Variation of salinity for different rivers (Year 2010 and 2015)	62
6.1	Sources of flows of Modhumoti river	65
6.2	Rating curve for Gorai Railway Bridge point of Gorai river	66
6.3	Time series of discharge at Gorai Railway Bridge point of Gorai river.	67
6.4	Historical annual maximum discharges at Gorai Railway Bridge.	67
6.5	Historical annual minimum discharges at Gorai Railway Bridge.	67
6.6	Time series of water level at Gorai Railway Bridge point of Gorai river.	68
6.7	Annual maximum water levels at Gorai Railway Bridge.	68
6.8	Annual minimum water levels at Gorai Railway Bridge.	69
6.9	Rating curve for Kamarkhali point of Gorai river.	69
6.10	Time series of discharge at Kamarkhali point of Gorai river.	70
6.11	Historical annual maximum discharges at Kamarkhali point of Gorai river	70
6.12	Historical annual minimum discharges at Kamarkhali point of Gorai river.	71
6.13	Time series of water level at Kamarkhali point of Gorai river.	71
6.14	Annual maximum water levels at Kamarkhali point of Gorai river.	72
6.15	Annual minimum water levels at Kamarkhali point of Gorai river.	72
6.16	Rating curve for Arial Khan river Off Take.	73

6.17	Time series of discharge at Arial Khan river Off Take.	73
6.18	Historical annual maximum discharges at Arial Khan river Off Take.	74
6.19	Historical annual minimum discharges at Arial Khan river Off Take.	74
6.20	Time series of water level at Arial Khan river Off Take.	75
6.21	Annual maximum water levels at Arial Khan river Off Take.	75
6.22	Annual minimum water levels at Arial Khan river Off Take.	76
6.23	Rating curve for Modhumoti Mollarhat Point.	76
6.24	Time series of discharge at Modhumoti Mollarhat Point.	77
6.25	Historical annual maximum discharges at Modhumoti Mollarhat Point.	77
6.26	Historical annual minimum discharges at Modhumoti Mollarhat Point.	78
6.27	Time series of water level at Modhumoti Mollarhat Point.	78
6.28	Annual maximum water levels at Modhumoti Mollarhat Point	79
6.29	Historical annual minimum discharges at Modhumoti Mollarhat Point	79

NOMENCLATURE

ADB	ASIAN DEVELOPMENT BANK
BWDB	Bangladesh Water Development Board
BOD	Biochemical Oxygen Demand
BMD	Bangladesh Metrological Department
COD	Chemical Oxygen Demand
DICL	Ductile Iron Cement Lined Pipe
EC	Eelectrical Conductivity
GBM	Ganges-Brahmaputra-Meghna
JICA	Japan International Cooperation Agency
KWASA	Khulna Water Supply And Sewerage Authority
MBR	Madaripur Beel Route
MLD	Million Liter Per Day
MSL	Mean Sea Level
NTU	Nephelometric Turbidity Unit
SWTP	Surface Water Treatment Plant
TDS	Total Dissolved Solids
USAID	United States Agency For International Development
WHO	World Health Organization
PTW	Production TubeWell
FPS	Feet per Second

CHAPTER 1

Introduction

1.1 BACKGROUND

Bangladesh is one of the most vulnerable countries in the world due to ground water level depletion, intrusion of saline water, increase of river water salinity, arsenic and iron contaminated water etc. which significantly affect the human life as well as living things and overall economic and social development of the country. To get potable water is an acute problem now a day which is increasing an alarming in southern region of Bangladesh. Khulna, the third largest city in Bangladesh, is located in the southwest of the country and has a population of 1.5 million.

Potable water is a prime requirement for daily life of human beings. Unfortunately, more than one in six people still lack is reliable access to this precious resource in developing country like Bangladesh (USAID, 2014). Most of the earth water is sea water. About 2.5% of the water is fresh water that does not contain significant levels of dissolved minerals or salt and two third of that is frozen in ice caps and glaciers. In total only 0.01% of the total water of the planet is accessible for consumption. Shallow groundwater, the primary water source in the Bangladesh basin, contains up to 100 times the WHO drinking-water guideline of $10 \mu\text{g } \Gamma^{-1}$ arsenic (As), threatening the health of 160 million people (Rahman et al. 2014; Shammi et al. 2012). Groundwater from a depth greater than 150 m, which almost uniformly meets the WHO guideline, has become the preferred alternative source (Burgess et al. 2010). The vulnerability of deep wells to contamination by Arsenic is governed by the geometry of induced groundwater flow paths and the geochemical conditions encountered between the shallow and deep regions of the aquifer (Nahar et al. 2014). Stratification of flow separates deep groundwater from shallow sources of Arsenic (As) in some areas. Oxidized sediments also protect deep groundwater through the ability of ferric hydroxides to adsorb As. Basin-scale groundwater flow modeling suggests that, over large regions, deep hand-pumped wells for domestic supply may be secure against Arsenic invasion for hundreds of years. By contrast, widespread deep irrigation pumping might effectively eliminate deep groundwater as an As-free resource within decades. But problem is due to extensive abstraction of ground water from deep aquifer that causes depletion of ground water source.

Water supply for Citizens in Khulna has been suffering from limited access to water supply services. Out of approximately one million of population, only 17% has access to piped water supply, and the rest resorts to alternative sources, such as shared public taps and tube wells built privately (ADB, 2011). The present water supply in Khulna is mainly from ground water sources drawn from both deep and shallow tube wells. In the long term as demand increases, conjunctive use of ground water and surface water will be required, even though surface water may suffer from salinity intrusion in dry season (KWASA, 2010). Due to increasing water demand in the city, the water supply system is vulnerable to supply required water to the people. Extensive abstraction of ground water from deep aquifer causes depletion of ground water level. Water in ground aquifer is not replenishing at the same rate of abstraction (Findikakis and Sato, 2011). In future it may not be possible to yield sufficient quantity of ground water necessary for Khulna city. To solve this acute problem of using ground water, the alternate way is to use of surface water by proper treatment before reaching it to the consumer. The Rupsa, Vairab, Modhumoti and Mayur are the rivers nearby and close vicinity to the Khulna city. Most of the rivers in southern zone contain much higher salinity as compare to the drinking water standard or domestic use (PUB, 2010). Moreover, most of the rivers in this region has almost no flow in dry season due to Farakka effect (Ali and Syfullah, 2012). However, to cope with current insufficient supply and increasing demand of potable and domestic water, it is necessary to allocate alternate source instead of groundwater. Therefore, a comparative study of water quality for different rivers in and around Khulna city is necessary.

1.2 OBJECTIVES OF THE WORK

The main objective of this study is to investigate the usability of surface water to reduce the vulnerability of ground water for the water supply system of Khulna City Corporation (KCC) area. The specific objectives of this study are outlined as below:

- To investigate the existing water supply condition and its Future Scenario to meet the water demand of Khulna city dwellers.
- To investigate the surface water quality of different rivers nearby and vicinity to Khulna city, and analyze their usability in mitigating the water supply demand of Khulna WASA.
- To study the suitability of raw water intake sites selection in nearby rivers and their sustainability based on temporal change of river discharge/depth, water quality and tidal effect including salinity intrusion.

1.3 SCOPE OF THE STUDY

At present KWASA uses ground water as the only water source. However, to minimize ground water depletion and to meet the future water demand, alternate source of water is necessary. In this regard Gorai- Modhumoti river system is considered as the main focus of this study. The Gorai River has been the major distributaries of the Ganges River, passing through the region, providing the majority of the dry season flow (DHV-WARPO, 2001). Main River systems of this region consist of the Gorai-Modhumoti-Baleswar river system and the Gorai-Bhairab-Pussur river system. The physical features of the study area have been dominated by surface water systems, the proximity of the sea in the south, the dynamic morphology that is greatly governed by sedimentation processes, and the human induced influence on the entire hydro-geophysical characteristics of the region. The region is endowed with surface water systems. The Modhumoti River is a distributary of the upper Ganges flowing through southwestern Bangladesh. It leaves the Ganges just north of Kushtia and flows 306 km before turning south across the Sundarbans and into the Bay of Bengal. In its upper course it is called the Gorai river, in its lower course it is known the Baleswar river and its estuary mouth which is 14 km wide is called the Haringhata River. The Baleswar river length is 57 km, and the Nabganga river from Bardia point to Gazirhat is 29 km. The length of Gorai-Modhumoti-Baleswar rivers is 371 km (37 km in Kushtia, 71 km in Faridpur, 92 km in Jessore and 104 km in Khulna and 67 km in Barisal in the eastern border of Sundarbans).The Bhairab river length is 250 km and it runs Jessore and Khulna region, the length of Chitra river is 170 km, The length of Nabaganga is 230 km (26 km in Kushtia and 204 km in Jessore).

1.4 ORGANIZATION OF THE THESIS

This thesis contains seven chapters. A brief description of organization of this report is given below.

Chapter 1 Provides the background, statement of the study and objectives.

Chapter 2 Focuses on the available literature and previous studies related to this thesis that would help to explain the findings of the present work.

Chapter 3 Describes the methodology of the study, details of study area, and the standard of drinking and surface water quality parameters.

Chapter 4 Describes the existing water supply scenario and required future demand of KCC /KWASA area

Chapter 5 Reveals the laboratory test results of water quality parameters of Gorai-Modhumoti river system. The water quality of Bhairab- Rupsha river is also presented for comparison.

Chapter 6 Flow depth and discharge of Gorai- Modhumoti river system is analyzed in the chapter.

Chapter 7 Represents the conclusions of the study and the recommendations provided for further extension of the works.

CHAPTER 2

Literature Review

2.1 GENERAL

In this chapter the origin of Modhumoti river, the water quality parameters, the standard of water quality for drinking and river water quality are described. Previous study about water quality of various rivers nearby the Khulna city (Bhairab, Rupsha and Mayur) have been also reviewed.

2.2 GANGES-BRAHMAPUTRA-MEGHNA (GBM) BASIN AND GANGES DELTA

Presently, the GBM combined average water discharge is among the highest in the world with peak discharges of 100,000 m³/s from the Brahmaputra, 75,000 m³/s from the Ganges, and 20,000 m³/s from the Upper Meghna, and 160,000 m³/s from the Lower Meghna (FAO, 2012). The Ganges and Brahmaputra systems drain the Himalayas and the Tibetan Plateau and provide the bulk of the sediment to the basin with a sediment flux of 316 million tons/yr and 721 million tons/yr respectively (Islam et al., 1999). The total sediment load is nearly 1037 million tons/yr, of which about 525 million tons/yr is deposited in the lower delta while the remainder (about 512 million tons/yr) offsets subsidence through floodplain deposition and riverbed aggradation (Islam et al., 1999). The modern delta continues to propagate into the Bay of Bengal, resulting in a combined sub aerial and submarine surface area of 140,000 km². Active deltaic feature formation occurs in the eastern delta, while the western delta receives little fluvial input and is predominantly tidal (Umitsu, 1993). As a result of strong semidiurnal tides with a range of 1.9 m in the west and 2.8 m in the east . As the tides propagate inland, the range can increase to as much as 5 m (Kuehl et al., 2005).

The GBM river basin spans 5 international borders – Bangladesh, Bhutan, China, India, and Nepal (Figure 2.1). The basin is home to an estimated 630 million people making it one of the most densely populated and poorest regions of the world (FAO, 2012). The Bengal Basin is often cited as being highly vulnerable to the effects of climate change and sea level rise through tropical cyclones and storm surges (Ali, 1996; Ali, 1999; IPCC, 2007; Dasgupta et al., 2010). The basin is relatively inactive in comparison with other tropical cyclone basins; however, its position at the confluence of the GBM system, high population density, lack of resources, and limited ability for preparation and management results in greater impacts during even small cyclonic events. The IPCC Fourth assessment report suggests that the frequency of these extreme

weather events will increase. This may result in cyclonic events becoming more frequent within the basin. However, a special report discusses the uncertainty in changes to extreme weather patterns at the local level (IPCC, 2012). Regardless, the impact of cyclonic storms will continue to increase in the Bengal Basin through population growth, continued progradation of the delta, and decreased resilience to storm surge through anthropogenic perturbations to the system.

The southwestern part of the Ganges delta is coastal area and a tidally active delta. It is dominated by coastal tidal currents. The tidally active delta actually is the southern part of the Sundarbans region. It covers an area of about 13500 km². The Tidally active delta includes the southern part of Bagerhat, Khulna, Sathkhira district of Bangladesh and south 24 Pargona district of West Bengal in India (Islam, 2006).



Figure 2.1: Route Map of Ganges River (www.mapsofindia.com)

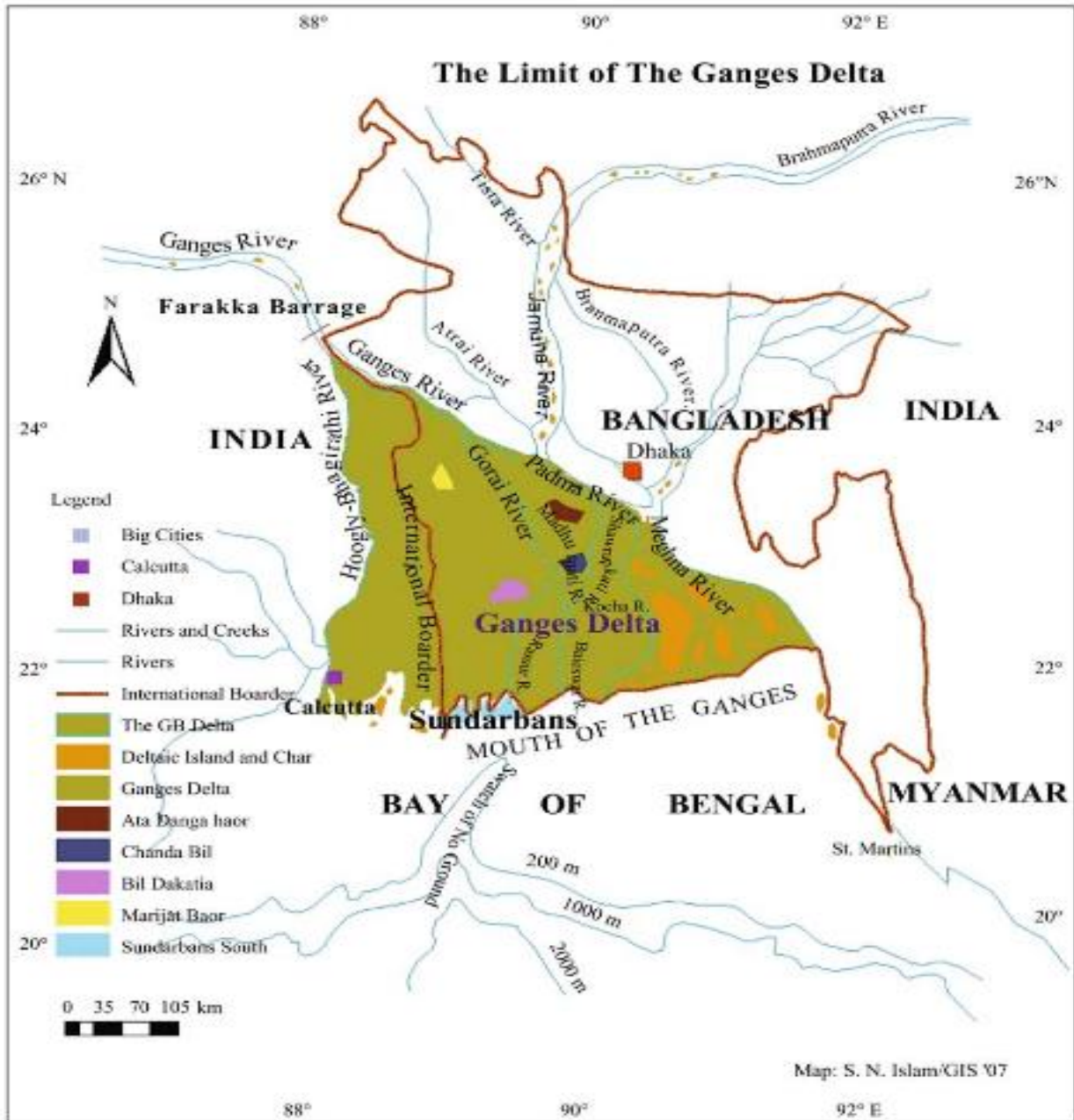


Figure 2.2: The limit of Ganges Delta (Islam and Gnauck, 2008).

The Ganges (also known as Ganga or Gonga), is the biggest river in the Indian subcontinent in terms of water flow. The length of the Ganga is 2,510 km or 1,560 miles. The river has its origin in the Western Himalayan Ranges in the state of Uttarakhand. The followers of Hindu religion regard the Ganges to be the most sacred of all the rivers in India. The river is revered as the deity Ganga in Hindu religion. The river also has significant historical values - a number of colonial or

royal capitals like Kannauj, Patliputra (modern day Patna), Allahabad, Kara, Baharampur, Murshidabad, and Kolkata are situated on the riverbanks of the Ganges.

The Ganges river catchment basin covers an area of 390,000 sq miles (1,000,000 sq km) and supplies to one of the maximum populated areas in the world. The average depth of the Ganges river is 16 m or 52 feet and the highest depth is 30 m or 100 feet. The river has been proclaimed as the National river of India. The first Prime Minister of India, Pandit Jawaharlal Nehru, cited a number of emblematic interpretations regarding the Ganges on the Indian subcontinent in his famous book, the Discovery of India (published in 1946).

Not only do humans affect the local environment, but they are also influenced by a number of environmental stressors – many of which are directly related to sea level rise and the impacts on coastal regions. Most recently, Cyclone Sidr (2007) and Cyclone Aila (2009) both caused catastrophic losses to human life, livestock, and land through embankment failure (United Nations, 2007; United Nations, 2010). Cyclone Aila caused large portions of the coastal populations to be displaced both locally (temporary relocation onto embankments) and regionally (migration into cities) (Kartiki, 2011). Furthermore, anthropogenic perturbations such as poldering and conversion of land to aquaculture may destabilize coastal systems, resulting in decreased resilience to storm surge (e.g., increased flooding – both sustained and temporary, land subsidence, and salinization of freshwater resources).

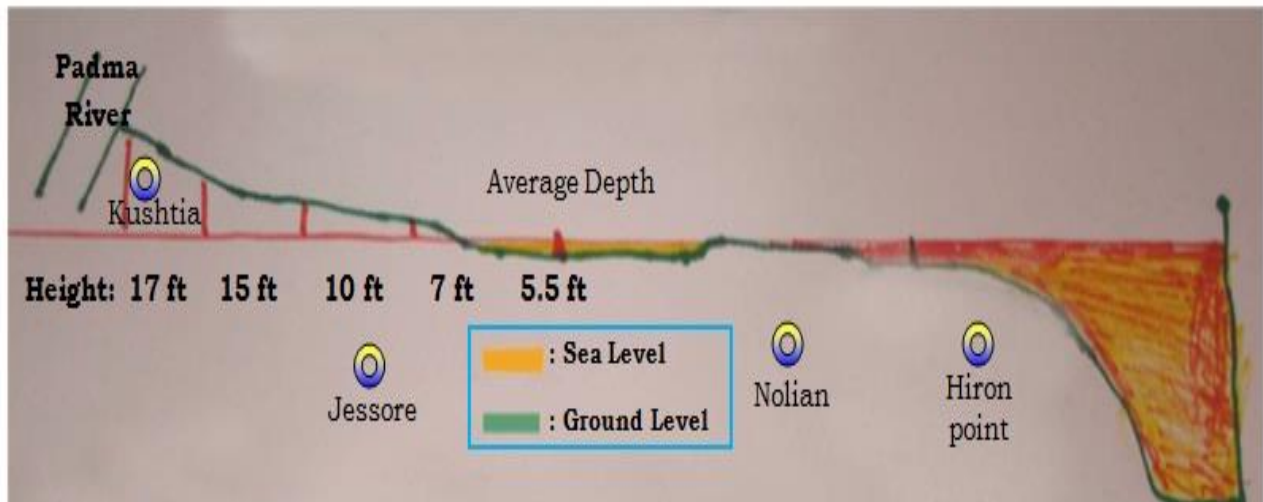


Figure 2.3: Ground level elevation of SW zone of Bangladesh (Islam and Gnauck, 2008).

2.3 THE ACTIVE GANGES FLOODPLAIN

It covers the char areas which have an irregular relief of broad and narrow ridges and depressions, interrupted by cut-off channels and active channels. The char formations are a result of bank erosion by shifting channels and due to the deposition of irregular thickness of new alluvium in every flood season. Complex mixtures of calcareous sandy, silty and clay alluvium, with some shallowly developed brown loamy soils on ridges and dark grey clays in depressions on older alluvial areas.

2.4 THE HIGH GANGES FLOODPLAIN

The high Ganges floodplain covers the upstream of the Ganges from the Gorai Off-take that covers a complex relief of broad and narrow ridges and inter-ridge depressions, separated by areas with smooth, broad bridges and basins.

The upper parts of high ridges stand above normal flood level. The lower parts of ridges and basin margins are seasonally shallowly flooded, but some deep basin centers are moderately deeply or deeply flooded. There is an overall pattern of olive-brown, silt loams and silty clay loams on the upper parts of floodplain ridges and dark grey, mottled brown, mainly clay soils on lower ridge sites and in basins. Most ridge soils are calcareous throughout. Some higher soils have non-calcareous upper layers with 30-60 cm. Non-calcareous layers are slightly acid or neutral, but they are strongly acid in some heavy basin clays.

2.5 THE LOW GANGES RIVER FLOODPLAIN

It covers the left bank of the Gorai River and extends up to Madaripur and Shariatpur districts. It covers a typical meander floodplain landscape of broad ridges and basins. The relief alongside rivers crossing the region generally is somewhat irregular, comprising broad and narrow ridges, inter ridge depressions and cut-off channels. Differences in elevation between ridge tops and basin centers are generally in the range 3-5 m, but are less near the northern and southern boundaries. The general soil pattern is olive-brown silt loams and silty clay loams on the highest parts of floodplain ridges and dark grey silty clay loams to heavy clays on lower sites.

2.6 SEDIMENT CARRIED BY GANGA

The Ganga–Brahmaputra rivers deposits nearly 1000 million tons of sediment per year. The sediment from these two rivers forms the Bengal Delta and the submarine fan, a vast structure that extends from Bangladesh to south of the Equator, is up to 16.5 Kilometres (10.3 mi) thick, and contains at least 1,130 trillion tonnes of sediment, which has accumulated over the last 17

million years at an average rate of 665 million tons per annum. The Bay of Bengal used to be deeper than the Mariana Trench, the present deepest ocean point. The fan has buried organic carbon at a rate of nearly 1.1 trillion mol/yr since the early Miocene period. The two rivers currently contribute nearly 8% of the total organic carbon (TOC) deposited in the world's oceans. Due to high TOC accumulation in the deep sea bed of the Bay of Bengal, the area is rich in oil and natural gas and gas hydrate reserves. Bangladesh can reclaim land substantially and economically from the sea area by constructing sea dikes, bunds, causeways and by trapping the sediment from its rivers.

2.7 GORAI RIVER

The Southwestern Region of Bangladesh has been subjected to a plethora of hydro-geo morphological hazards which include poor drainage through its river systems, high rates of sedimentation on river beds, acute low flow conditions during the dry season, salinity ingress along the rivers, cyclonic storm surge, moisture stress in the dry season, rise in sea level, and to a lesser extent, flood (WARPO, 2001). The region is located in the coastal zone, and is significantly influenced by tidal effects. According to available statistics on Coastal Zone, majority of the land is within one meter from mean sea level, a significant proportion of which again falls below high-tide level.

The Gorai river has been the major distributary of the Ganges river, passing through the region, providing the majority of the dry season flow (DHV-WARPO, 2001). Main river systems of this region consist of the Gorai-Madhumati-Baleswar river system, the Gorai-Bhairab-Pusur river system, the Bhadra-Gengrail river system, the Hari-Teka-Mukteswari river system, Sibsa river, the Kobadak-Betna-Kholpetua river system and the Mathabhanga-Ichamati-Kalindi river system. These river systems criss-cross the region through a complex network of smaller rivers and rivulets. Through a natural process of gradual east-ward migration of the Ganges river – the primary source of freshwater for all these river systems, many smaller rivers lost their drainage capacity over the past two centuries (Williams, 1919; Sarker, 2004). The physical features of the study area have been dominated by surface water systems, the proximity of the sea in the south, the dynamic morphology that is greatly governed by sedimentation processes, and the human induced influence on the entire hydro-geophysical characteristics of the region. However, the latter has been the most dominant influence of all in recent decades, leading to profound subsequent implications on social and economic aspects of the inhabitants. The region is endowed with surface water systems, as discussed earlier. The land is mostly floodplains of the major rivers. However, along the southern reaches of the area, there are inter-tidal floodplains that are generally inundated twice diurnally. In the floodplains, there are wetland areas. A few

wetlands such as beel and baor wetlands have been formed naturally, proving ecosystem support to aquatic species. This in turn has provided for ecosystem services to humans, in the form of fish, weeds/reeds (as construction materials) etc. Simultaneously, a few other wetland systems such as ponds and constructed water bodies (locally known as ghers, i.e., captive wetlands) have been created by human beings to maximize ecosystem services further. Moreover, the encircled embankments (i.e., polders) have been created since early 1970s to safeguard agricultural activities from tidal/saline influence. Polders therefore have become a permanent feature on the land, which also have influenced sedimentation dynamics of the area. The estuary not only provides an interface between seawater and freshwater, it also provides significant ecosystem services, often in the form of estuarine small-scale fisheries. The production of tiger prawn (*Penaeus monodon*) in the ghers is largely supported by shrimp larvae, which are generally caught in the estuarine rivers and creeks. Sediments carried out by the major rivers have been deposited over millennia on the shallow continental shelf, which paved the path for land formation to the south. Meanwhile, tides carried seeds of a large variety of mangrove species to newly accreted lands and propagated the natural spread of mangrove forest at the southern reaches of both Satkhira and Khulna. The Sundarbans, located in the Southern most reaches of the SW region, is the largest patch of productive mangrove forest ecosystem in the world. It provides various ecosystem services to approximately one million households living in the SW region and the South-central region. The forest often takes on the first blow of cyclonic storms rushing to the SW region, thereby reducing the extent of damages, as it has been observed in the cases of cyclones of 1986 and 2007. Furthermore, the forest is the natural habitat for a number of endemic species such as Bengal Tiger (*Panthera tigris*). Due to its richness in biodiversity and its great ecosystem service to millions of people, apart from its beauty, it has been regarded as an UNESCO Global Heritage Site since 1996.

The Gorai river, one of the right bank distributaries of the Ganges river, is the main source of sweet water in the southwest region of Bangladesh. This river also plays an important role for maintaining the ecosystem of the world's largest mangrove forest, the Sundarbans. Since 1970, after the construction of the Farakka Barrage in India, the dry season flow has been reduced drastically. Morphological changes in the Ganges at the Gorai Off-take also have impacted the flow through the Gorai which has caused the steady declining of dry and monsoon flow during the last three decades.

The impact of such hydro-morphological changes of the Ganges and Gorai river system is quite significant in terms of increased salt-water intrusion in the region. Like many other right bank distributaries, the Gorai river was probably one of the abandoned courses of the Ganges river. The morphology of the Ganges river at the Gorai Off-take determines the flow in the Gorai river.

Reduction of the monsoon flow causes overbank flow to cease. A CEGIS (2012) study shows that riverbank erosion along the Gorai river has been reduced with the reduction of monsoon flow turning it into an under-fit river.

2.8 RESTORATION OF GORAI

The Government of Bangladesh (GoB) has taken initiatives for restoring the Gorai river flow through dredging and river training works and requested the World Bank to take up the work. It has become clear now that to harness the benefit from the Gorai, dry season as well as the monsoon hydrograph of the Gorai should be restored. Many ideas and concepts were developed, giving shape to a development intervention applied over the past decades, which has culminated into the present latest measure.

Length of gorai is 199 km which can be divided in 5 distinct reaches according to morphologically consideration (EGIS, 2000). Gorai 1 - Off-take to Railway Bridge –11 km, Gorai2 - Railway Bridge to Kamarkhali – 87 km, Gorai 3 - Kamarkhali point to 4thReach - 110 km, Gorai 4 -4th Reach to 5thReach point-125 km, Gorai 5 - 125 km to Bardia point - 199 km.

The Gorai river reach from Gorai 1 to Gorai 4 is the non tidal condition and the tidal nature of Gorai river is the 5th reach which is called tidal lower course is extremely active and flowing (EGIS, 2000). The Modhumati river is a distributary of the upper Ganges flowing through southwestern Bangladesh. It leaves the Ganges just north of Kushtia and flows 306 km before turning south across the Sundarbans and into the Bay of Bengal. In its upper course it is called the Gorai river, in its lower course it is known the Baleswar river and its estuary mouth which is 14 km wide is called the Haringhata river. The Baleswar river length is 57 km, and the Nabganga river from Bardia point to Gazirhat is 29 km. The length of Gorai-Modhumati-Baleswar rivers is 371 km (37 km in Kushtia, 71 km in Faridpur, 92 km in Jessore and 104 km in Khulna and 67 km in Barisal in the Eastern border of Sundarbans).The Bhairab river length is 250 km and it runs Jessore and Khulna region, the length of Chitra river is 170 km. The length of Nabaganga is 230 km (26 km in Kushtia and 204 km in Jessore). The Mathabhanga river length is 56 km (16 km in Rajshahi and 140 km in Kushtia). The Gorai river has been largest perennial distributary of the Ganges river in Bangladesh. The Mathabhanga and Bhairab also provided fresh water inflow during dry season in earlier times, there were disconnected from the Ganges. This natural process involving the decay of distributaries has taken place as the Ganges itself had moved its route. The dry season flow in the Gorai is also strongly influenced by the dry season hydrology and platform evolution of the Ganges river. The dry season flow of the Ganges has decreased since the commissioning of the Farakka Barrage. The slow natural decline of the Gorai has

however been hastened by the diversion of water by the Farakka Barrage since 1975. There has been no natural dry season flow in the Gorai since 1988 (Islam, 2008 & 2009; EGIS, 2000).

2.9 PROBLEM OF GORAI RIVER

The Ganges upstream freshwater is carrying to the southwest region and to the Sundarbans, such as the Bhairab and Mathabanga river. The Gorai river is playing a potential role to maintaining, environmental, social and economy of the region. The Gorai river was free from anthropogenic influence and pollution.

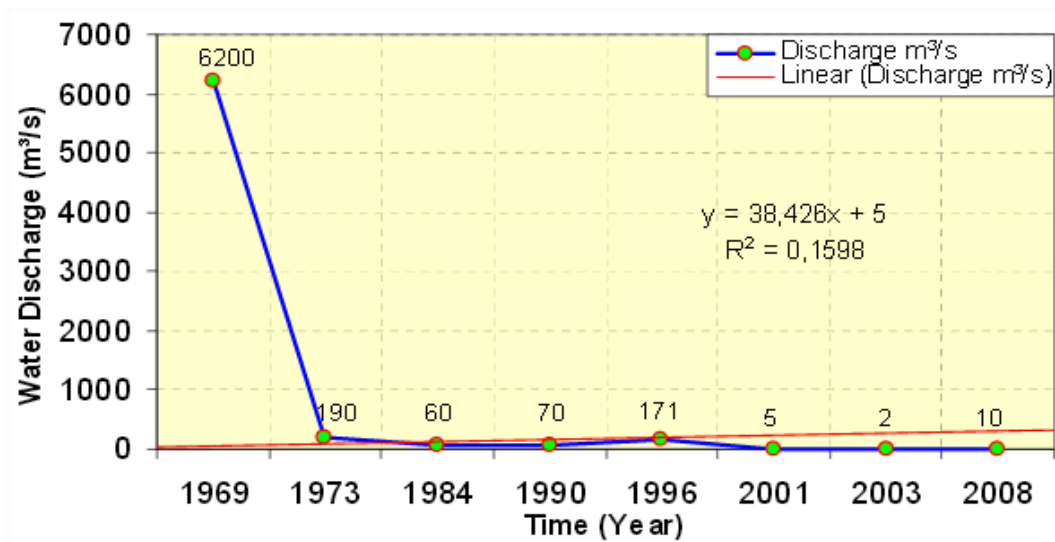


Figure 2.4: Water discharge of Gorai River for 1969-2008 (Samshad et al. 2014)

But after construction of Farakka Barrage and withdrawal of upstream fresh water at the Farakka point, the water discharge has decreased drastically (Figure 2.4). As a result two types of environmental impacts have been created in the Gorai catchment area. (1) The sediment particles are settling down on the Gorai river bed rapidly, which is one of the major problems of Gorai river morphology protection. (2) On the other hand the saline sea water penetrated in the upstream area due to capillary upward movement. The Gorai river is presently called a distributary of the Ganges river. Figure 2.4 shows the Gorai water flow tendency from 1969 to 2008, the polynomial behaviour of Gorai river water flow gradually decreasing trends where the regression value $R^2 = 0.1598$ it is not acceptable value but this value is showing the average grade from 1973 when the water flow already in the lowest discharge passing in the Gorai Railway Bridge.

The Gorai is a meandering river until the upper part (116 km) which is non tidal tendency and the downstream of the river is tidal tendency. At Bardia, the river bifurcates into Nabaganga and

Modhumati. The Nabaganga river carries the major part of the flow of the Gorai River. The upper Nabaganga river is an inland non-tidal river joins with the inland tidal river at downstream of Bardia, such as Chitra and Bhairab and Passur river into the Bay of Bengal . The Passur and Sibsa rivers are connected through lower Salta, Jhapjhapia and Chunkuri rivers upper stream of Mongla port (CEGIS, 2000). The Kabadak is a large river in the south western region it is also declining. The lower part of this river is tidal and joins with tidal river Arpongasia and it is joins with the Malancha river falls into the Bay of Bengal. Kabadak also joins with Sibsa river near Paikgacha. The present water salinity values range are 54025 dS/m to 69152 dS/m and the area has been extended from south to north and east to west direction which is extremely high and it is threats for the mangrove ecosystem services in the Sundarbans region as well as in the whole Gorai catchment area in Bangladesh (Islam, 2006; CEGIS, 2012).

