

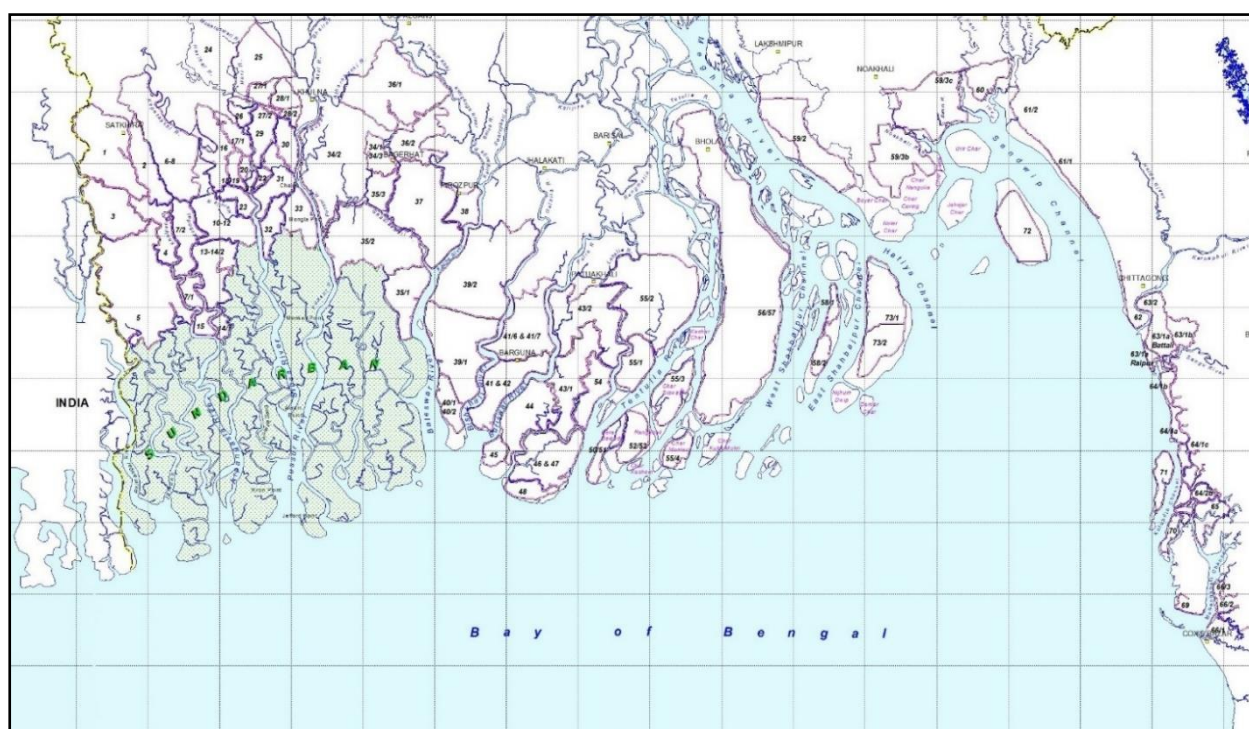
Ministry of Water Resources



Bangladesh Water Development Board

Coastal Embankment Improvement Project, Phase-I (CEIP-I)

Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)



Component-4D: The Effect of Climate Change on Water Levels, Salinity Intrusion and Storm Surges Interim Report on Salinity Modelling Current Situation

September 2021



Ministry of Water Resources



Bangladesh Water Development Board

Coastal Embankment Improvement Project, Phase-I (CEIP-I)

**Long Term Monitoring, Research and Analysis of
Bangladesh Coastal Zone (Sustainable Polders Adapted to
Coastal Dynamics)**

**Component-4D: The Effect of Climate Change on Water Levels,
Salinity Intrusion and Storm Surges
Interim Report on Salinity Modelling Current Situation**

September 2021



Table of contents

1	Introduction.....	1
2	Description of Study Area	3
2.1	Rationale of the Study	3
2.2	South West/Southcentral Hydrological Region	3
2.3	Impact of Upstream flow condition on River Salinity	4
3	Survey & Data Collection	11
3.1	Data Collection Plan	11
3.2	Salinity long Profile variation along the River	16
3.3	Variation of salinity across the Depth	20
4	Development of Mathematical Model	27
4.1	Framework of mathematical Model	27
4.2	Description of Bay of Bengal Model	32
4.2.1	Mesh Generation & Study area Discretization	32
4.2.2	Boundary Condition	32
4.2.3	Bed Roughness	33
4.2.4	Bathymetric Data	35
4.2.5	Advection Dispersion Co-efficient.....	35
4.2.6	Calibration of 2D Hydrodynamic & Advection Dispersion Model	35
4.3	Description of South West Regional Model.....	39
4.3.1	Model simulation.....	39
4.3.2	Boundary Conditions	39
4.3.3	Bed Resistance.....	42
4.3.4	Sensitivity of Bed resistance (Manning's M) observed in 1D SWRM model	42
4.3.5	Dispersion co-efficient used in the 1D mathematical model (SWRM).....	44
4.3.6	Sensitivity of Dispersion co-efficient observed from SWRM	45
4.3.7	Calibration of Hydrodynamic & Advection Dispersion of SWRM	47
5	Spatial Variation of Salinity.....	59
5.1	Methodology for Interpretation of Model result.....	59
6	Future Work Plan	64
7	Reference	66

List of Figures

Figure 2-1: South west region is divided into three regions according to salinity level and availability of fresh water.	4
Figure 2-2: Schematics of Gorai- Nabaganga-Rupsha-Pussur river system.....	5
Figure 2-3: Change of salinity at Mongla in Pussur River with the flow of Gorai river.....	6
Figure 2-4: Salinity change at Nabaganga River (Bardia) for Dredging of the Gorai river	7
Figure 2-5: Salinity change at Rupsha River (Khulna) for Dredging of the Gorai river.....	7
Figure 2-6: The longitudinal profile of saline intrusion from the Bay due to sea level rise (Without Ganges Barrage, with Ganges Barrage, with Ganges Barrage + 59 cm sea level rise) (Source: Ganges Barrage Study Project, 2012)	9
Figure 3-1: Salinity Monitoring stations.....	12
Figure 3-2: Seasonal variation of surface water salinity at Pussur River (Hironpoint), Baleswar river (Char Doani), Bishkhali river (downstream), Buriswar River (Amtali)	13
Figure 3-3: Seasonal variation of surface water salinity at Andharmanik River (Kalapara), Rabnabad Channel (Modhupara), Mohipur channel and Lower Meghna River (Daulatkhan).	15
Figure 3-4: Long profile salinity measurement along the highlighted channel.....	17
Figure 3-5: Salinity variation along the length of river shown in Figure 3-4.....	19
Figure 3-6: Location of salinity measurement (vertical profiling)	21
Figure 3-7: Vertical Salinity and Temperature Profile at Betmargang River. (Date of measurement: 20th November, 1991) (Source: SWMC, 1993)	22
Figure 3-8: Vertical Salinity and Temperature Profile at Arpangashia River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)	22
Figure 3-9: Vertical Salinity and Temperature Profile at Pussur River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)	22
Figure 3-10: Vertical Salinity and Temperature Profile at Sibsa River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)	23
Figure 3-11: Vertical Salinity and Temperature Profile at Lower Meghna River. (Date of measurement: 14th March, 1991) (Source: SWMC, 1993).....	23
Figure 3-12: Vertical Salinity and Temperature Profile at Char Zahiruddin (Lower Meghna River). (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)	23
Figure 3-13: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993).....	24
Figure 3-14: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993).....	24
Figure 3-15: Across depth salinity variation at Karnaphuli.....	25
Figure 4-1: Flow chart of salinity model	27
Figure 4-2: Superposition of SWRM model domain onto BoB model domain.	28
Figure 4-3: Boundary generation obtain from SWRM for upstream flow of Bay of Bengal	30
Figure 4-4: Down Stream boundaries of SWRM One dimensional model	31
Figure 4-5: Bay of Bengal Model Boundary	33
Figure 4-6: Manning map used in two-dimensional Mathematical model.....	34
Figure 4-7: Comparison of Observed and Simulated Water Level at Charduani (Baleswar River) (left) and Amtali (Buriswar River) (right).....	36
Figure 4-8: Comparison of Observed and Simulated water level at Hironpoint (Pussur River) (left).....	36
Figure 4-9: Comparison of Observed and Simulated Salinity at Hironpoint (Pussur River) (right) and Daulatkhan (Lower Meghna River) (left)	37
Figure 4-10: Comparison of Observed and Simulated Salinity at Charduani (Baleswar River) (right) and Modhupara (Andharmanik river) (left)	37
Figure 4-11: River network system & boundary condition in South west regional model.....	40
Figure 4-12: Optimization of manning's roughness with trial simulation of different bed resistance (at Bishkhali River).	42
Figure 4-13: Optimization of manning's roughness with trial simulation of different bed resistance (at Pussur River).	43

Figure 4-14: Optimization of manning’s roughness with trial simulation of different bed resistance (at Sibsa River).	43
Figure 4-15: Optimization of manning’s roughness with trial simulation of different bed resistance (at Baleswar River).....	44
Figure 4-16: Optimization of dispersion co-efficient with trial simulation (for Rupsha River).	45
Figure 4-17: Optimization of dispersion co-efficient with trial simulation (for Baleswar River). ...	46
Figure 4-18: Optimization of dispersion co-efficient with trial simulation (for Buriswar River). ...	46
Figure 4-19: Optimization of dispersion co-efficient with trial simulation (for Sibsa River).	47
Figure 4-20: Water level and flow calibration location.	48
Figure 4-21: Calibration plot of Dry season flow at Bishkhali (left) and Pussur (right)	49
Figure 4-22: Calibration plot of Dry season flow at Sibsa (left) and Baleswar (right)	50
Figure 4-23: Calibration plot of Monsoon season flow at.....	51
Figure 4-24: Calibration plot of Water level data in Buriswar river at Amtali (left) and in Pussur river at Joymoni (Right)	52
Figure 4-25: Calibration plot of Water level data in Sibsa river at Nalian (left) and in Baleswar river at Charduani (Right)	53
Figure 4-26: Salinity calibration plot at Rupsha River	54
Figure 4-27: Salinity calibration plot at Sibsha River	55
Figure 4-28: Salinity calibration plot at Sibsha River	55
Figure 4-29: Salinity calibration plot at Chapilaghat (Madhumati River).....	56
Figure 4-30: Salinity calibration plot at Patgati (Madhumati River).....	56
Figure 4-31: Salinity calibration plot at Amtali (Buriswar River)	57
Figure 4-32: Salinity calibration plot at Amtali (Buriswar River)	57
Figure 4-33: Salinity calibration plot at Ghashiakhali River	58
Figure 4-34: Salinity calibration plot at Gangril River.....	58
Figure 5-1: 1ppt salinity contour at Southwest regional model in dry season.	60
Figure 5-2: 2 ppt salinity contour at Southwest regional model in dry season	61
Figure 5-3: Salinity Raster during March, 2019	62

List of Table

Table 2-1: Proposed flow diversions for salinity control (Source: Ganges Barrage Study Project, 2012)	8
Table 4-1: Dispersion Coefficient used in the mathematical model.....	35
Table 4-2: Boundary Conditions applied to a One-dimensional South West regional model.....	41
Table 4-3: Dispersion co-efficient used in the major river systems	44
Table 4-4: Comparison of simulated and observed maximum ebb flow and flood flow	49
Table 4-5: Comparison of simulated and observed maximum ebb flow and flood flow	50
Table 4-6: Comparison for statistics of water level for simulated and observed data	52
Table 4-7: Comparison for statistics of water level for simulated and observed data	53



ACRONYMS AND ABBREVIATIONS

HD-Hydrodynamic

WL-Water Level

IWM-Institute of Water Modelling

BWDB-Bangladesh Water Development Board

BTM-Bangladesh Transverse Mercator

DTU-Technical University of Denmark

PPT-Parts Per Thousand

BoB-Bay of Bengal

SWRM-South West Regional Model

1D-One Dimensional

2D-Two Dimensional

1 Introduction

The present report is primarily a technical report, describing the work done so far on the modelling of salinity intrusion into the Southwest and South-Central Delta in Bangladesh. At this point the modelling framework has been calibrated and verified to be capable of predicting the distribution of salinity in time and space within the modelled area. This ensures that the modelling framework is suitable for future studies including factors such as climate change (change in rainfall and sea level rise) and subsidence.

Salinity intrusion Modelling is one of the major tasks defined under **component 4**. Component 4 covers the long-term modelling processes in the coastal zone of Bangladesh. Component 4 has four different sections. And salinity modelling is included under **component 4D**. **Component 4D covers the following objectives:**

1. Salinity level at river system in base and future condition (for sea level rise in climate change condition);
2. Devise scenarios (by redistributing flow within river system) and strategies to optimise salinity level in the coastal zone.
3. Reports showing the Explanation of geo spatial variation of salinity for different scenarios.

However, this report describes the problems caused by an increasing salinity intrusion, due to a lowering of transboundary flow. It is also illustrated how dredging in Ganges distributaries (in Gorai River) have a significant impact on salinity. This is followed by a description of the study area and the available salinity measurements.

Section 4 describes the model framework consisting of a 2-dimensional model of Bay of Bengal and a detailed 1-dimensional model of the Southwest Region model. These two models are solved in an iterative manner to achieve proper boundary condition for the 1-dimensional regional model, which finally is used to depict salinity intrusion into the delta. The results of the model calibration are presented, followed by presentations of some special salinity plots. It is concluded that the model is suitable for further studies of saline intrusion.

Finally, the report offers a plan for future work. After finalization of future scenarios, (such as sea level rise under emission scenario, land subsidence and engineering interventions etc.). Then salinity simulation will be carried out and corresponding geo spatial analysis done for these scenarios. Then all the objectives of component 4D (relating to salinity intrusion) will be achieved.

2 Description of Study Area

2.1 Rationale of the Study

Over the past few decades, salinity in the coastal areas has increased greatly due to decrease of transboundary flow and increase sea levels. Increased salinity intrusion in the coastal belt, especially in the south-west region of Bangladesh affects public health, livelihoods and coastal ecosystem of the area. Climate change is already taking place, adding pressures on the management of scarce water resources.

Scarcity of freshwater in the near future would reduce the availability of safe drinking water and sufficient food, and negatively impact social conditions. The saline water intrusion is depleting the surface water irrigation water during the dry period. Due to increased salinity levels in the rivers, the practice of shrimp culture inside the embankments increased over the years, decreasing the extent of agricultural land. As a result of these adverse environmental and ecological effects, and serious social problems between the farmers and fishermen community has become evident. Major shrimp culture activities exist around Satkhira, Khulna and Bagerhat districts in the western zone, and also in Chokoria, Cox's Bazar and Moheshkhali upazilas under the Cox's Bazar District in the east. Moreover, the ecology of the Sundarbans, a large mangrove forest in this area and a world heritage site, is also being affected by salinity intrusion and sea level rise.

River salinity is highly variable with space and seasons. This study will simulate the spatial and seasonal variation of surface water salinity under present conditions as well as in the future.

2.2 South West/Southcentral Hydrological Region

The problem of salinity intrusion in the southwest coastal zone (presented in Figure 2-1) is acute. Gorai River is the largest tributary of Ganges River. Moreover, there are other tributary rivers, such as Mathabhanga, Ichamoti and Baral (upper). However, almost all these tributaries of Ganges River are disconnected from the Ganges and tidal influence is stronger during dry season because of minimum downward push of fresh water flow. As a result, salinity intrusion is higher during the dry season.

Gorai River is one of the major tributaries of Ganges River that supplies fresh water flow to southwest and southcentral region. Offtake of the river remains dry from December to March and the river comes alive during monsoon season. Salinity of Rupsha River, Pussur River and Sibsha River depends on the flow of Gorai River.

Unlike Gorai River, Arial Khan River is very much alive in all seasons. Arial Khan River is a tributary of Padma River. Buriswar, Bishkhali and Baleswar Rivers receive fresh water flow from Arial Khan river and Lower Meghna River and therefore, salinity intrusion in these rivers are lesser compared to the Ganges-dependent and Gorai dependent rivers.

Lower Meghna and Tentulia rivers receive fresh water from Padma, Upper Meghna and Brahmaputra Rivers. Combined Fresh water flow of these rivers, push down the salinity and salinity level in these rivers remain much less even during the dry season. The mixed zone (Figure 2-1) is dependent on both Padma and Meghna rivers.

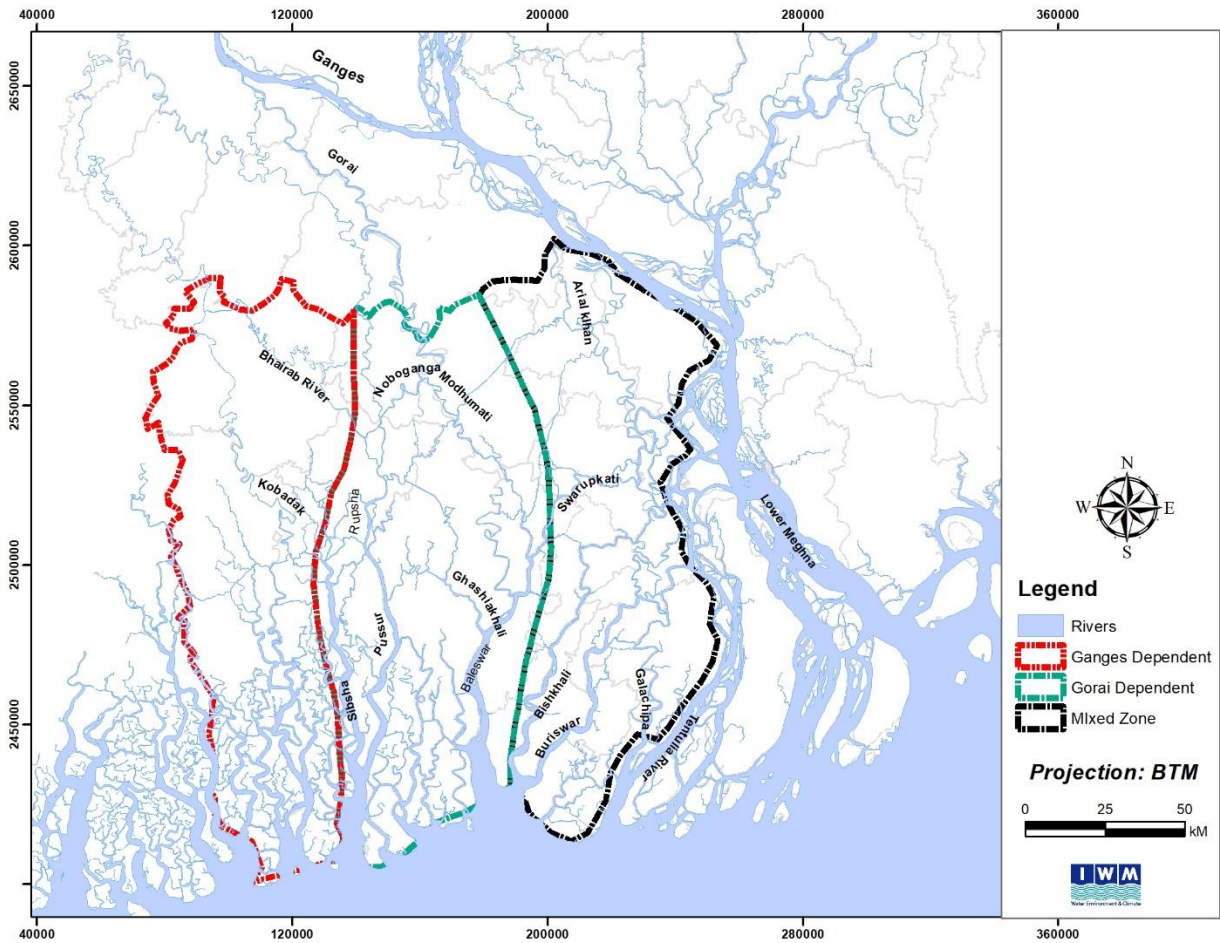


Figure 2-1: South west region is divided into three regions according to salinity level and availability of fresh water.

2.3 Impact of Upstream flow condition on River Salinity

Transboundary flow significantly affects the salinity intrusion in the river system of Bangladesh. Fresh water flow pushes down the saline water. In the southwest region, salinity intrusion in the Ganges and Gorai-dependent area (shown in **Figure 2-1**) is dependent on fresh water flow of Gorai River. Salinity increases with decreased flow in Gorai River, alternatively salinity decreases with high flow of Gorai River.

Figure 2-2 shows the “Gorai-Nabaganga-Rupsha-Pussur” river system. Available salinity monitoring station (for year 2019-2021) in this river system is super-imposed. However, effect of Gorai river flow on the salinity level at Nabaganga and Pussur River will be discussed on following paragraphs.

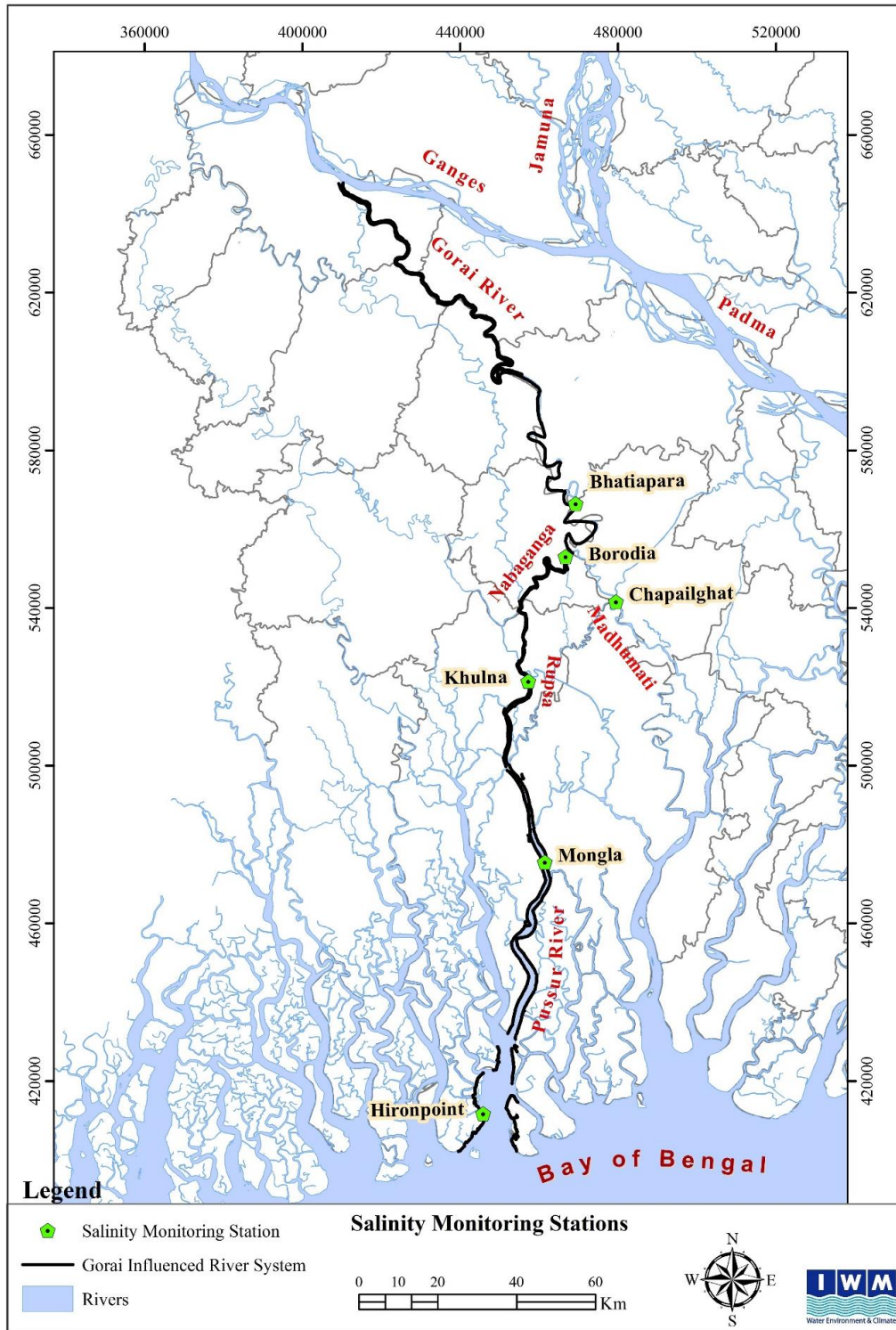


Figure 2-2: Schematics of Gorai- Nabaganga-Rupsha-Pussur river system.

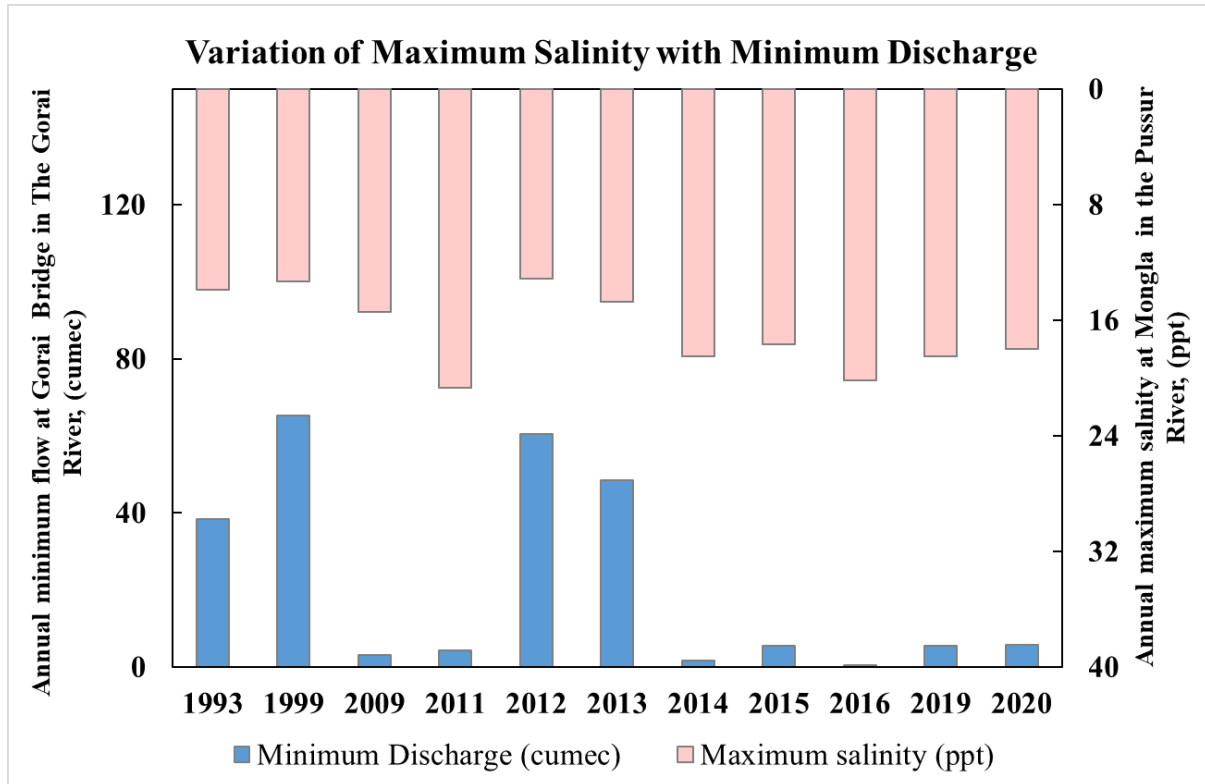


Figure 2-3: Change of salinity at Mongla in Pussur River with the flow of Gorai river.

Figure 2-3 shows change of maximum salinity at Mongla in Pussur River with the dry season flow of Gorai River. Mongla is on the bank of Pussur River at about 62 km north of the Bay of Bengal coast. Gorai does not receive adequate flow from Ganges River in dry season due to siltation at its offtake. Government of Bangladesh has a project to dredge the offtake of Gorai River periodically. The Gorai offtake was dredged and had significant dry season flow in **2012-2013** and consequently, salinity drastically reduced in the Gorai dependent area. This scenario also indicates the influence of water flow through the Gorai River on salinity intrusion in the river system. **Figure 2-4** and **Figure 2-5** shows comparison of salinity at Bardia and Khulna before dredging (**year 2011**) and after dredging conditions (**year 2012**).

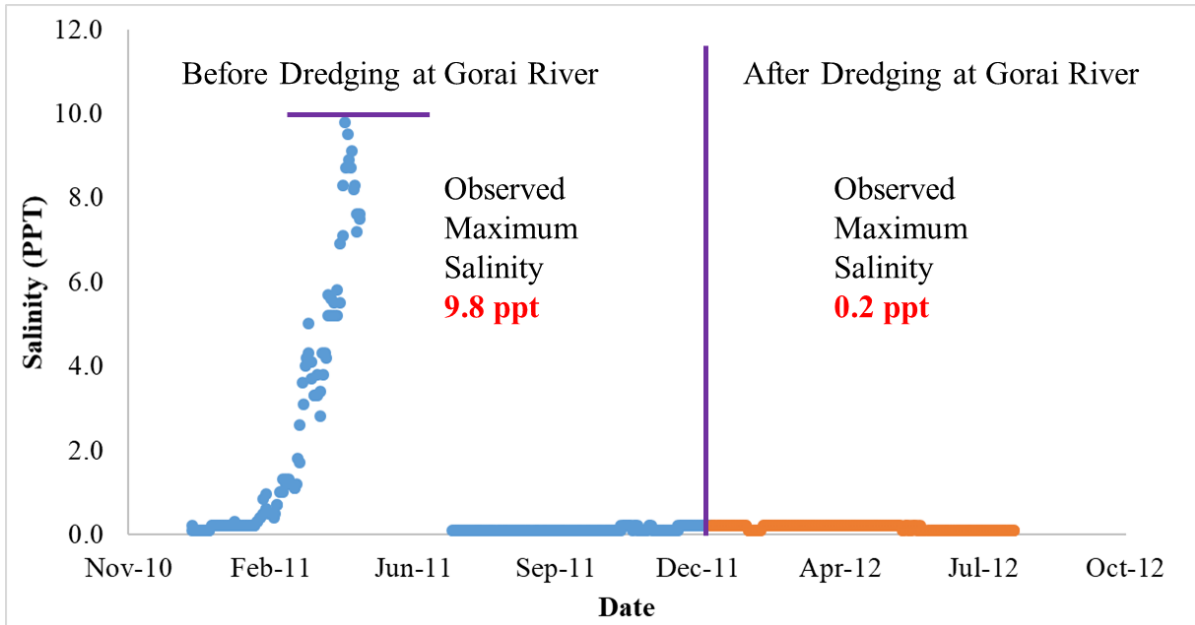


Figure 2-4: Salinity change at Nabaganga River (Bardia) for Dredging of the Gorai river

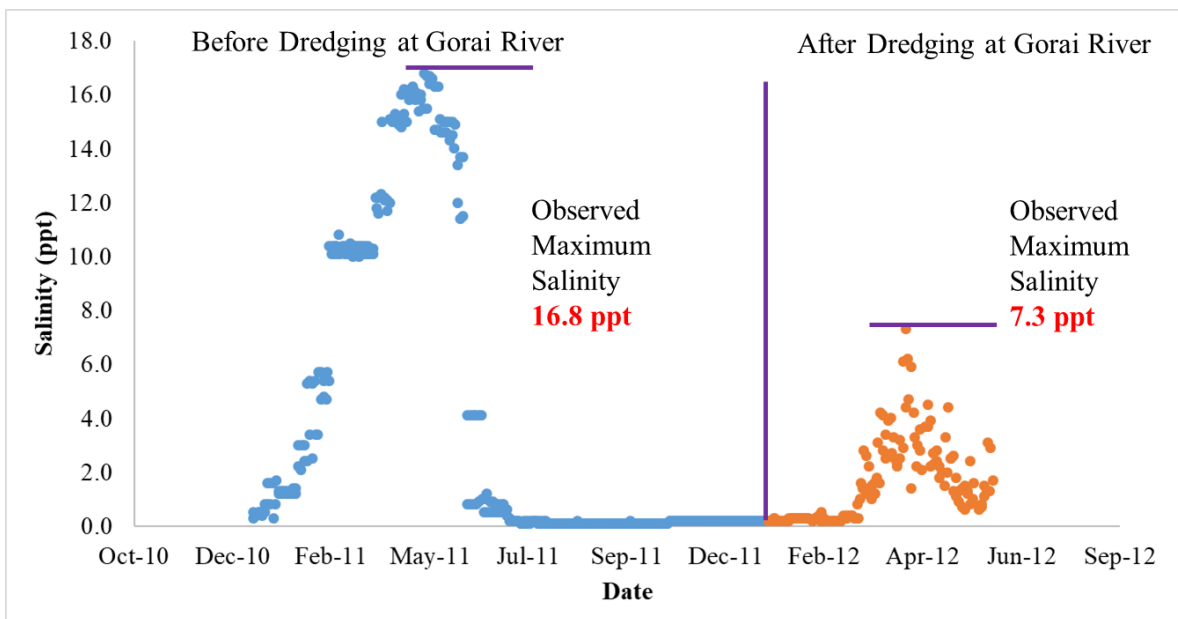


Figure 2-5: Salinity change at Rupsha River (Khulna) for Dredging of the Gorai river.

However, it is apparent that, flow augmentation of Gorai River is necessary to check the salinity intrusion at the Ganges dependent area. And this can be achieved with Engineering intervention, such as Ganges Barrage.

In the Ganges Barrage Study Project (2012), IWM simulated the calibrated salinity model as per planned flow diversions from Ganges River for limiting salinity considering the proposed Ganges Barrage in operation mode. The Main Consultant (MC) suggested two options for flow diversions (**Table 2-1**) in the Gorai River, Bhairab Upper River + Mukteswari - Hari River, Kobadak River + Harihar River and Betna River for limiting salinity level at key locations.

Table 2-1: Proposed flow diversions for salinity control (**Source:** Ganges Barrage Study Project, 2012)

River Name	Flow diversion (m ³ /s) for salinity control		
	No diversion (Base)	With diversion	
		Option-1	Option-2
Gorai	0	150	150
Bhairab Upper	0	25	10
Mukteswari-Hari	--	0	15
Kobadak	0	50	25
Harihar	--		25
Betna	0	25	39

The model simulation was conducted from January to June. The model results indicate that in **option-1** and **option-2**, some of the major rivers such as Gorai-Madhumati, Nabaganga, Chitra, Atai, Bhairab Upper would be saline free and all other rivers will have significant reduction of salinity. **Figure 2-6** shows the comparison of long profile salinity along Gorai -> Nabaganga -> Rupsha -> Pussur river system for without Ganges barrage (on year 2010-2011), with Ganges barrage condition (on year 2010-2011) and with Ganges Barrage (year 2010-2011+ 67 cm Sea level rise).

Figure 2-6 shows the long profile of maximum salinity (month April and May) intrusion for year 2011. The profile starts from Hironpoint (Downstream) to inland propagation up to Bhatiapara. The profile is shown for no flow diversion and flow diversion scenarios (Ganges Barrage, **Option-2**). The maximum salinity intrusion occurs up to Bhatiapara, approximately 220 km upward from the Bay following waterway, for no flow diversion scenario. While for with Ganges Barrage condition, salinity level propagation reduces up to Khulna, approximately 100 km down from Bhatiapara.