2.10 FLOW DISTRIBUTION AMONG THE GANGES AND THE GORAI RIVERS

The time series ratio of annual flow volume shows that the sharing of the Ganges flow by the Gorai has been decreasing over time and has especially started to fall since the 1980s (Figure 2.5). The ratio of the peak discharges of the Gorai and the Ganges also shows a decreasing trend (Figure 2.6). The rate of decrease was very high in the 1980s and the 1990s. In early 1980 the sharing of the Gorai river was 13%, which reduced to 9% in the late1990s. In the preceding decade it increased to 10%. The ratio of peak flow between the Ganges and the Gorai also showed a similar trend (Figure 2.6). The peak discharge in the Gorai river was about 14% in the early 1970s, which dropped to 9% in the late 1990s. This indicates a significant reduction of flooding in the Gorai river floodplain.

Daily flow distribution between the Ganges and the Gorai during 1988-1999 and 2000-2010 are shown in (Figures 2.7, 2.8). The Ganges flow distribution in the Gorai river varied from 0% during low flow to a maximum of 16% during the Ganges flow around 12,000 m³/s (Figure 2.7). The average flow sharing was 10% during the high flow in 1988-97. In the following decade (2000-2010) the pattern of flow sharing changed, especially during low flow of the Ganges river and sharing of the Gorai river varied widely from 0% to 22% (Figure 2.8). During dredging works under the PPW, flow sharing of the Gorai river increased in the dry season. The dredging had probably made the sharing of very high flow in the dry season possible. It is required to investigate the possibility of diverting about 15% to 16% of the Ganges river dry season flow through the Gorai river without capital or maintenance dredging.

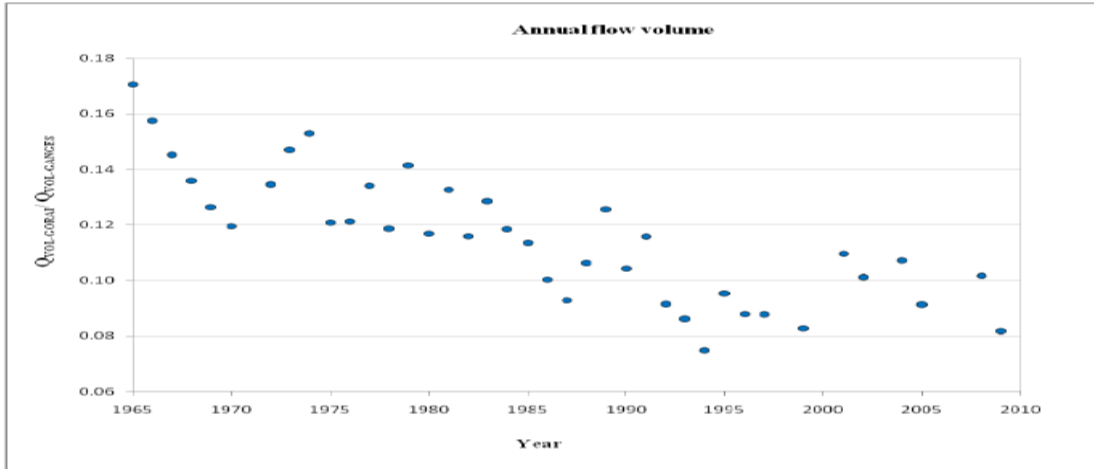


Figure 2.5: Ratio of annual flow volume between Gorai and the Ganges rivers (Hore, et al. 2013)

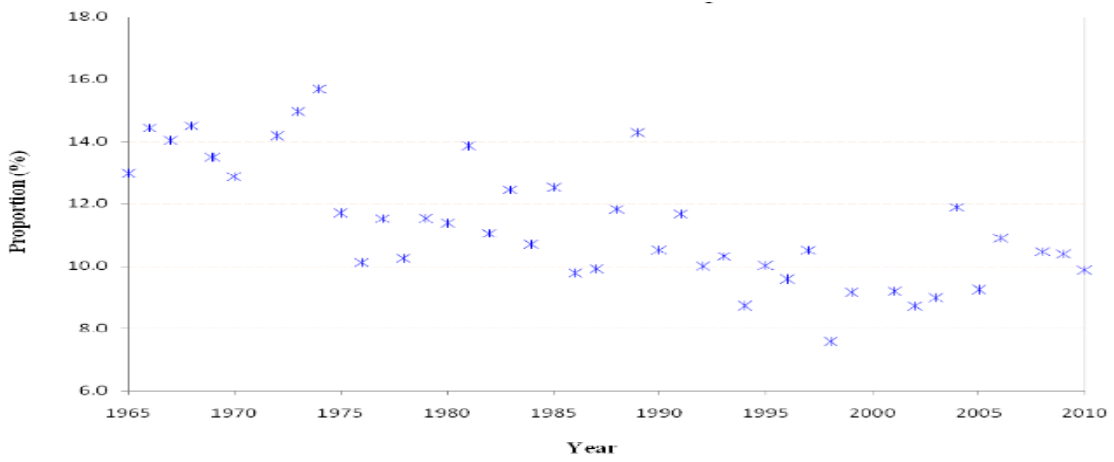


Figure 2.6: Proportion of peak discharge of Gorai river compared to the Ganges river (Hore et al. 2013)

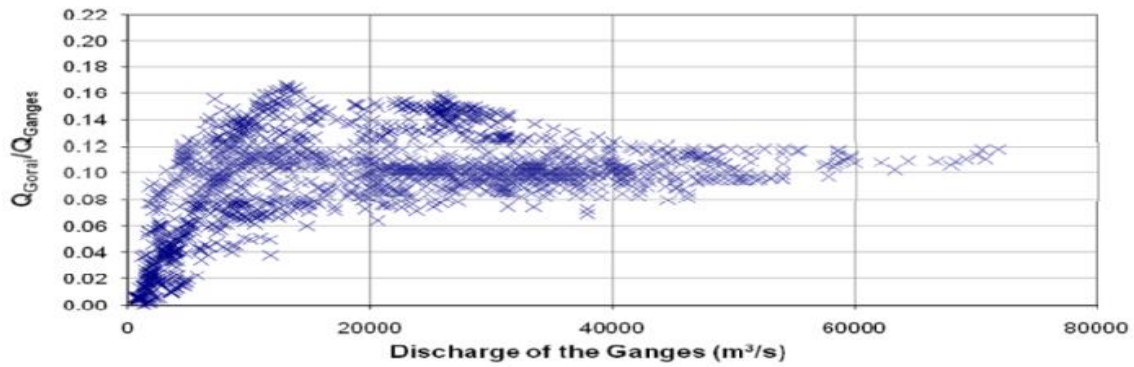


Figure 2.7: Changes in the ratio between the Ganges and Gorai flow during 1988-99 (CEGIS, 2012)

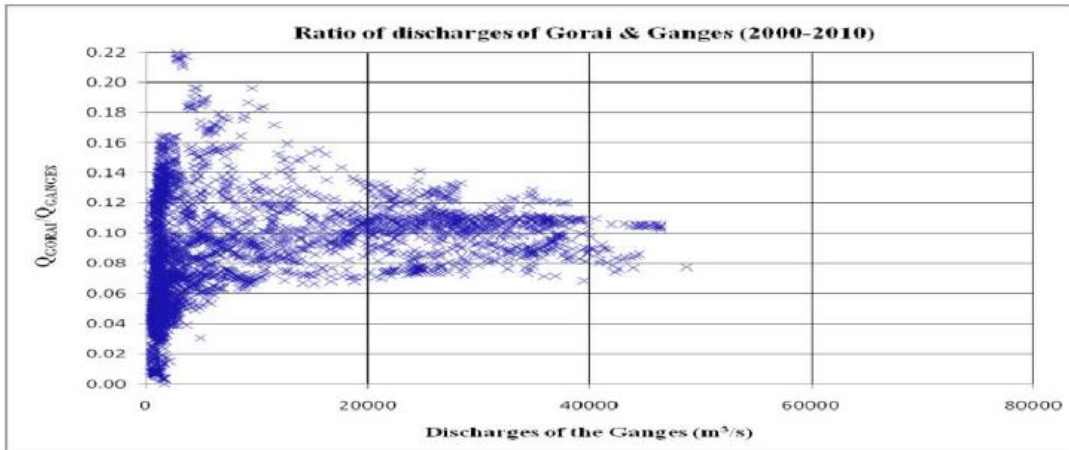


Figure 2.8: Changes in the ratio between the Ganges and the Gorai during 2000-2010 (CEGIS, 2012)

CEGIS has carried out three float tracking campaigns since October 2011 in the Ganges river from the upstream of Talbaria to the G-K ghat in the Gorai river to monitor surface flow velocity and directions in the channels. The maximum flow velocity was 1.35 m/s along the right bank of the Ganges river during 26-27 October 2011 (Figure 2.9) while the flow velocity varied from 0.9 to 1.15 m/s along the Gorai river (Figure 2.10). However, the flow velocity reduced to below 1.0 m/s during the month of January in 2012 and the Gorai velocity was also reduced. The surface velocity was found to be more than 1 m/s in the channel at the end of January 2012.

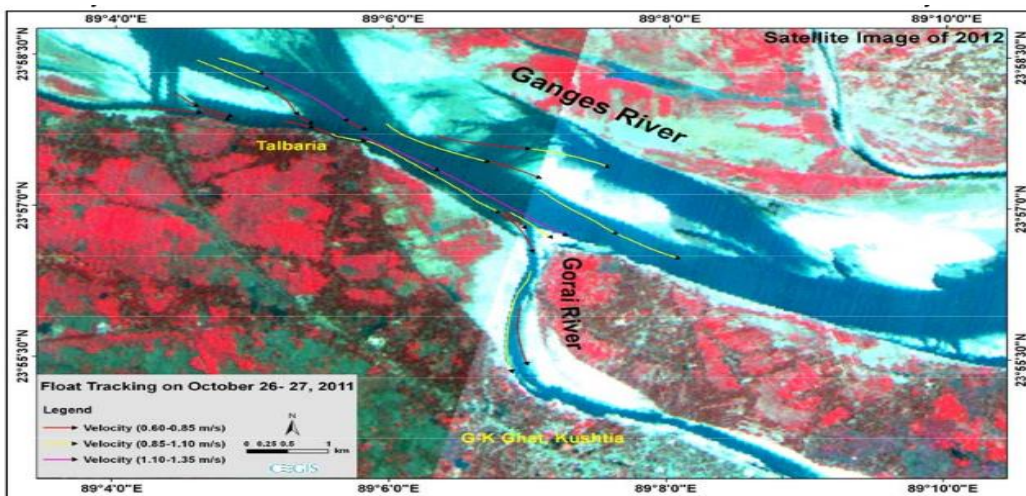


Figure 2.9: Velocity measurement of Ganges and Gorai river (CEGIS, 2012)

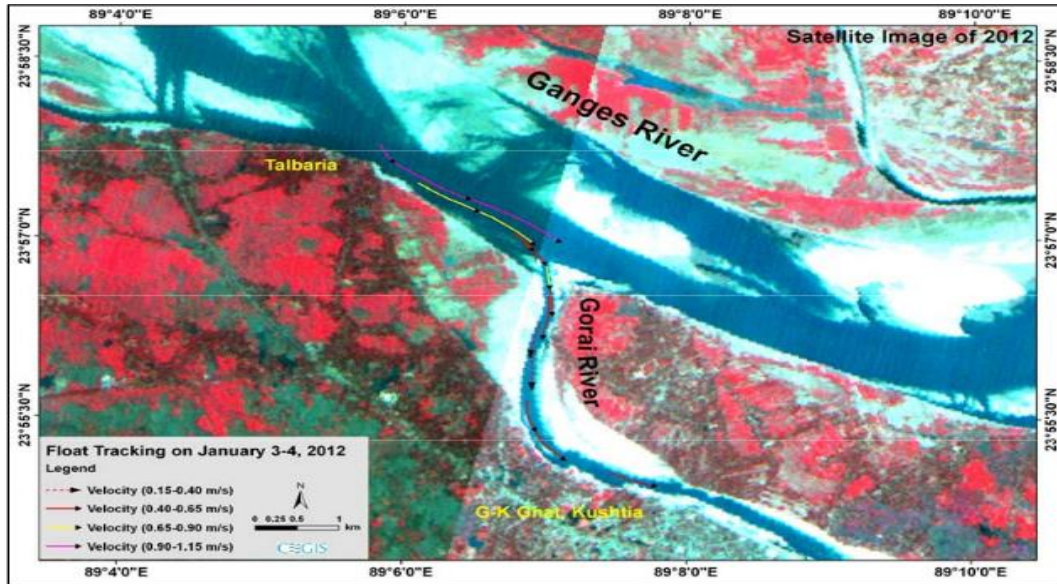


Figure 2.10: Float tracking along the Ganges and the Gorai (CEGIS, 2012)

2.11 SEDIMENT TRANSPORT IN THE GANGES AND GORAI RIVERS

The bed materials of the Ganges and Gorai rivers are fine sand, median diameter (D_{50}) of the bed materials are 0.17 mm and 0.16 mm at Hardinge Bridge in the Ganges and at Gorai Off-take in the Gorai respectively. Delft Hydraulics (DHI, 1996) found the fining trend of bed materials size in the Ganges, which is about 0.04 mm per 100 km. Reduction of the size of the bed materials from the Hardinge Bridge to the Gorai Off-Take might be due to the sediment fining process in the Ganges river.

Sediment transport in an alluvial channel takes place in two modes: bed load transport and suspended load transport. Suspended load transport can be divided into two types: suspended bed material transport and wash load transport. Suspended bed material is defined in terms of grain size and comprises particles exceeding 60 μm . To transport the bed material fraction of sediment a river has to spend energy and thus it has pronounced influence on the river morphology fluvial reaches. Wash load is the material that is so fine that it remains continuously in suspension with insignificant effect on flow velocity. The river does not need to spend substantial energy to transport this type sediment.

In the fluvial reach of the river, this sediment has less influence on the morphological process. Sediment concentrations measured by FAP 24 (DHI, 1996) in 1994-96 are presented in Figure 2.13. The total suspended sediment concentration was separated into bed material and wash load concentrations. In the Ganges and the Gorai system the concentration of wash load may reach several thousand mg/l during the monsoon, whereas, it may only be a few tens of mg/l in the case

of bed material concentration (Figure 2.12). Concentrations of suspended sediments both in the Ganges and Gorai rivers are very close if the measurements are done in closer intervals. Recent measurements of suspended sediment concentration by the IWM (2010) are presented in Figure 2.15. The IWM measured the sediment concentration in the Ganges at the Hardinge Bridge and in the Gorai river at the GK Ghat and Gorai Railway Bridge. The sediment concentrations are very close to those measured by FAP 24 (DHI, 1996) in the mid-1990s. The number of measurements carried out by the IWM is too few to reach a conclusion but it appears that during the flood recession of 2011, sediment concentration at the Gorai Railway Bridge was higher than at GK Ghat in the Gorai and also from the Ganges river. The dredge spoil dumped along both banks might have caused the downstream sediment to increase at the Gorai Railway Bridge.

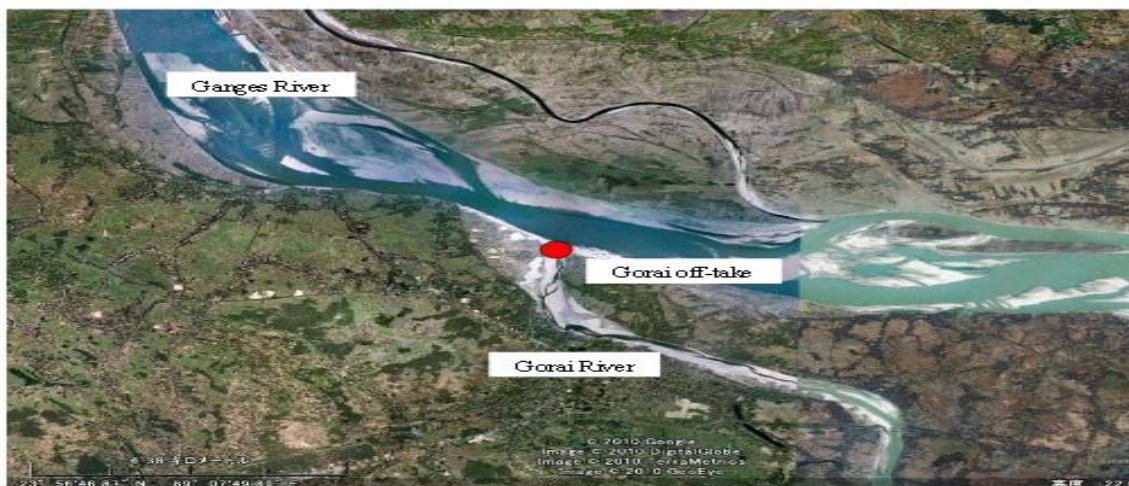


Figure 2.11: Image of Gorai off-take (DHI, 1996)

The sediments carried by the tides performed two functions. One was re-fertilizing the land with the organic matter contained in it. The other was land development (compensating for the subsidence of the loose delta soil), which is natural for all delta regions in the world. Tidal suspended and sludge-silt now depositing inside rivers, as a result, the riverbeds gradually rose to levels higher than the level of the land within the polders, and also blocked the exits of the sluice gates on the embankments.

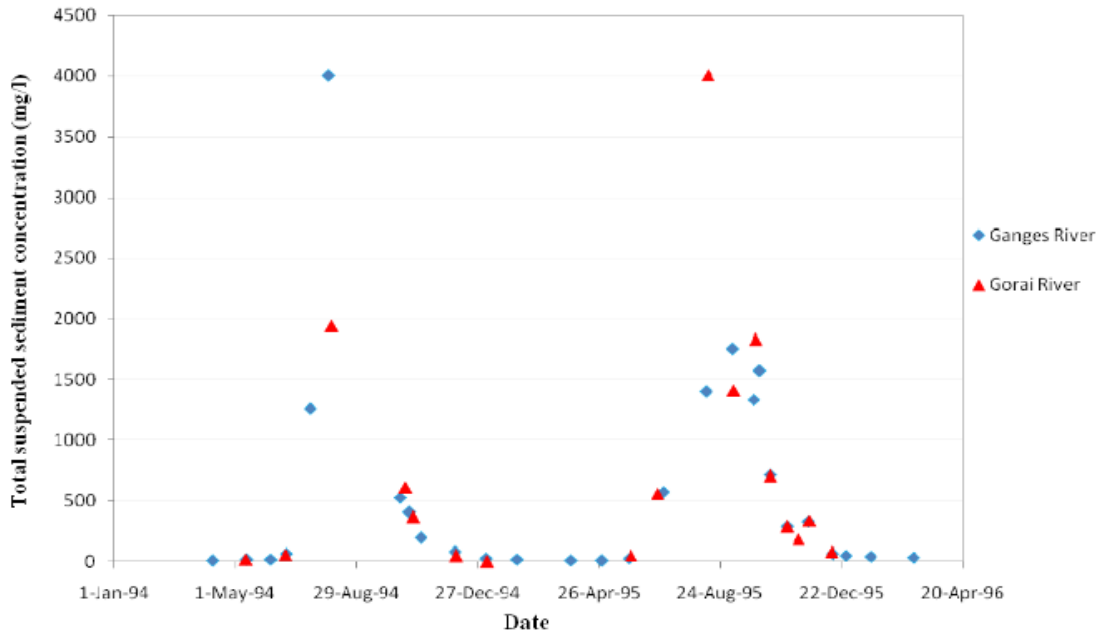


Figure 2.12: Total suspended sediment concentration of Ganges and Gorai River (DHI, 1996)

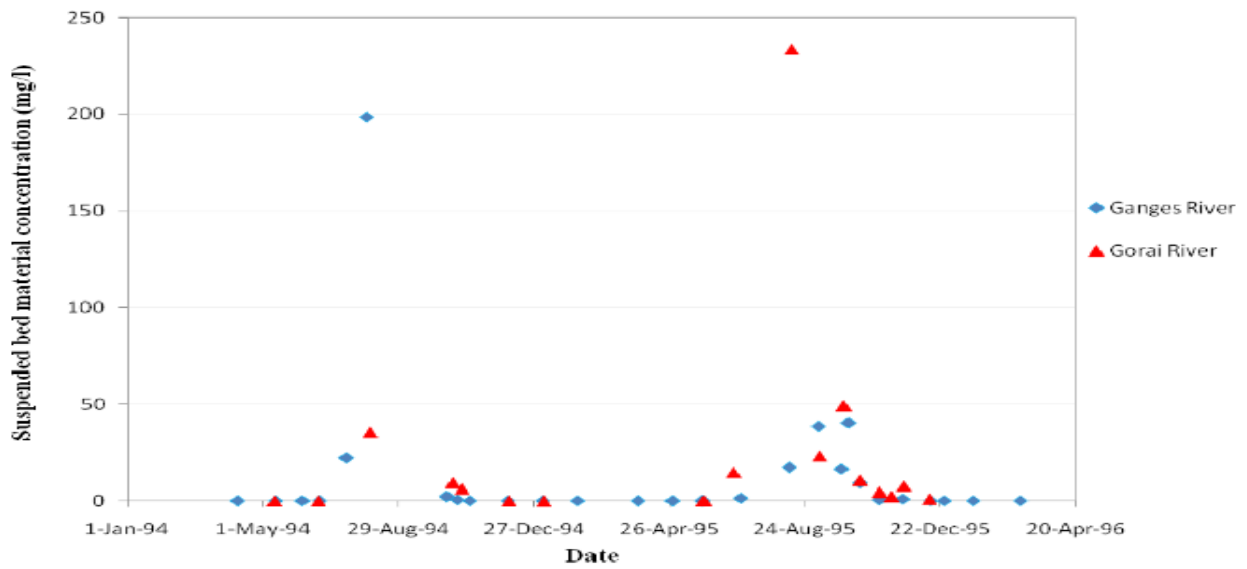


Figure 2.13: Sediment concentration measurement by FAP 24 (DHI, 1996)

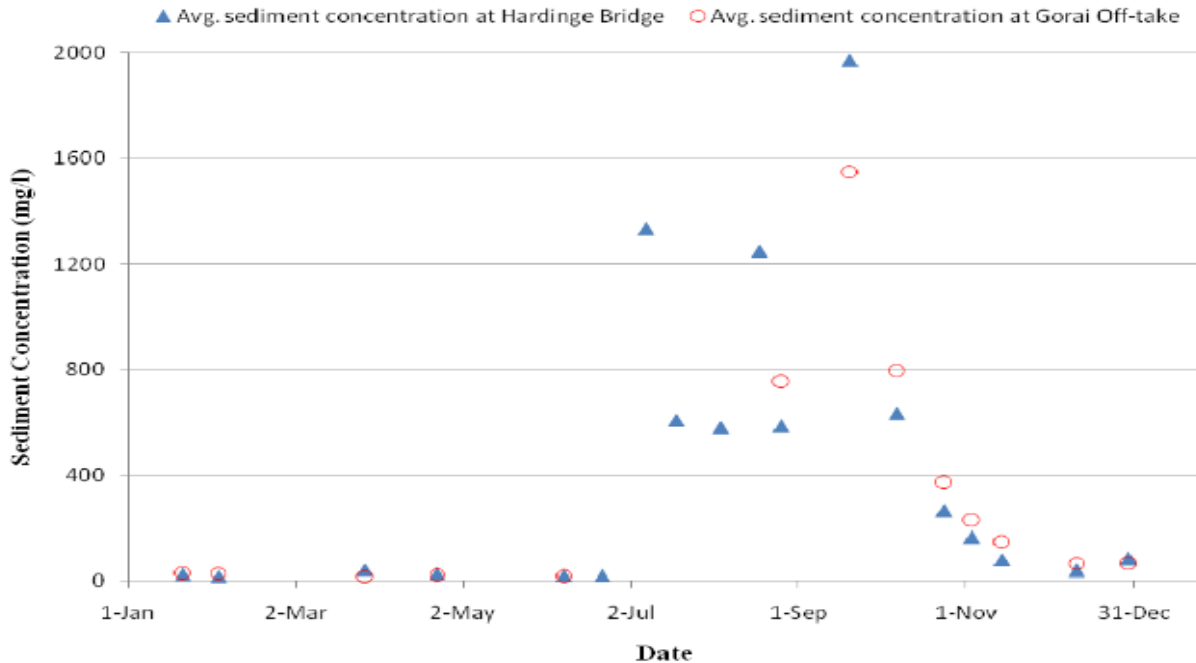


Figure 2.14: Sediment concentration at Hardinge Bridge and Gorai Off-Take (DHI, 1996)

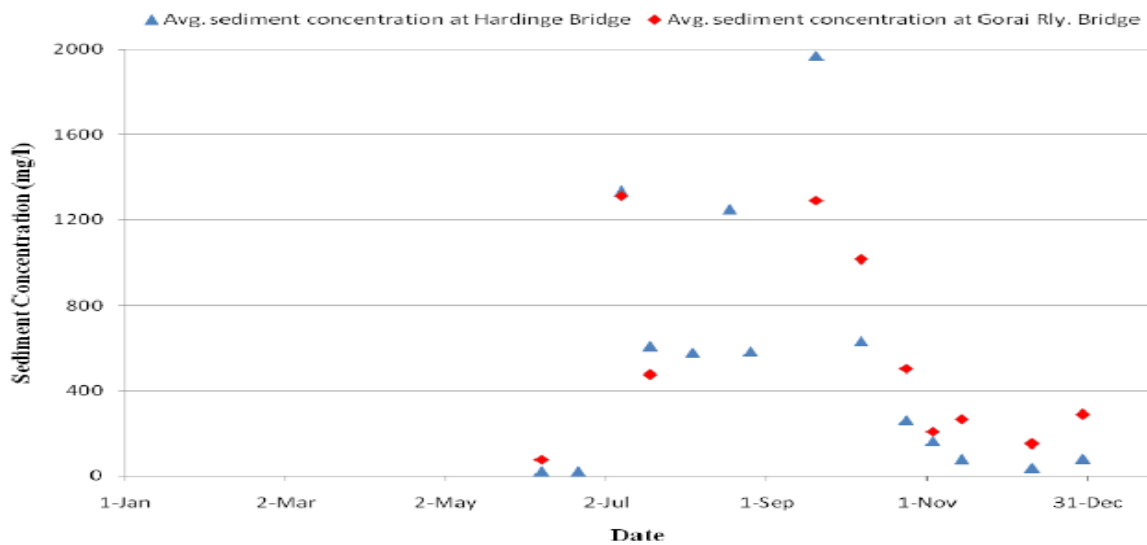


Figure 2.15: Sediment concentration at Hardinge Bridge and Gorai Railway Bridge (IWM, 2010)

2.12 CAUSES OF DETERIORATION OF THE GORAI RIVER FLOW

The Gorai river was the perennial distributary of the Ganges river for several decades. Past records indicate that perennial flow was impeded in the early 1950s for a few years and from the late 1980s, and continued till PPW in the late 1990s. The PPW included mass-scale dredging in

the Gorai Off-take and it continued for successive three years. As a result, dry season flow was restored till 2005. Analysis of the flow regime of the Gorai river during the GRRP study carried out by CEGIS (2000) showed that the monsoon flow regime of the Gorai river had also been deteriorating since the 1980s. Sarker (2004) indicated that continuation of a similar situation in the Gorai Off-take in the 1980s and 1990s may be responsible for the Gorai river becoming merely a flood spill channel of the Ganges in the coming decades.

Several studies such as Delft Hydraulics and DHI (1996), Sarker et al.(1999) as well as Sarker (2004) attempted to identify the causes of deterioration of the Gorai river. They have analyzed the hydro-morphological processes and marked a number of causes that were liable for such deterioration. Two main reasons for the observed declining trend of the flow through the Gorai river identified by these studies are: (a) morphological change in the Ganges river at the Gorai Off-take, which can be considered to be a part of the natural process rather than a consequence of human interventions, and (b) the change in the hydraulic regime of the Ganges, which is related to the dry season diversion of water through the Hooghly river by the Farakka Barrage and withdrawal of water upstream. The different morphological aspects that contributed in deteriorating the Gorai river are: (i) angle of the Ganges approach channel at the Gorai Off-take, (ii) protrusion scour due to Talbaria clay outcrops and (iii) riverbank erosion at the upstream of Talbaria. The Farakka Barrage has contributed through shortening the flood recession period due to the operation of the Farakka Barrage and lowering of dry season discharge. The changes in hydrograph limit the retarded scour at the Gorai Off-take and cause the piling up of sediment over time. Moreover, decrease in dry season flow causes to decrease the flow, or even fully interrupt the flow during the dry season in the Gorai river.

2.13 EFFECTS OF FARAKKA BARRAGE

The effect of the Farakka Barrage on the Gorai river has been studied by different agencies such as (DHI, 1996; DHV-WARPO, 2001). Their findings are limited to two aspects: (i) the Farakka Barrage contributed to shorten the recession period of flood at the Hardinge Bridge and thus the flow had less time for removing the sediment from the Gorai Off-take through retarded scour and caused the gradual piling up of sediment in the Gorai, and (ii) the Farakka Barrage reduces dry season flow and lowers the water level significantly in the Ganges at the Hardinge Bridge and thus causes the dry season flow in the Gorai river to cease. These aspects however, explain the reduction in both monsoon and dry season flow in the Gorai river. Analysis of discharge of the Ganges river in the recent past showed that the discharge hydrograph has been broadened and the recession period was much longer than in the past (than even the pre-Farakka period) . The water level hydrograph at the Hardinge Bridge also showed that during the last decade water level

during the flood recession also increased. However, due to changes in local morphology of the Ganges at the Hardinge Bridge the water level hydrograph does not fully reflect the changes in discharge. This would have positive impact on the Gorai river. The specific gauge analysis at the Hardinge Bridge regarding the broadening of hydrograph showed that in the last decades, the stages during the flows below 10,000 m³/s had been lowered by one meter . The stage for 20,000 m³/s was lowered about 0.5 m. A comparison of the water level and discharge hydrographs of the Ganges at the Hardinge Bridge also supports the result of specific gauge analysis. The specific gauge analysis, however, suggests the lowering of the effective low flow riverbed of the Ganges, which results in the reduction of the low flow slope at the downstream. The reason for this change is, however not clear; and therefore further investigation is required.

2.14 CLAY AT GORAI OFF-TAKE

During the PPW, the then dredging contractor had encountered a clay layer at the Gorai Off-take for about 700m length in the dredging alignment. They dredged the clay layer to form the dry season channel. Later, the BWDB dredging carried out in 2009-10 and 2011-12 maintained the same channel. To increase the freedom of the channel development processes at the Gorai-Off-take, the clay layer at the Off-take has to be dredged at a reasonable depth or alignment. To know the present condition of the lateral and vertical extents of the clay layer a subsurface soil investigation has been done by CEGIS at the Gorai Off-take in 2012. For this purpose the geotechnical boreholes were constructed using the wash boring method. In this investigation, 16 (sixteen) boreholes were prepared . The bore logs of the 16 (sixteen) boreholes and a detailed description of the bore logs are presented in Annexure-A of this report. The material of the subsurface reveals that the eastern bank of the Gorai river is mostly made of clay layers and the western bank of the Gorai river is mostly made of sand layers. The clay layers were found at shallow depth in the channel area and at surface in the floodplain of the east bank, whereas the sand layers were found in the west bank from the surface to a depth of 20 m or more. So, it is concluded from the borehole analysis that the subsurface of the eastern margin of the Gorai Off-Take is comprised of clay.

2.15 GORAI RIVER'S SALINITY CONDITION

The salinity level in the western part of the South West region remains higher than the eastern part. This is because the Gorai river, tributary from the Ganges, is the only significant upstream fresh water source in the western part of the region, suffers a serious decline in dry season freshwater inflows under post Farakkha condition. The eastern part of South West region remains less saline as it receives freshwater flow from the Padma and lower Meghna river

through Arial Khan, Bishkhali and Buriswar river (IWM, 2014). As a result, salinity levels in the region decrease from west to east as well as from south (the Bay of Bengal) to north.

Seasonal distribution of salinity concentration in the region completely follows the seasonality of the region's hydrology. Average salinity concentrations at the coast are higher in the dry season than in the monsoon, due to lack of freshwater flows from upstream. The salinity normally builds up from October to the late May, and it remains higher during the dry season, usually from February to May. At the end of May, salinity level drops sharply due to upstream flows and rainfall (IWM, 2014).

The salinity conditions have been deteriorated in the last few decades because of the decrease in flow of the Ganges and empoldering effect. The role of freshwater inflows through the Gorai river to push back the salinity intrusion from the Bay has been reported in many journal papers and project reports. One of such study, carried out by IWM and CGIAR (IWM, 2014), reported that in 1975, India commissioned Farakka Barrage on the Ganges at about 17 km upstream of the Indo-Bangladesh border to divert about 40,000 m³/s of flow into Bhagirathi-Hoogly river system. As a consequence of such a large-reduction of the available flow, the Ganges dependent area in Bangladesh was exposed to serious fresh water shortage. The withdrawal of freshwater flow has resulted in landward movement of salinity front in the Ganges dependent coastal area of Bangladesh. In 1996, Bangladesh and India signed Ganges Water Treaty (GWT) for Ganges water sharing between the two countries. The treaty ensured minimum flow in the Ganges River in Bangladesh during dry season, which improved the salinity condition in the South West of Bangladesh. However, during dry season the Gorai intake is almost cut off from the Ganges and there is no freshwater flow through this river. As result salinity water comes through the major rivers namely Pussur, Jamuna, Malancha and Sibsa in the western part of southwest region and increases the salinity level in the dry period. In 2012, Gorai dredging restored the dry season flow temporarily into the area decreasing the salinity level slightly.