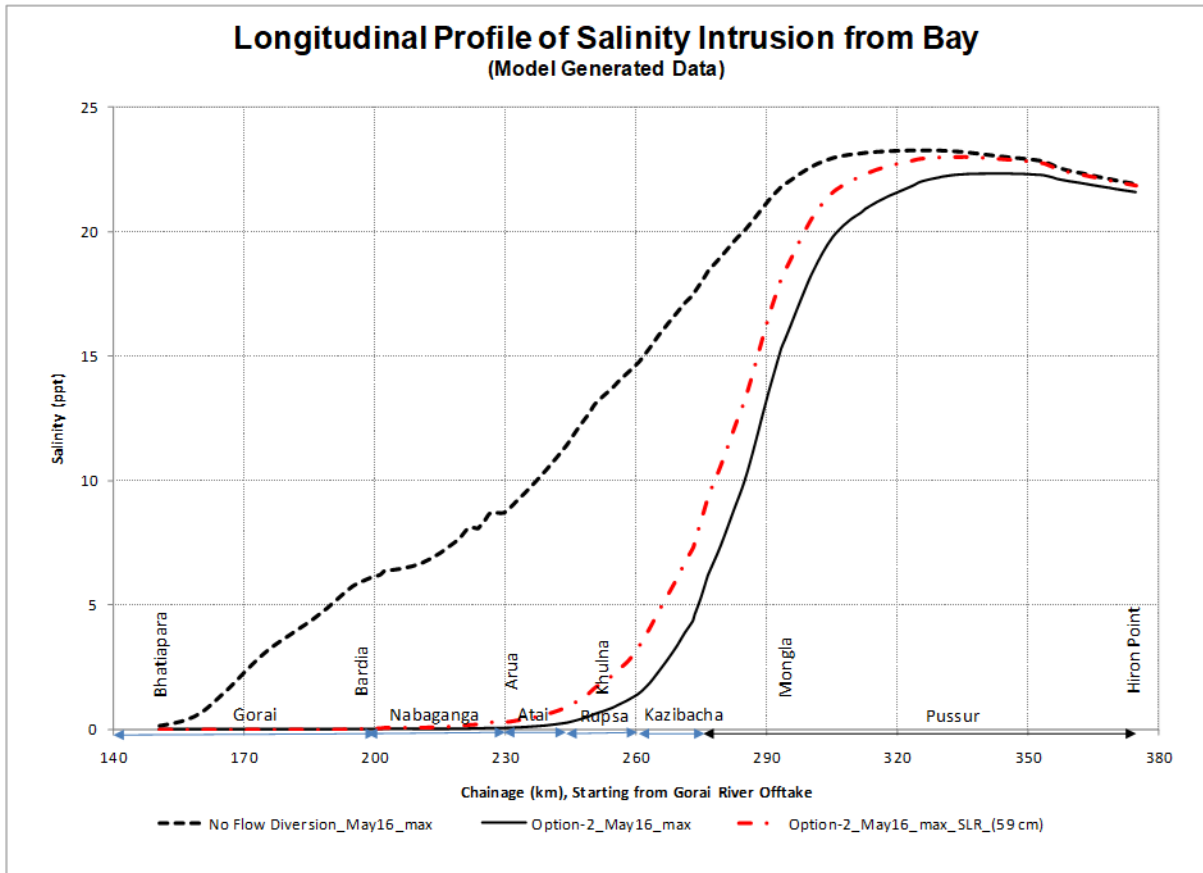


Figure 2-6: The longitudinal profile of saline intrusion from the Bay due to sea level rise (Without Ganges Barrage, with Ganges Barrage, with Ganges Barrage + 59 cm sea level rise) (Source: Ganges Barrage Study Project, 2012)

3 Survey & Data Collection

3.1 Data Collection Plan

The coastal zone of Bangladesh is primarily divided into three hydrological regions:

- a. South west/southcentral zone
- b. South East Hydrological zone
- c. Eastern Hill Hydrological zone

Salinity measurements are proposed to cover up these three hydrologic zones. A total of 30 nos. of salinity monitoring stations are established from February 2019 to continuously monitor salinity of surface water at the major rivers. Among the salinity monitoring stations, 23 are situated in southwest/ south central zone, 4 stations are situated in south east hydrological zone and 3 stations are situated in Eastern Hill hydrological zone. **Figure 3-1**, shows the location of salinity monitoring stations. For surface water salinity measurement saline water samples are collected from top of the river water.

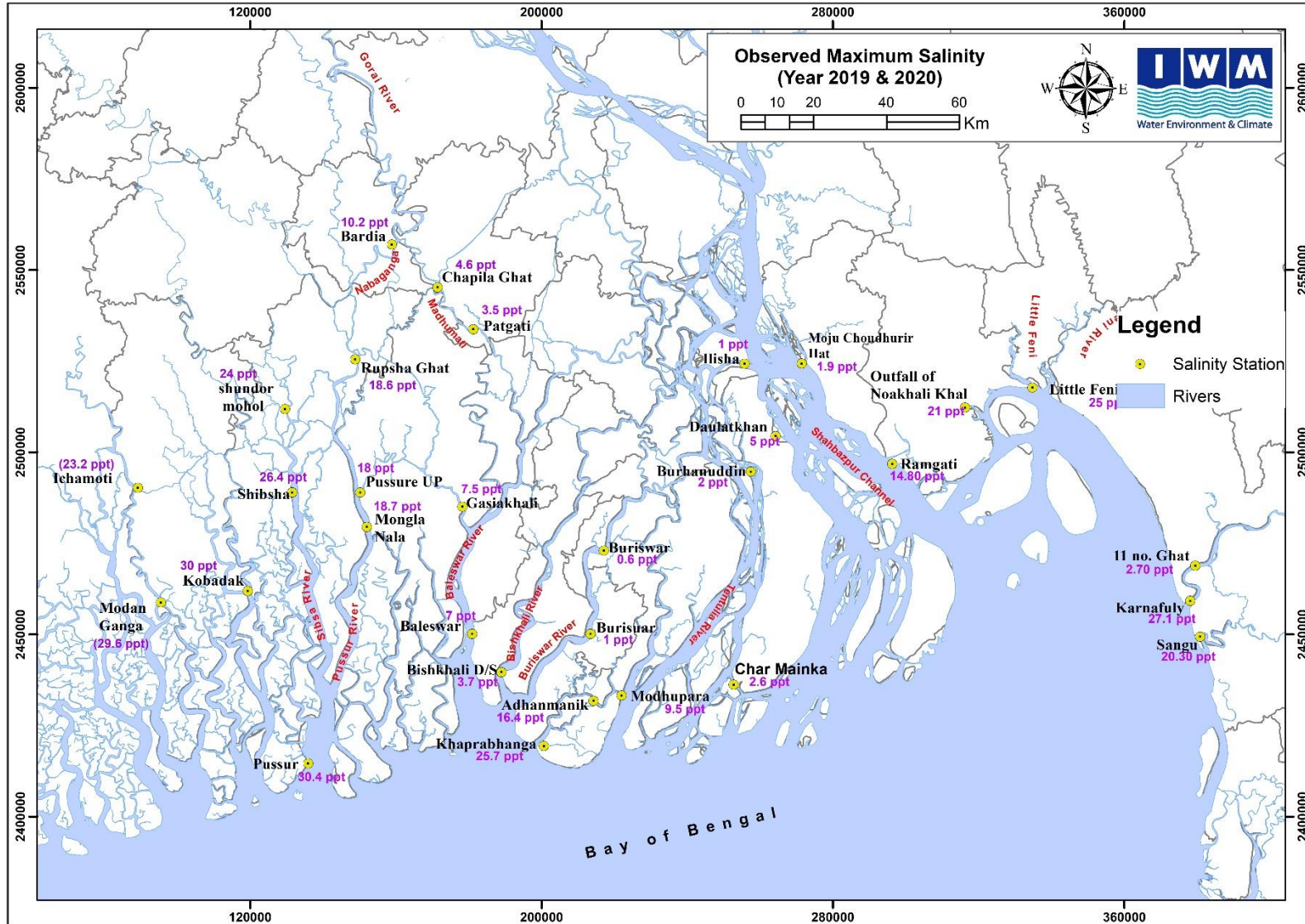


Figure 3-1: Salinity Monitoring stations.

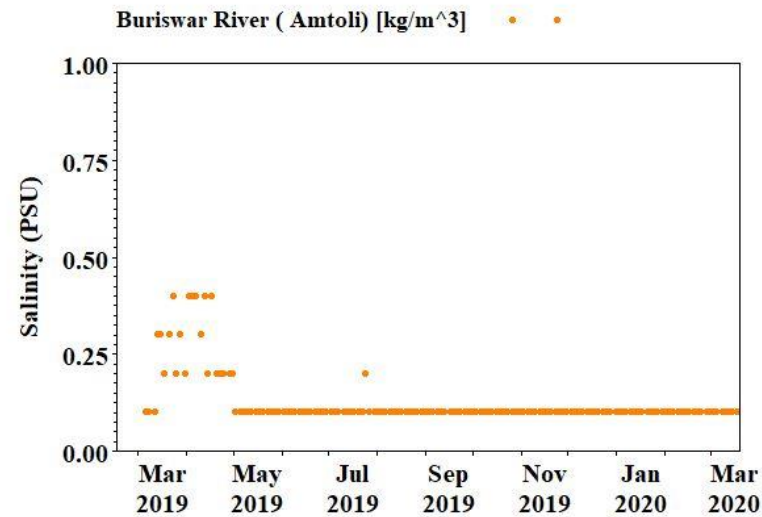
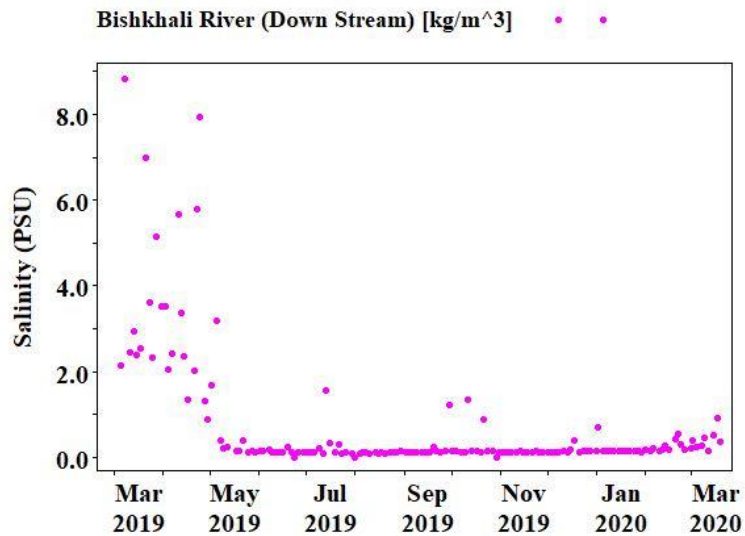
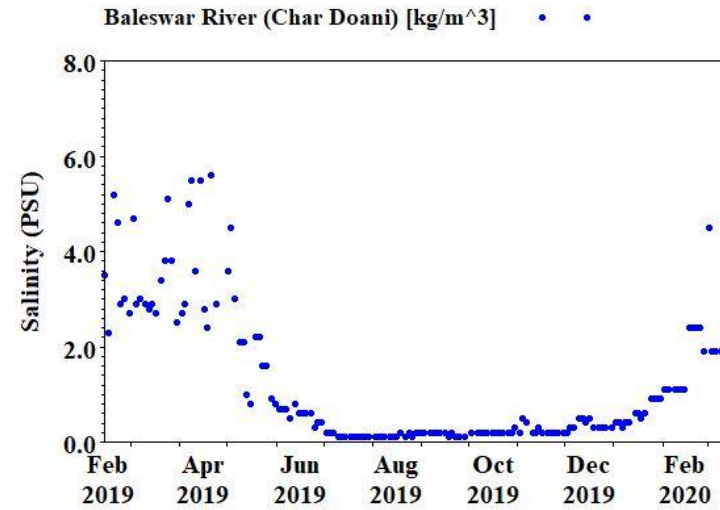
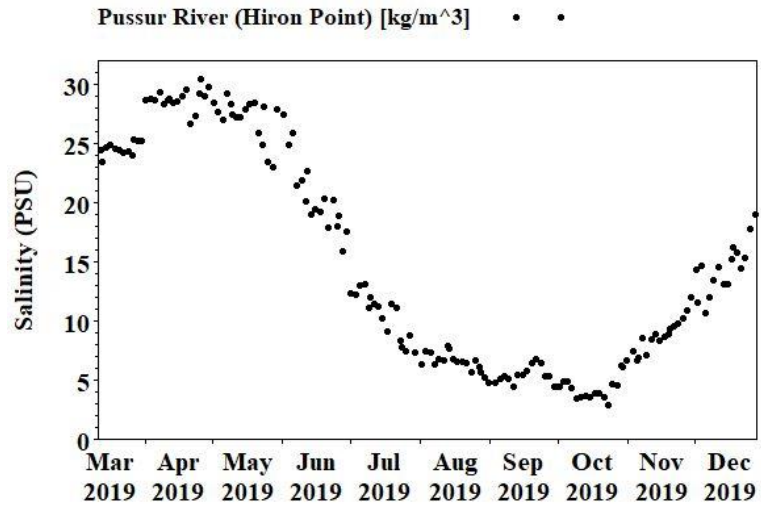


Figure 3-2: Seasonal variation of surface water salinity at Pussur River (Hironpoint), Baleswar river (Char Doani), Bishkhali river (downstream), Buriswar River (Amtali)

Location of salinity monitoring stations are shown in **Figure 3-1**. **Figure 3-2** and **Figure 3-3** shows the time series of river salinity at Pussur River (Hironpoint), Baleswar river (Char Doani), Bishkhali river (downstream), Buriswar River (Amtali), Andharmanik River (Kalapara), Rabnabad Channel (Modhupara), Mohipur channel and Lower Meghna River (Daulatkhan). The Graphs show that, river salinity begins to rise up from December and the salinity level reaches to maximum level at the end of March/beginning of April. Afterwards, salinity level begins to drop down, because upstream fresh water contributes to channel. It is apparent from the graphs that salinity is higher in Pussur river. Pussur Sibsar river system receives freshwater water from Gorai River. Gorai River receives little fresh water during the dry season.

On the contrary, Baleswar, Buriswar, Bishkhali, Tentulia and Lower Meghna Rivers obtain enough fresh water from upstream; hence river salinity in the downstream reaches of these rivers is much less than that of the Southwest river systems.

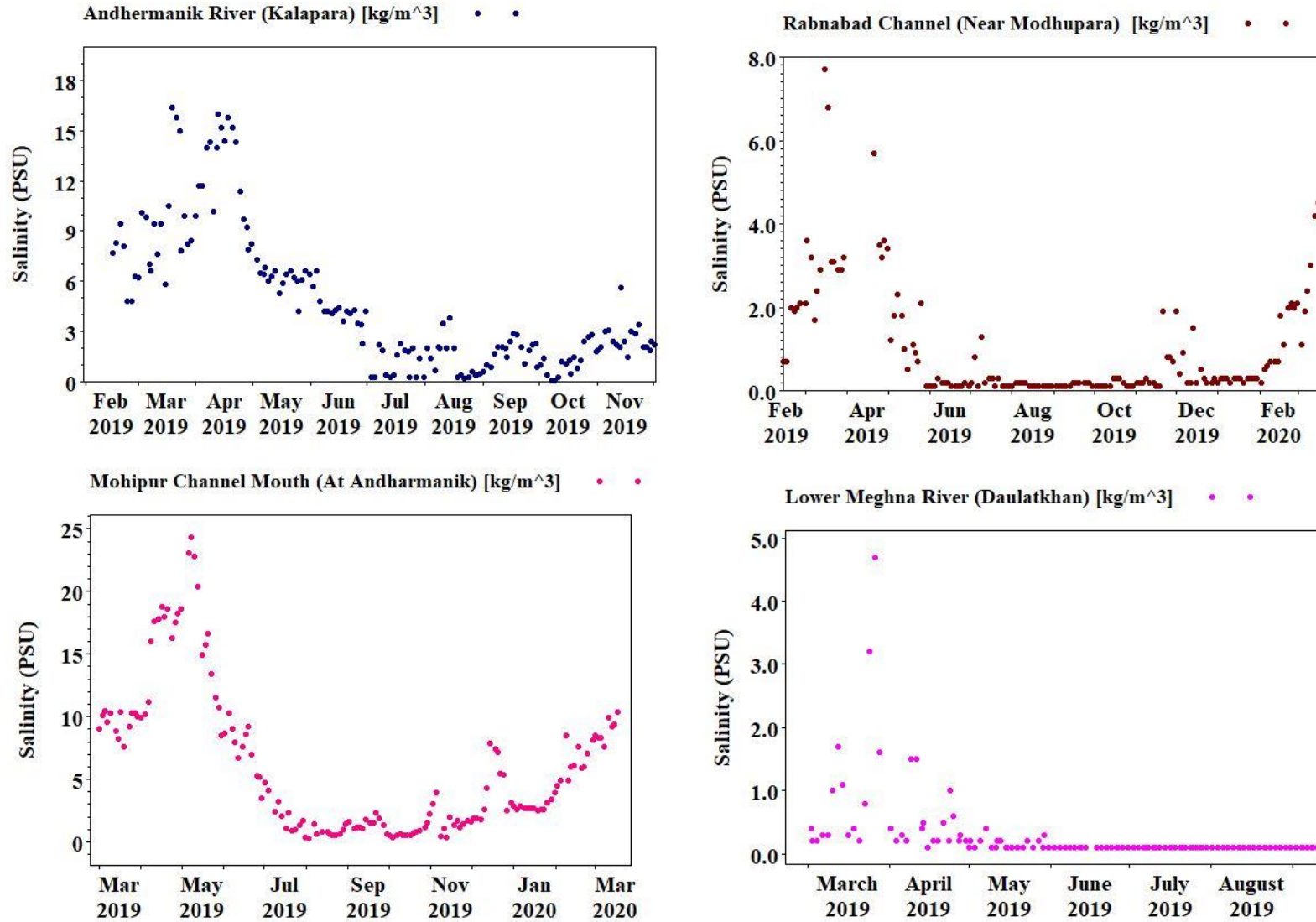


Figure 3-3: Seasonal variation of surface water salinity at Andharmanik River (Kalapara), Rabnabad Channel (Modhupara), Mohipur channel and Lower Meghna River (Daulatkhan).

In the south-central region, salinity in Rabnabad channel (near Modhupara) and Lower Meghna River (near Daulatkhan) is low because these rivers receive combined fresh water from Padma, Jamuna and Upper Meghna Rivers. Fresh water contribution from Rabnabad channel in Andharmanik River and Mohipur channel is minimum. Therefore, salinity in these rivers is high and it is dominated by tidal influence from sea.

3.2 Salinity long Profile variation along the River

Figure 3-2 to Figure 3-3 shows the timely varying salinity at a single point. Along the river variation of salinity is a crucial information. Long profile variation of salinity depends primarily on longitudinal dispersion of salinity and supply of upstream freshwater flow. Long profile salinity measurement was conducted along eight major rivers namely, Kobadak River, Pussur River, Sibsha River, Baleswar River, Buriswar River, Bishkhali River, Tentulia River and Lower Meghna River.

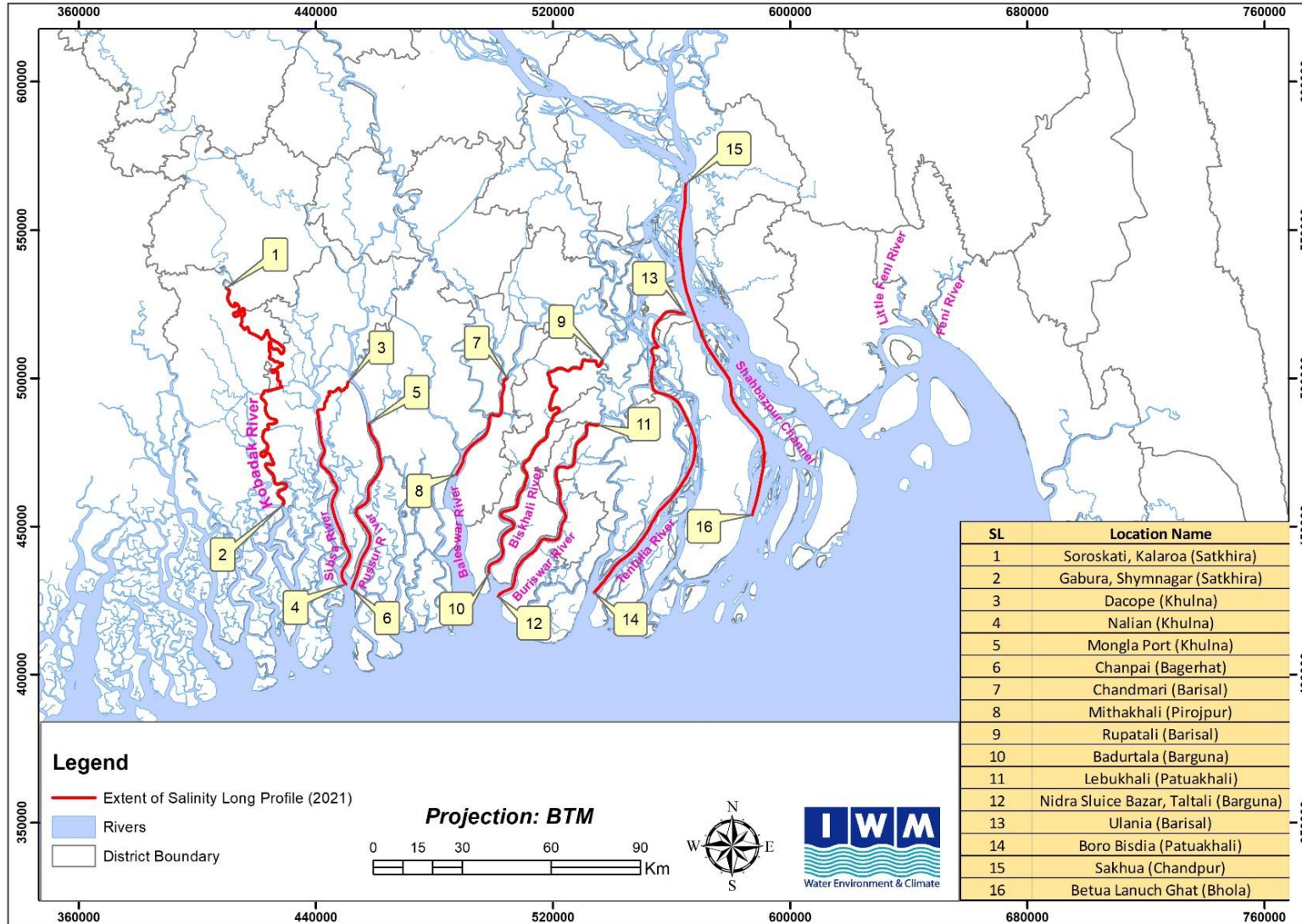
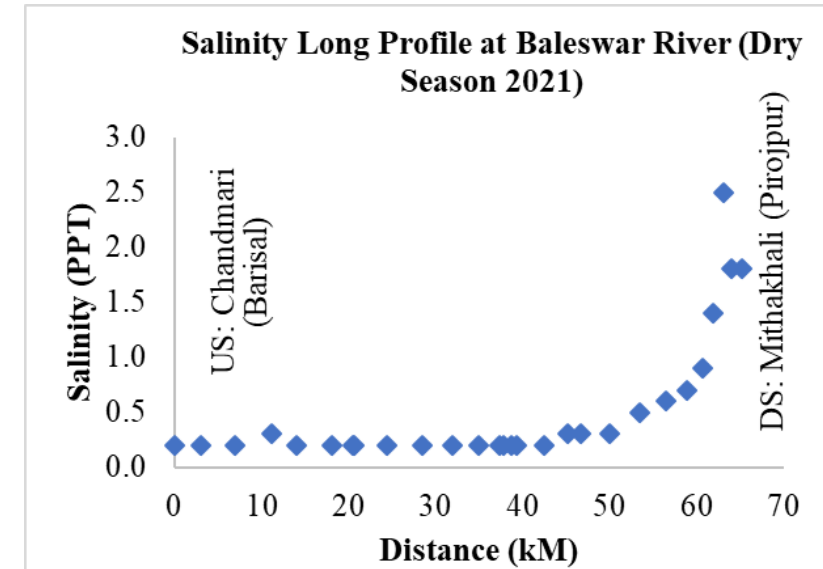
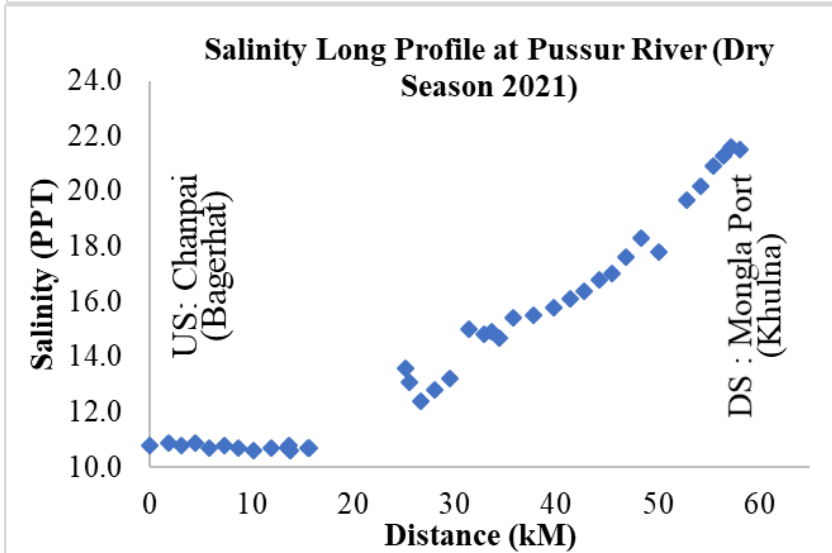
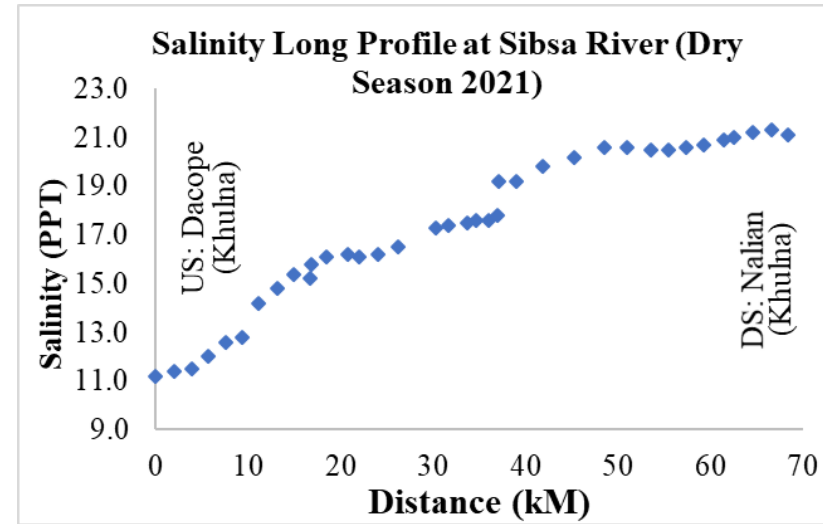
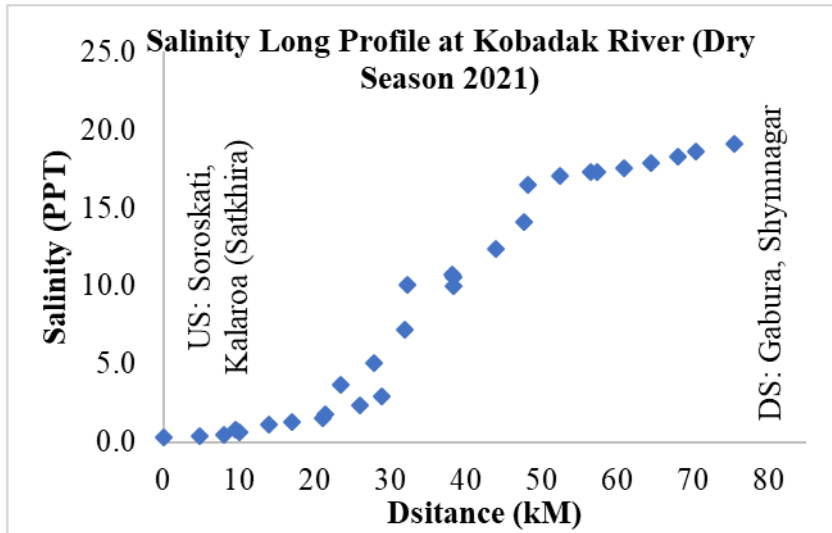


Figure 3-4: Long profile salinity measurement along the highlighted channel.



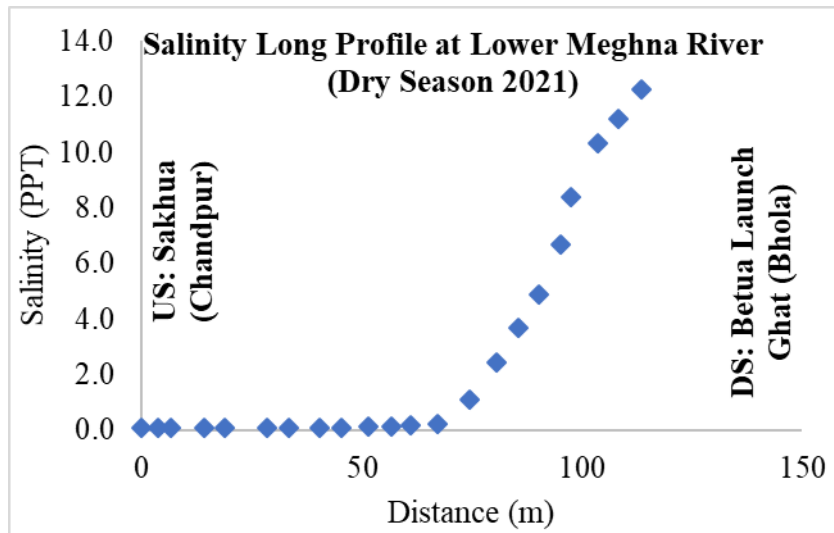
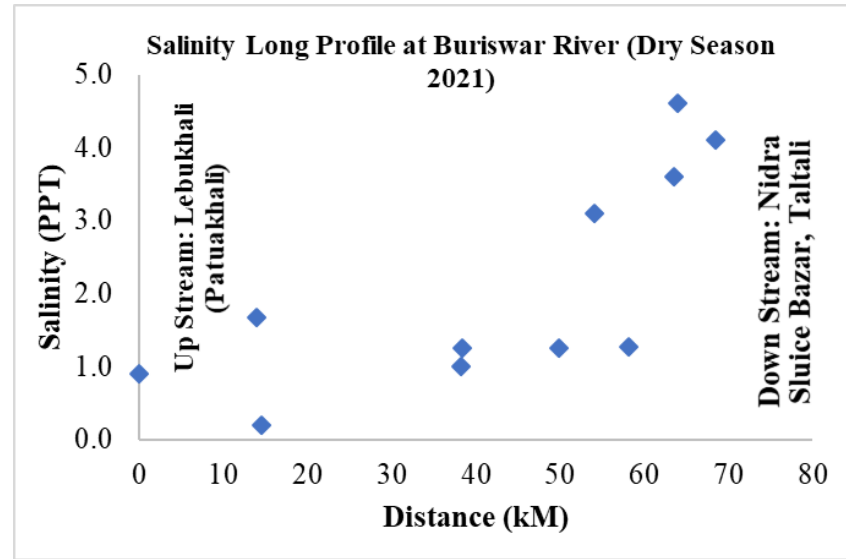
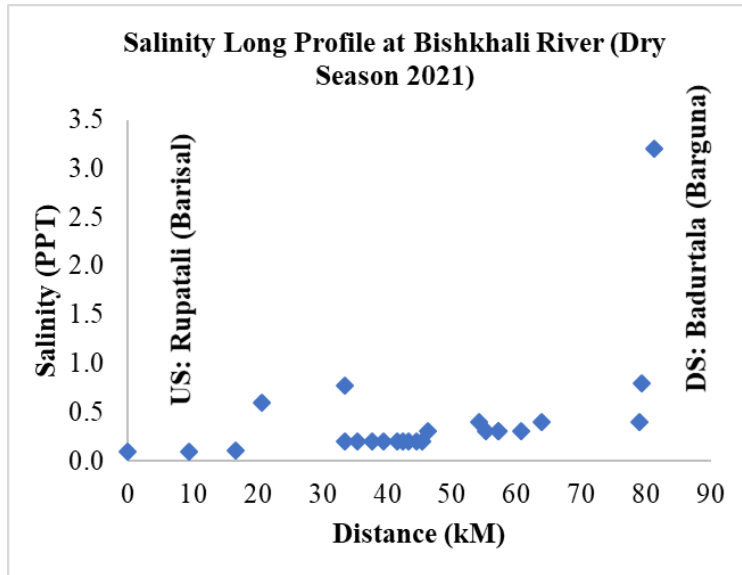


Figure 3-5: Salinity variation along the length of river shown in Figure 3-4

To measure the change of salinity along the length of the river, a boat was equipped with salinometer and it was moving from downstream towards upstream. Bottle of river water was collected from the surface of river/channel at 2 km interval. A unique Id of salinity bottle was conserved for a geocentric co-ordinate.

From the coordinate distance between the salinity sample was calculated. A long profile salinity plot was created with calculated distance and magnitude of salinity data thereby shown in **Figure 3-5**. Salinity long profile data shows that, from the upstream to downstream, the increment of salinity is exponential at Baleswar, Pussur, Bishkhali, Payra and Lower Meghna River is exponential. In Sibsa River, the long profile curve is almost linear. Dominant of fresh water flow at Lower Meghna River, Baleswar River, Bishkhali River and Payra River is quite evident. For Baleswar river, at Pirojpur the salinity value is 3.0 ppt. salinity is reduced to below 1 ppt just 3 km upstream. At Bishkhali River, near Barguna, salinity value is 2 ppt, just 1 km upstream salinity value reaches to 0.4 ppt. Salinity value at Betua launch ghat is 12 ppt at 40 km upstream along the Lower Meghna River it reduces to 1 ppt. Lower Meghna is a large river and effect of tide is dominant that's why salinity gradient in the downstream side of the river is milder than Baleswar, Bishkhali and Buriswar river.

3.3 Variation of salinity across the Depth

River and estuarine salinity variation across the depth is negligible. In 1991 an extensive survey was carried out by SWMC in co-operation with DANIDA project. The vertical profile measurement was conducted within South west region and in Meghna estuary during dry season, 1991. Typical graph of vertical salinity and temperature variation is shown in **Figure 3-7** to **Figure 3-14**. Location of the vertical profile measurement is shown in **Figure 3-6**.

Station 11, station 36, station 41 and station 45 are situated within southwest zone. And station 14, station 15, station 20, station 26/27 are situated within Meghna estuary. However, station 30 and station 31 are situated Chittagong coastal zone.