Hence, the mitigating role of Gorai inflows to control the salinity intrusion in the western part of South West region is very much understandable. Figure 2.16 shows this perfectly by plotting salinity concentration at Khulna on the Rupsha river against the upstream inflows through the Gorai river.

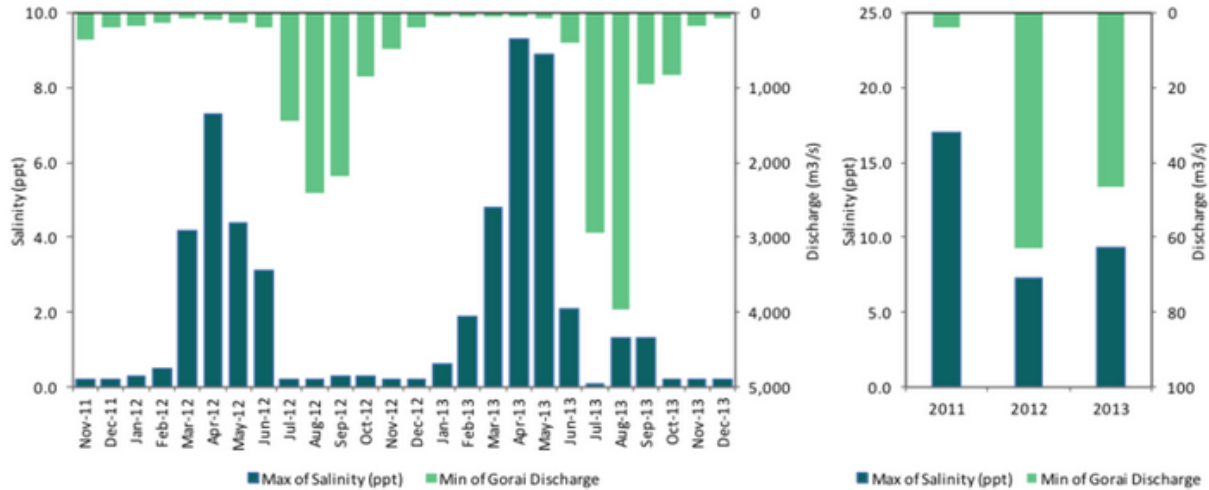


Figure 2.16: Monthly salinity variation at Khulna on the Rupsha river with upstream fresh water flow (IWM, 2014)

2.16 GEO-MORPHOLOGICAL AND PHYSIOGRAPHIC SETTINGS OF THE MODHUMOTI RIVER

The Modhumati river is a distributary of the upper Ganges (Padma) flowing through southwestern Bangladesh. It leaves the Padma just north of Kushtia and flows 306 km before turning south across the Sundarbans and into the Bay of Bengal. In its upper course it is called the Gorai river, in its lower course it is known the Baleswar river and its estuary mouth which is 14 km wide is called the Haringhata river. The Baleswar river length is 57 km, and the Nabganga River from Bardia point to Gazirhat is 29 km. The length of Gorai-Modhumati-Baleswar rivers is 371 km (37 km in Kushtia, 71 km in Faridpur, 92 km in Jessore and 104 km in Khulna and 67 km in Barisal in the Eastern border of Sundarbans). The Gorai river reach from Gorai 1 to Gorai 4 is the non tidal condition and the tidal nature of Gorai river is the 5th reach which is called tidal lower course is extremely active and flowing . At Bardia, the river bifurcates into Nabaganga and Modhumati.

2.17 ARIAL KHAN RIVER

In the 1970s, there were more than one off-take of the Arial Khan and they were about 300 m wide. With the abandonment of the other off-takes, the width of the existing channel was increased. The 1943 Topo-maps show that the Arial Khan river had four off-takes from the Padma river. The width has started to increase since the early 2000s, whereas the average width of the Upper Kumar river is 135 m which shows it to be very steady in nature.

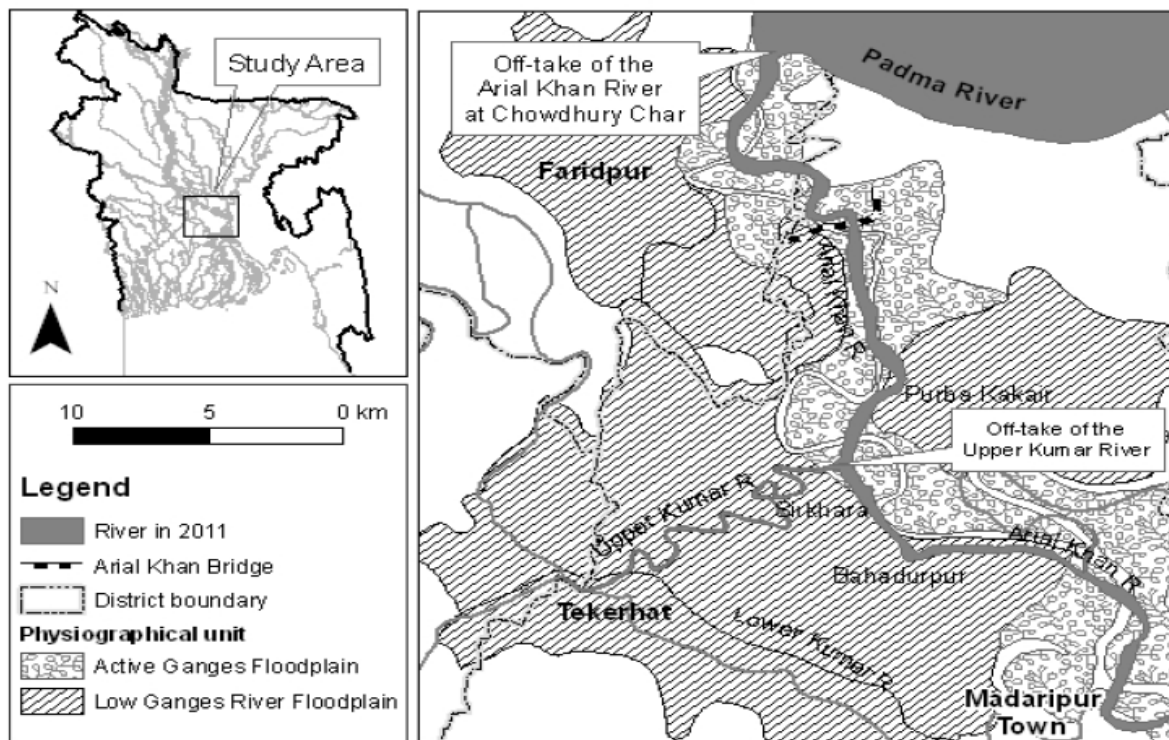


Figure 2.17: Arial Khan River Off Take (Akter *et al.* 2013)

A number of cut-offs have occurred in the Arial Khan river during the last three decades, but the Upper Kumar river did not have a similar experience in that period. In fact, the underlying soil of the Upper Kumar river is of the low Ganges Floodplain, which is relatively less susceptible to erosion and has less stream power. The erodible material of the active Ganges Floodplain makes the Arial Khan river very vulnerable to erosion and cut-off. A cut-off occurred between 1973 and 1984 as shown in Figure 2.17. Another cut-off occurred at the same place after the construction of the Arial Khan Bridge between 1999 and 2003. The cut-off ratio of this location was about 3. Another great cut-off occurred close to the off-take of the Upper Kumar river and hence the Off Take of the Upper Kumar river shifted by several kilometers.

The sinuosity of a river reach is the ratio of meandering length and the straight chord length. The Arial Khan river has a tendency to be straightened at a high rate. The Upper Kumar river is sinuous and during the last four decades its sinuosity was highest in the early 2000s. Reach A as shown in Figure 9, has a decreasing trend and presently the sinuosity has dropped below 1.5. The lower part of Reach A is bounded by the bridge and guide bunds of the bridge and hence this part has become more or less controlled. On the other hand, the upstream part of Reach B is also

confined by the bridge and guide bunds. Before the construction of the bridge, the sinuosity of Reach B was increasing. However, there was a sudden drop after the constructing of the bridge. The guide bunds and associated structures are determining the river direction and so Reach B is about to become straight and then the sinuosity will become close to one. Probably the river response to the guide bunds is still continuing and spatial coverage may be up to the end of this reach. Reach C has a decreasing sinuosity trend. The figure for this reach is not representative as a huge loop cut occurred within this reach. In addition, the very dynamic off-take of the Upper Kumar river is placed within this reach. The straightening behaviours formed in the upstream reaches are propagating downward and causing Reach C to become less sinuous.

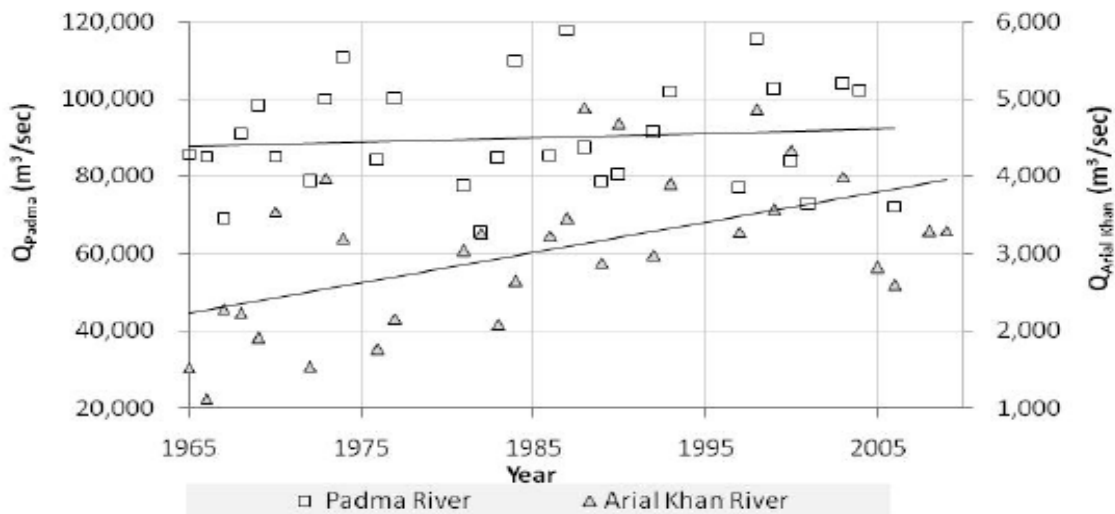


Figure 2.18: Annual maximum flow of the Arial Khan and Upper Kumar rivers (Shammi, et al 2012)

Presently, Chowdhury Char is the perennial off-take of the Arial Khan river. The seasonal and annual variability of discharge in this river is very high. The hydro-morphological condition of the river depends on the position of the off-take and the deviation of flow direction to the off-take from the parent river, the Padma. During the last few decades, the location and geometry of the off-take have been changed several times (PUB, 2010). Figure 2.18 shows the annual maximum flow of Chowdhury Char and the present off-take of the Arial Khan river with respect to the annual maximum flow of the Padma river at Mawa. Maximum discharge data from 1965 to 2005 show that the trend is increasing in the Arial Khan river. However, data indicate that the flow volume of the Arial Khan was reducing rapidly during the first decade of the current century. The flow in the Arial Khan river is highly characterized by seasonal variation, as shown

in Figure 2.18. The average flow during February and March is less than 50 m³/s, whereas the average flow of August and September is more than 2000 m³/s, indicating a very high variability of mean monthly flow.

2.18 STANDARDS FOR WATER

The standards for water quality in Bangladesh are based on the Environment Conservation Rules (ECR, 1997). Table 2.1 shows the Standard for drinking water and Table 2.2 shows that for inland surface water.

Table 2.1 : Standard for Drinking Water for Bangladesh (DoE, 1997)

Parameter	Unit	Standards	Parameter	Unit	Standards
1. Aluminum	mg/L	0.2	26. Hardness (as CaCO ₃)	mg/L	200-500
2. Ammonia	mg/L	0.5	27. Iron	mg/L	0.3-1.0
3. Arsenic	mg/L	0.05	28. Kjeldahl Nitrogen (total)	mg/L	1
4. Barium	mg/L	0.01	29. Lead	mg/L	0.05
5. Benzene	mg/L	0.01	30. Magnesium	mg/L	30-35
6. BOD ₅ 20°C	mg/L	0.2	31. Manganese	mg/L	0.1
7. Boron	mg/L	1.0	32. Mercury	mg/L	0.001
8. Cadmium	mg/L	0.005	31. Manganese	mg/L	0.1
9. Calcium	mg/L	75	32. Mercury	mg/L	0.001
10. Chloride	mg/L	150-600	33. Nickel	mg/L	0.1
11. Chlorinated alkanes	mg/L		34. Nitrate	mg/L	10
Carbontetrachloride		0.01	35. Nitrite	mg/L	<1
Dichloroethylene	mg/L	0.001	36. Odor	mg/L	od or less
dichloroethylene	mg/L	0.03	37. oil and grease	mg/L	0.01
tetrachloroethylene	mg/L	0.03	38. p ^H	--	6.5-8.5
trichloroethylene	mg/L	0.09	39. Phenolic compounds	mg/L	0.002
12. Chlorinated phenols			40. Phosphate		6
pentachlorophenol	mg/L	0.03	41. Phosphorus	mg/L	0
trichlorophenol	mg/L	0.03	42. Potassium	mg/L	12
13. Chlorine (residual)	mg/L	0.2	43. Radioactive materials (gross alpha activity)	Bq/L	0.01
14. Chloroform	mg/L	0.09	44. Radioactive materials (gross beta activity)	Bq/L	0.1
15. Chromium (hexavalent)	mg/L	0.05	45. Selenium	mg/L	0.01
16. Chromium (total)	mg/L	0.05	46. Silver	mg/L	0.02

Parameter	Unit	Standards	Parameter	Unit	Standards
17. COD	mg/L	4	47. Sodium	mg/L	200
18. Coliform (fecal)	n/100mL	0	48. Suspended particulate matters	mg/L	10
19. Coliform (total)	n/100mL	0	49. Sulfide	mg/L	0
20. Color	Hazen unit	15	50. Sulfate	mg/L	400
21. Copper	mg/L	1	51. Total dissolved solids	mg/L	1000
22. Cyanide	mg/L	0.1	52. Temperature	°C	20-30
23. Detergents	mg/L	0.2	53. Tin	mg/L	2
24. DO	mg/L	6	54. Turbidity	JTU	10
25. Fluoride	mg/L	1	55. Zinc	mg/L	5

Table 2.2: Standard for Inland Surface Water for Bangladesh (DoE, 1997)

Best Practice based classification	pH	BOD mg/L	DO mg/L	Total Coliform number/100
a. Source of drinking water for supply only after disinfecting	6.5-8.5	2 or less	6 or above	50 or less
b. Water usable for recreational activity	6.5-8.5	3 or less	5 or above	200 or less
c. Source of drinking water for supply after conventional treatment	6.5-8.5	6 or less	6 or above	5000 or less
d. Water usable by fisheries	6.5-8.5	6 or less	5 or above	---
e. Water usable by various process and cooling industries	6.5-8.5	10 or less	5 or above	500 or less
f. Water usable for irrigation	6.5-8.5	10 or less	5 or above	1000 or less
Notes : 1. In water used for pisciculture, maximum limit of presence of ammonia as Nitrogen is 1.2 mg/L 2. Electrical conductivity for irrigation water -- 2250 μ mhos/cm (at a temperature of 25°C); Sodium less than 26%; boron less than 0.2%				

CHAPTER-3

Approach and Methodology

3.1 INTRODUCTION

The specific objectives of this study can be outlined in three subtopics that includes (i) to investigate the existing water supply condition and its Future Scenario to meet the water demand of Khulna City Dwellers; (ii) to investigate the surface water quality of different rivers nearby and vicinity to Khulna City, and analyze their usability in mitigating the water supply demand of Khulna WASA and (iii) to study the suitability of raw water intake sites selection and their sustainability based on temporal change of river discharge/depth, water quality and tidal effect. In this chapter the methodologies are explained through which the answers of the above mentioned research questions are searched.

3.2 EXISTING WATER SUPPLY CONDITION AND FUTURE SCENARIO OF KWASA

The objective of ground water level and surface water availability survey is to provide a baseline assessment to develop a better understanding of the ground water abstraction and surface water availability and its future scenario in Khulna city. The scope of the study includes collecting the information on ground water abstraction from deep aquifer by production tubewell and the quality of water from different sources based on secondary source. The existing situation of water supply scenario, future demand of KCC/KWASA as well as their future plan to mitigate the demand is also studied. For this study, secondary data are collected from KWASA and KCC office and related published research reports.

3.3 BEHAVIOUR OF GORAI-MODHUMOTI RIVER SYSTEM

This study mainly concentrates on Gorai-Modhumoti river system. The Modhumoti river is mainly fed by the upstream discharge from Gorai and a small portion from the Kumar river (which is a branch of Arial khan river). Time series data/information on water level and discharge on different selected points are collected from local offices of Bangladesh Inland Water Transport Authority (BIWTA) and Bangladesh Water Development Board (BWDB). Rainfall data is collected from Bangladesh Metrological Department (BMD). Other required data are collect from the published relevant sources. Secondary data is collected for discharge and water level for Ganges (at Gorai Railway Bridge station), Gorai river (Kamarkhali Bridge station), Kumar river (at Arial khan Off take point) and Modhumati river (at Mollarhat Bridge Point).

3.4 SURFACE WATER SAMPLING AND LABORATORY ANALYSIS

Primary and Secondary data on water quality parameters were collected for both the branches of Gorai river: Gorai- Bhairab— Rupsha and Gorai—Modhumati river system. Special emphasis is given for the Gorai—Modhumati river system and primary water quality for the selected sites of that river is measured at a certain time series pattern by collecting the water sample from rivers and testing in the laboratory instantly. The water samples are collected adopting the air tight bottles. Soon after collecting the samples, it is taken to Environmental laboratory of KUET for testing different water parameters, such as chloride (Cl^-), salinity, electrical conductivity (EC), etc.

3.4.1 WATER SAMPLES COLLECTION

The water quality parameters of Modhumoti river at four stations are measured and compared with other rivers vicinity to Khulna region such as Bhairab, Rupsha and Mayur river. The water sample collection stations in Gorai-Modhumoti river system is shown in Figure 3.1

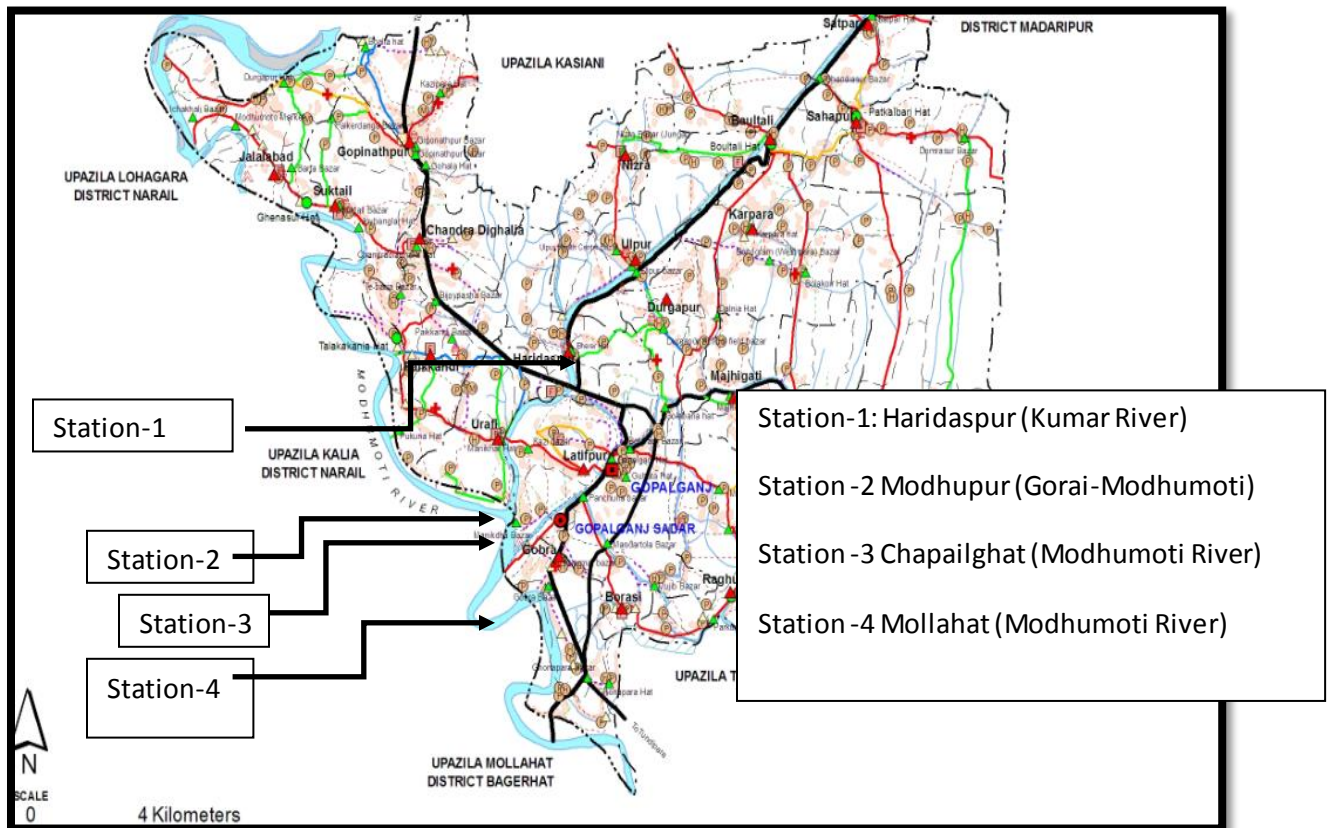
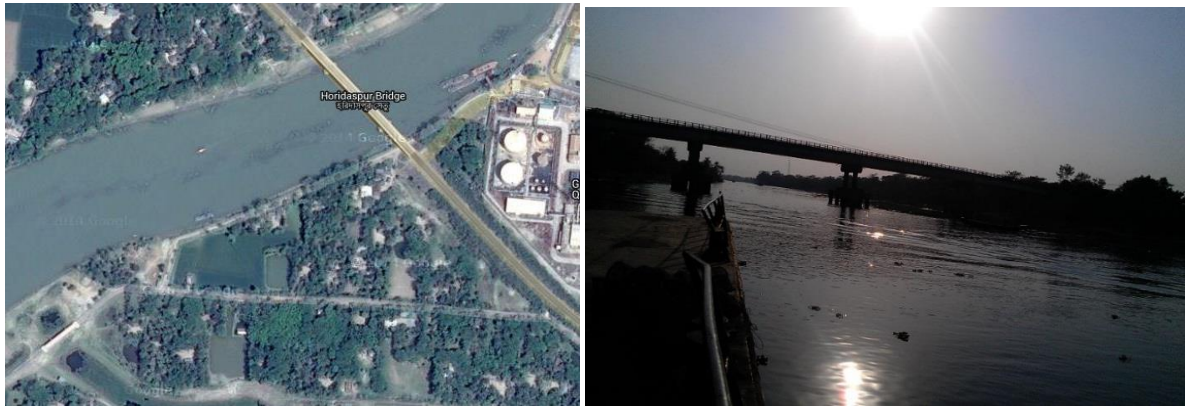


Figure 3.1: Water sample collection stations in Gorai-Modhumoti river system

The samples were collected from four stations: two stations are upstream (Haridaspur, Modhupur) and others two are downstream (Chapailghat, Mollahat) of Modhumoti River. It is collected from middle of the river by small boat or launch from surface of the river in sterilized plastic bottle and immediately after collecting samples they were brought in environmental engineering laboratory within 5-6 hours. Figure 3.2 shows the Pictorial view of water sample collection stations in Gorai-Modhumoti river system.



(a) Station 1: Haridaspur in Kumar River



(b) Station 2: Modhupur in Gorai-Modhumoti river.



(c) Station 3: Chapailghat Bridge in Modhumoti River



(d) Station 4: Mollar hat Bridge in Modhumoti River

Figure 3.2: Pictorial view of water sample collection stations in Gorai-Modhumoti river system

For Bhairab-Rupsha branch of Gorai, two sampling stations have been selected. On which one in Rupsha ferry ghat to another in Fultala Bazar ghat. Details of sampling stations are provided in Table 3.1.

Table 3.1: Global Position of Two Sampling Station of Bhairab- Rupsha River, Khulna.

Station ID	Sampling Stations	Latitude	Longitude	Chainage (Km)	Relative Distance (Km)
S ₁	Rupsha Ferry Ghat	22 ⁰ 48'2.22" N	89 ⁰ 34'58.52" E	0.0	0.0
S ₂	Fultala Bazar Ghat	22 ⁰ 58'30.41" N	89 ⁰ 28'42.77" E	25.09	4.41

3.4.2 LABORATORY TESTS

The collected samples were used for some important water quality parameters test namely chloride concentration, salinity, electrical conductivity, total Hardness, SO_4^{2-} , TDS, P^H, BOD, COD Color and Turbidity. All the tests were carried out in KUET environmental engineering laboratory. Chloride concentration, total hardness and COD were determined by titration method, salinity is determined by Digital Conductivity Meter, pH is determined by pH meter, BOD is determined by DO meter, electrical conductivity is measured by Digital Conductivity Meter, turbidity is determined by Hellige turbid meter and TDS are determined by weight measurement. The water quality parameters are assessed by comparing the test results with both Bangladesh Drinking Water Standard (DoE, 1997) and World Health Organization (WHO) guidelines for drinking water quality (WHO, 2006). Analytical equipments reference model used in laboratory tests are described in Table 3.2.

Table 3.2 Measurement of Parameters and Analytical Method:

Parameters	Unit	Analytical Equipments	Lab. Name
pH	-	pH meter	Env. Eng. Lab. KUET
Turbidity	NTU	Turbid meter	Env. Eng. Lab. KUET
Conductivity	μS/cm	Conductivity meter	Env. Eng. Lab. KUET
Alkalinity	mg/l	Titration Method	Env. Eng. Lab. KUET
Hardness	mg/l	Titration Method	Env. Eng. Lab. KUET
Total solids	mg/l	Gravimetric Method	Env. Eng. Lab. KUET

Parameters	Unit	Analytical Equipments	Lab. Name
Total Dissolved Solids	mg/l	Gravimetric Method	Env. Eng. Lab. KUET
Suspended Solids	mg/l	Gravimetric Method	Env. Eng. Lab. KUET
Chloride	mg/l	Titration Method	Env. Eng. Lab. KUET
Dissolved Oxygen	mg/l	DO meter with probe	Env. Eng. Lab. KUET
BOD ₅	mg/l	DO meter, BOD incubator and bottle	Env. Eng. Lab. KUET
COD	mg/l	Titration Method	Env. Eng. Lab. KUET
Salinity	mg/l	Salinity meter	Env. Eng. Lab. KUET
Arsenic	mg/l	Atomic absorption spectrophotometer	DPHE
Iron	mg/l	Atomic absorption spectrophotometer	DPHE

CHAPTER 4

Water supply scenario of KWASA

4.1 INTRODUCTION

Bangladesh is one of the most vulnerable countries in the world due to ground water level depletion, intrusion of saline water, increase of river water salinity, arsenic and iron contaminated water etc. which significantly affect the human life as well as living things and overall economic and social development of the country. To get potable water is an acute problem now a days, which is increasing an alarming in southern region of Bangladesh. Figure 4.1 shows the area map of KCC. The area of Khulna city is 59.57 sq. km and its elevation is 9 m above MSL. Khulna Municipal Council was founded on 12 December 1884, and promoted to a "municipal corporation" in 1984. It has declared a "city corporation" in 1990. There are 31 wards in the City Corporation area. KCC is located in south-western Bangladesh at 22°49'0"N 89°33'0"E, on the banks of the Rupsha and Bhairab river. The literacy rate among the urban people of Khulna is 59.1%, which is higher than the national average of 56.5%. Khulna has an annual average temperature of 26.3 °C (79.3 °F) and monthly means varying between 12.4 °C (54.3 °F) in January and 34.3 °C (93.7 °F) in May. Annual average rainfall of Khulna is 1,809.4 millimeters (71.24 in). Approximately 87% of the annual average rainfall occurs between May and October.

This study includes mainly three parts: (1) To determine the future demand of KCC area (2) Analyze the water quality of surrounding rivers (3) Suitability of selecting the water intake point at Mollarhat point to mitigate the scarcity of Khulna City water supply. In this chapter the existing situation of water supply scenario and future demand of KCC/KWASA is presented. The water quality of ground water in this area is also studied.



Figure 4.1: Map of KCC area

4.2 GROUND WATER QUALITY IN KWASA AREA

Previous study of KWASA (2010) reported that ground water storage and level comprise of three hydro-geological units in and around Khulna City. These three units are called commonly upper aquifer, shallow and deep aquifer. Later two are confined type. Upper shallow aquifer is most of the time confined or semi – confined in Khulna City area, discontinuous and poorly permeable. Its range varies from 0 to about 50m deep. Its average conductivity over the time is 2600 $\mu\text{S}/\text{cm}$. After that, there is a shallow aquifer mostly confined between 80 and 125 m lying over a geological discontinuity which can be identified in almost every litho log. The aquifer is formed of fine sand and seems to have a nation-wide extension. Its average conductivity over the time is 3200 $\mu\text{S}/\text{cm}$.

The deep confined aquifer is variable in thickness, which can be found between 220 and more than 300 m deep. It is a composite aquifer mainly composed of medium sand with local coarse as well as very fine sand and clay. Good hydrodynamic properties characterize this aquifer whose water level (under pressure) rises up to a few meters below the surface. This aquifer is the main aquifer for the water supply of Khulna City and is highly solicited. Its average conductivity over the time is 1200 $\mu\text{S}/\text{cm}$ which shows that this aquifer has the lowest salinity of the whole groundwater system around Khulna. Water quality data are collected from KWASA office and Table 4.1 shows the result of water quality parameters for different types of tubewells located in KCC area.

Table 4.1: The Summary of the Results for Ground water quality of KWASA area for the Year of 2015

Category of Wells	Sample (Nos./ Location)	Level	pH	Temp(°C)	As ($\mu\text{g}/\text{L}$)	Fe (mg/L)	Mn (mg/L)	Cl- (mg/lt)	T-coli (Cfu/100ml)	F-coli (Cfu/100ml)
Production Tube Wells	32	Ave.	8.2	30	1.5	1.2	0	168	0	0
		Min.	7.6	26	0.0	0.2	0	34	0	0
		Max	8.9	33	5.5	3.6	0	475	0	0
Mini Production Tube Wells	10	Ave.	7.8	29	1.3	1.2	0.0	327	0	0
		Min.	6.6	23	0.0	0.3	0.0	34	0	0
		Max.	8.7	33	10.5	3.3	0.6	836	0	0
Hand Pumps	10	Ave.	7.5	28	3.6	1.7	0.2	228	0	0
		Min.	6.5	26	0.0	0.3	0.0	34	0	0

		Max.	8.9	31	26.8	6.5	1.4	689	4	8
Private Wells	10	Ave.	8.3	28	1.2	0.9	0	146	0	0
		Min.	7.8	25	0.2	0.3	0	45	0	0
		Max	8.8	31	8.6	1.5	0.02	249	0	0
Tap Wells	20	Ave.	7.8	27	1.0	0.8	0.05	-	-	-
		Min.	7.3	21	0.1	0.2	0	-	-	-
		Max	8.5	37	6.5	1.9	0.07	-	-	-
	Standard		6.5-8.5	-	0.05	0.3-1.0	-	150-500	-	-

It is observed that KWSA uses production tubewells of different sizes such as 6''X14'' PTW, Mini PTW (3''X8'') and discharge are varies from 0.5 MLD (3''x8'') to 2.4 MLD (6''x14''). They generally use 6''X14'' PTW, which has a mean velocity of water extracting as 4 FPS. From the tested result, it is observed that, the pH of the study area ranges from 6.5 to 8.9 having an average value of 7.9. Maximum value was recorded at Phultala Upazila and minimum value at Biyara in Dighalia Upazila. In few samples, the result crosses the maximum allowable limit of 8.5. The Chloride is found to present in all natural waters that indicates the salinity of that water. The Cl⁻ ion concentration of the study area ranges from 34 mg/l to 836 mg/l. For mini-production and hand pump tubewells, the concentration is found to be exceeded the allowable limit of 500 mg/L. The Fe²⁺ ion concentration of the study area ranges from 0.2 to 6.5 mg/l in groundwater. In most of the cases, the upper limit exceeds the allowable limit. The Arsenic concentration for all the sources are found to be exceeded the allowable limit. The most severe case is observed for hand pump tubewells.

Table: 4.2 Water demand projection of KWASA

Item/Year	Eq ⁿ .	2009	2010	2015	2020	2025	2030
(1) Population (in Thousand)		957	976	1,078	1,190	1,314	1,450
(2) Per-capita Domestic Water Demand (lpcd)		82	90	97	105	113	120
(3) Proportion of Non- domestic Water Demand to Total Water Demand (%)		20	20	16	13	10	10
(4) Domestic Water Demand (m ³ /d)	(1)x(2)	78,474	87,515	104,925	124,950	148,044	174,483
(5) Non-domestic Water Demand (m ³ /d)	(6)-(4)	19,619	21,879	19,986	18,671	16,449	19,387
(6) Domestic & Non- domestic Water Demand (m ³ /d)	(4)/(1- (3))	98,093	109,393	124,911	143,621	164,493	193,870
(7) Leakage after WTP(%)		18	18	18	18	18	18
(8) Average Day Water Requirement (m ³ /d)	(6)/(1- (7))	119,625	133,407	152,331	175,147	200,602	236,427
(9) Peak Factor		1.15	1.15	1.15	1.15	1.15	1.15
(10) Maximum Day Water Requirement (m ³ /d)	(8)x(9)	137,569	153,417	175,180	201,419	230,692	271,891
(11) Existing Supply Capacity (m ³ /d)		119,100	119,100	125,850	125,850	125,850	125,850
(12) Deficit					75,569	104,842	146,041

4.3 EXISTING WATER SUPPLY SCENARIO IN KWASA AREA

Table 4.2 shows the existing and future water demand for the KCC area. It is shown that in 2009 the per capita water demand was 82 lpcd that increases with years and reached 97 lpcd in 2015. It is expected that the demand will increase further to 105, 113 and 120 lpcd for the years of 2020, 2025 and 2030 respectively (KWASA 2010). The non domestic water demand is taken as 16%, 13%, 10% and 10% for the years of 2015, 2020,2025 and 2030 respectively. Leakage of water in the system is assumed as 18% of domestic water. The predicted populations for different years are also shown in the Table. For the year 2020, 2025 and 2030 the water demand are projected. For instance, calculation for the years of 2025 and 2030 are given below.