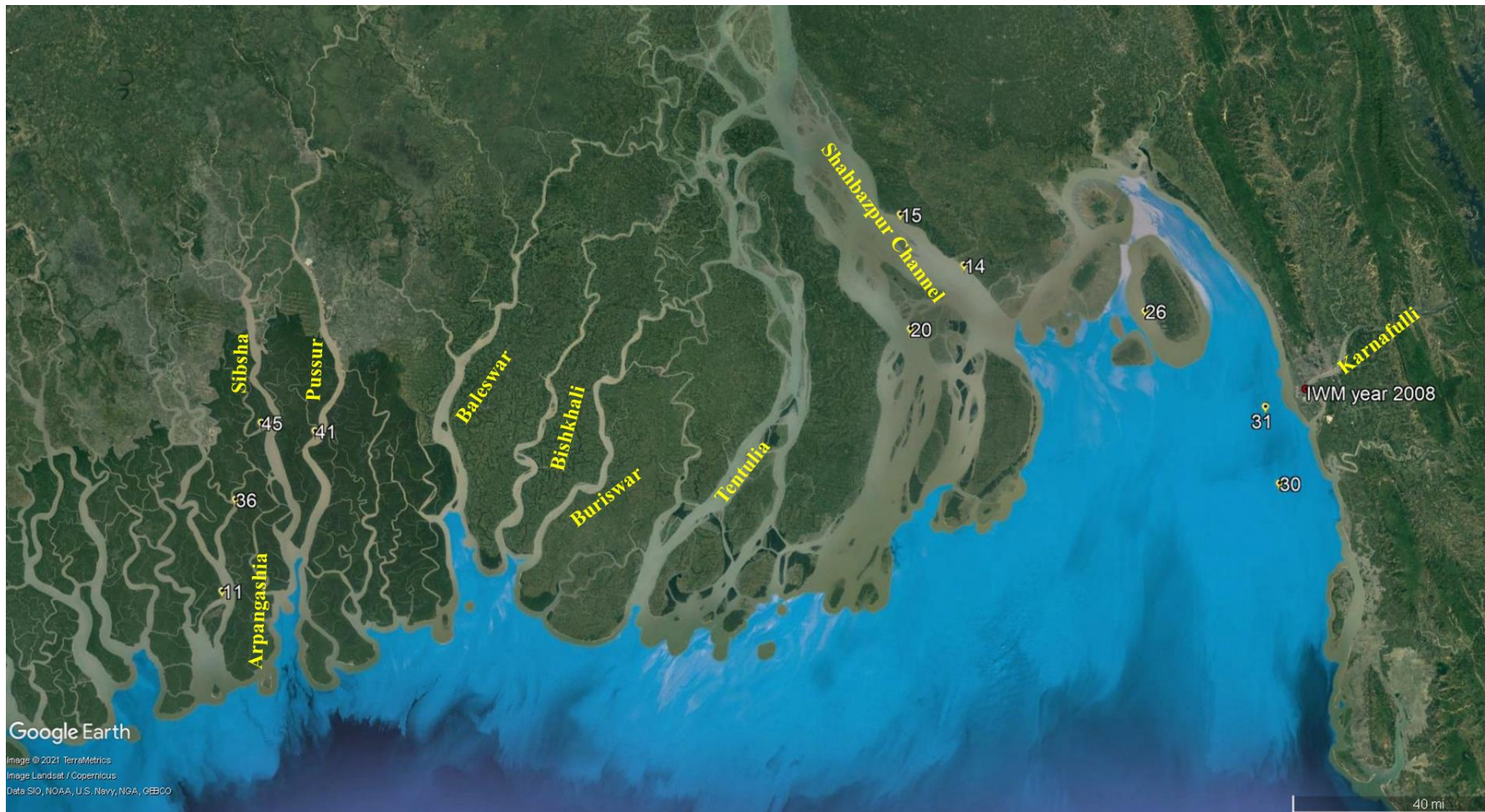


Figure 3-6: Location of salinity measurement (vertical profiling)

Vertical Temperature and Salinity Profile at Southwest Region (Sundarban)

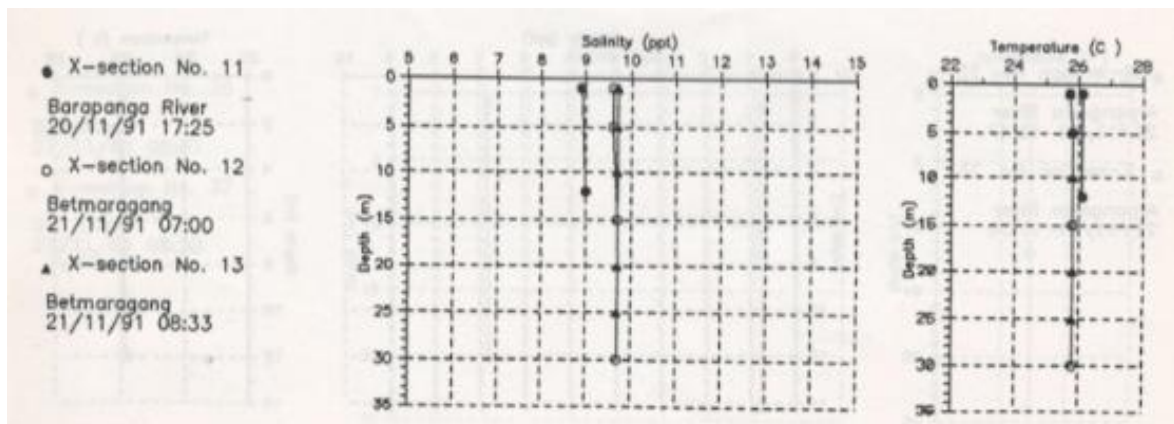


Figure 3-7: Vertical Salinity and Temperature Profile at Betmarang River. (Date of measurement: 20th November, 1991) (Source: SWMC, 1993)

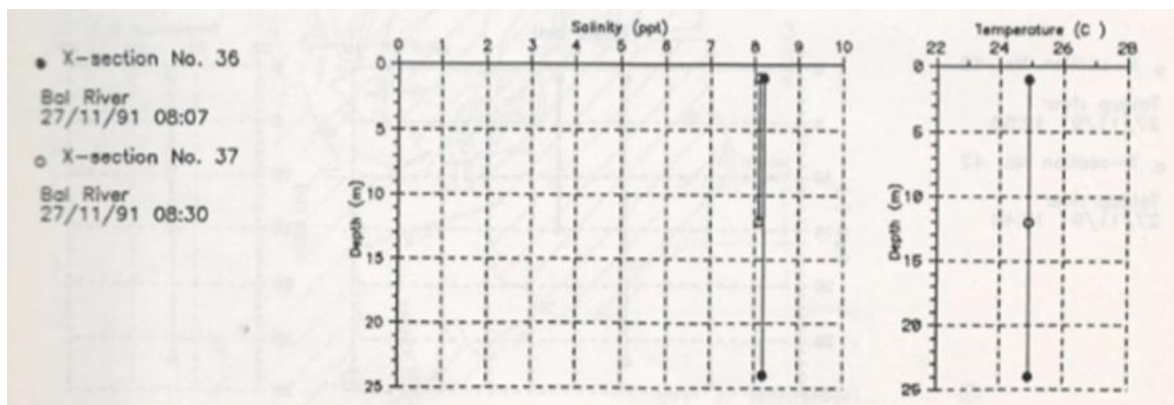


Figure 3-8: Vertical Salinity and Temperature Profile at Arpangashia River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

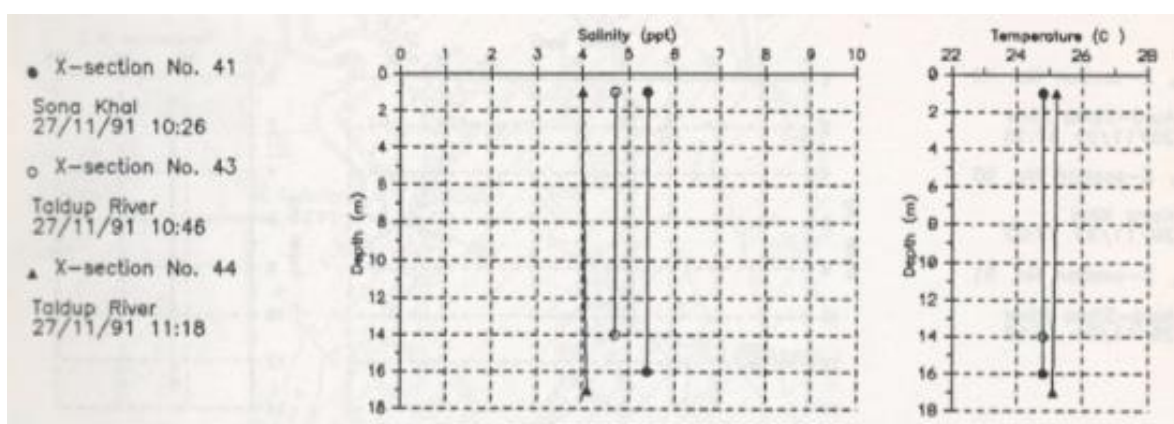


Figure 3-9: Vertical Salinity and Temperature Profile at Pussur River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

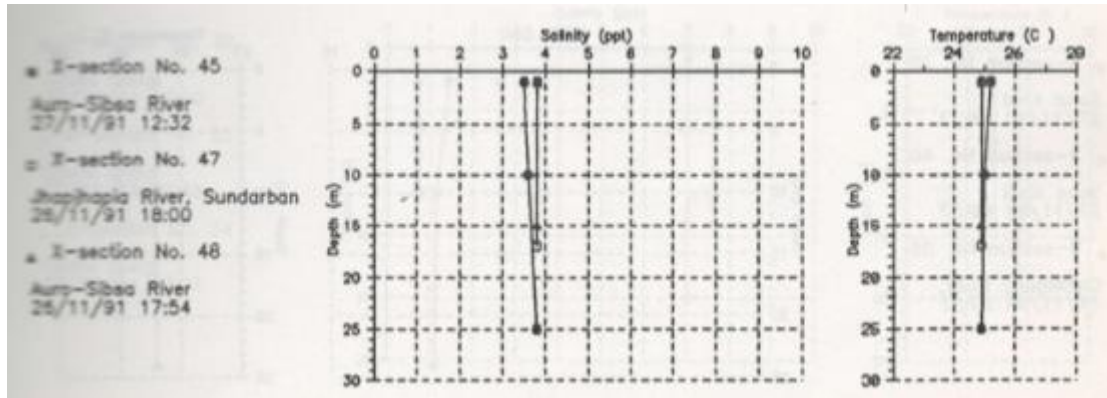


Figure 3-10: Vertical Salinity and Temperature Profile at Sibsa River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

Vertical Temperature and Salinity Profile at Meghna Estuary

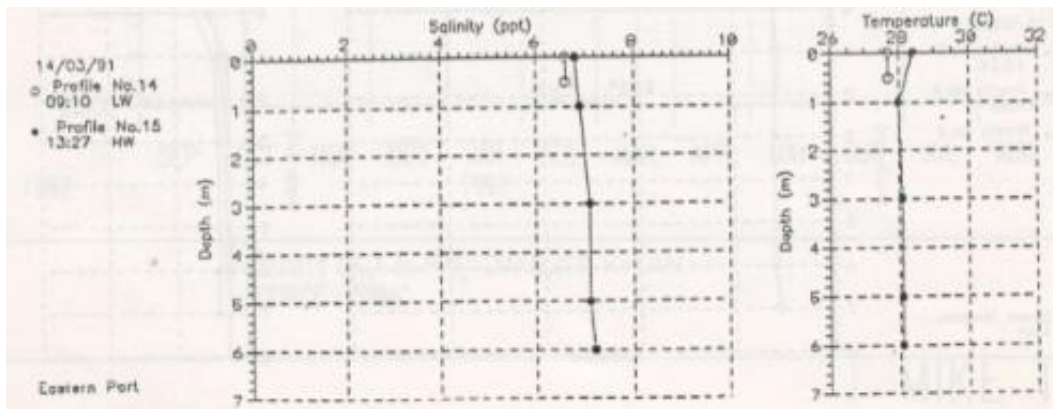


Figure 3-11: Vertical Salinity and Temperature Profile at Lower Meghna River. (Date of measurement: 14th March, 1991) (Source: SWMC, 1993)

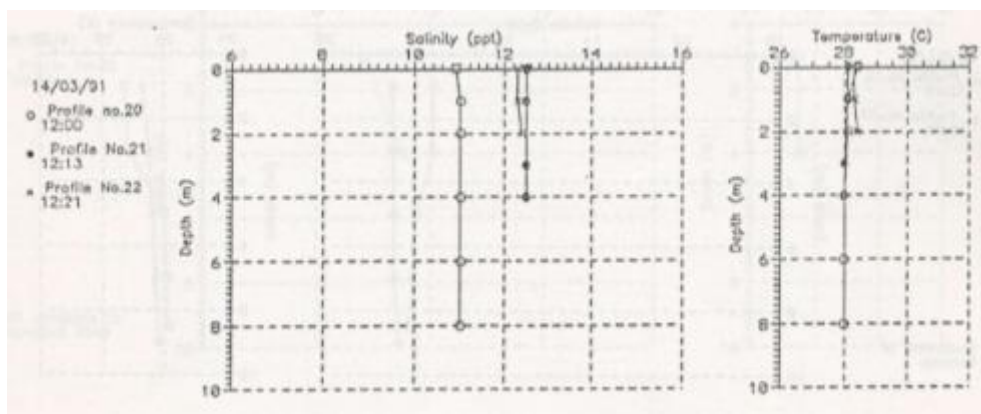


Figure 3-12: Vertical Salinity and Temperature Profile at Char Zahiruddin (Lower Meghna River). (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

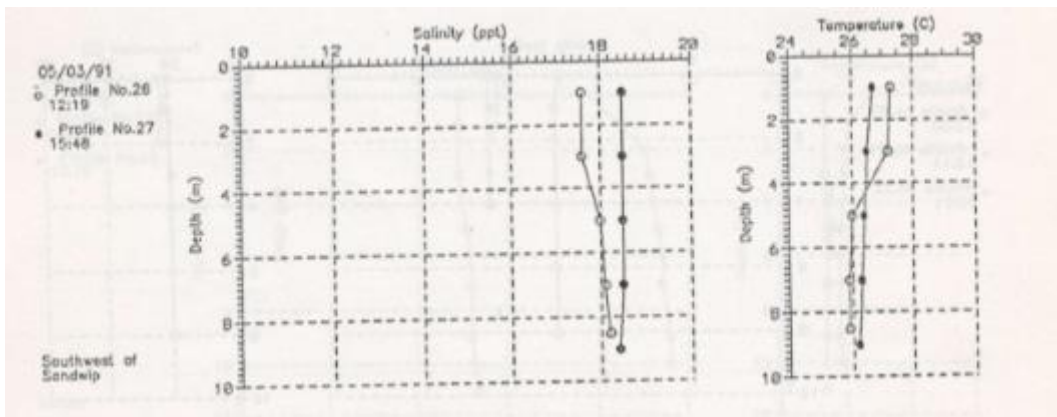


Figure 3-13: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

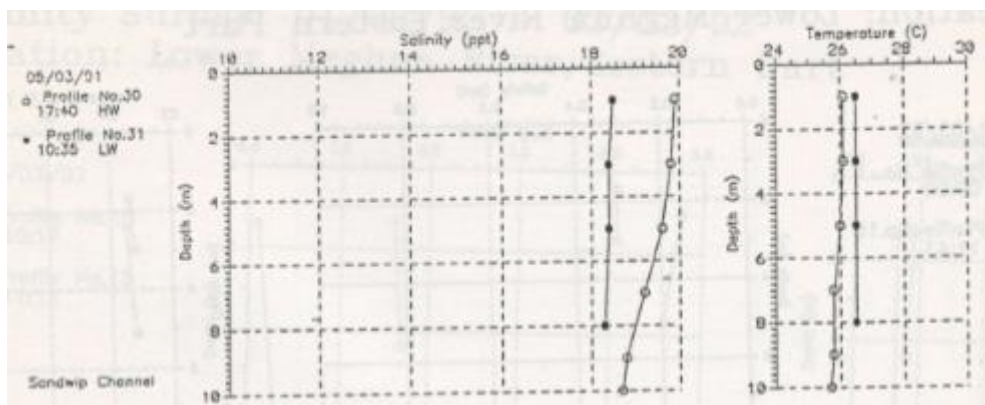


Figure 3-14: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

Above graph shows that, in most of the cases, slope of salinity change along the depth of river/channel is almost negligible. For example, in Sandwip Channel (**Figure 3-13** and **Figure 3-14**), for 10-meter difference of depth salinity in the bottom of the river increases to 1ppt only.

Therefore, it can be said that Salinity in Bangladesh is well mixed across the depth and 3-dimension model is not necessary. Two-dimensional depth average model is suitable enough to capture the scenario. Above data are measured during 1991. Recently however, in 2008 another measurement was conducted at Karnaphuli river during December, 2008. This plot is shown in **Figure 3-15**.

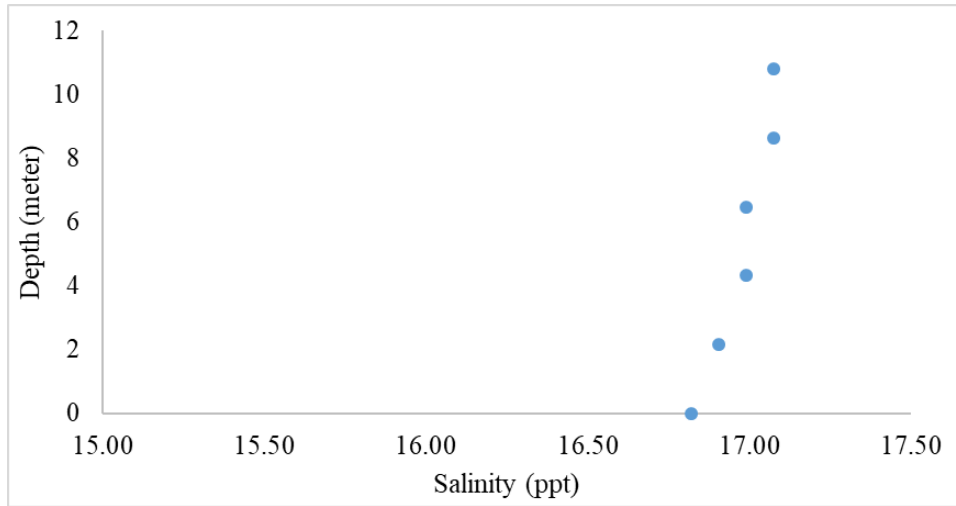


Figure 3-15: Across depth salinity variation at Karnaphuli

4 Development of Mathematical Model

4.1 Framework of mathematical Model

Establishing salinity value at major river system is a challenging task. Salinity in the river, strongly depends on seasonal rainfall and transboundary flow. Tidal water movement from Bay of Bengal also plays a key role for salinity intrusion.

Two different regional models, e.g., Bay of Bengal (BoB) regional model and South West Regional model (SWRM) are used to simulate salinity intrusion. Bay of Bengal model is a two-dimensional model. Domain of the model extends from the Bay of Bengal to Chandpur. For upstream flow boundary of BoB is dependent on SWRM. South west regional model on the hand is a one-dimensional model. SWRM network is superimposed on BoB model domain thereby shown in **Figure 4-2**. Detailed description of the model is shown in **Section 4.2**.

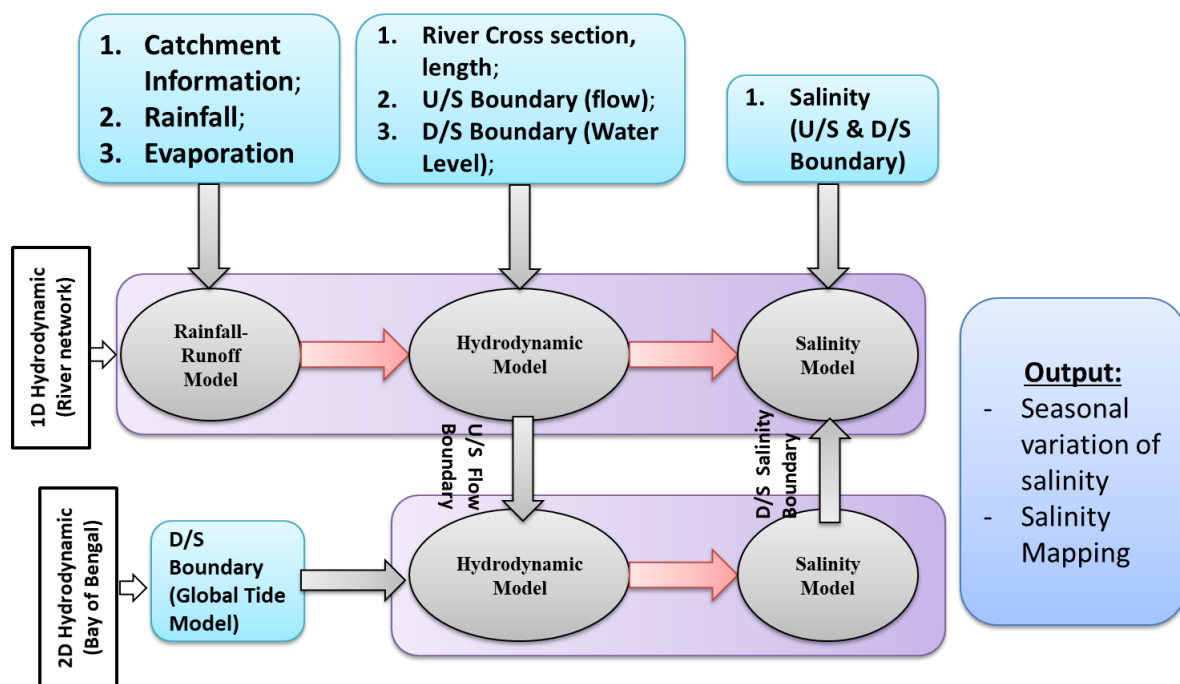


Figure 4-1: Flow chart of salinity model

Downstream water level and salinity boundary **SWRM model** is obtained from BoB model. For Boundary generation both 1D and 2D model depends on each other. Several trial simulations are required therefore, to obtain a suitable boundary for two dimensional and one-dimensional model setups. The trial process can be elaborated in five steps, thereby discussed in following articles.

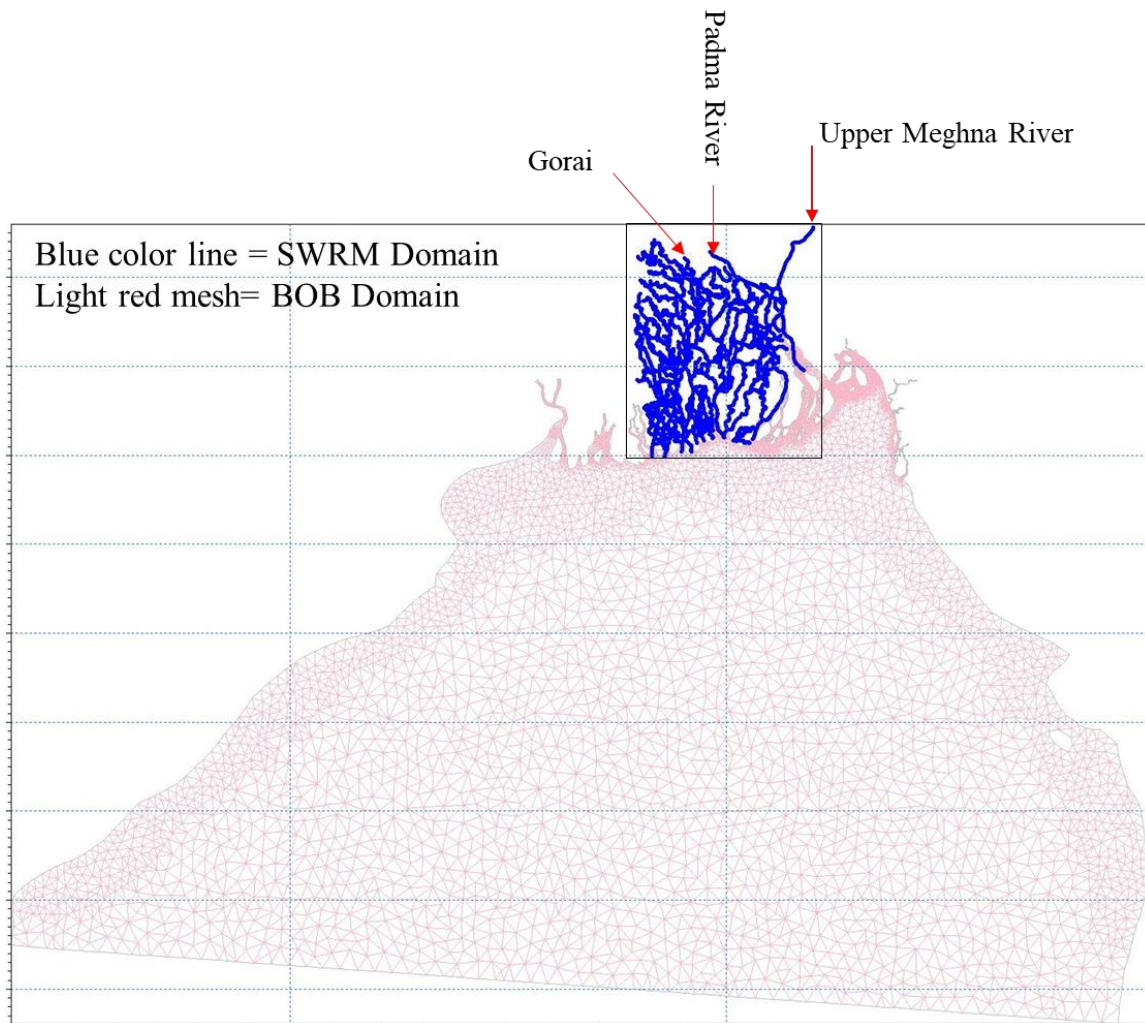


Figure 4-2: Superposition of SWRM model domain onto BoB model domain.

Southwest regional model is a one-dimensional model and it cover all the major river systems of Southwest region of Bangladesh. South West regional model considers the contribution of rainfall generated runoff into the river, which is not considered in the 2D Bay of Bengal model.

According to definition of Long-term project, the Macro scale model cover the whole Ganges deltaic region, Meso scale model cover the regional scale river system/estuaries and micro scale model covers the polder level model. Tentative boundary of Macro scale, meso scale and micro scale model is shown in **Figure 4-4**.

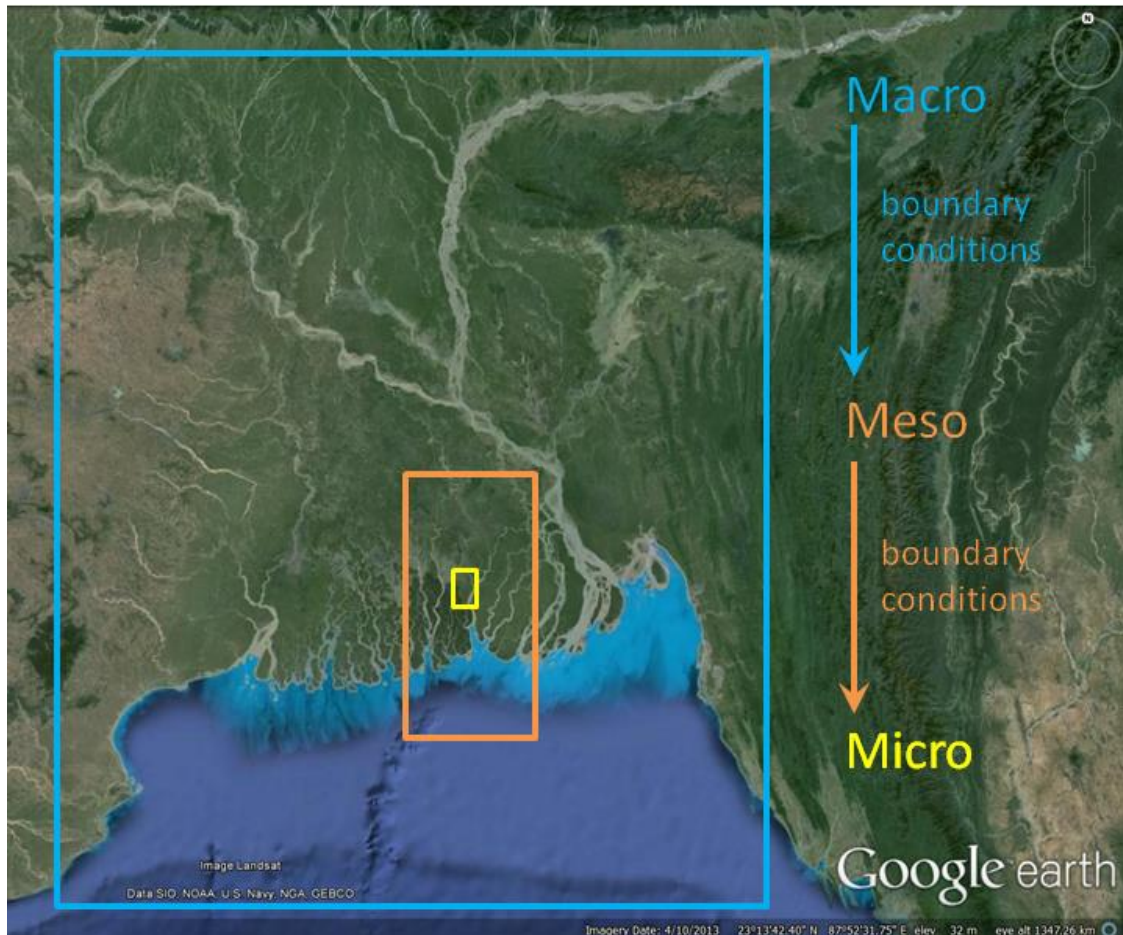


Figure 4.3 Cascade of modelling scales, the macro-scale is studied in this report.

Considering the definition of Macroscale, Mesoscale and Microscale model, BoB model can be classified as Macro scale model and SWRM can be classified as Mesoscale model. Description of BoB model is shown in **section 4.2** and SWRM model is shown in **section 4.3**.

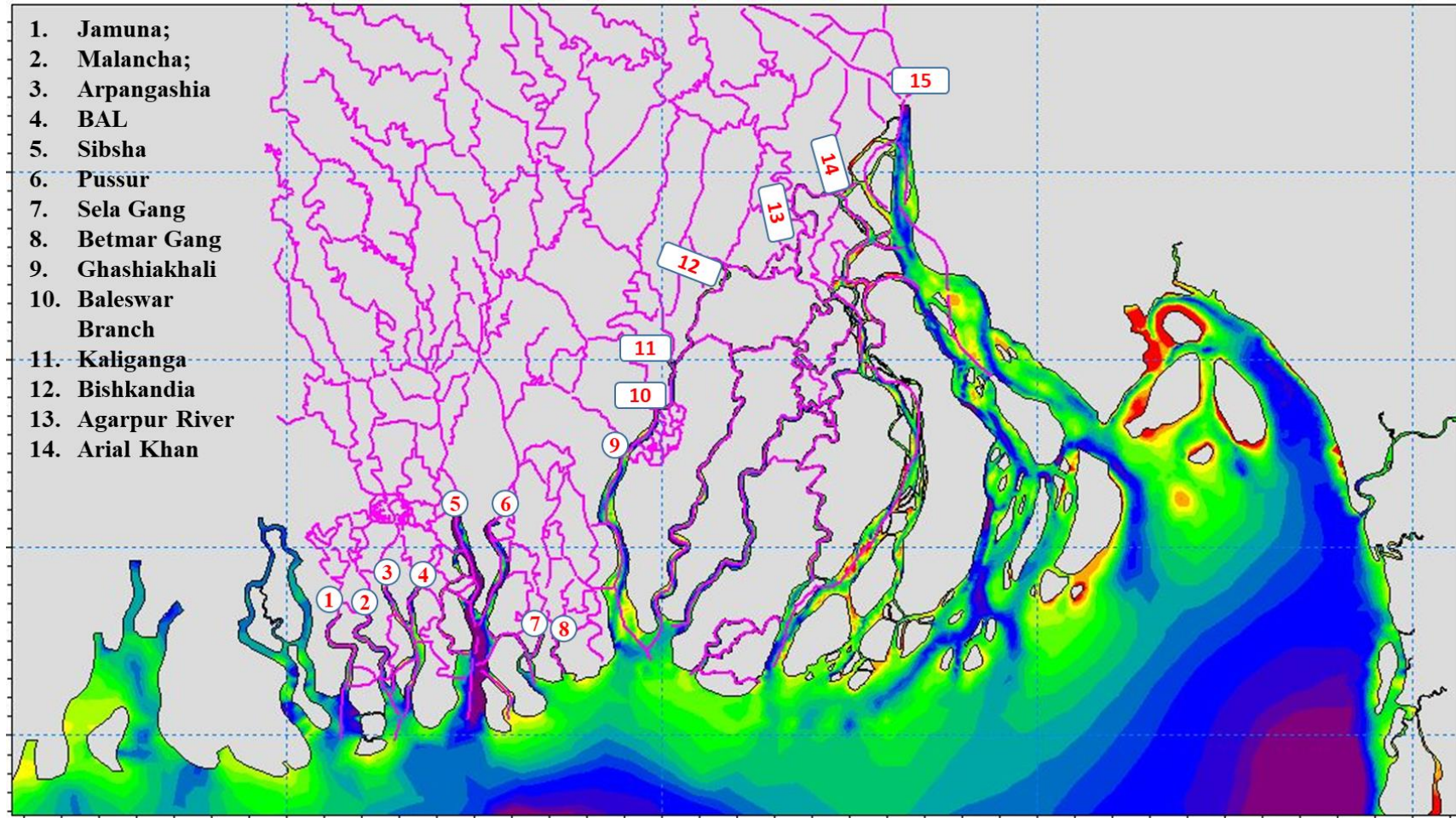


Figure 4-4: Boundary generation obtain from SWRM for upstream flow of Bay of Bengal

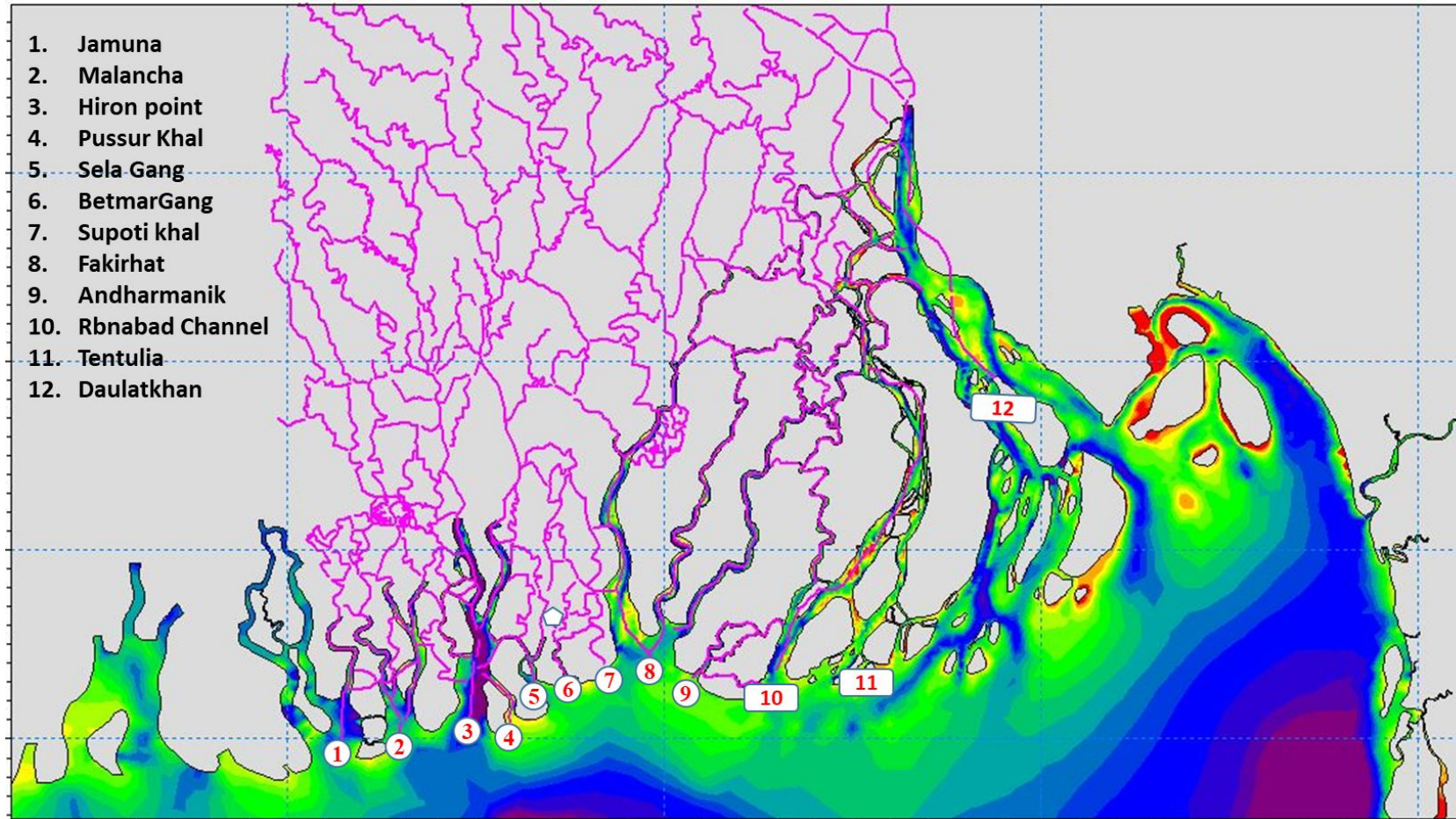


Figure 4-5: Down Stream boundaries of SWRM One dimensional model

Step-1: - Major upstream boundary of SWRM is Gorai (Gorai Railway Bridge), Padma (Baruria) and Upper meghna (Bhairab Bazar) they can be easily determined. Downstream water level data is available in some location (downstream of Pussur and Sibsha, downstream of Buriswar, Bishkhali and Baleswar river, Rabnabad river and Lower Meghna River), Downstream of Rabnabad channel. Other downstream boundaries are obtained from global tide model though it is inappropriate. With boundary, 1D hydrodynamic model is simulated. Description of South West Regional Model (**SWRM**) is shown in **section 4.3**

Step-2: - 2D hydrodynamic model contains major rivers and estuaries. The upstream boundaries of the rivers are obtained from the simulation result of 1D hydrodynamic model (As shown in **Figure 4-4**). With the Upstream boundary 2D hydrodynamic model is simulated. From the simulation result water level at the downstream of the river can be obtained. And this water level is again used as a boundary in **Step-1 (as shown in Figure 4-5)**. If usable observed data is available, then it is used instead of simulated data. Description of Bay of Bengal Model (**BoB**) is shown in **section 4.2**

Step-3:- Step-1 and Step-2 is carried out several times until reasonable result is obtained;

Step-4:- After development of Hydrodynamic model the salinity model needs to be prepared. In a salinity model, salinity time series are provided at upstream and downstream river boundary. Firstly, 1D hydrodynamic model is prepared. Salinity in the upstream of the boundary of southwest regional model is zero. Downstream boundary is obtained from measured survey data (downstream of Pussur and Sibsha, downstream of Buriswar, Bishkhali and Baleswar River, Rabnabad River and Lower Meghna River) (As described in **Table 4-2**). Where downstream boundary is not available, it is taken from the nearby rivers. A trial simulation was carried out with these boundary condition.