Target year: 2025

Population	: 1,314,000 persons
Consumption/ capita/day for domestic use	: 113 lpcd
Water for non-domestic use	: 10 %
Water Loss	: 18 %
Domestic water demand	: 149,000 m ³ /day
Non-domestic water demand	: 17,000 m ³ /day
Water loss	: 37,000 m ³ /day
Total water demand	: 203,000 m ³ /day
Existing supply capacity	: 125,850 m ³ /day
Deficit	: 104,842 m ³ /day

Target year: 2030

Population	: 1,450,000 persons
Consumption/ capita/day for domestic use	: 120 lpcd
Water for non-domestic use	: 10 %
Water Loss	: 18 %
Domestic water demand	: 175,000 m ³ /day
Non-domestic water demand	: 20,000 m ³ /day

Water loss	: 43,000 m ³ /day
Total water demand	: 238,000 m ³ /day
Existing supply capacity	: 125,850 m ³ /day
Deficit	: 146,041 m ³ /day

It is found that in the year of 2020, 2025 and 2030, the water demands are 201419, 230692 and 271891 m³/d, respectively. However the existing supply capacity is 125850 m³/d only. Therefore, the water deficit for KWASA in the year of 2020, 2025 and 2030 will be 75569, 104842 and 146041 m³/d, respectively.

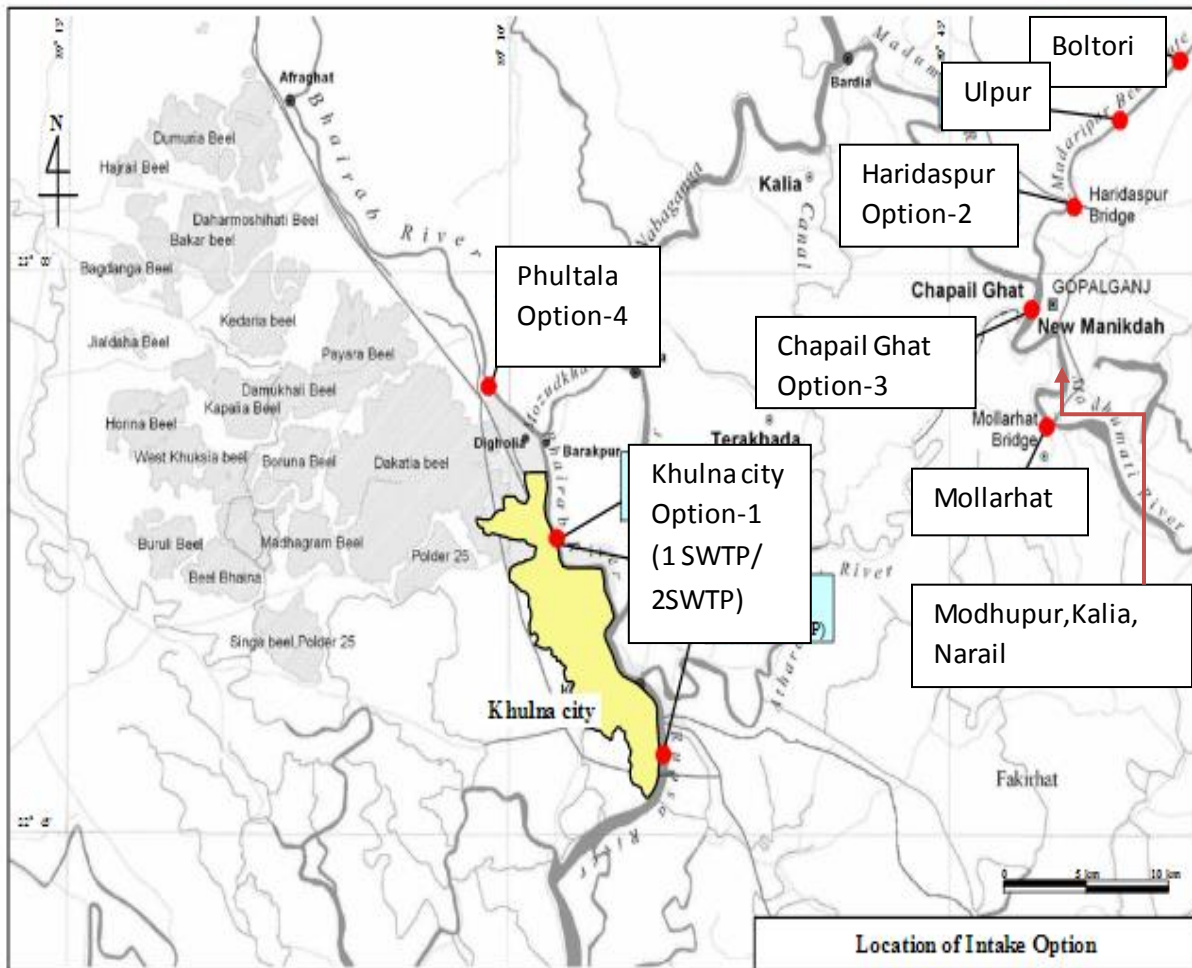


Figure 4.2: Options of raw water intake points (KWASA, 2010)

4.4 FUTURE PLAN OF KWASA

To meet the additional demand of domestic water in Khulna city and to reduce the dependency on ground water, KWASA is planned to use river water and they have studied the feasibility for two raw water intake locations in Bairab-Rupsha river and three intake points in Gorai-Modhumoti river. The study sites are shown in Figure 4.2 and the options are described below based on their feasibility study report.

Option-1: Khulna city (Bhairab and Rupsha river)

Proposed raw water intake point is set by Rupsha River located within Khulna city area. The length of raw water transmission pipe can be minimized compared with the other 4 Cases. On the other hand, water intake in Khulna city is located nearer to the sea than those of the other cases and therefore the expected saline infected days was counted as 180 days a year. Further, as there are no available lands which can be utilized for vast impounding reservoir within the city and its surroundings, some desalination process is required in SWTP.

One of the proposed raw water intake point is along with the Bhairab River and the other is along with the Rupsha River. This intake point is supposed to be affected by salinity around 180 days a year. Latitude and Longitude for the Bhairab river Intake is “N22° 52’ 57.4, E89°31’ 20.9” respectively, and for the Rupsha river Intake is “N22° 47’ 09.0”, E89°35’ 13.8” respectively.

Option-2: Haridaspur (MBR=Madaripur Beel Route) , Gopalganj

Proposed raw water intake point is located in Modhumoti river at Haridaspur. It requires DICL (1400mm) pipe length more 25 Km as compared to other option (Option 5). Costing due to more pipe laying length is high as compared to other options because of additional costing imposed due to river crossing of pipe line at Mollarhat bridge.

Option-3: Chapail Ghat

Proposed raw water intake point is located in Modhumoti river at Chapalighat point. It Requires DICL (1400mm) Pipe Length more 25 Km as compared to other option (Option 5). Costing due to more pipe laying length is high as compared to other options because of additional costing imposed due to river crossing of pipe line at Mollarhat bridge.

Option-4: Phultala

According to salinity investigation at Phultala conducted by DOE on 2005 to 2009 exceeded chloride concentration day can be supposed as 150 days. It means, IPR retention time is 150 days due to high salinity effect. So, IPR land required is more and construction costing will be High. Therefore, degree of feasibility is low.

Option -5: Near Mollarhat Bridge Point

Proposed water intake point of Option-5 is set at Mollarhat, 28 km north-east from Khulna city in order to reduce salinity influence. Raw water is taken from the Madhumati River. Impounding reservoir is required since salinity influence is expected for 80 days at this area. This site is at Mollarhat bridge on the Madhumati River in Bagerhat District. Latitude and longitude is ‘N22°55’ 53.7”, E89° 48’ 30.8” respectively. Based on the analysis on the previous measured records and current JICA Study Team’s measuring record for the new water supply system it is better to provide an impounding reservoir of which retention period is 45 days. In this option, Impounding Reservoir is proposed to be construct at samontosena of Rupsha Upazilla with the Capacity (IPR) of Treatment plant as 775 MLD or 775200 cubic meter (16 ha).

Based on comparative study among the options, Mollarhat Bridge Point of Gorai-Modhumoti river was selected as raw water intake point. Figure 4.3 shows the selected site of raw water intake for KWASA water supply project.

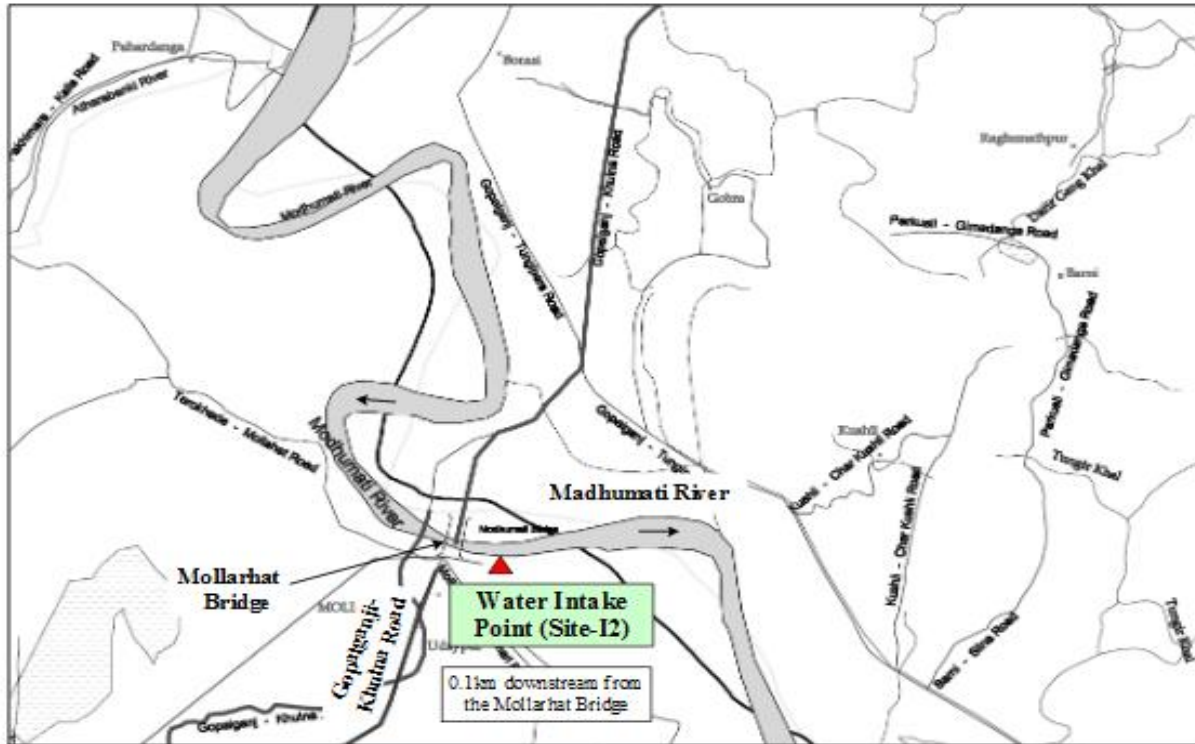


Figure 4.3: Selected site of raw water intake for KWASA water supply project (KWASA, 2010)

Water quality parameters

5.1 INTRODUCTION

Khulna is humid during summer and pleasant in winter. Khulna has an annual average temperature of 26.3 °C (79.3 °F) and monthly means varying between 12.4 °C (54.3 °F) in January and 34.3 °C (93.7 °F) in May. The water quality in most of the rivers varies with the seasonal rainfall. Figure 5.1 shows the variation of rainfall and temperature in Khulna region (in the abscissa, January to December months are represented as 1 to 12, respectively). It is observed that the rainy season starts in the month of June and continued till September. The rest of the year have rare rainfall, is almost dry. Annual average rainfall of Khulna is 1,809.4 millimeters (71.24 in). Approximately 87% of the annual average rainfall occurs between May and October.

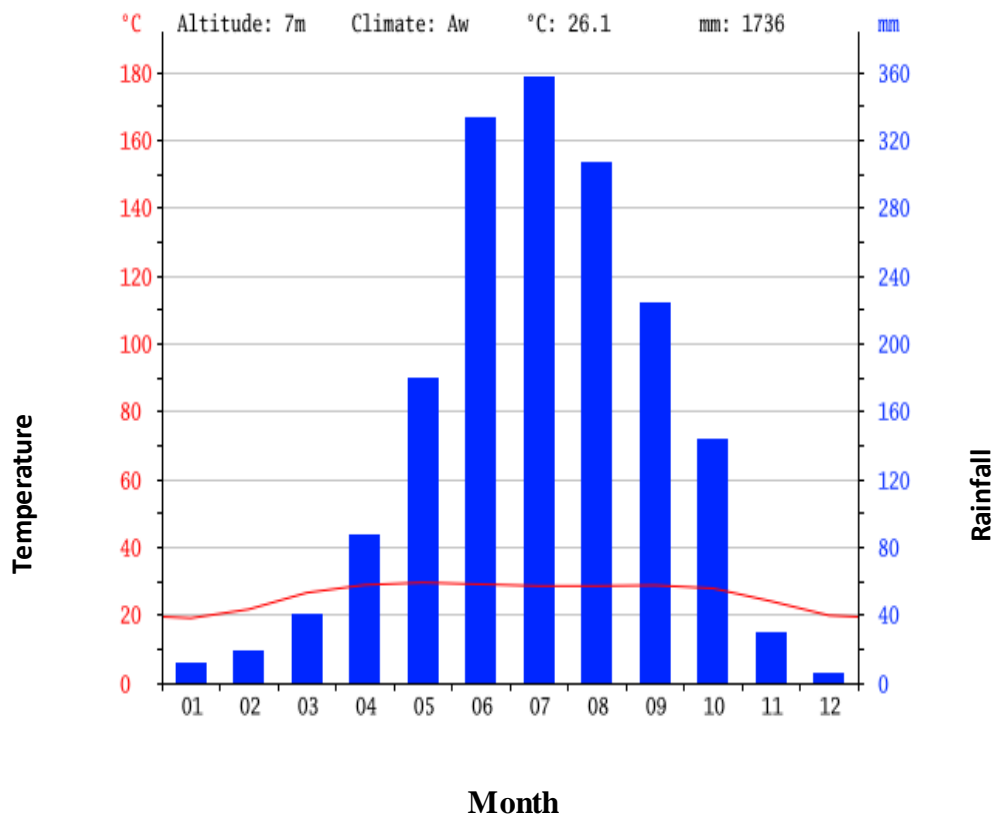


Figure 5.1: Monthly variation of Rainfall and Temperature in Khulna region (KCC, 2014)

In this chapter, firstly the water quality parameters for four station of Gorai- Modhumoti river system are presented. These stations are Station-1: Haridaspur (Kumar river), Station -2: Modhupur (Gorai-Modhumoti river), Station -3: Chapailghat (Modhumoti river) and Station -4: Mollarhat (Modhumoti river). After that the water quality parameters of Rupsha- Bhairab river system will be presented. Among the water quality parameters turbidity, pH, TDS, EC, chloride, salinity etc. are tested in the laboratory. Mayur river has not been considered in this study due to its insufficient water flow and its upstream source is almost moribund. The main water flow source of Mayur river is mainly KCC drainage waste water and rain water in rainy season.

5.2 WATER QUALITY PARAMETERS FOR GORAI- MODHUMOTI RIVER

Figure 5.2 shows the monthly variation of turbidity at different locations for Modhumoti River for the time period of November, 2014 to August, 2015. Turbidity was found higher from June to August and from November to June the turbidity is low. Generally, turbidity has direct relation with presence of solid particle (Finely divided organic matter, plankton and micro-organisms) in water sample. With the starting of rainy season the amount of organic matter and micro-organisms are found to be increasing. The figure shows higher turbidity in August. Chapailghat station contains lower turbidity in March as compare to the other station and it contain higher turbidity in August.

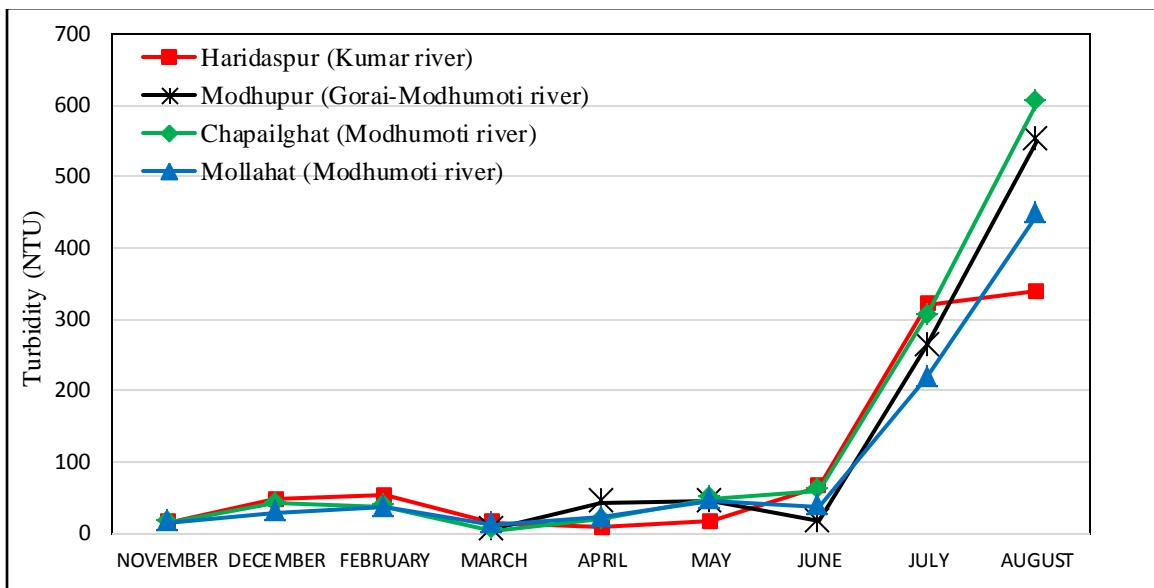


Figure 5.2: Variation of turbidity at different locations for Modhumoti River (2014-2015)

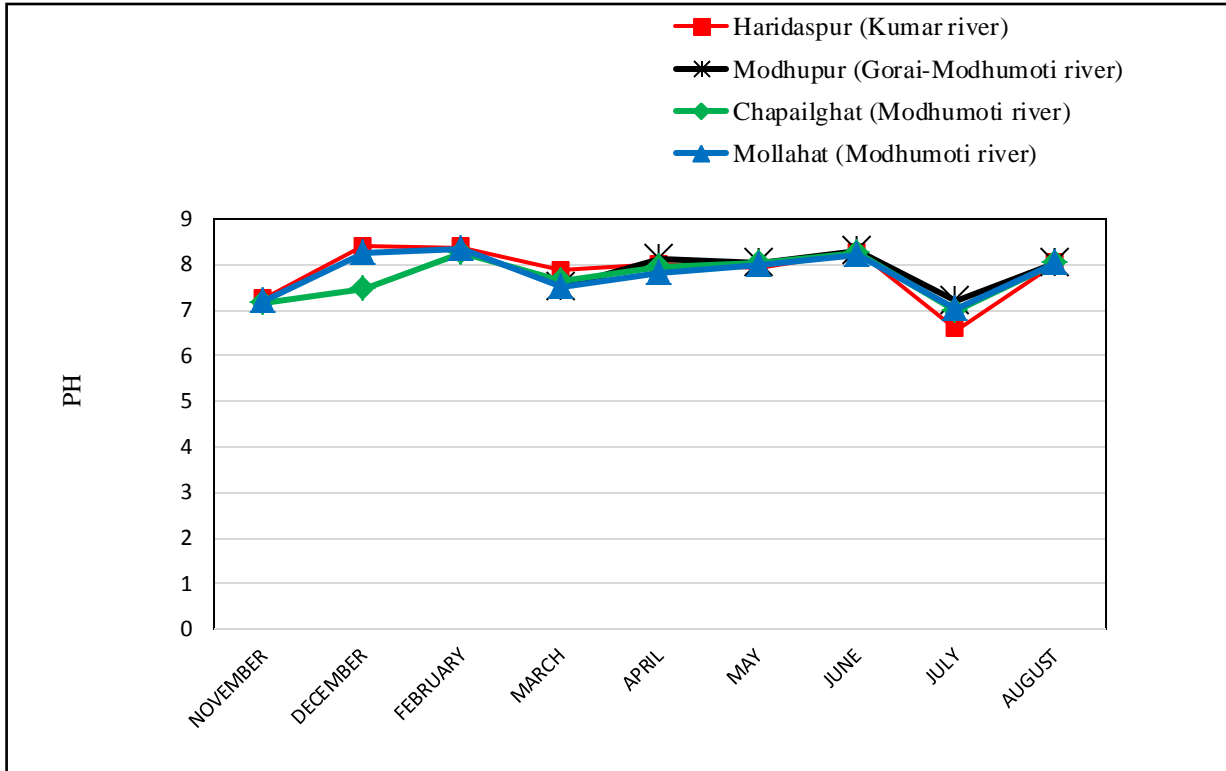


Figure 5.3: Variation of P^H at different locations for Modhumoti River (2014-2015).

Figure 5.3 shows the monthly variation of P^H at different locations for Modhumoti River for the time period of November, 2014 to August, 2015. According to DoE (1991), standard of p^H for aquaculture is 6.5 to 9. From the analyses, pH of Modhumoti river water was found to be within allowable range in most of the months. Only November and July shows the water characteristics in acidic. It shows that Haridaspur station contain higher P^H at December and lowest at July.

Chemical oxygen demand (COD) is found to be varied in the range of 32 to 224 mg/L (Figure 5.4). COD term was referred as indicator to measure organic matter that exists in the water. Since the origin of chemical oxygen demand is the organic and inorganic matter that are soluble in water. It increases in rainy season due to the higher organic matter with their flow. Figure 5.4 shows that highest COD at Modhupur station in the month of June and the lowest COD at Mollahat station in November.

Figure 5.5 shows the monthly variation of Biochemical Oxygen Demand (BOD) for different locations of Gorai-Modhumoti River. The concentration is found to be varies in the range of 0.35 to 2.41. For Bangladesh the standard demand is 0.2 mg/l. But the test value of BOD is quite

higher than standard value. It shows highest BOD in December at Haridaspur and lower value at Mollahat in July.

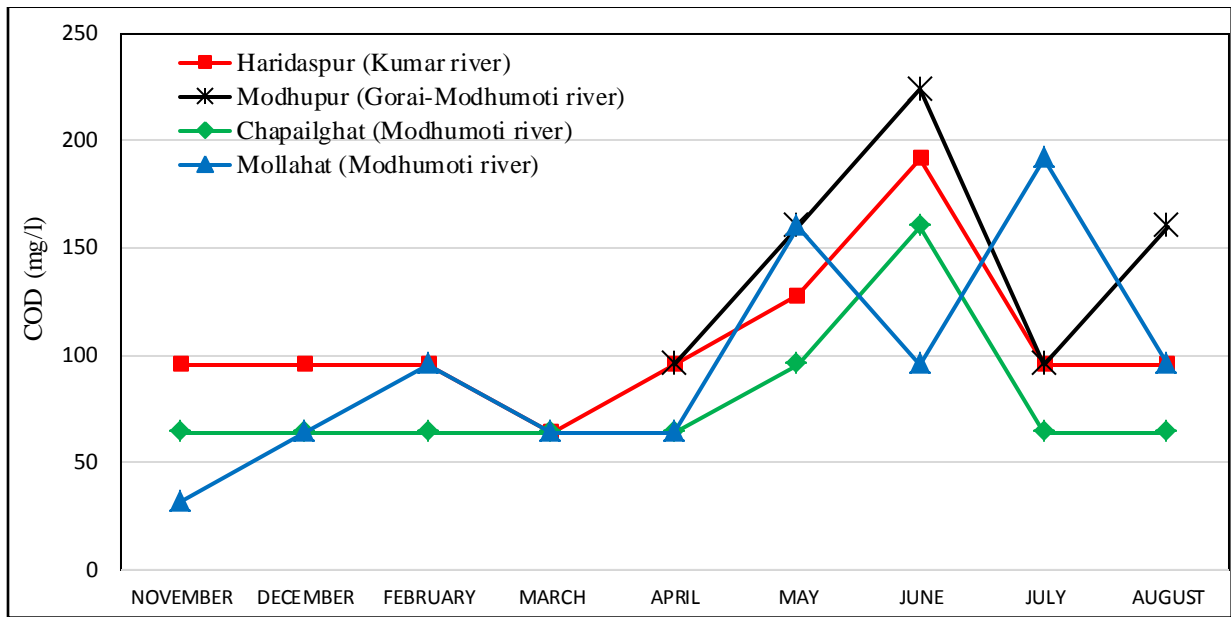


Figure 5.4: Variation of COD at different locations for Modhumoti River (2014-2015).

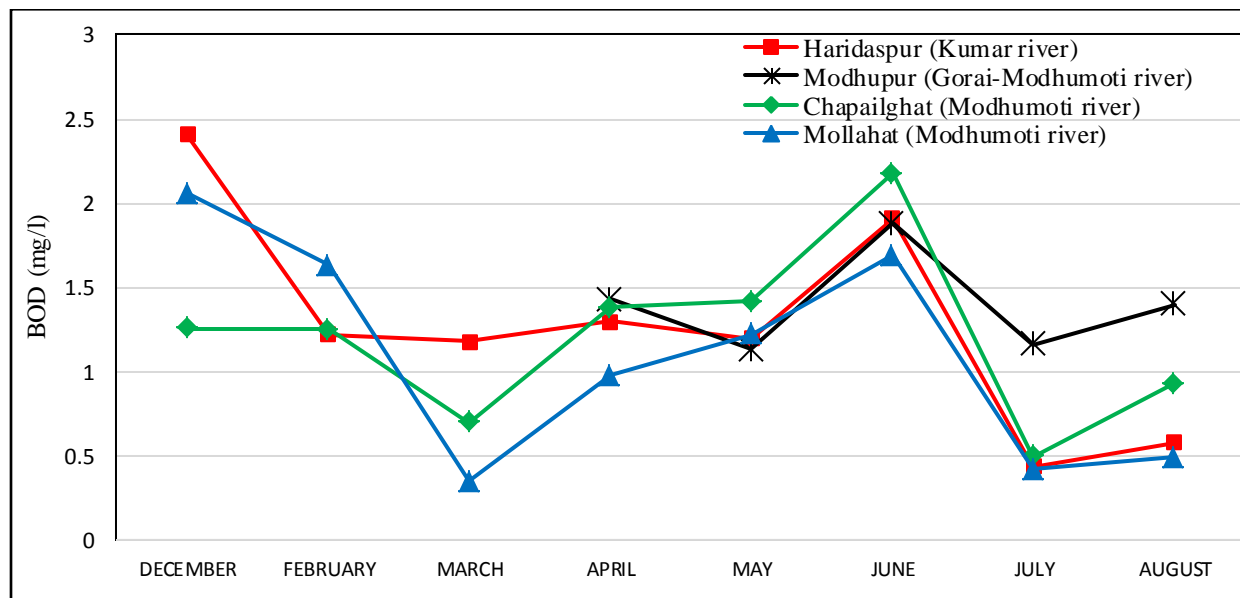


Figure 5.5: Variation of BOD at different locations for Modhumoti River (2014-2015).

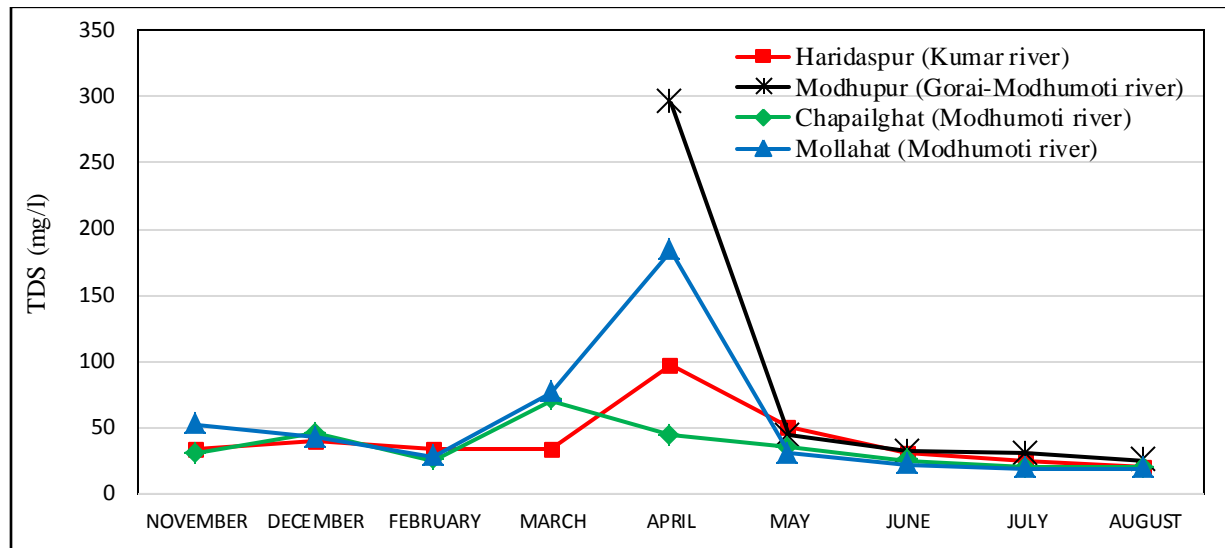


Figure 5.6: Variation of Total dissolve solid at different locations for Modhumoti River (2014-2015).

Total dissolved solids (TDS) combine the sum of all ion particles that are smaller than 2 microns (0.0002 cm). This includes all of the disassociated electrolytes that make up salinity concentrations, as well as other compounds such as dissolved organic matter. In “clean” water, TDS is approximately equal to salinity. While TDS measurements are derived from conductivity, some states, regions and agencies often set a TDS maximum instead of a conductivity limit for water quality. The relation among TDS salinity and conductivity is linear. With the increases of salinity the TDS is increased. Figure 5.6 shows the variation of TDS at different locations of Modhumoti river. It is observed that its value is high in the month of April, from May to August its value is very low and started to increase from November to reach its peak in April.

Figure 5.7 shows the variation of hardness at different locations of Modhumoti river. It is found that its value is ranges from 97 to 1344 mg/l. Calcium, magnesium and ferrous ions are responsible for this hardness value. The highest value is recorded at Modhupur station in April. All of station contain higher hardness in April exception is that Haridaspur station. It contains higher hardness in March. Hardness decreases from April and reach its lowest value in August. That means the river water contains higher hardness in summer and lower hardness in rainy season.

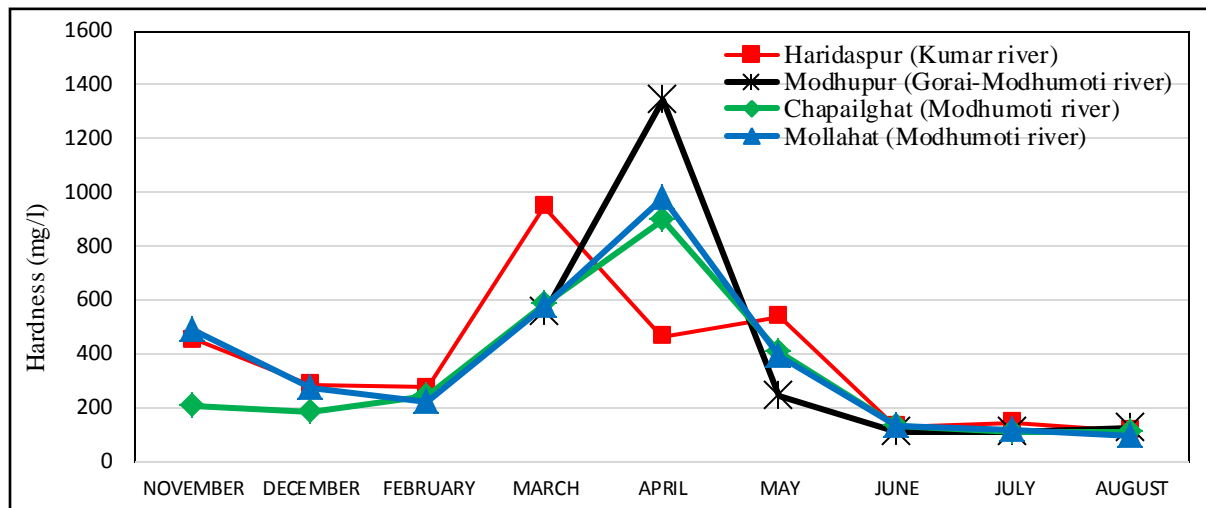


Figure 5.7: Variation of hardness at different locations for Modhumoti River (2014-2015).

Electrical Conductivity is one way to measure of the inorganic materials including calcium, bicarbonate, nitrogen, phosphorus, iron, sulphur and other ions dissolved in a water body. It is measured by placing a conductivity probe in the sample and measuring the flow of electricity between the electrodes. Salinity is the component of conductivity that is critical to the survival of some aquatic plants and animals. Conductivity is measured with a meter in micro Siemens per centimeter units ($\mu\text{S}/\text{cm}$). The natural conductivity of fresh water varies from very low values ($30\mu\text{S}/\text{cm}$) to very high values ($2000\mu\text{S}/\text{cm}$) that is unsuitable for irrigation.