Step-5:- From the result of 1D hydrodynamic model, upstream salinity boundary of 2D advection dispersion model is prepared and the model is simulated (As shown in **Figure 4-4**). After simulation, downstream salinity boundary is extracted from result of 2d boundary and is used in **Step-4 (as shown in Figure 4-5)**.

4.2 Description of Bay of Bengal Model

4.2.1 Mesh Generation & Study area Discretization

Mike21FM module has the capability to generate an unstructured grid in the horizontal plane is used comprising of triangles or quadrilateral element. This particular feature is very helpful for mesh generation in the estuarine area. Unstructured grid allows changing the resolution over a large domain (e.g., the entire enclosed bay) and refining the resolution where fine scales are important, without increasing the total computation time too much. Extent of 2 Dimensional hydrodynamic model is shown in **Figure 4-6**.

4.2.2 Boundary Condition

Time series water flow is used as upstream boundary condition of the Bay of Bengal model. Time series flow boundary are obtained from SWRM. On the other hand, water level is used as the downstream boundary.

Upstream Boundary Condition

In the model, upstream boundaries are provided at Chandpur, Pussur, Sibsa, Arpangashia, Selagang and Ghashiakhali River etc. Upstream flow and salinity time series is obtained from southwest regional model. Schematics of boundary extraction for BoB model from the result from SWRM regional model is shown in **Figure 4-4**.

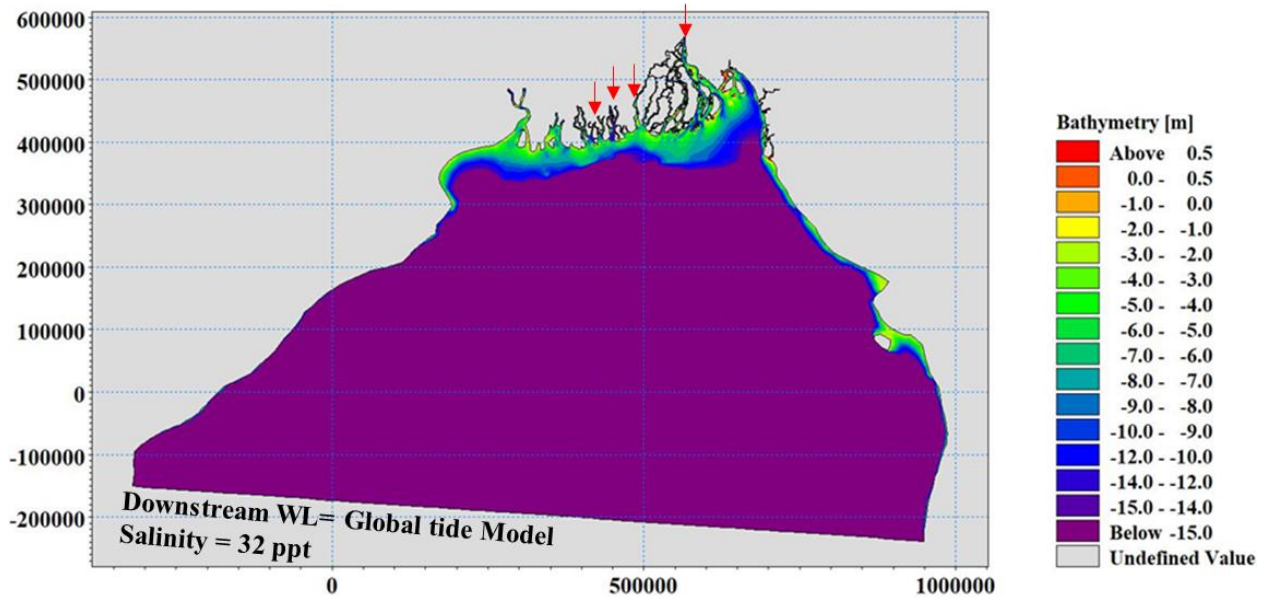


Figure 4-6: Bay of Bengal Model Boundary

Downstream Boundary Condition

Downstream boundary of the Bay of Bengal model is water level which is estimated with the help of “Global Tide Model”. The global tide model calculates water level from tidal constituent. The water level varies along the long line of south boundary and it also varies with time. The Global Tide model is developed by DTU space (<https://www.space.dtu.dk/>). The Global Tide model is available on 0.125x0.125-degree resolution grid for the major 10 constituents in the tidal spectra.

4.2.3 Bed Roughness

The bed resistance is adjusted to calibrate the model. In this study, a bed resistance map is used. The relation between Manning number (M) and bed roughness length, K_s can be estimated using the following formula: Manning map used in the study is shown in **Figure 4-7**.

$$M = \frac{25.4}{K_s^{1/6}} \dots \dots \dots (3.1)$$

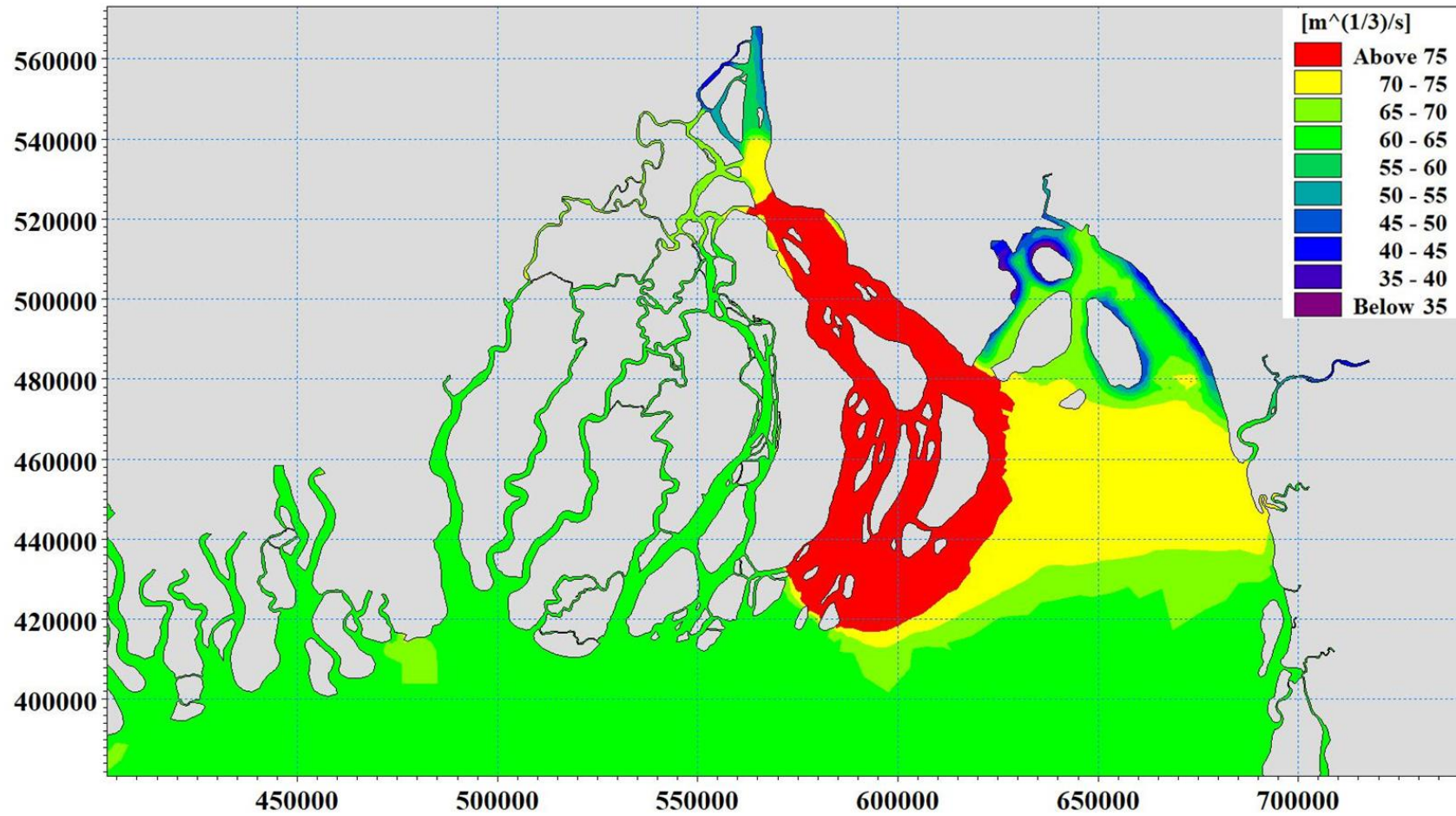


Figure 4-7: Manning map used in two-dimensional Mathematical model.

4.2.4 Bathymetric Data

Bathymetry of Bay of Bengal model is updated with latest surveyed data. IWM surveyed river bathymetry in February 2020.

4.2.5 Advection Dispersion Co-efficient

Salinity from the sea intrudes towards the upstream of a river is transported by means of two processes, Advection and dispersion. Advection defines as the transport of temperature, moisture or a substance from one place to another by bulk motion of a fluid. On the other hand, dispersion, in fluid dynamics, is the spreading of mass from highly concentrated areas to less concentrated areas.

In a one dimensional flow problem longitudinal dispersion govern the the transport of salinity. In the estuary however, transverse mixing is another phenomenon that, explains mixing of fresh water and sea saline water at the estuary, which happens due to turbulence in bed shear stress.

Fisher et al. 1979 shows the longitudinal dispersion co-efficient in rivers and estuaries. It observed that in small rivers dispersion co-efficient changes from (50- 85) m^2/s and in the estuary, it varies between 400 m^2/s to 1600 m^2/s . Dispersion co-efficient used in mathematical model.

Table 4-1: Dispersion Coefficient used in the mathematical model

Location/Domain	Dispersion factor Used (m^2/s)
Pussur – Sibsa Estuary	400
Burisarwar- Baleswar -Bishkhal Estuary	200
Tentulia and Meghna Estuary	1200

Dispersion co-efficient of major rivers in southwest regional model is shown in **Table 4-1**.

4.2.6 Calibration of 2D Hydrodynamic & Advection Dispersion Model

This section discusses the performance of 2D Advection dispersion module of the Bay of Bengal Model. Calibration of advection dispersion model is conducted for measured salinity. Downstream salinity boundaries of one-dimensional advection dispersion model are to be extracted from two-dimensional model, that's why Calibration of 2D advection dispersion model is important. **Figure 4-8** and **Figure 4-9** show the water level calibration. **Figure 4-10** and **Figure 4-11** show the comparison of observed salinity and simulated salinity for the year 2019.

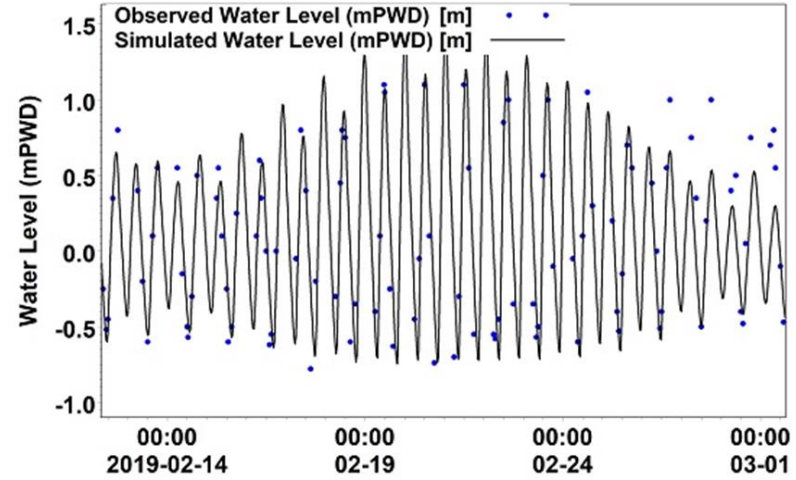
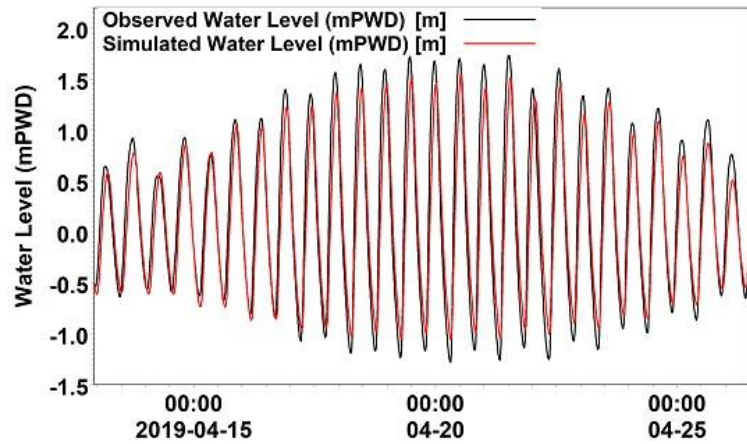


Figure 4-8: Comparison of Observed and Simulated Water Level at Charduani (**Baleswar River**) (left) and Amtali (**Buriswar River**) (right)

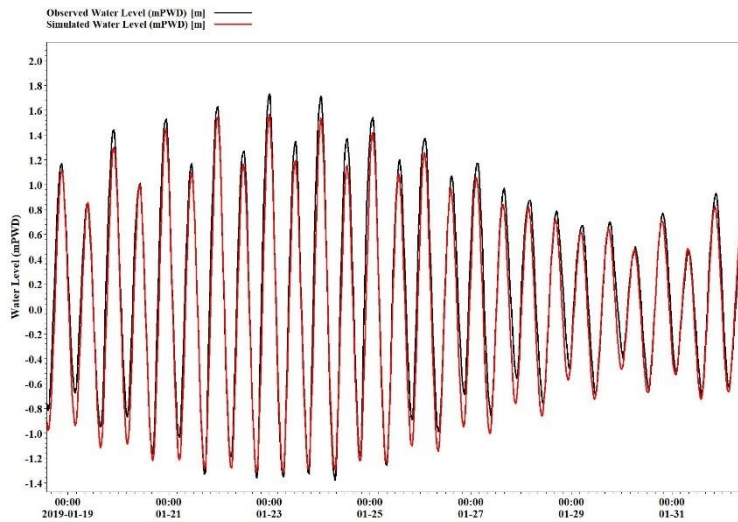


Figure 4-9: Comparison of Observed and Simulated water level at **Hironpoint (Pussur River)** (left)

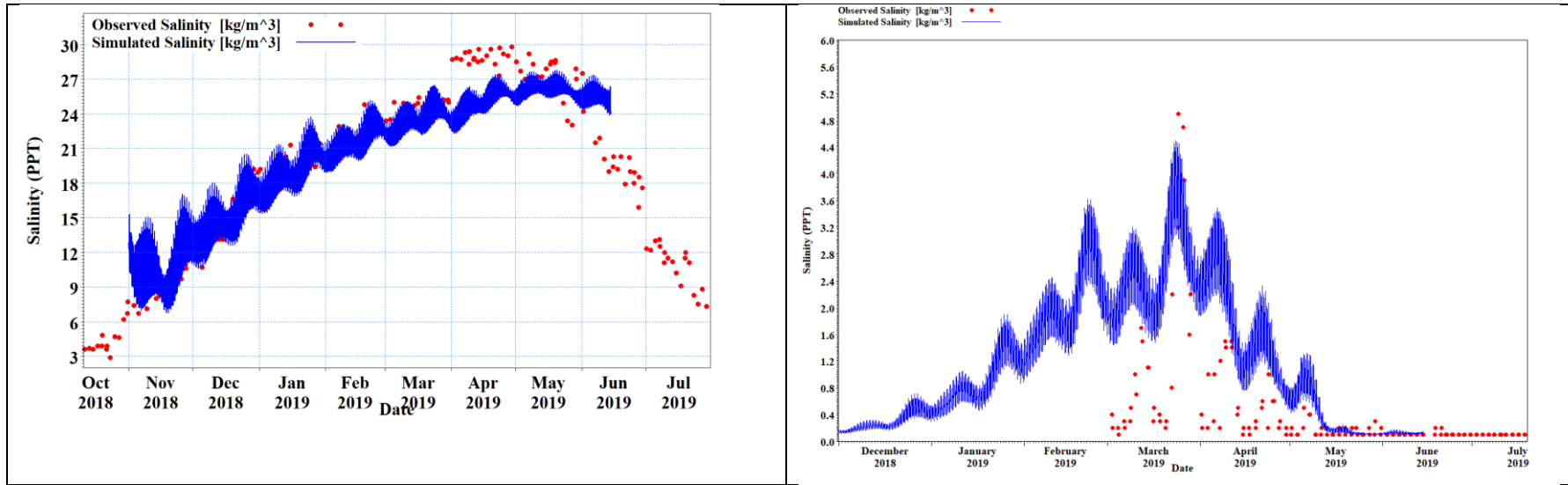


Figure 4-10: Comparison of Observed and Simulated Salinity at Hironpoint (Pussur River) (right) and Daulatkhan (Lower Meghna River) (left)