Conductivity is dependent on water temperature, salinity and TDS. Water flow and water level changes can also contribute to conductivity through their impact on salinity. Water temperature can cause conductivity levels to fluctuate daily. In addition to its direct effect on conductivity, temperature also influences water density, which leads to stratification. Stratified water can have different conductivity values at different depths. Conductivity and salinity have a strong correlation. As conductivity is easier to measure, it is used in algorithms for estimating salinity and TDS, both of which affect water quality and aquatic life. Figure 5.8 shows the variation of electrical conductivity at different locations for Modhumoti river. Since the temperature increases at march and April, electrical conductivity is in peak in March- April with a maximum value of about $260\mu\text{S}/\text{cm}$. As shown in figure, Modhupur and Haridaspur stations contain higher electrical conductivity due to its higher salinity in water.

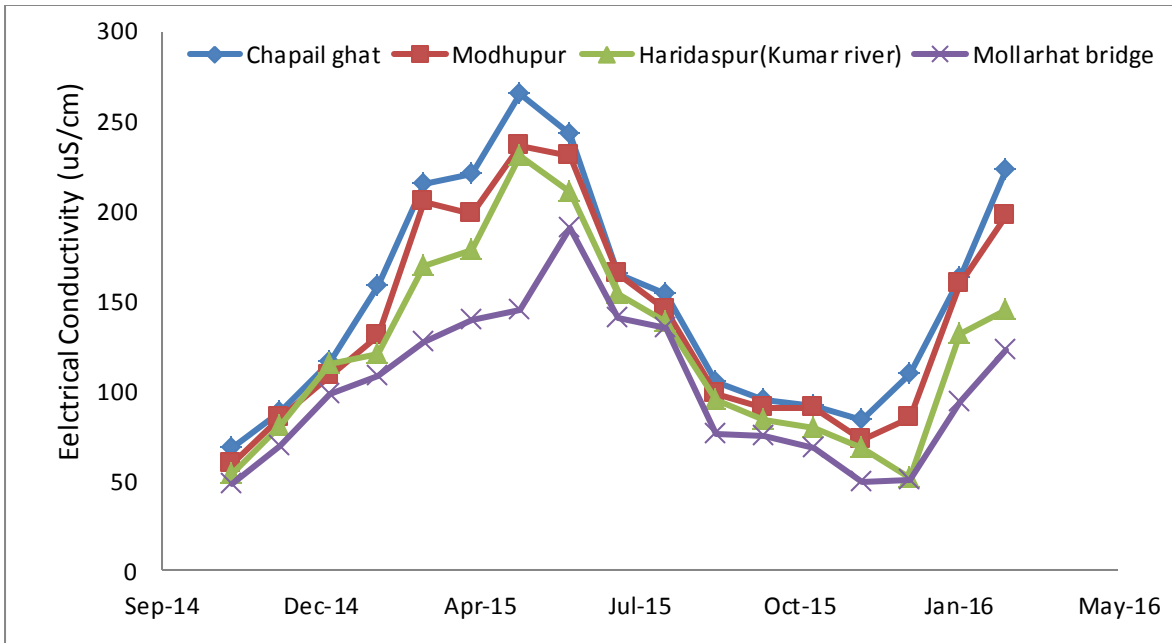


Figure 5.8: Variation of Electrical Conductivity (EC) at different locations for Modhumoti River (Sep 2014-May 2015).

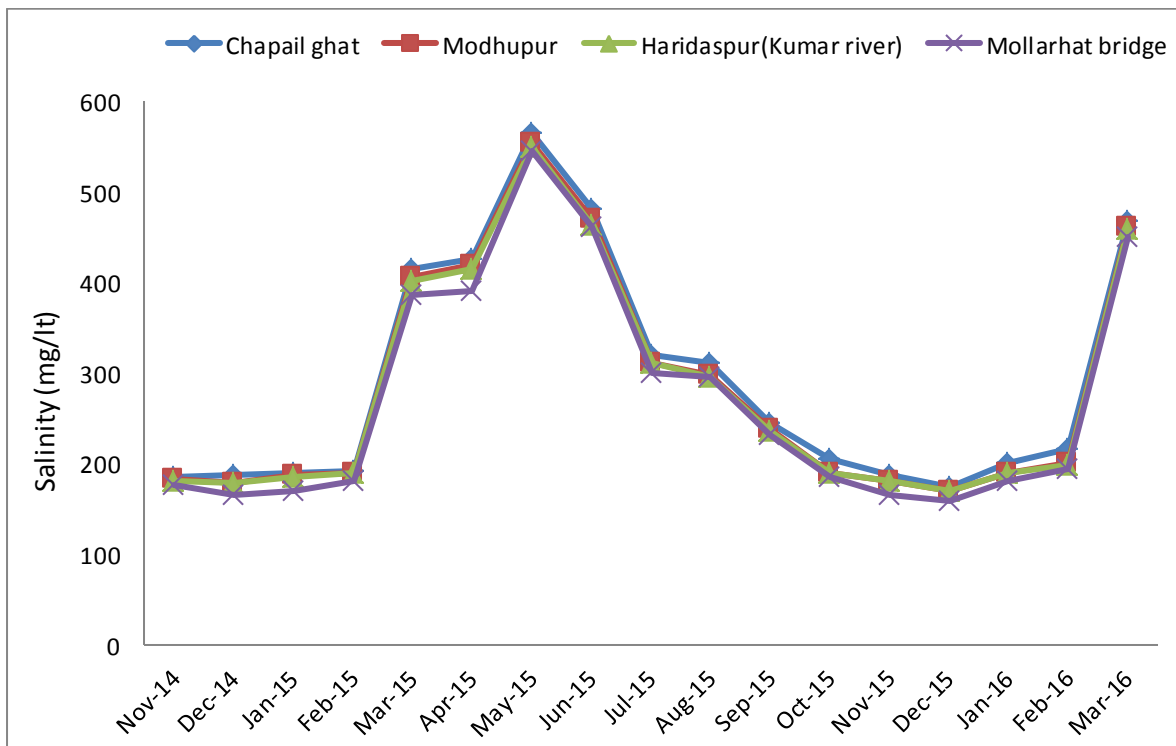


Figure 5.9: Variation of salinity at different locations for Modhumoti River (Nov 2014-Mar 2016)

Salinity is the total of all non-carbonate salts dissolved in water, usually expressed in parts per thousand (1ppt = 1000 mg/L), unlike chloride (Cl^-) concentration. Salinity is a measure of the total salt concentration, comprised mostly of Na^+ and Cl^- ions. Even though there are smaller quantities of other ions in sea water (e.g., K^+ , Mg^{2+} , or SO_4^{2-}), sodium and chloride ions represent about 91% of all sea water ions. So salinity is increasing with the increases of (Cl^-) concentration. The temporal and spatial variation of salinity is shown in the Figure 5.9. Figure shows that salinity is increasing from February and peak in April. Chapailghat, Modhupur and Haridaspur stations are found almost same salinity; highest is average 500 mg/lit and lowest is 90 mg/lit. Mollarhat contained lowest salinity among the four stations. All of stations contain higher salinity in summer due to lower discharge of river. For low discharge the sea water enter the downstream of river easily and contain higher salinity as compare to the upstream of the river.

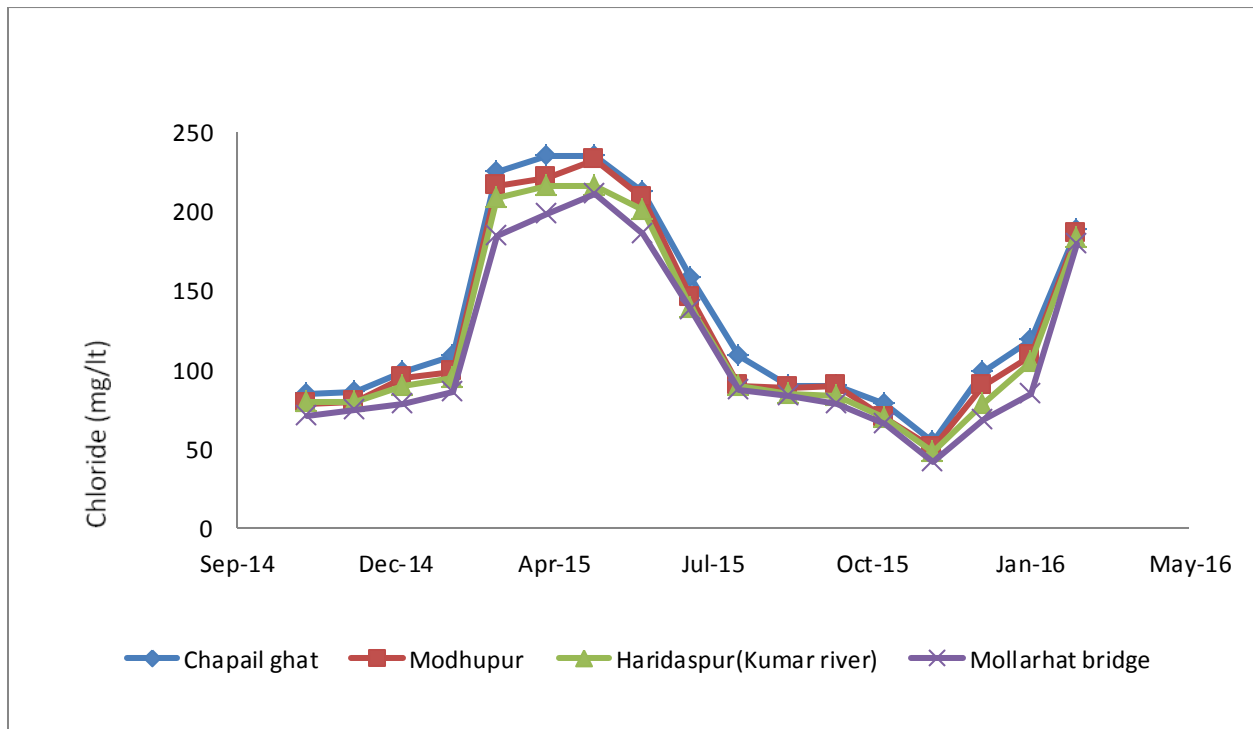


Figure 5.10: Variation of chloride concentration at different four (4) locations for Modhumoti rivers (Sep2014- May-2016)

Monthly variation of chloride concentration for different stations is shown in Figure 5.10. Figure shows that chloride concentration is increasing from February and peak in April. Haridaspur station contain higher chloride concentration as compare to the other station. Chapailghat and Mollarhat contain lower chloride concentration as compared to other two stations. All of stations contain higher chloride in summer due to lower discharge of river. For low discharge the sea

water enter the downstream of river easily and contain higher chloride as compare to the upstream of the river. In April, the chloride concentration is higher in all the four station. Increase of salinity is may be due to the effect of high tide and intrusion of saline water in the downstream of Modhumoti river.

5.3 WATER QUALITY ANALYSIS RUPSHA- BHAIKAB RIVER SYSTEM

Monthly variation of salinity for the station of Rupsha Ghat is shown in Figure 5.11 shows that salinity is increasing from February and peak in April. In the month of May highest salinity is found about 18000 mg/l which is gradually decreasing in the following month. Due to dry season in between March –May salinity have been maximum as compared to the remaining month.

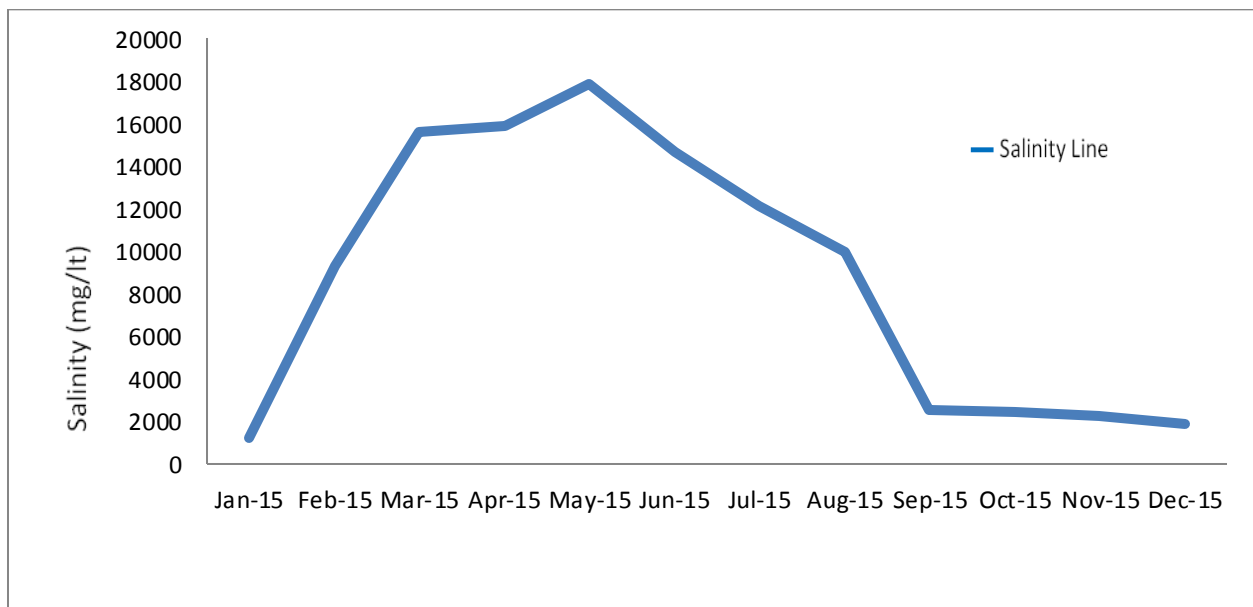


Figure 5.11: Monthly variation of salinity at Rupsha Ghat of Rupsha river (Year 2015)

Figure 5.12 shows the temporal variation of monthly pH at Rupsha Ghat of Rupsha river. Highest value 8.30 recorded in August while the minimum found 6.97 in September. Monthly variation of pH is minor and close to each other. Highest and lowest values are within BDS permissible limit for drinking water. Standard value for surface water quality for pH is 6.5-8.5 according to ECR'97.

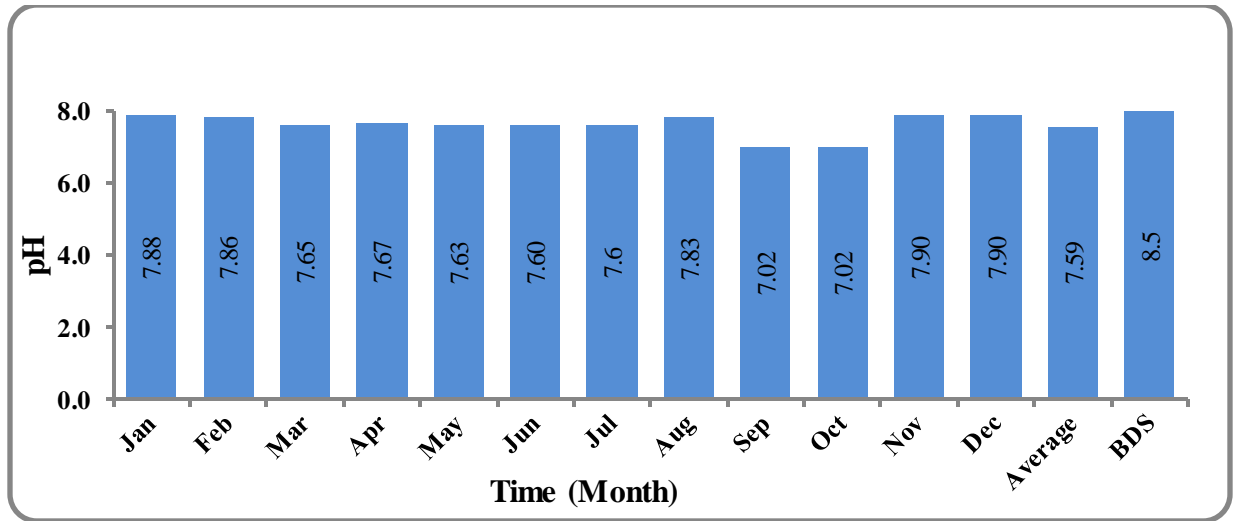


Figure 5.12: Temporal variations of pH at Fultala station of Bhairab River (Year 2015)

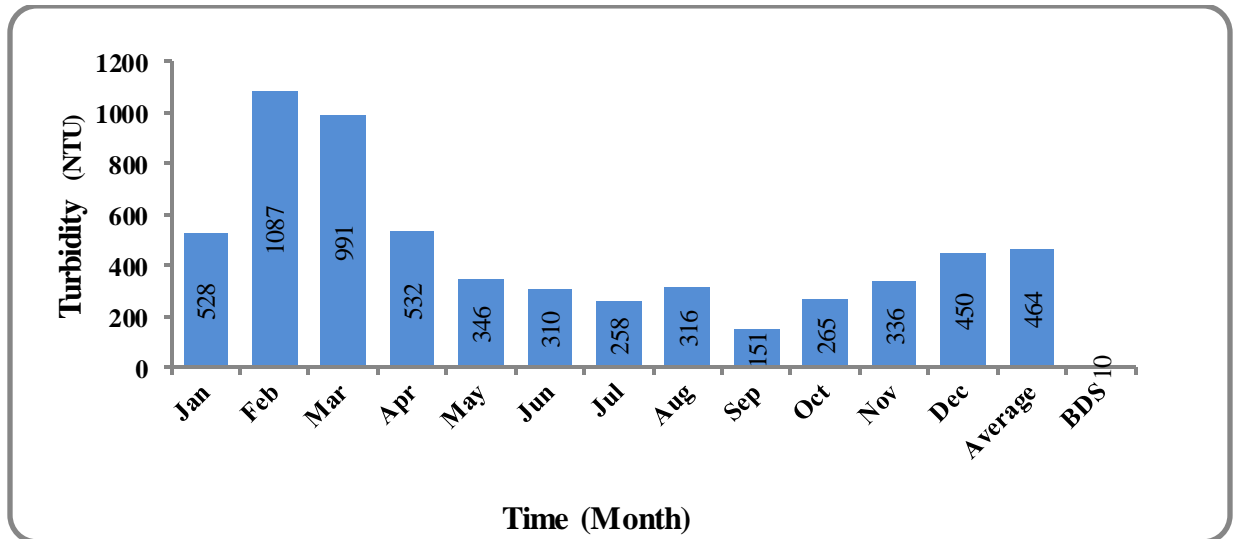


Figure 5.13: Temporal variations of turbidity of Bhairab River (Year 2015)

In the Figure 5.13 Monthly average turbidity found 464 NTU. Year highest turbidity was recorded 1087 NTU in February while the lowest was 151 NTU in September. The monthly variation of the turbidity was too high. Allowable limit of turbidity according to BDS for drinking water is 10 NTU and there is no standard limit for recreation and irrigation. Maximum and minimum both values are exceeded allowable drinking limit.

In the Figure 5.14, Monthly conductivity through the year 2015 are shown where the highest value were recorded 9165 $\mu\text{S}/\text{cm}$ at in June and the lowest was 145 $\mu\text{S}/\text{cm}$ in December. The monthly variation of the conductivity was too high specially for the month of January to April.

Permissible value for BDS of conductivity is 500-700 $\mu\text{S}/\text{cm}$ for drinking water. Highest and average value exceeded BDS permissible value while the lowest value remains within it and there is no standard limit for recreation and irrigation.

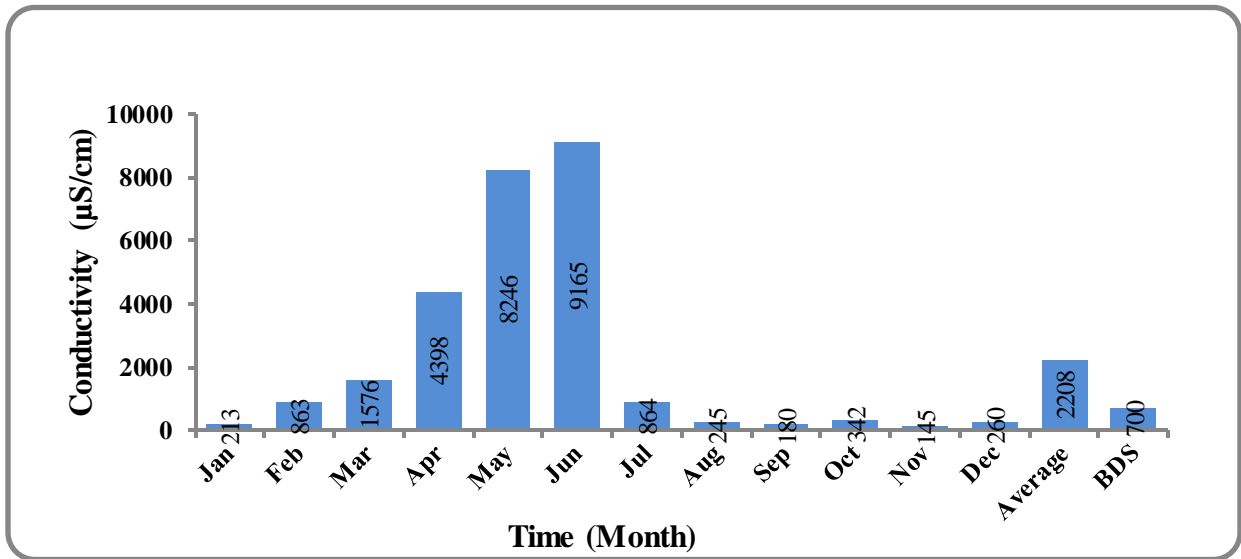


Figure 5.14: Temporal variations of conductivity of Bhairab River (Year 2015)

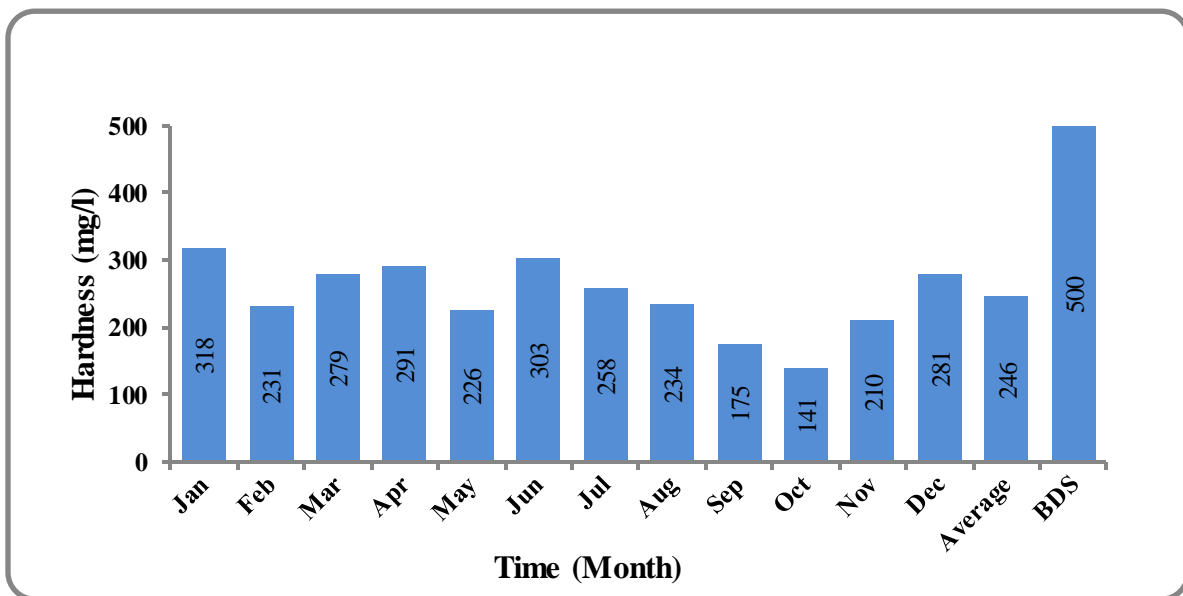


Figure 5.15: Temporal variations of Hardness of Bhairab/Rupsha River (Year 2015)

In the study period monthly hardness were shown in Figure 5.15. Highest value of hardness was recorded 318 mg/l in April while the lowest was 141 mg/l in May. Both highest and lowest values are within the BDS drinking water limit. The monthly variation of hardness over the year was

negligible. Bangladesh drinking water quality standard for hardness is 200-500mg/l. All of the hardness value of different station and months are within BDS limit.

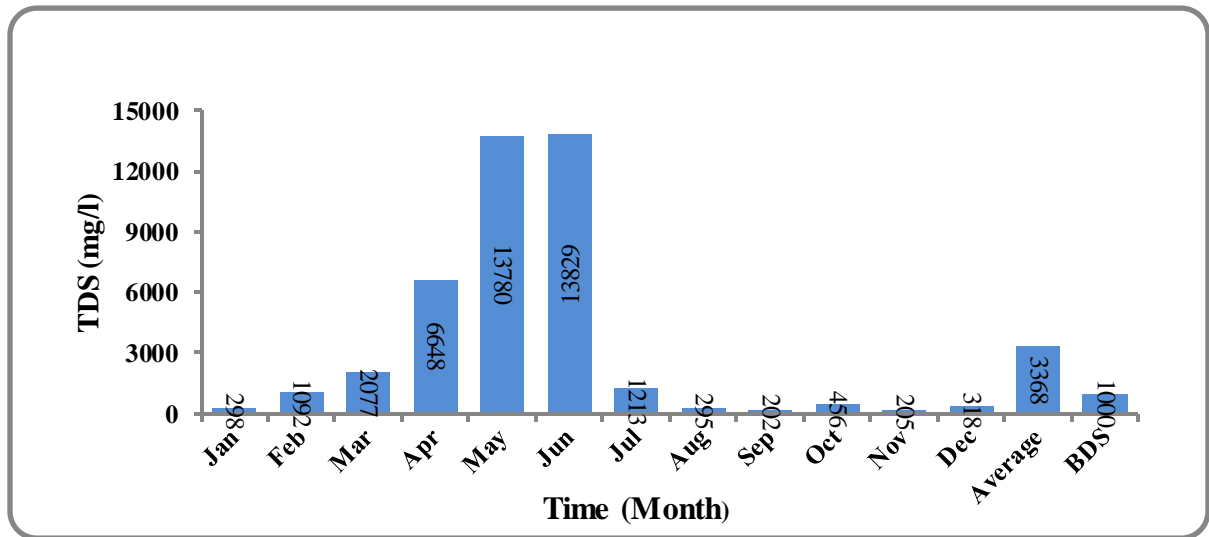


Figure 5.16: Temporal variations of TDS of Bhairab River (Year 2015)

Through the year 2015 monthly average TDS were shown in Figure 5.16. Year highest TDS was 13829 mg/l in June while the lowest was 202mg/l at in September. The monthly fluctuation of the TDS was significant. TDS concentration starts rising from March and drastically reached high concentration (13829 mg/l) in June due to mounting chloride content in water. Its Bangladesh drinking standard is 1000 mg/l and there is no standard limit for recreation, irrigation.

Monthly average chloride content of Study River was shown in the Figure 5.17. Highest chloride was recorded 13165 mg/l in June and the lowest one was 24 mg/l in November. From the Figure it is observed that chloride content rises from March and get peak in June. In this dry period Bhairab River water remains high salinity. Bangladesh water quality standard for drinking is 1000 mg/l for coastal area and 150-600 mg/l for other area and there is no standard limit for recreation, irrigation and aquaculture.

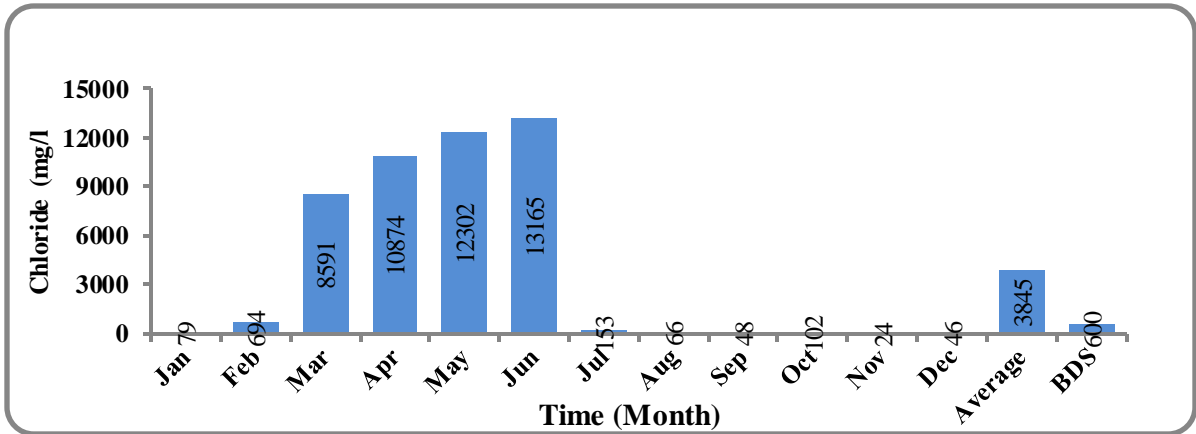


Figure 5.17 Temporal variations of Chloride of Bhairab River(Year 2015)

In the study monthly average BOD concentrations were shown the Figure 5.18 during the study period. Highest BOD was 1.34 mg/l in March and the lowest one was 0.48 mg/l in April. BOD content was observed high in every month. High BOD indicates sewage pollution. Permissible value for BOD is 0.20 mg/Lt. for drinking water. Hence the Bhairab River water is not suitable for drinking purpose based on BOD concentration.

In the test result monthly average COD were shown in the Figure 5.19: Monthly average, highest and lowest values were 145mg/l, 234 mg/l and 77 mg/l respectively are exceeded Bangladesh standard drinking water level 4mg/l. Monthly fluctuation of COD was remarkable. COD concentration over the study period was too high in all sampling station. It indicates industrial pollution of water. So the Bhairab River water is not suitable for drinking but usable for other purpose based on COD.

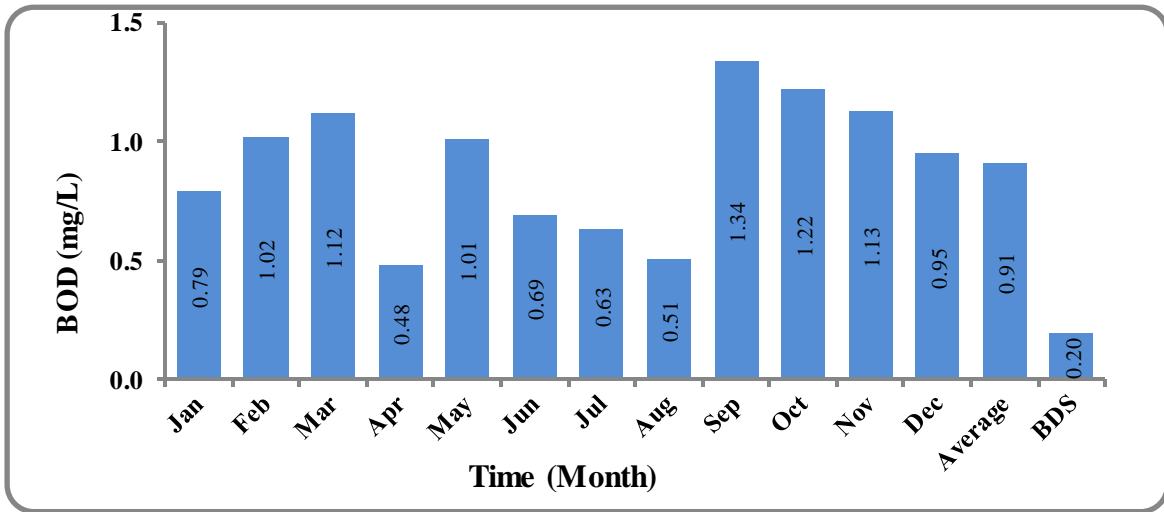


Figure 5.18: Temporal variations BOD of Bhairab River (Year 2015)

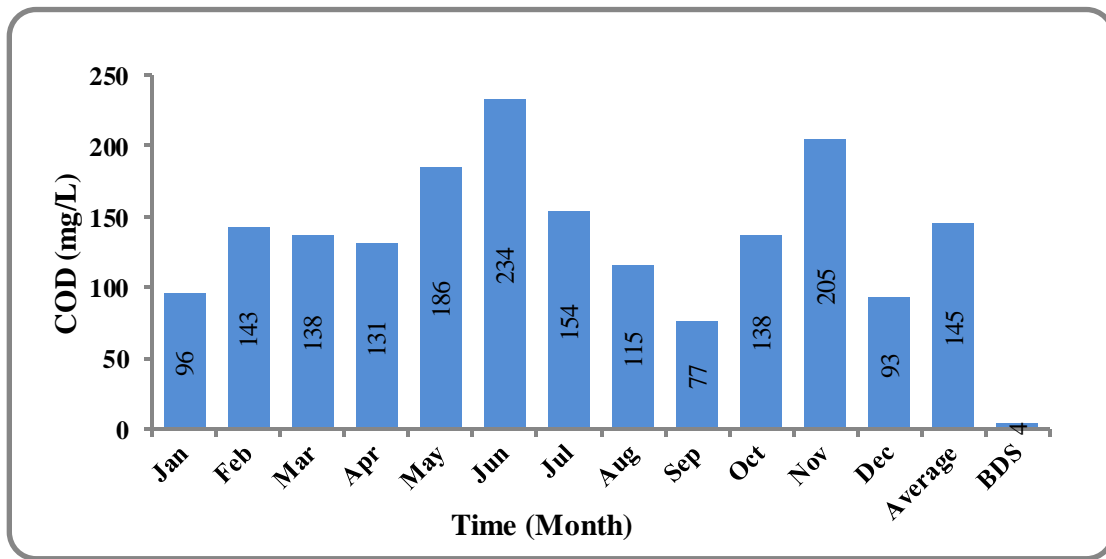


Figure 5.19: Temporal variations of COD of Bhairab River (Year 2015)

5.4 WATER QUALITY ANALYSIS OF ARIAL KHAN RIVER

Figure 5.20 show the variation of salinity at Off Take point of Arial Khan river. Its salinity is found to be varied from 43 to 583 mg/lt, having highest in March-April and Lowest in October. Though the low salinity level of Arial Kha river is much lower compared to Modhumoti river, the highest level of salinity of both the rivers are of same order. Bhairab-Pussur river system has the much higher salinity compared to Modhumoti and Arial Kha rivers.

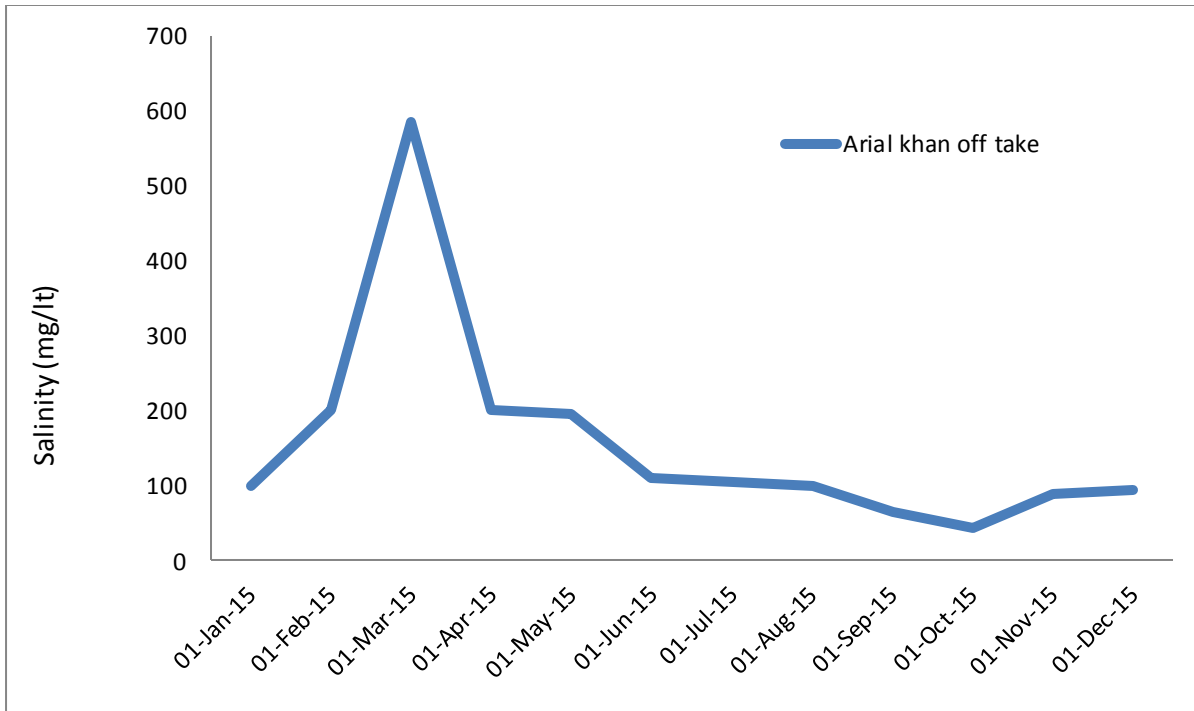


Figure 5.20: Temporal variations of salinity at Arial Khan river off take

5.5 COMPARISON OF WATER QUALITY AMONG DIFFERENT RIVERS

Figure 5.21 shows the variation of chloride among three rivers (Bhairab, Rupsha and Modhumoti) in 2015. Figure shows that chloride concentration is increasing from February and peak in June for Rupsha and Modhumoti but Bhairab peak in May. Rupsha contain higher amount of chloride and Modhumoti contain lower amount of in every month.

The information on Chloride concentration was collected for three rivers (Modhumoti, Vairab and Rupsha) for 2014 (Source: KWASA), and the data for Mayur river was collected for 2014 (Shammi et al, 2012). The data are compared in Figure 5.22. It is found that the chloride concentration at Rupsha is higher than Bhairab and Mayur. The concentration at Modhumoti river is the lowest among four rivers. Figure 5.23 shows the variation of Electrical Conductivity for four rivers for the year of 2015.

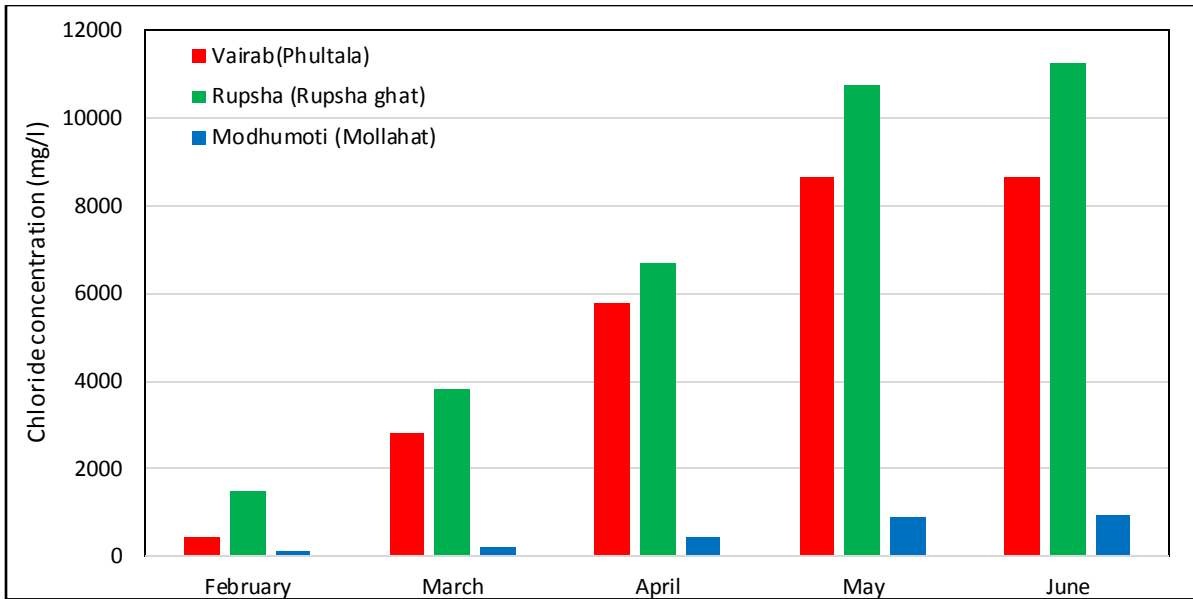


Figure 5.21 Variation of chloride concentration of different rivers in 2015

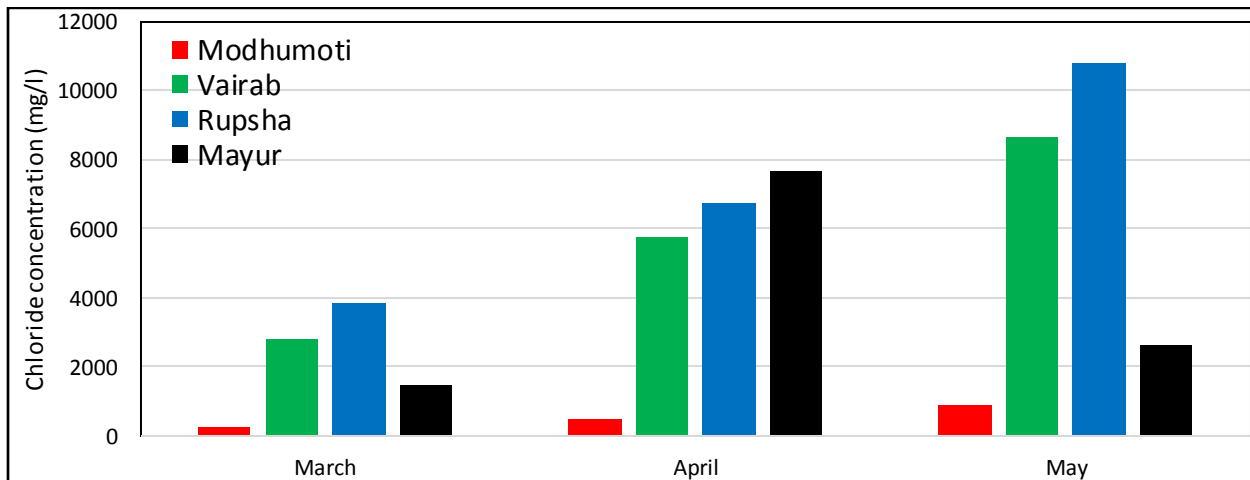


Figure 5.22 Chloride concentration of different rivers for 2014. (Source: KWASA, 2014)

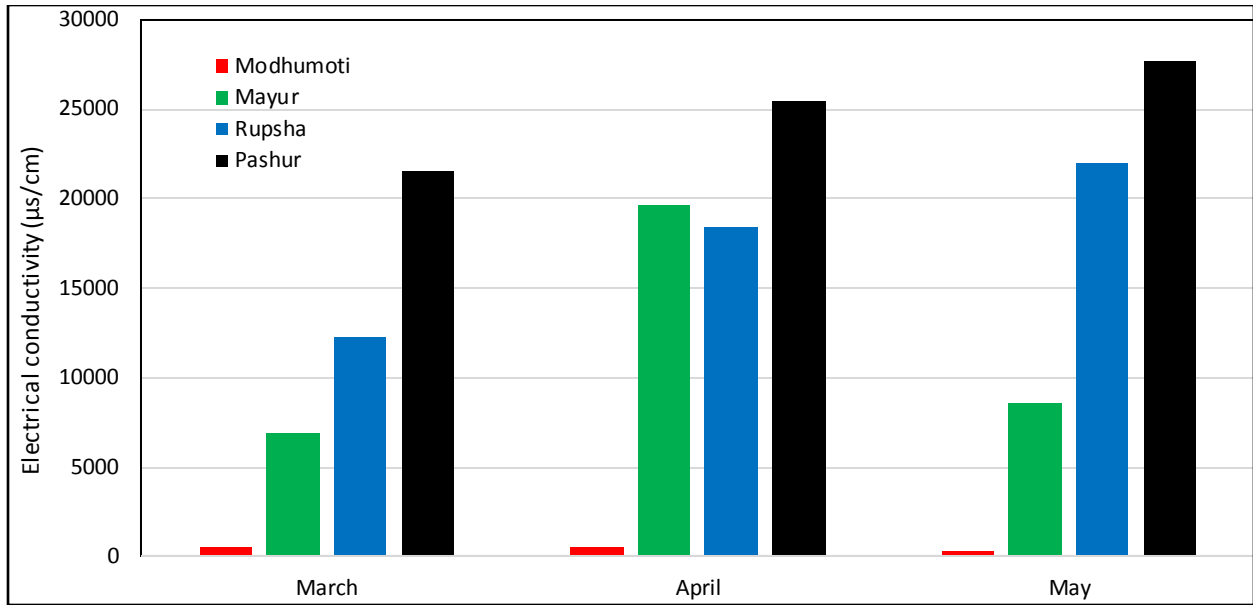


Figure: 5.23 Electrical conductivity of different rivers (Year 2015)

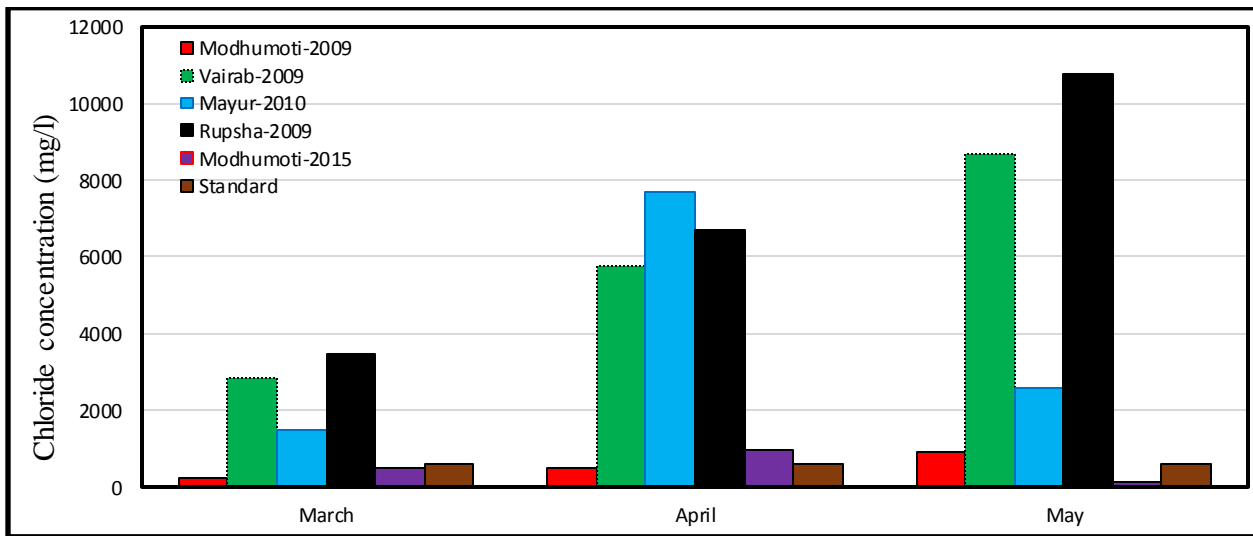


Figure 5.24 Spatial Variation of chloride Concentration of different river (Year 2009 and 2015).

Figure 5.24 shows the spatial variation of Chloride concentration of different rivers. Among them Rupsha river contain higher chloride as compare to the other river. In Bhairab, chloride concentration peak at April, and Rupsha peak at May. Modhumoti contain always lower amount of chloride. But it increases at 2015 as compare to 2009.

From Figure 5.25, it is found that the rivers contain higher salinity in April as compare to March. Among three rivers Vairab contain higher salinity in April and Rupsha in March. Modhumoti contain lower salinity as compare to the other rivers. But the amount of saline increased at 2015 as compare to 2010 in Rupsha-Vairab.

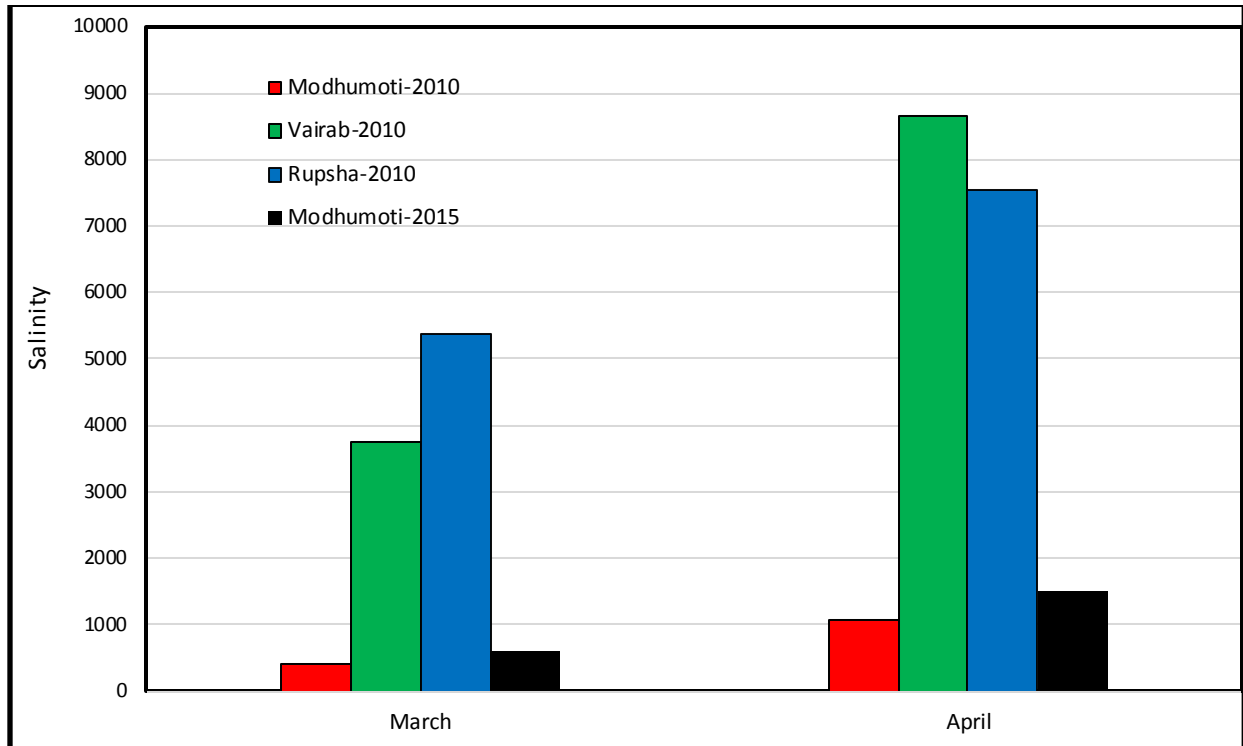


Figure 5.25: Variation of salinity for different rivers (Year 2010 and 2015)

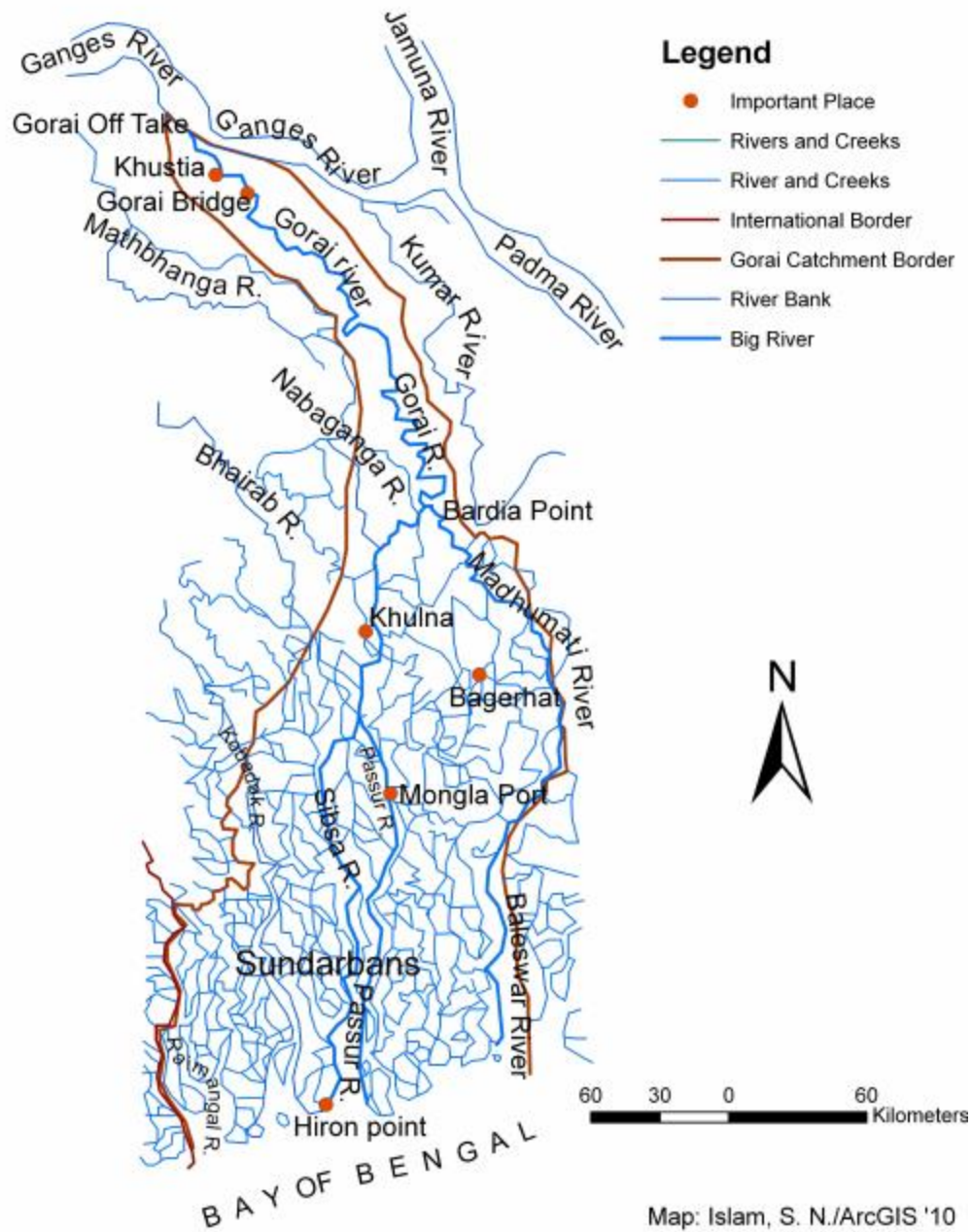
CHAPTER 6

River Flow Behaviour

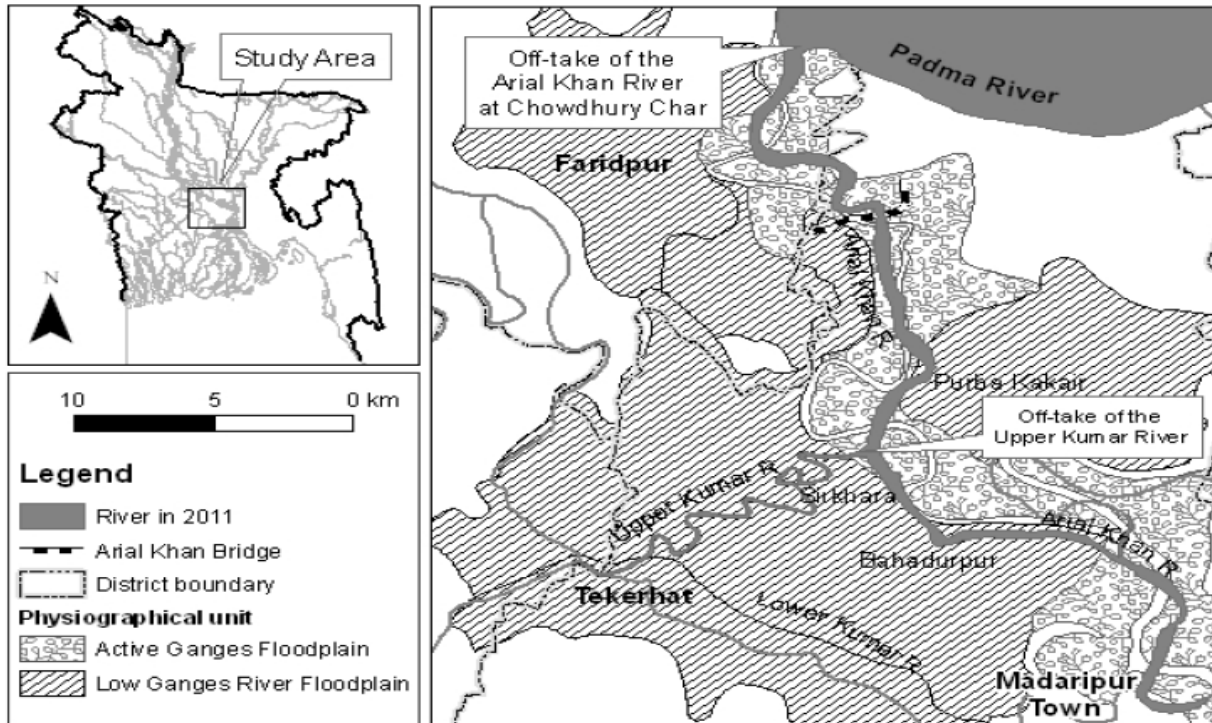
6.1 GENERAL

The Gorai River is the major distributary of the Ganges River in the right bank and important provider of fresh water inflows to southwestern region of Bangladesh. It is a crucial instrument for maintaining both the environment and economy of the region. It has a meandering and braiding tendencies. The length of the river is 199 km. The area of the Gorai river catchment is 15160 km². The Gorai river is bifurcated into two streams at Bardia and its flow is distributed between the Nabaganga and Madhumati rivers. The Gorai-Modhumoti branch used to discharge into the Bay of Bengal through the Madhumati and Baleswar Rivers (Fig. 6.1a). The Gorai-Nabaganga, is the another drainage path of the Gorai water, which reaches the Bay mainly via the Passur and Sibsa rivers. It also brings fresh water in the region through Bhairab and Mathbhanga Rivers. In the downstream of Bardia, the Kumar river (which is a branch of Arial kha river) is connected with Modhumoti river (Fig. 6.1b).

In the previous chapter, the water quality of different rivers vicinity to Khulna has studied. It is observed that Mollahat point of Modhumoti river is the nearest point to Khulna city having comparatively less salinity. As per KWASA (2010), this is the reason to select the Mollahat point as intake of raw water for the alternate water source. In this chapter, the historical flow characteristics of Gorai-Modhumoti river is studied to explain the sustainability of the raw water intake site for KWASA. Four stations are studied namely Gorai railway bridge point, Gorai-Kamarkhali bridge point, Arial Kha off-take point and Modhumoti Mollahat point.



(a) Catchment area of Gorai River with its branches (Islam and Gnauck, 2008)



(b) Catchment area of Upper Kumar River (Akter *et al.* 2013)

Figure 6.1: Sources of flows of Modhumoti river

6.2 GORAI RAILWAY BRIDGE POINT

Rating Curve:

Hydrological models often disregard the fact that river flow data are affected by a significant uncertainty. This is despite the fact that river discharges are almost never directly measured, as opposite to the water stage. Usually, observed river stage values are converted into river discharges by means of a stage–discharge relationship, the so-called rating curve. The main sources of uncertainty that affect river discharge data, obtained using the rating curves, are: (1) errors in the individual stage and discharge measurements; (2) errors induced by the presence of unsteady flow conditions; and (3) errors induced by the extrapolation of the rating curve beyond the range of measurements used for its derivation. Depending on the specific case study, additional sources of uncertainty can be significant. These include the presence of relevant backwater effects (caused by downstream confluent tributaries, lakes and regulated reservoirs) and temporal changes in the hydraulic properties governing the stage–discharge relationship (e.g. scour and fill, vegetation growth and ice build-up during cold periods). Concerning the measurement uncertainty (case 1), Pelletier (1987) reviewed 140 publications and concluded that the overall uncertainty in a single determination of river discharge can be more than 8% at the 95% confidence level. More recent studies reported errors around 5–6% (e.g. Le´onard et al.

2000) that could possibly be reduced by using appropriate discharge measurement techniques (Lintrup 1989; European ISO EN Rule 748 1997).

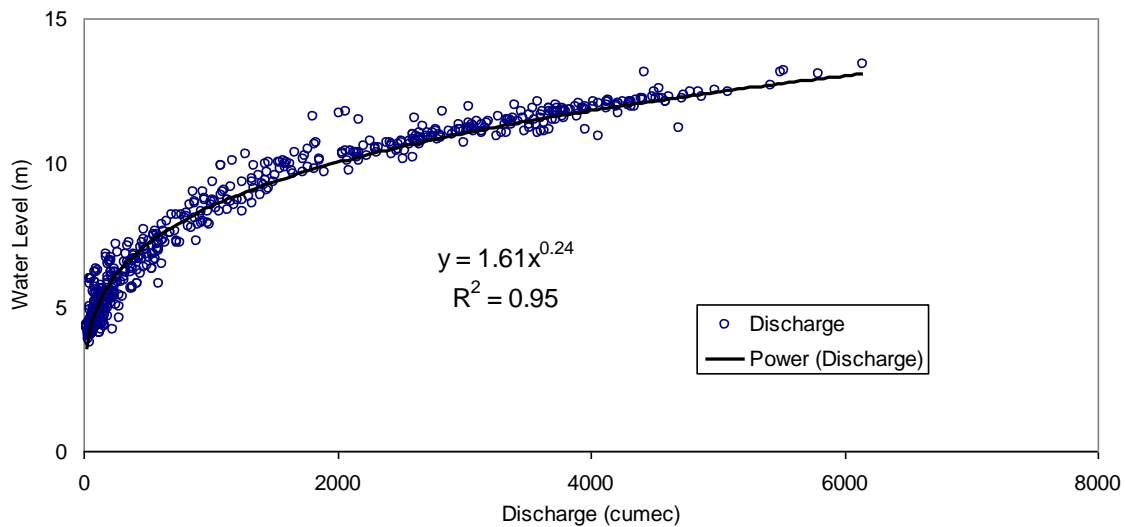


Figure 6.2: Rating curve for Gorai Railway Bridge point of Gorai river.

Figure 6.2 shows the relationship between water level and discharge at Gorai Railway Bridge point of Gorai river. For this point the equation of rating curve is expressed as $y = 1.61 x^{0.24}$, where y is the water level in m and x represents the discharge in cumec. The rating curve is prepared using the depth- discharge data of 1995 to 2015 collected from Bangladesh water development Board.

Discharge :

Figure 6.3 shows the temporal variation of discharge at Gorai Railway Bridge point. The discharge is found to be varies nearly zero at winter season to over 6000 cumec in monsoon. Figure 6.4 shows annual maximum discharge for last two decades for the Gorai river at Gorai Railway Bridge Station. This Discharge is found almost over 4000 cumec in every year. The maximum annual discharge is found in decreasing trend with time. From an average maximum flow of 5232 cumec in 1995, it is decreasing by 85.3 cumec per year. Figure 6.5 shows annual minimum discharge for last two decades for the same Station. This Discharge is found to be varied from zero to 400 cumec for different years. In the 20 years of data about 7 years have the nearly zero discharge.

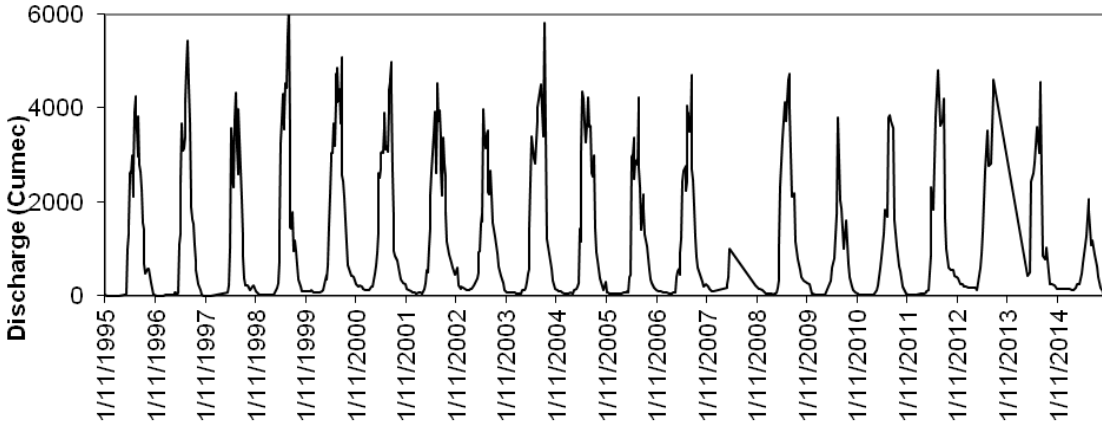


Figure 6.3: Time series of discharge at Gorai Railway Bridge point of Gorai river.

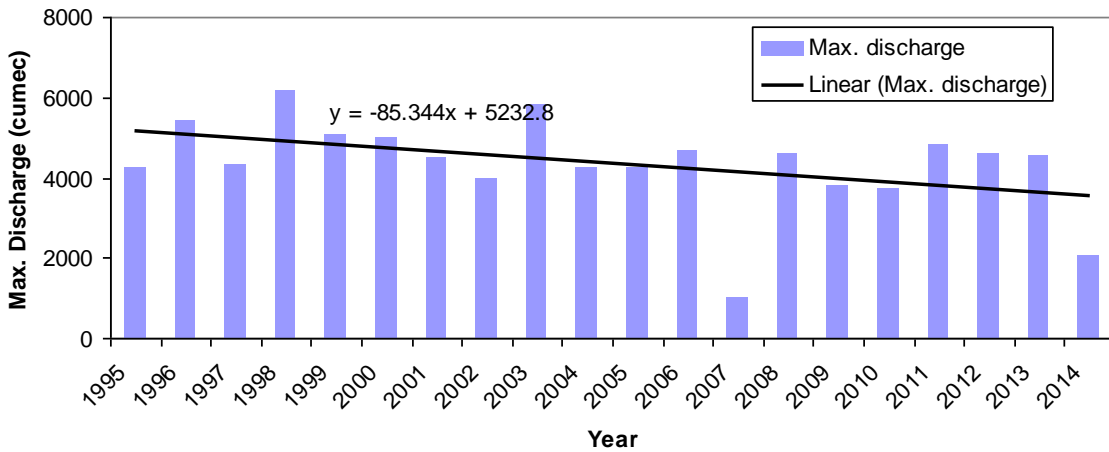


Figure 6.4: Historical annual maximum discharges at Gorai Railway Bridge.

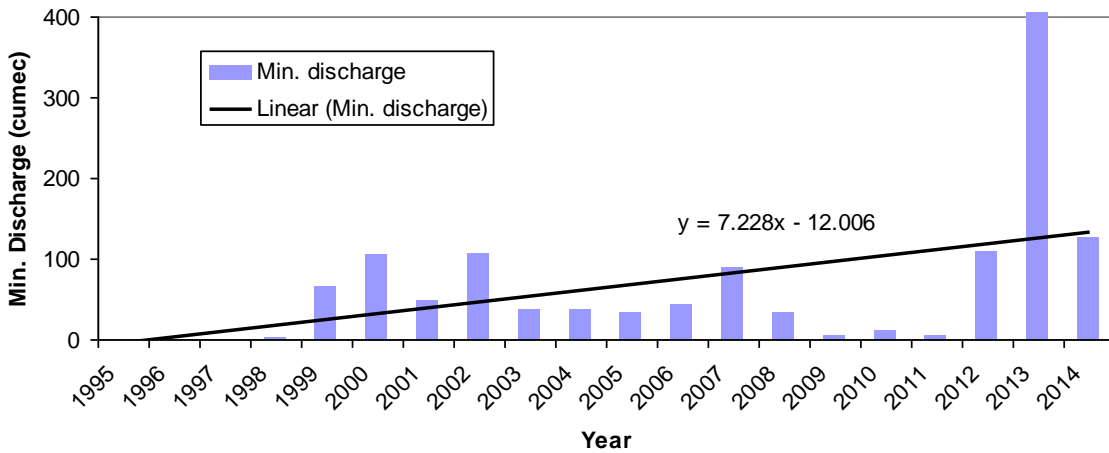


Figure 6.5: Historical annual minimum discharges at Gorai Railway Bridge.

Water Level:

Figure 6.6 shows the temporal variation of water level at Gorai Railway Bridge point. Like discharge, water level is found to be varies with seasons from nearly 4 m at winter season to over 12 m in monsoon. Figure 6.7 shows annual maximum water level for last two decades for the Gorai river at Gorai Railway Bridge Station. This water level is almost over 12 m in every year. The maximum annual water level is found in decreasing trend with time. From an average maximum water level of 12.4 m in 1995, it is decreasing by 0.048 m per year. Figure 6.8 shows annual minimum water level for last two decades for the same Station. This water level is varied from 3.5 to 6 m for different years. From an average maximum water level of 4.3 m in 1995, it is decreasing by 0.004 m per year.

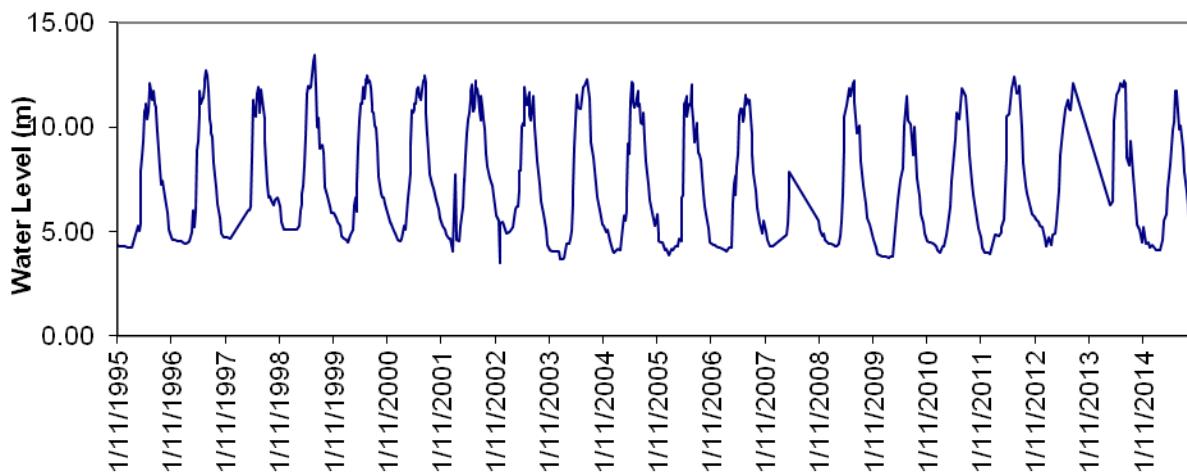


Figure 6.6: Time series of water level at Gorai Railway Bridge point of Gorai river.

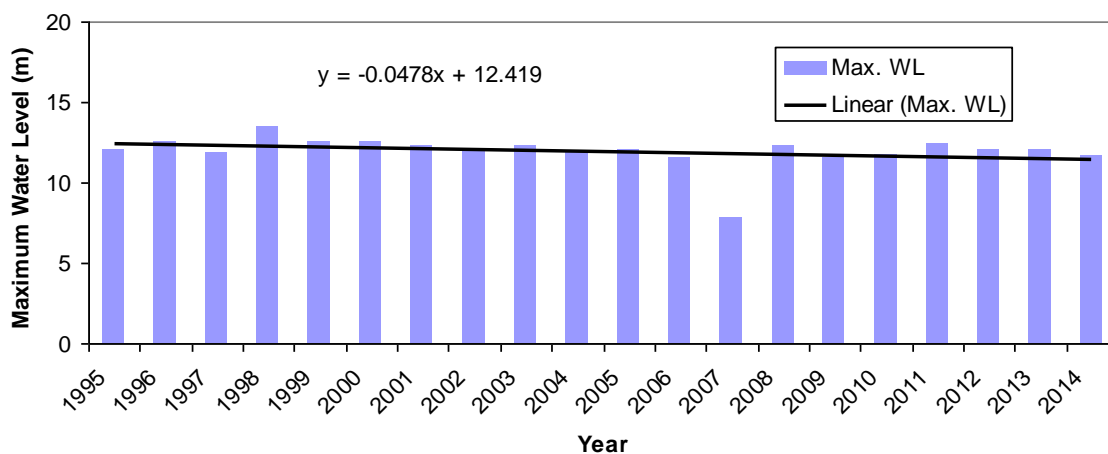


Figure 6.7: Annual maximum water levels at Gorai Railway Bridge.

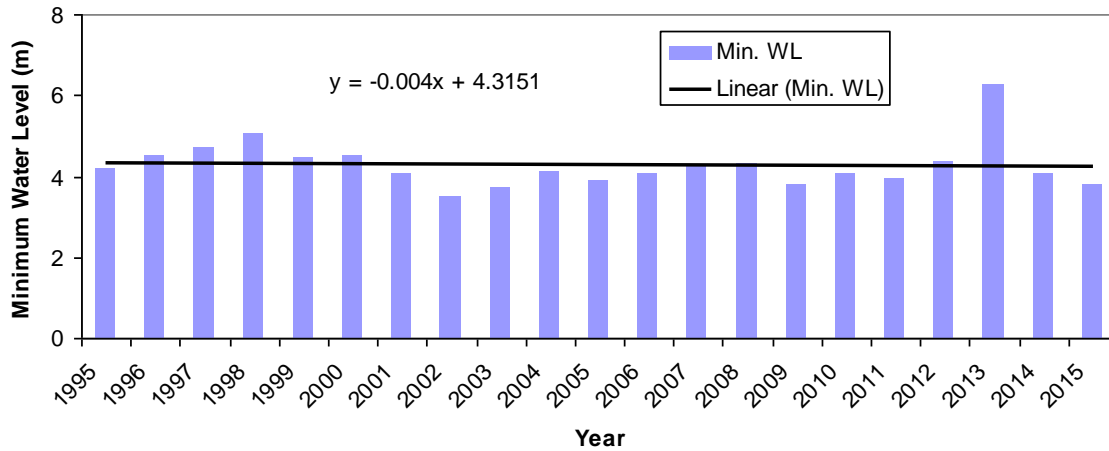


Figure 6.8: Annual minimum water levels at Gorai Railway Bridge.

6.3 GORAI -KAMARKHALI POINT

Rating Curve:

Figure 6.9 shows the relationship between water level and discharge at Kamarkhali point of Gorai river. For this point the equation of rating curve is expressed as $y = 0.495 x^{0.34}$, where y is the water level in m and x represents the discharge in cumec. The rating curve is prepared using the depth- discharge data of 1995 to 2015 collected from Bangladesh water development Board.

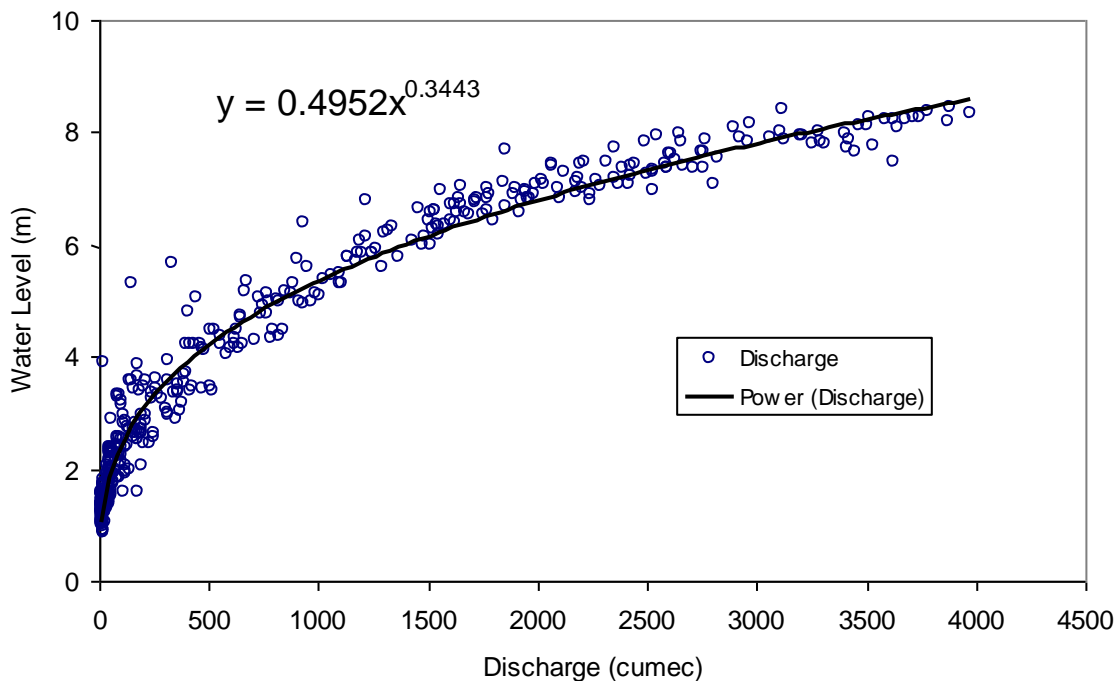


Figure 6.9: Rating curve for Kamarkhali point of Gorai river.

Discharge :

Figure 6.10 shows the temporal variation of discharge at Kamarkhali point of Gorai river. The discharge is found to be varies nearly zero at winter season to about 4000 cumec in monsoon. Very low discharge is observed in the year of early 2007 and 2009. Figure 6.11 shows annual maximum discharge for last two decades for the Gorai river at Kamarkhali point. The maximum annual discharge does not show linear increasing or decreasing trend, but a low discharge period at mid of the time span is observed. However, it is found to be varies from 1500 to 4000 cumec per year. Figure 6.12 shows annual minimum discharge for last two decades for the same Station. This Discharge is varied from zero to 50 cumec for different years. Very low discharges are observed in the years of 2008 to 2011. Due to the dredging at the mouth of Gorai river in 2011, the discharge is increased in 2012. The discharge is again decreased in the following years due to siltation at the mouth of Gorai.

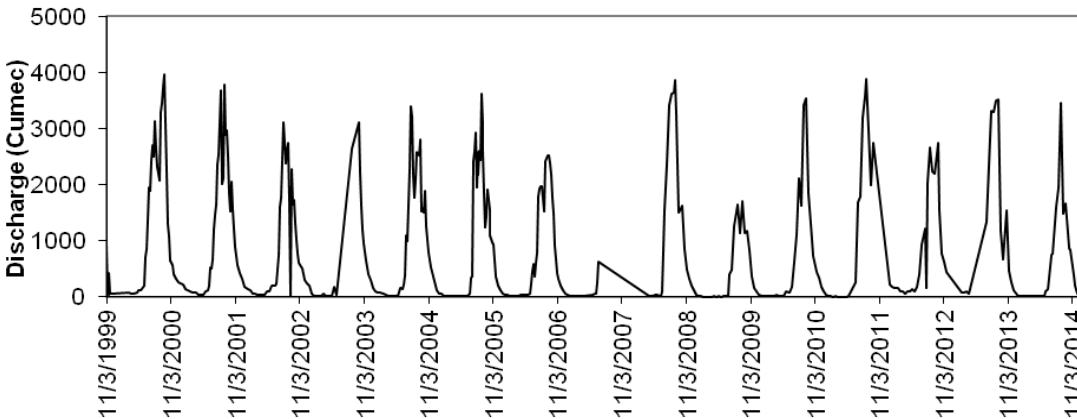


Figure 6.10: Time series of discharge at Kamarkhali point of Gorai river.

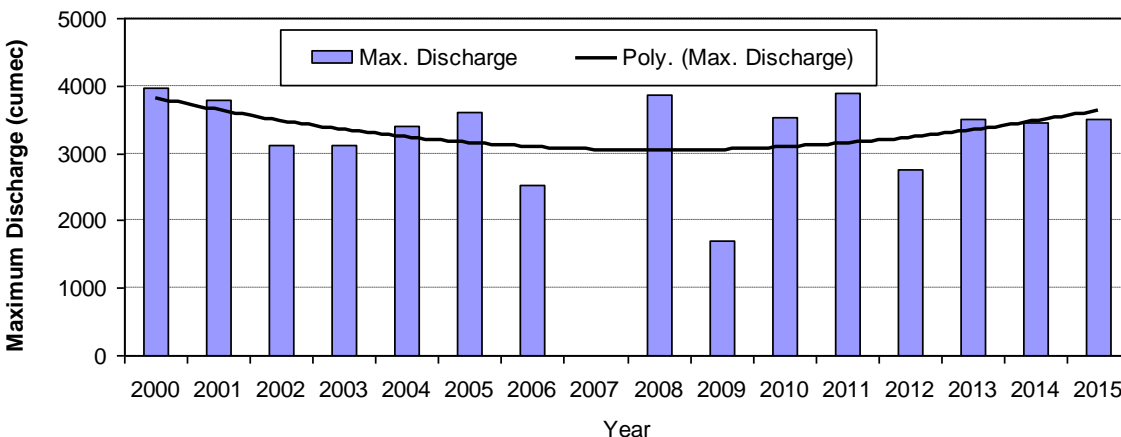


Figure 6.11: Historical annual maximum discharges at Kamarkhali point of Gorai river.

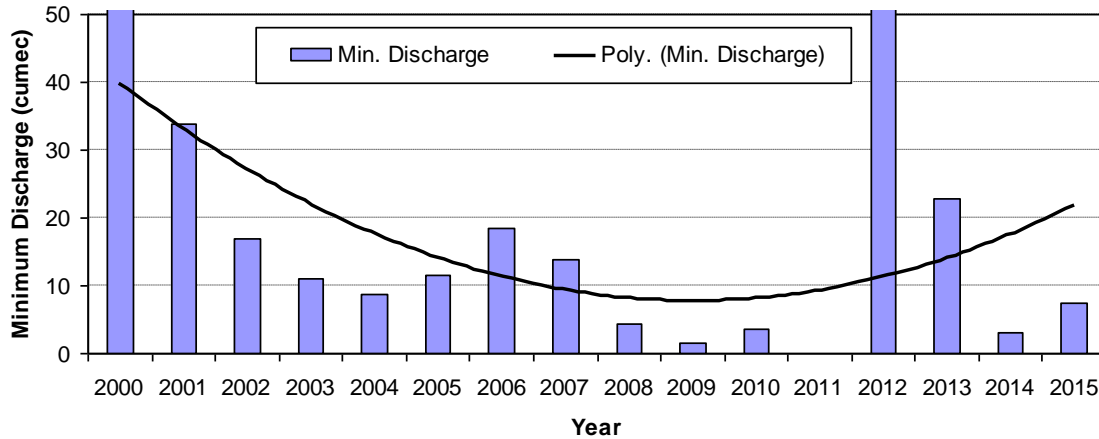


Figure 6.12: Historical annual minimum discharges at Kamarkhali point of Gorai river.

Water Level:

Figure 6.13 shows the temporal variation of water level at Kamarkhali point of Gorai river. Like discharge, water level is found to be varies with seasons from nearly 1 m at winter season to over 8 m in monsoon. Figure 6.14 shows annual maximum water level for last two decades for the Gorai river at Kamarkhali point of Gorai river. This water level is almost over 8 m in every year. No sudden decrease or uneven increase of water level is observed in the previous decades. The maximum annual water level does not show linear increasing or decreasing trend, but a low water level period at mid of the time span is observed. Figure 6.15 shows annual minimum water level for last two decades for the same Station. This water level is varied from 1.0 to 3 m for different years. As discussed above, due to the dredging at the mouth of Gorai river in 2011, the water level is increased in 2012, which is again gradually decreased in the following years due to siltation at the mouth of Gorai.

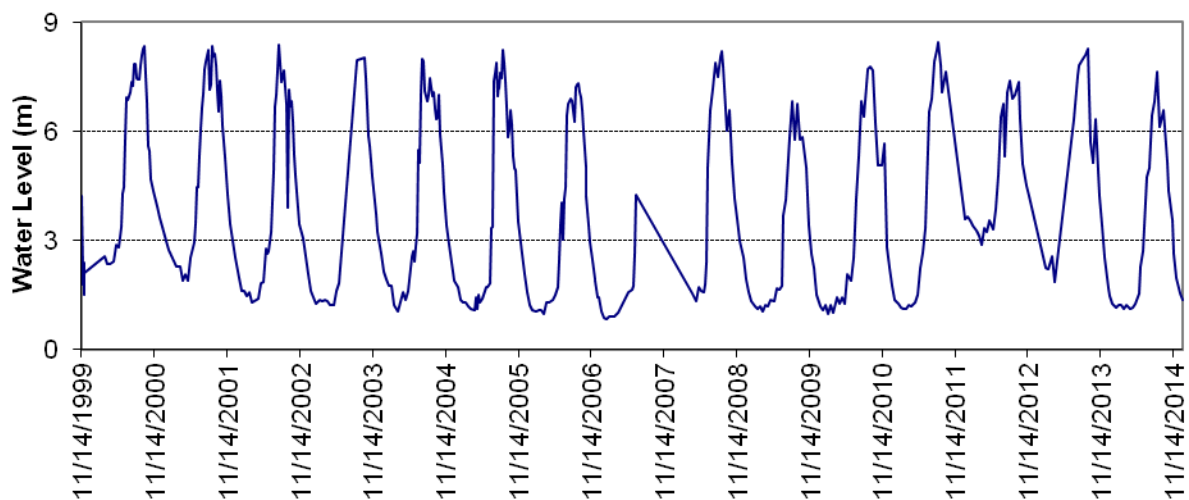


Figure 6.13: Time series of water level at Kamarkhali point of Gorai river.

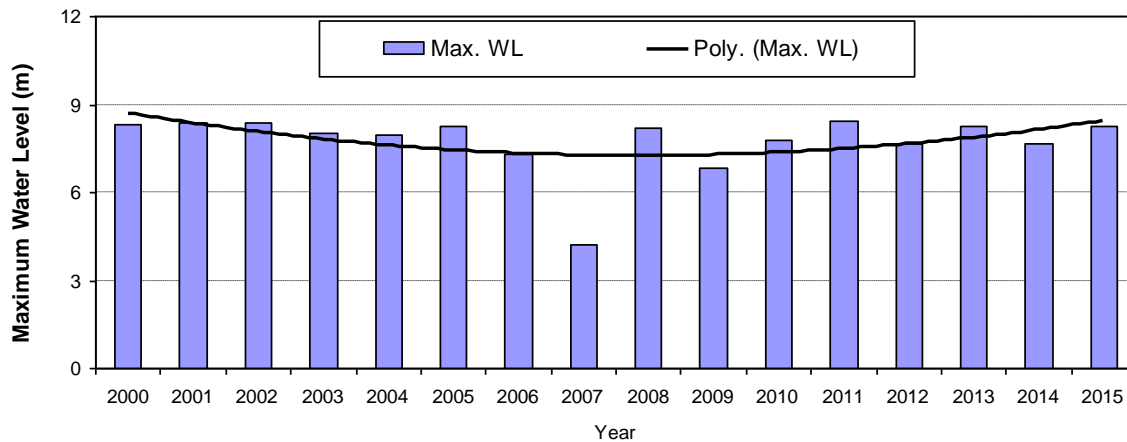
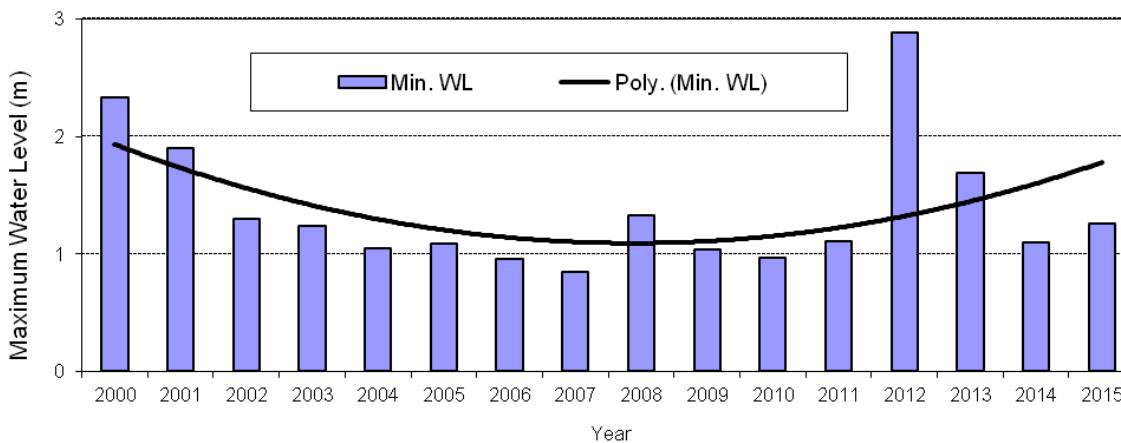


Figure 6.14: Annual maximum water levels at Kamarkhali point of Gorai river.



Figure

6.15: Annual minimum water levels at Kamarkhali point of Gorai river.

6.4 ARIALKHAN OFFTAKE POINT

Rating Curve:

Figure 6.16 shows the relationship between water level and discharge at off take . For this point the equation of rating curve is expressed as $y= 0.11 x^{0.496}$, where y is the water level in m and x represents the discharge in cumec. The rating curve is prepared using the depth- discharge data of 1995 to 2015 collected from Bangladesh water development Board.

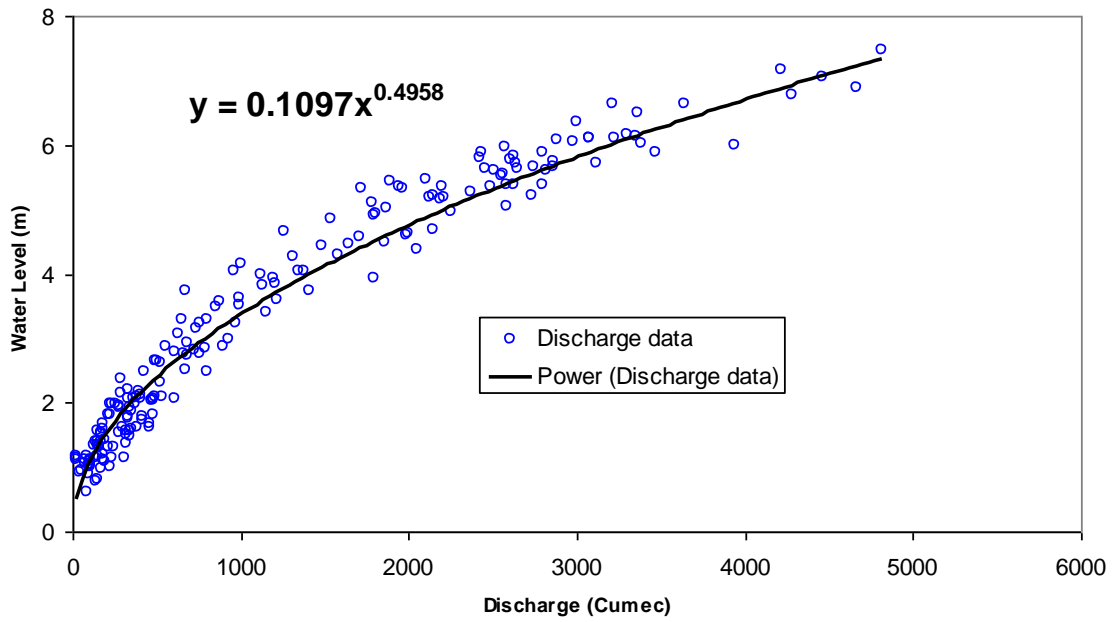


Figure 6.16: Rating curve for Arial Khan river Off Take.

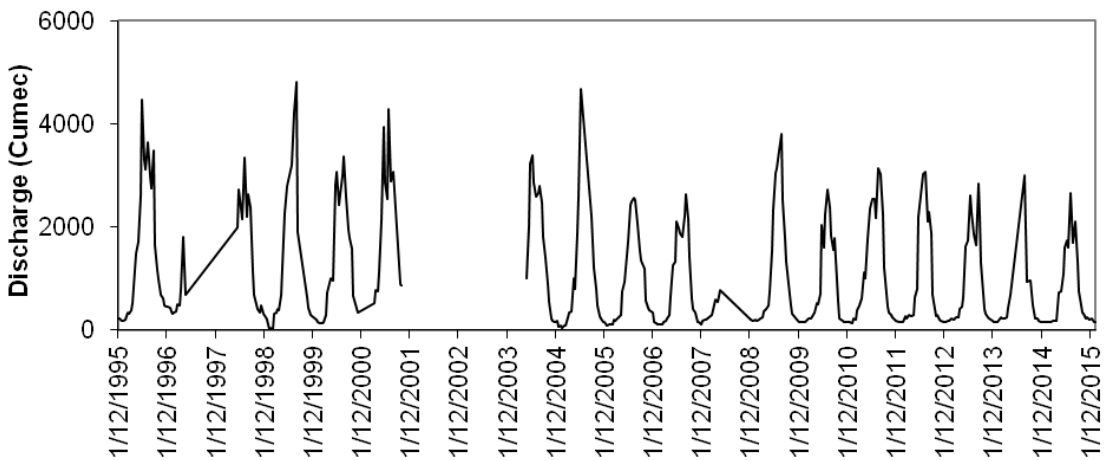


Figure 6.17: Time series of discharge at Arial Khan river Off Take.

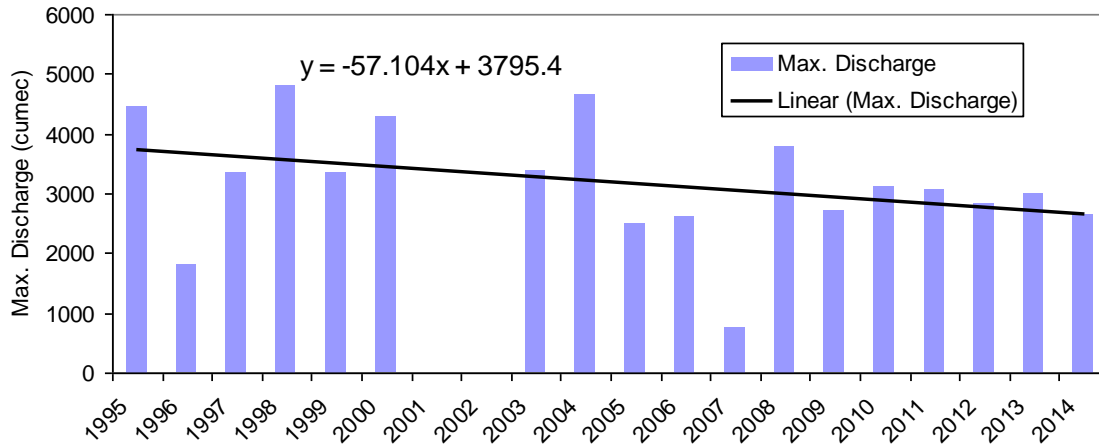


Figure 6.18: Historical annual maximum discharges at Arial Khan river Off Take.

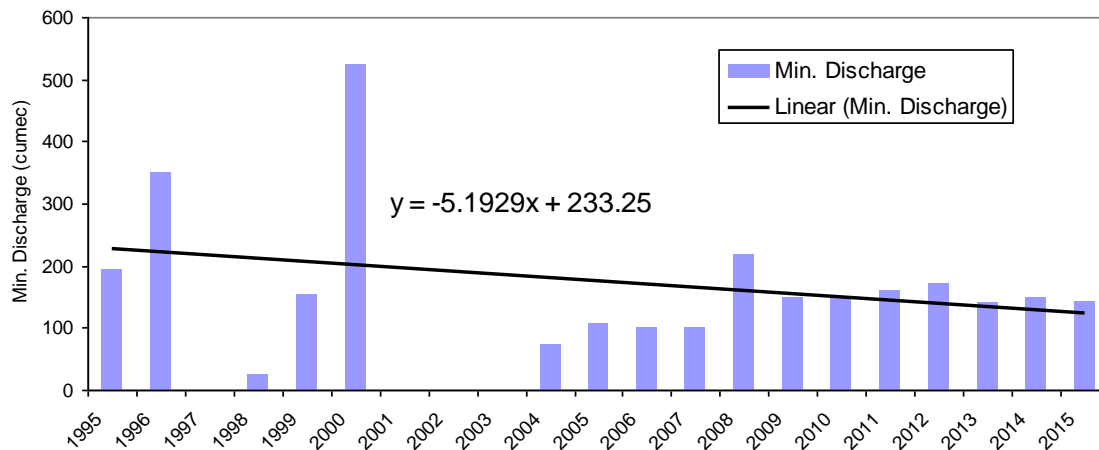


Figure 6.19: Historical annual minimum discharges at Arial Khan river Off Take.

Discharge :

Figure 6.17 shows the temporal variation of discharge at Arial Khan river Off Take. The discharge is found to be varies nearly 10 cumec at winter season to about 4000 cumec in monsoon. Figure 6.18 shows annual maximum discharge for last two decades for the at Arial Khan river Off Take. Very low monsoon discharge is observed in the year of early 2007 about 500 cumec. Except this year, the maximum discharge is found to be varied from about 2000 to 5000 cumec for the reported time span. The maximum annual discharge is found in decreasing trend with time. From an average maximum flow of 3795.4 cumec in 1995, it is decreasing by 57.3 cumec per year. Figure 6.19 shows annual minimum discharge for last two decades for the same Station. This Discharge is found to be varied from nearly zero to 500 cumec for different years. The minimum annual discharge is also found in decreasing trend with time with about 5.2 cumec per year.

Water Level:

Figure 6.20 shows the temporal variation of water level at Arial Khan river Off Take. Like discharge, water level is found to be varies with seasons from nearly 1.0 m at winter season to over 6.0 m in monsoon. Figure 6.21 shows annual maximum water level for last two decades for the Arial Khan river at its Off Take. This water level is almost over 6.0 m in every year. The maximum annual water level is found in decreasing trend with time. From an average maximum water level of 6.31m in 1995, it is decreasing by 0.032 m per year. Figure 6.22 shows annual minimum water level for last two decades for the same Station. This water level is varied from 0.75 to 2.1 m for different years. From an average maximum water level of 1.4 m in 1995, it is decreasing by 0.034 m per year.

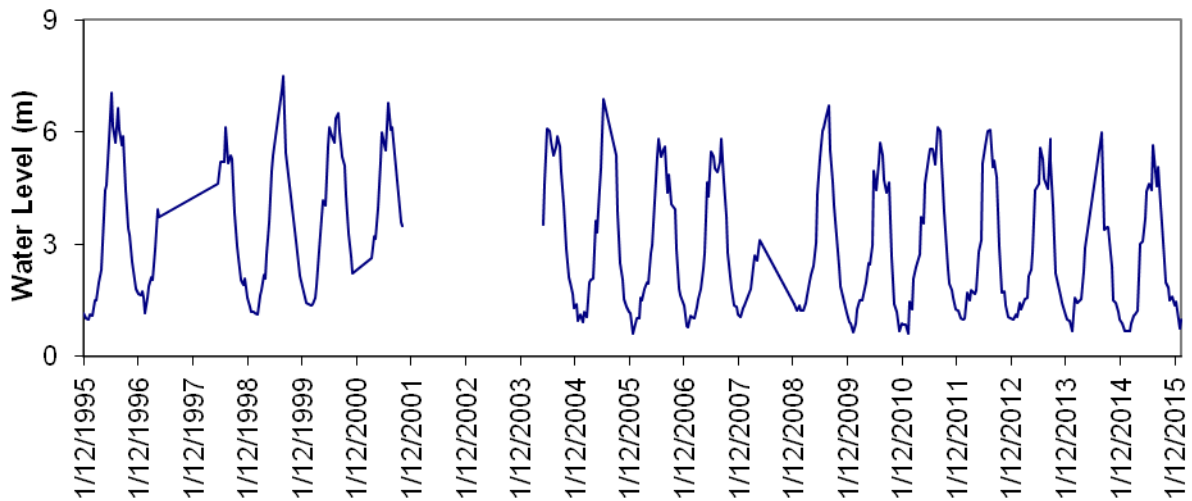


Figure 6.20: Time series of water level at Arial Khan river Off Take.

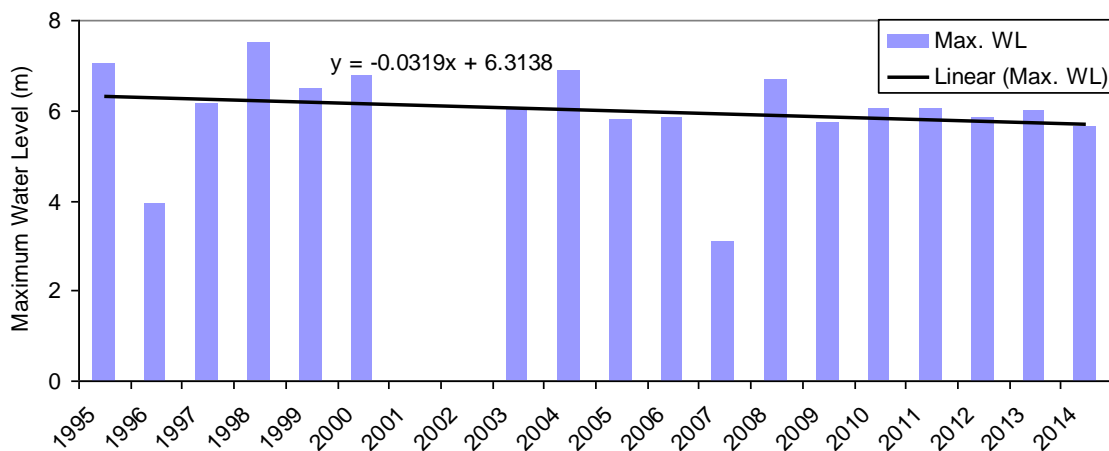


Figure 6.21: Annual maximum water levels at Arial Khan river Off Take.

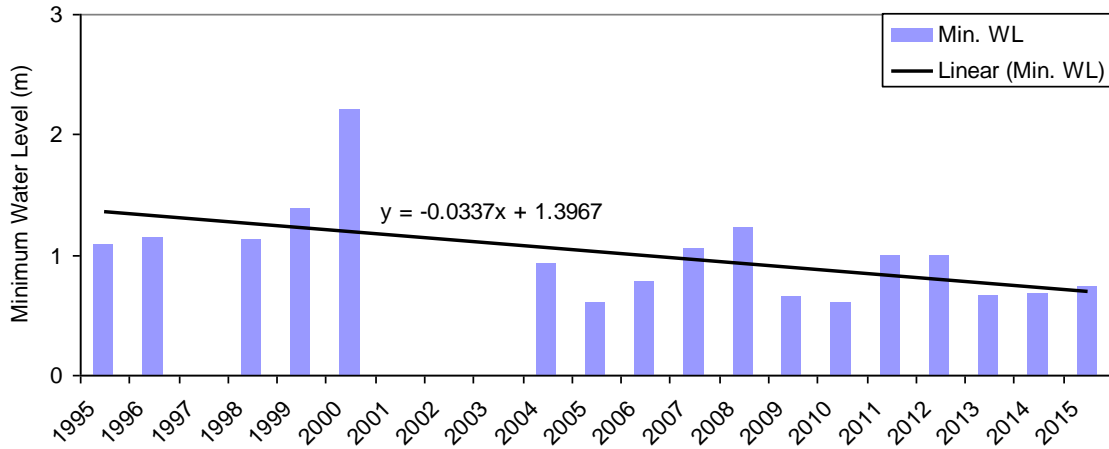


Figure 6.22: Annual minimum water levels at Arial Khan river Off Take.

6.5 MODHUMOTI MOLLAR HAT POINT

Rating Curve:

Figure 6.23 shows the relationship between water level and discharge at Mollarhat point of Modhumoti river. For this point the equation of rating curve is expressed as $y = 0.51 x^{0.337}$, where y is the water level in m and x represents the discharge in cumec. The rating curve is prepared using the depth- discharge data of 1995 to 2015 collected from Bangladesh water development Board.

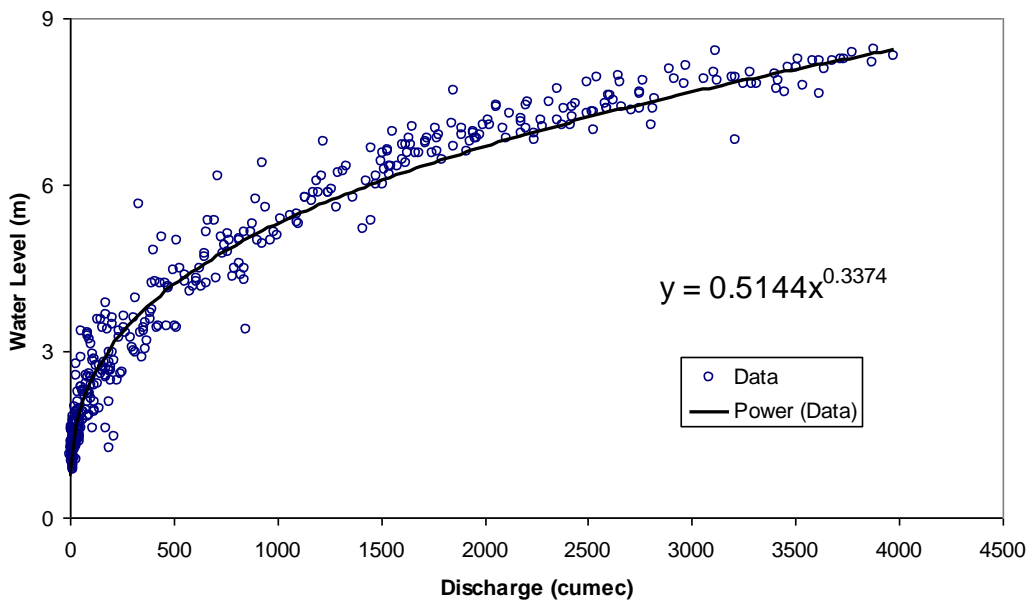


Figure 6.23: Rating curve for Modhumoti Mollarhat Point.

Discharge :

Figure 6.24 shows the temporal variation of discharge at Mollarhat point of Gorai-Modhumoti river. The discharge is found to be varies nearly zero at winter season to about 4000 cumec in monsoon. Very low discharge is observed in the year of early 2007 and 2009. Figure 6.25 shows annual maximum discharge for last two decades for the at Mollarhat point of Gorai-Modhumoti river. The maximum annual discharge does not show linear increasing or decreasing trend, but a low discharge period at mid of the time span is observed. The very low monsoon discharge is observed in the year of 2007. Except this year, the maximum discharge is found to be varied from 1500 to 4000 cumec per year. Figure 5.26 shows annual minimum discharge for last two decades for the same Station. This Discharge is varied from zero to 85 cumec for different years. Very low discharges are observed in the years of 2009 to 2011. Due to the dredging at the mouth of Gorai river in 2011, the discharge is increased in 2012. The discharge is again decreased in the following years due to siltation at the mouth of Gorai.

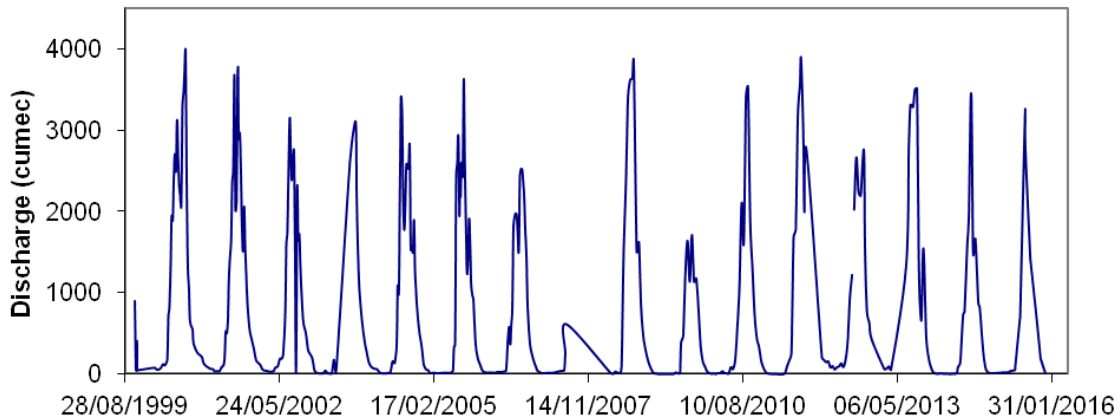


Figure 6.24: Time series of discharge at Modhumoti Mollarhat Point.

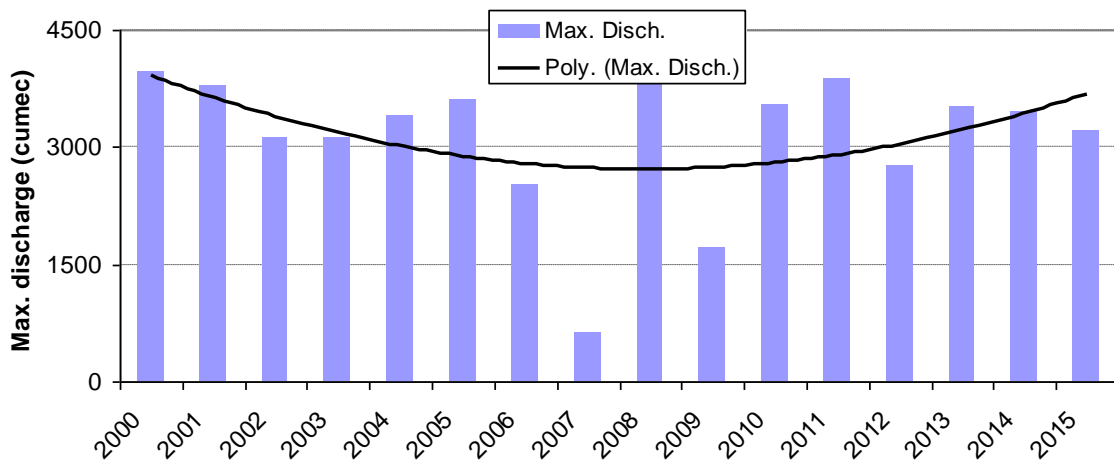


Figure 6.25: Historical annual maximum discharges at Modhumoti Mollarhat Point.

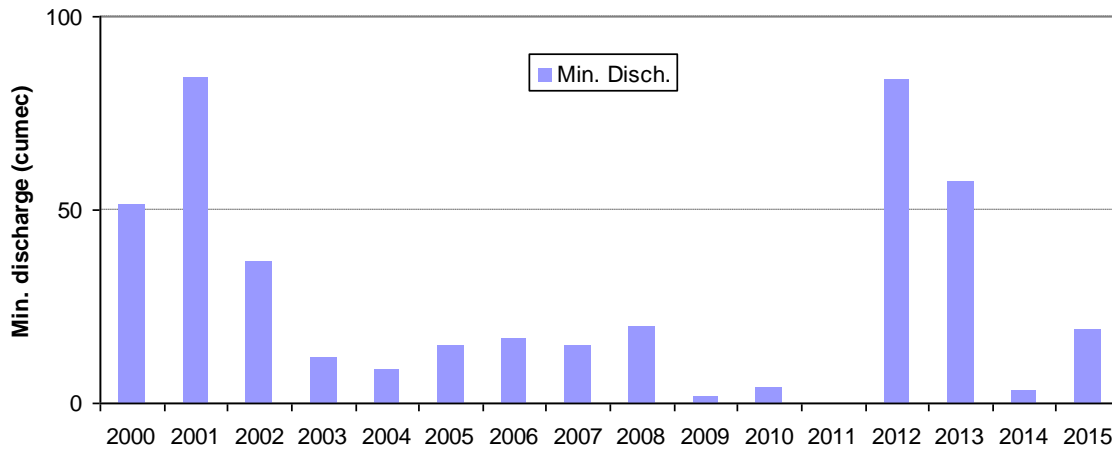


Figure 6.26: Historical annual minimum discharges at Modhumoti Mollarhat Point.

Water Level:

Figure 6.27 shows the temporal variation of water level at Mollarhat point of Gorai-Modhumoti river. Like discharge, water level is found to be varies with seasons from nearly 1 m at winter season to about 8 m in monsoon. Figure 6.28 shows annual maximum water level for last two decades for the Gorai river at Mollarhat point of Gorai-Modhumoti river. This water level is over 8 m in every year. No sudden decrease or uneven increase of water level is observed in the previous decades. From the linear trend line it is observed that from an average maximum water level of 8.23 m in 1995, it is decreasing by 0.056 m per year. Figure 6.29 shows annual minimum water level for last two decades for the same Station. This water level is varied from 1.0 to 3.0 m for different years. As discussed above, due to the dredging at the mouth of Gorai river in 2011, the water level is increased in 2012, which is again gradually decreased in the following years due to siltation at the mouth of Gorai.

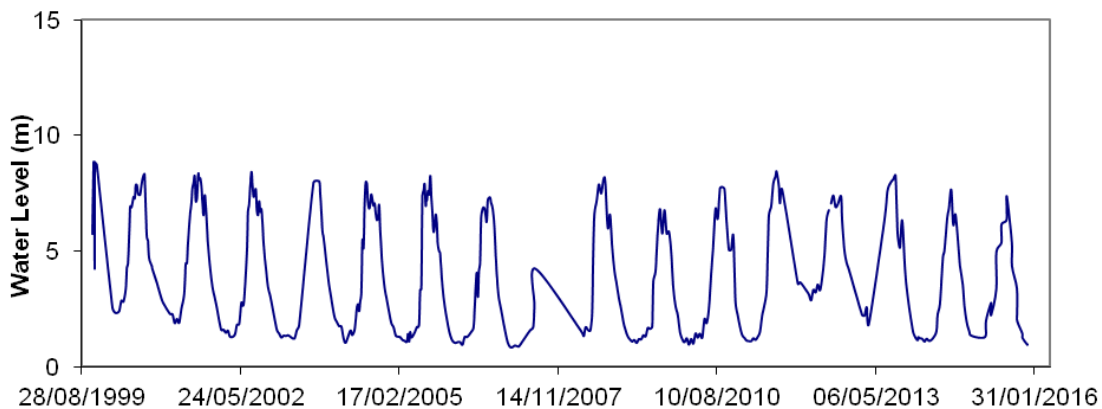


Figure 6.27: Time series of water level at Modhumoti Mollarhat Point.

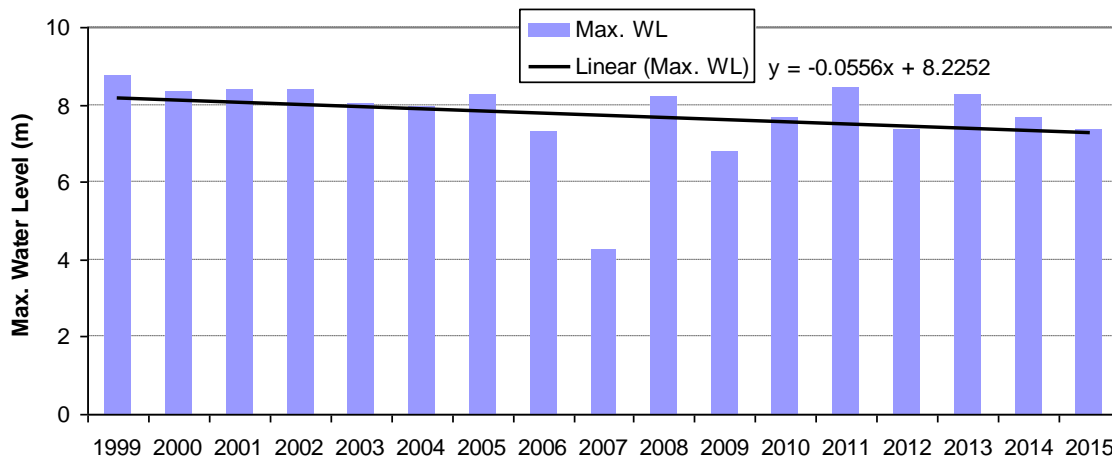


Figure 6.28: Annual maximum water levels at Modhumoti Mollarhat Point.

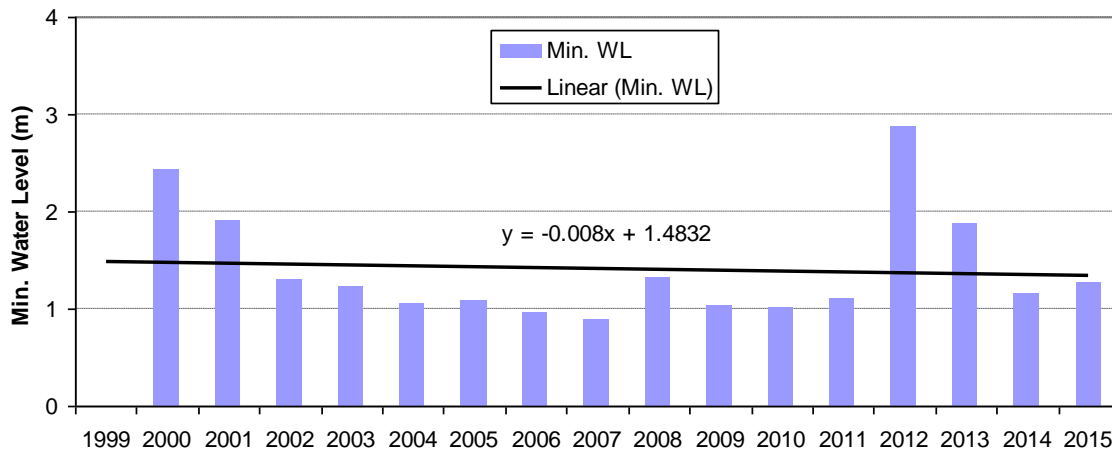


Figure 6.29: Historical annual minimum water level at Modhumoti Mollarhat Point.

6.6 AVAILABILITY OF DISCHARGE AT RAW WATER INTAKE POINT

In the low water flow season, the average water flow rate in Modhumoti river is 25.5 m³/sec in 2015 (Figure 6.26). The planned water intake volumes for Khulna City by KWASA are 110,000 m³/day (= 1.273 m³/ sec) in 2025 and 220,000 m³/day (= 2.546 m³/ sec) in 2030. Therefore, in low flow season the water will be drawn by a rate of 5.0% in 2025 and 10.0% in 2030. However, the feasibility study of KWASA assumed that safe amount to intake water from the river is less than 5%.

CHAPTER 7

Conclusion and Recommendation

7.1 INTRODUCTION

In this thesis, firstly the water quality parameters for four stations of Gorai- Modhumoti river system are presented. These stations are Station-1: Haridaspur (Kumar river), Station -2: Modhupur (Gorai-Modhumoti river), Station -3: Chapailghat (Modhumoti river) and Station -4: Mollarhat (Modhumoti river). After that the water quality parameters of Rupsha- Bhairab river system will be presented. Among the water quality parameters turbidity, pH, TDS, EC, chloride, salinity etc. are tested in the laboratory. Mayur river has not been considered in this study due to its insufficient water flow and its upstream source is almost moribund. The main water flow source of Mayur river is mainly KCC drainage waste water and rain water in rainy season.

It is observed that Mollarhat point of Modhumoti river is the nearest point to Khulna city having comparatively less salinity. As per KWASA (2010), this is the reason to select the Mollarhat point as intake of raw water for the alternate water source. In this study, the historical flow characteristics of Gorai-Modhumoti river is also studied to explain the sustainability of the raw water intake site for KWASA. Four stations are studied namely Gorai railway bridge point, Gorai-Kamarkhali bridge point, Arial Kha off-take point and Modhumoti Mollarhat point.

7.2 SALINITY IN MODHUMOTI, VAIRAB, RUPSA AND ARIAL KHAN RIVER

The result shows that salinity is increasing from February and peak in April. Chapailghat, Modhupur and Haridaspur stations are found almost same salinity; highest is about 500 mg/l and lowest is 90 mg/l. Mollarhat contained lowest salinity among the four stations. All of stations contain higher salinity in summer due to lower discharge of river. For low discharge the sea water enter the downstream of river easily and contain higher salinity as compare to the upstream of the river. Similarly, electrical conductivity is found in peak in March- April with a maximum value of about 260 uS/cm. Modhupur and Haridaspur stations contain higher electrical conductivity due to its higher salinity in water. Monthly variation of chloride concentration shows that it is increasing from February and peak in April varying from about 50 mg/l to 250 mg/l. Haridaspur station contain higher chloride concentration as compare to the other stations. Chapailghat and Mollarhat contain lower chloride concentration as compared to other two stations. All of stations contain higher chloride (with a peak value of about 250 mg/l) in summer due to lower discharge of river. For low discharge the sea water enter the downstream of river

easily and contain higher chloride as compare to the upstream of the river. In April, the chloride concentration is higher in all the four stations.

Monthly variation of salinity for the station of Rupsha River shows that salinity is increasing from February and peak in April. In the month of May highest salinity is found about 18000 mg/lit which is gradually decreasing in the following month. Due to dry season in between March –May salinity have been maximum as compared to the remaining months. For Bhairab river, monthly conductivity through the year 2015, the highest value were recorded 10463 μ S/cm at in June and the lowest was 118 μ S/cm in December. The monthly variation of the conductivity was too high specially for the month of January to April. Permissible value for BDS of conductivity is 500-700 μ S/cm for drinking water. In Bhairab river, highest chloride was recorded 14300 mg/l in June and the lowest one was 18 mg/l in November. It is observed that chloride content rises from March and get peak in June. In this dry period Bhairab River water remains high salinity.

For Off Take point of Arial Khan river, Its salinity is found to be varied from 43 to 583 mg/lit, having highest in March-April and Lowest in October. Though the low salinity level of Arial Kha river is much lower compared to Modhumoti river, the highest level of salinity of both the rivers are of same order. Bhairab-Pussur river system has the much higher salinity compared to Modhumoti and Arial Khan rivers.

7.3 WATER FLOW IN MODHUMOTI RIVER

At Gorai Railway Bridge point, the discharge of Ganges river is found to be varies nearly zero at winter season to over 6000 cumec in monsoon. The maximum annual discharge is found in decreasing trend with time. From an average maximum flow of 5232 cumec in 1995, it is decreasing by 85.3 cumec per year. Annual minimum discharge is found to be varied from zero to 400 cumec for different years. Annual minimum water level is varied from 3.5 to 6 m for different years. From an average maximum water level of 4.3 m in 1995, it is decreasing by 0.004 m per year.

At Arial Khan river Off Take the discharge is found to be varies nearly 10 cumec at winter season to about 4000 cumec in monsoon. The maximum annual discharge is found in decreasing trend with time. From an average maximum flow of 3795.4 cumec in 1995, it is decreasing by 57.3 cumec per year. The minimum annual discharge is also found in decreasing trend with time with about 5.2 cumec per year.

Modhumoti river is mainly comes through Gorai river from Ganges. A small part comes from ariakha River trough upper Kumar river. In both the source rivers, the discharges are found in decreasing trend both in monsoon and winter.

At kamarkhali Point of Gorai River the discharge is found to be varies nearly zero at winter season to about 4000 cumec in monsoon. The maximum annual discharge is found to be varies from 1500 to 4000 cumec and the annual minimum discharge is varied from zero to 50 cumec for different years. The minimum water level is varied from 1.0 to 3 m for different years. Due to the dredging at the mouth of Gorai river in 2011, the discharge and water level is found to be increased in 2012. The discharge is again decreased in the following years due to siltation at the mouth of Gorai.

At Mollarhat point of Gorai-Modhumoti river, the discharge is found to be varies nearly zero at winter season to about 4000 cumec in monsoon. The maximum discharge is found to be varied from 1500 to 4000 cumec per year. Annual minimum discharge is varied from zero to 85 cumec for different years. Very low discharges are observed in the years of 2009 to 2011. Like discharge, water level is found to be varies with seasons from nearly 1 m at winter season to about 8 m in monsoon. From the linear trend line it is observed that from an average maximum water level of 8.23 m in 1995, it is decreasing by 0.056 m per year. Annual minimum water level is varied from 1.0 to 3.0 m for different years. As discussed above, due to the dredging at the mouth of Gorai river in 2011, the water level is increased in 2012, which is again gradually decreased in the following years due to siltation at the mouth of Gorai.

7.4 CONCLUSION AND RECOMMENDATION

- There are many rivers flow through south western zone into or nearby the Khulna city and meet with Bay of Bengal in southern part of Bangladesh. Those are the Bhairab, Rupsha, Kobadak, Pashur, Mayur, Modhumoti etc. Most of the rivers contain higher salinity which is not permissible in drinking. From comparison it is found that Modhumoti River contains very low amount of chloride concentration and salinity as compare to the other rivers.
- However, the salinity level is found to be increasing with time. Increasing upstream Gorai river flow is the principal option for the sustainability of water quality. Avoiding shrimp culture near the Gorai- Modhumoti river bank may protect the river water from local salinity intrusion.
- In the low water flow season, the average water flow rate in Modhumoti river was 25.5 m³/sec in 2015. The planned water intake volumes for Khulna City by KWASA are 110,000 m³/day (= 1.273 m³/ sec) in 2025 and 220,000 m³/day (= 2.546 m³/ sec) in 2030. Therefore, in low flow season the water will be drawn by a rate of 5.0% in 2025 and 10.0% in 2030. However, the feasibility study of KWASA assumed that safe amount to intake water from the river is less than 5%.
- Modhumoti River is mainly comes through Gorai river from Ganges. A small part comes from Arial khan River trough upper Kumar river. In both the source rivers, the discharges are found in decreasing trend both in monsoon and winter.

- It is evident from the Gorai river discharge and dredging history at Gorai mouth that dredging effectively increases the flow in Gorai river, though huge siltation affect negatively afterwards. Therefore, to increase the discharge of Gorai river, it is necessary to keep dredging on a regular basis of Gorai River, which will maintain potential flow of Modhumoti River. Dredging length of Gorai- Modhumoti project period have to divide into two stages, i.e. capital dredging for some years and maintenance dredging followed after that as per requirements.
- In addition, Kumar river bed dredging to divert flow of Arial Khan river may help further to increase the flow in Modhumoti River.
- Flow Divider at Gorai Off-take can be installed to divert Ganges Flow into Gorai-Modhumoti river.

7.5 RECOMMENDATION FOR FUTURE STUDY

Following studies are recommended for the further study for the better understanding of quality and available quantity of Gorai river and its tributaries.

- The correlation between salinity and river flow for the Gorai river system including its main two branches can be investigated.
- The tidal effect on the salinity of river flow and its extend in upward direction can be considered an interested topic for further study .
- Mathematical modeling of flow and sediment transport and effect of sediment quality on salinity of river flow can be considered as further study.
- Flow simulation on Divider at Gorai Off-take and its impact on downstream river system is recommended as another further study.
- Flow-duration analysis of Gorai river system and time series analysis of salinity for different stations of the river route can be considered as future study.

REFERENCES

ADB (2011) Preparing the Khulna Water Supply, Technical Assistance Consultant's Report, Project Number: P 42171-012, For Government of the People's Republic of Bangladesh, Asian Development Bank, Manila, Philippines.

Adhikary, S.K., Das Gupta, A. and Babel, M.S., 2011. Modeling groundwater flow and salinity intrusion by advective transport in the regional unconfined aquifer of southwest Bangladesh. Proc. of the 3rd Int. Conf. of European Asian Civil Engineering Forum (EACEF-2011), Yogyakarta, Indonesia, September 20-22, 2011, 2, 91-97.

Ali, M. S. and Syfullah, K. (2012) Possible Effect of Sea Level Rise on the Livelihood of Beel Dakatia: Local Peoples' Perception, Journal of Engineering Science (JES), KUET, Bangladesh, ISSN 2075-4914, Vol. 3, No. 1, pp. 68-78.

Akter, J., Sarker, M. H. and Haque, P. (2013) Morphological Processes and Effective River Erosion Management: A case Study of the Arial Khan River in Bangladesh, 4th International conference on Water & Flood management (ICWFM-2013), IWFM, BUET, Bangladesh.

Ali, A., 1999, Climate change impacts and adaptation assessment in Bangladesh: Climate Research, v. 12, p. 109–116.

Ali, A., 1996, Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges: Water, Air, & Soil Pollution, v. 92, no. 1, p. 171–179.

Burgess, W. G., Hoque M. A., Michael H. A., Voss C. I., Breit G. N. and Ahmed K. M. (2010) Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic, Nature Geoscience, Vol. 3, pp. 83 - 87

CEGIS (2012) Planform analysis and Gorai river restoration project, Final report, Bangladesh Water Development Board, Ministry of water resources, Government of Bangladesh.

DHI (1996) River Survey Project (FAP 24) - Geomorphology and channel dimensions: special report no. 7; Morphology of Gorai off-take: special report no. 10; Sediment balance: special report no. 12; Floodplain levels and bankfull discharge: special report no. 16. WARPO, Dhaka, Bangladesh.

DHV-WARPO (2001) Feasibility Report on Gorai River Restoration Project, Bangladesh Water Development Board, Ministry of water resources, Government of Bangladesh.

Dasgupta, S., Huq, M., Khan, Z.H., Ahmed, M.M.Z., Mukherjee, N., Khan, M.F., and Pandey, K. (2010) Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost: Environment, April, p. 54.

ECR (1997) The environment conservation rules 1997. Bangladesh Gazette no. DA-1, Ministry of Environment and Forest, Dhaka, Bangladesh, pp 1324-1327.

EGIS (2000). Environmental and Geographical Information Studies Bangladesh Water Development Board-Environmental baseline of Gorai River restoration project. (EGIS-I, EGIS-II, and EGIS-III). Environment and GIS support project for water sector planning, Ministry of Water Resources, Government of the Peoples Republic of Bangladesh, EGIS, Dhaka, 190.

FAO (2012) Irrigation in Southern and Eastern Asia in figures: AQUASTAT Survey -2011: Food and Agriculture Organization of the United Nations, 1–487.

Findikakis, A. N. and Sato, K. (2011) Groundwater Management Practices, IAHR Monographs, CRC Press, USA.

Gain, A. K. and Giupponi, C. (2014) Impact of the Farakka Dam on Thresholds of the Hydrologic Flow Regime in the Lower Ganges River Basin (Bangladesh), Water 2014, Vol. 6, pp. 2501-2518.

Hore SK , Sarker MH, Ferdous MR, Ahsan M , and Hasan MI (2003) Study of the Off-Take Dynamics for Restoring the Gorai River, 4th International Conference on Water & Flood Management (ICWFM-2013), IWFM, BUET, Bangladesh.

IPCC (2007) Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson, Eds.): Cambridge University Press, Cambridge, UK.

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (C. B. Field, V. Barros, T. F. Stockner, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds.): Cambridge University Press, Cambridge, UK.

Islam S N and Gnauck A (2008). Mangrove wetland ecosystems in Ganges-Brahmaputra delta in Bangladesh. Front Earth Sci. China, 2(4), 439–448.

Islam S (ed.,) (2006). Banglapedia: Ganges-Padma River System, National Encyclopaedia of Bangladesh, Asiatic Society of Bangladesh. Asiatic civil Military Press, Dhaka. <http://www.banglapedia.org/English/Index.htm>.

Islam, M.R., Begum, S.F., Yamaguchi, Y., and Ogawa, K. (1999) The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation: *Hydrological Processes*, v. 13, no. 17, p. 2907–2923

IWM (2014) *Salinity in the South West Region of Bangladesh*. Institute of Water Modelling, Bangladesh.

IWM (2010) *Ganges River Basin Modeling, Final Report prepared for World Bank*, Institute of Water Modeling, Bangladesh.

Kartiki, K. (2011) *Climate change and migration: a case study from rural Bangladesh: Gender & Development*, v. 19, no. 1, p. 23–38

Kuehl, S.A., Allison, M.A., Goodbred, S.L., and Kudrass, H. (2005) *River Deltas: Concepts, Models, and Examples*, in Giosan, L. and Bhattacharya, J.P. eds., *Holocene*, SEPM (Society for Sedimentary Geology), p. 413–434

KWASA (2010). *Feasibility study for Khulna water Supply improvement project in Bangladesh*, Khulna WASA, Bangladesh.

Mirza, M.M.Q., 1996. Diversion of the Ganges water at Farakka and its effects on salinity in Bangladesh, *Journal of Environmental Management*, 22, 711-722.

Nahar MS, Zhang J, Ueda A, and Yoshihisa F. (2014) Investigation of severe water problem in urban areas of a developing country: the case of Dhaka, Bangladesh. *Environ Geochem Health*, Vol. 36(6), Paper no. 1079-94. doi: 10.1007/s10653-014-9616-5.

Palash, W., Quadir, M.E., Shah-Newaz, S.M., Kirby, M.D., Mainuddin, M., Khan, A.S., Hossain, M.M. (2014) *Surface Water Assessment of Bangladesh and Impact of Climate Change*, Chapter 7, Institute of Water Modelling, Bangladesh and Commonwealth Scientific and Industrial Research, Australia.

PUB (2010) *Environmental baseline of Gorai River restoration project, Pāni Unnāyana Borda*, Environment and GIS Support Project for Water Sector Planning, Bangladesh. Ministry of Water Resources, Bangladesh.

Rahman, M., Das, R., Hassan, N., Roy, k., Haque, F., Akber, A. (2014). ‘Environmental Study on water quality of Mayur river with reference to suitability for irrigation, *International Journal of Environmental Science*, volume 4, No 6.

Sarker, M.H. (2004) *Impact of Upstream Human Interventions on The Morphology of the Ganges-Gorai System*, in M.M.Q. Mirza (Ed.), *The Ganges Water Diversion: Environmental Effects and Implications*, Kluwer Academic Publishers, Dordrecht, pp. 49-80.

Sarker M.H, Kamal M.M and Hassan K, 1999, The Morphological Changes of a distributary of Ganges in response to the Declining Flow using Remote Sensing”, Proceedings of the 20th Asian Conference on Remote Sensing, Vol.1.

Shammi, M., Abedin, J.G.M.B., Kamal, A. K.I., Rahman, R.M., Rahman, M.M., Uddin, M.K., (2012) Investigation of salinity occurrences in Kumar-Modhumoti River of Gopalganj District, Bangladesh, Journal of Natural Science and Sustainable Technology, Volume 6, Number 4.

Shamsad, S. Z. K. M., Islam, K. Z., Mahmud, M. S., Hakim, A. (2014) Surface Water Quality of Gorai River of Bangladesh. Journal of Water Resources and Ocean Science. Vol. 3, No. 1, pp. 10-16.

USAID (2014) Safeguarding The World’s Water, USAID Report of Water Sector Activities, Water and Development Strategy Implementation, Fiscal Year 2014, USA. (<https://www.usaid.gov/sites/default/files/documents/1865/>).

Umitsu, M. (1993) Late quaternary sedimentary environments and landforms in the Ganges Delta: Sedimentary Geology, v. 83, no. 3-4, p. 177–186, doi:10.1016/0037-0738(93)90011-S.

United Nations (2010) Cyclone Aila: Joint UN Multi-Sector Assessment & Response Framework, pp. 1-44.

United Nations (2007) Cyclone Sidr: United Nations Rapid Initial Assessment Report, pp. 1–14.

WARPO (2001) National Water Management Plan, Bangladesh Water Development Board, Ministry of water resources, Government of Bangladesh. 1–227.

WHO (2006) Guidelines for drinking water quality, World Health Organization, WHO Press, Geneva, Switzerland .

Williams, C.A. (1919) History of the Rivers in the Ganges Delta 1750-1918, Bengal Secretariat Press, 1919, Reprinted by East Pakistan Inland water Transport Authority, 1966.