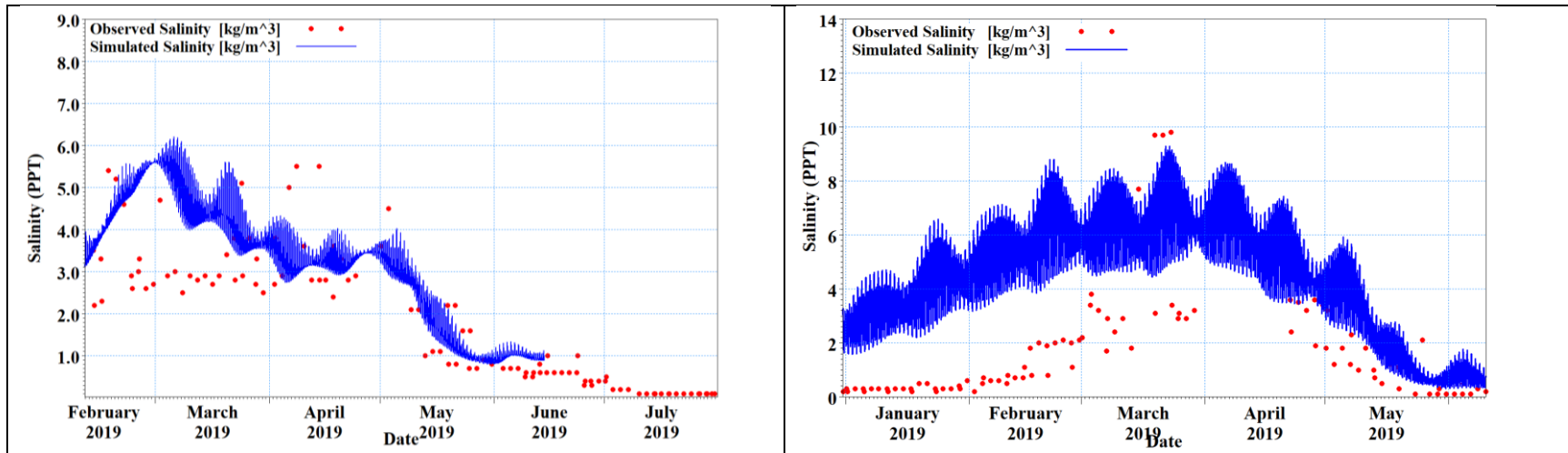


Figure 4-11: Comparison of Observed and Simulated Salinity at Charduani (Baleswar River) (right) and Modhupara (Andharmanik river) (left)



4.3 Description of South West Regional Model

4.3.1 Model simulation

Domain of 1D hydrodynamic model covers the major river system in the southwest and south-central region lying to the south of the Ganges and west of the Meghna estuary. The Model is simulated for the year 2019. It is evident from **Figure 3-2** and **Figure 3-3** that, a complete salinity cycle is observed from November to June, hence, the salinity model is simulated for this time period.

4.3.2 Boundary Conditions

Time series water flow data is used at the upstream boundaries of the 1D hydrodynamic model. Three upstream boundaries are dominant with freshwater flow from the Ganges-Brahmaputra-Meghna basin. These three boundaries are at Gorai Railway Bridge on Gorai River, Baruria on Padma River and Bhairab Bazar on Upper Meghna River. At Bhairab Bazar, satisfactory rating curves cannot be generated due to scattered data and tidal influence during dry period. Hence, time series flow at this river is defined from model simulation of north east regional model.

Schematics of boundary condition for the 1D hydrodynamic model (South West Regional Model) is shown in **Figure 4-12**.

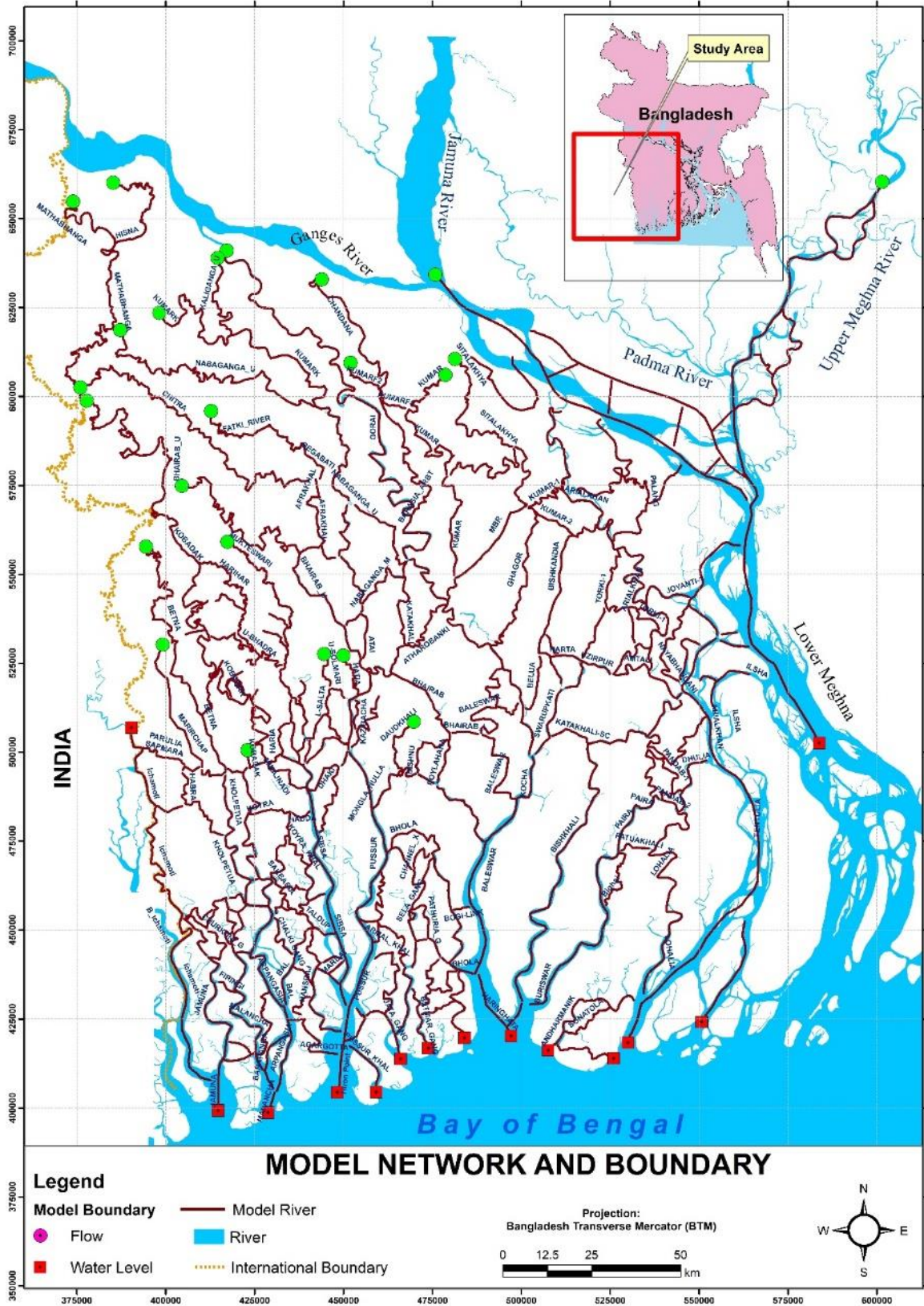


Figure 4-12: River network system & boundary condition in South west regional model

Table 4-2: Boundary Conditions applied to a One-dimensional South West regional model

Boundary Type	River Name	Time series Boundary For hydrodynamic model	Time series Boundary For salinity model
Up Stream Boundary	Gorai	Rated flow from measurement at Gorai Railway Bridge. ;(Source: IWM & BWDB)	Zero Salinity
	Padma	Rated flow from measurement at Baruria; (Source: BWDB)	Zero Salinity
	Upper Meghna	Simulated flow from North East Regional model. (To capture dry season tidal effect)	Zero Salinity
	ICHAMOTI	Measure water level from BWDB (at Basantipur); Remarks: ichamoti is situated along the border between India & Bangladesh, it is strongly influence by tide and flow measurement is difficult to measure flow in this river	Measured Salinity at Ichamoti River
	Other rivers	From the runoff	
Down Stream Boundary	ANDHARMANIK	WL from BoB model	From BoB Salinity simulation
	BETMAR GANG	WL from BoB model	From BoB Salinity simulation
	JAMUNA SW	WL from BoB model	From BoB Salinity simulation
	MALANCHA	WL from BoB model	From BoB Salinity simulation
	PUSSUR KHAL	WL from BoB model	From BoB Salinity simulation
	SELA GANG	WL from BoB model	From BoB Salinity simulation
	SUPOTI KHAL	WL from BoB model	From BoB Salinity simulation
	TENTULIA EAST	WL from BoB model	From BoB Salinity simulation
	KHAPRABHANGA	WL from BoB model	From BoB Salinity simulation
	HARINGHATA (outfall of Buriswar, Bishkhali & Baleswar River)	Water level measurement at Fakirhat	From BoB Salinity simulation
	TENTULIA	Water level measurement at Kawar Char	From BoB Salinity simulation
	SHAHABAZ-1	Measured Water level at Daulatkhan	From BoB Salinity simulation
PUSSUR	Measure water level at Hiron Point	From BoB Salinity simulation	

4.3.3 Bed Resistance

River Bed resistance is an important calibration parameter. Value of bed resistance can be assessed indirectly from d_{50} of river bed material. It can also be fixed by trial error. For example, water level and river flow are measured in a channel. A trial simulation was then conducted to assess time series flow and water level in that particular channel. Flow and water level value is obtained from the simulation is then compared with measured value. If the value is less than observed data, then Manning's roughness is reduced, alternatively if simulated flow/water level is higher than observed value then, bed roughness value is increased. This procedure is carried out several times until simulated value comes close to measured value.

Manning's roughness value in the downstream rivers such as Pussur, Kholpetua, Sibsa, Baleswar, Bishkhali, Buriswar, Tentulia and Lower Meghna Rivers varies from 65 to 70. The Upstream rivers for example, Bhrirab, Mathabhanga, Hisna, Gorai, Nabaganga, Arial Khan, Rupsha and Kocha river etc. bed resistance value varies from 40 to 60.

4.3.4 Sensitivity of Bed resistance (Manning's M) observed in 1D SWRM model

Figure 4-13 to Figure 4-16 shows a plot of time series simulated river flow at Bishkhali River for manning's number 40, 50, 60 and 70 respectively. Time series observed flow is also superimposed on the graph. Manning's number 70 is most suitable as it's corresponding flow value almost coincide with the discharge during flood flow and ebb flow. Similar type of plot for manning sensitivity is shown in **Figure 4-15 to Figure 4-16**.

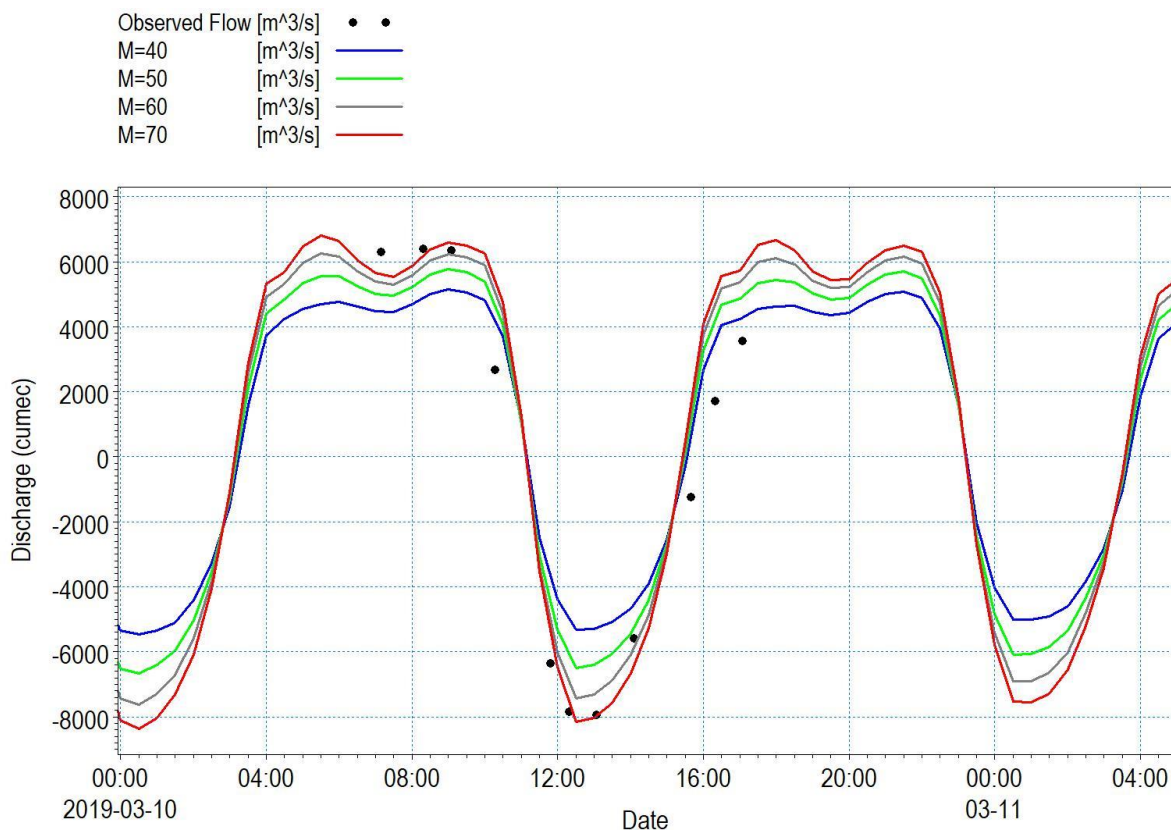


Figure 4-13: Optimization of manning's roughness with trial simulation of different bed resistance (at Bishkhali River).

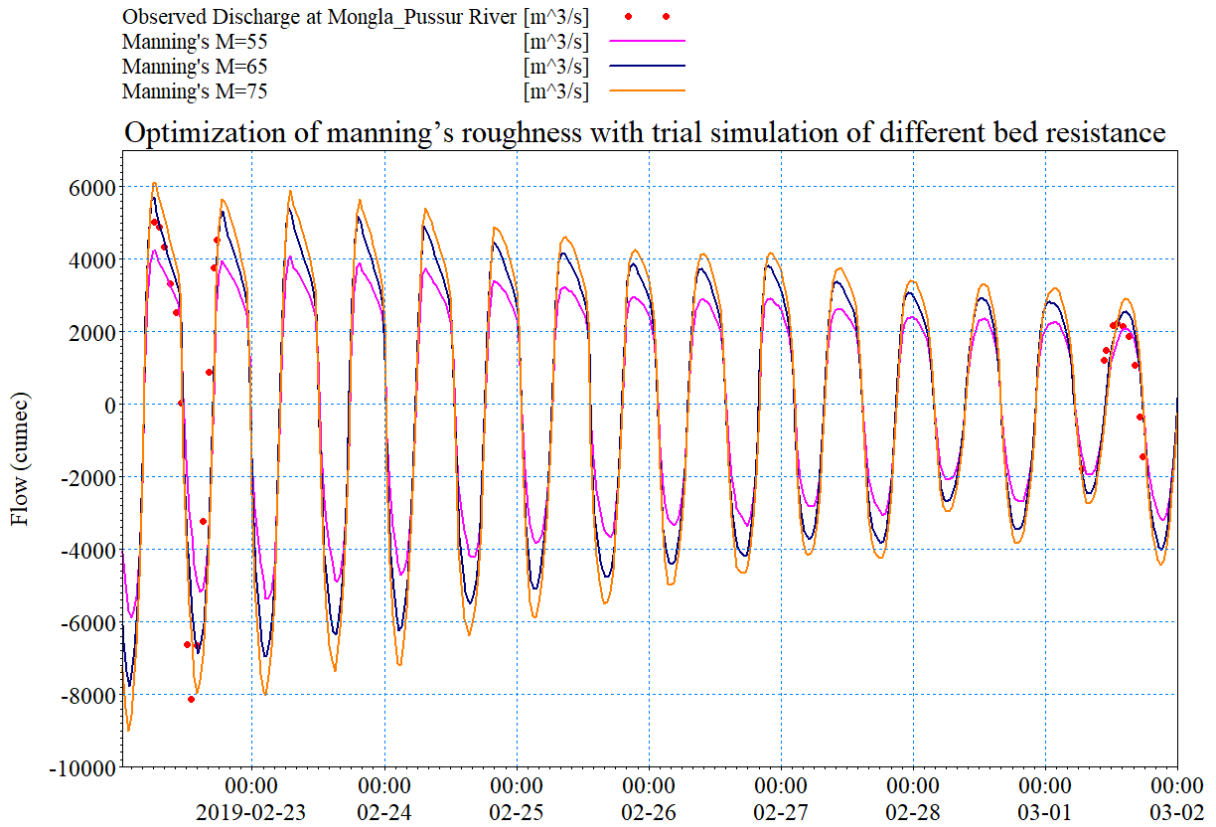


Figure 4-14: Optimization of manning's roughness with trial simulation of different bed resistance (at Pussur River).

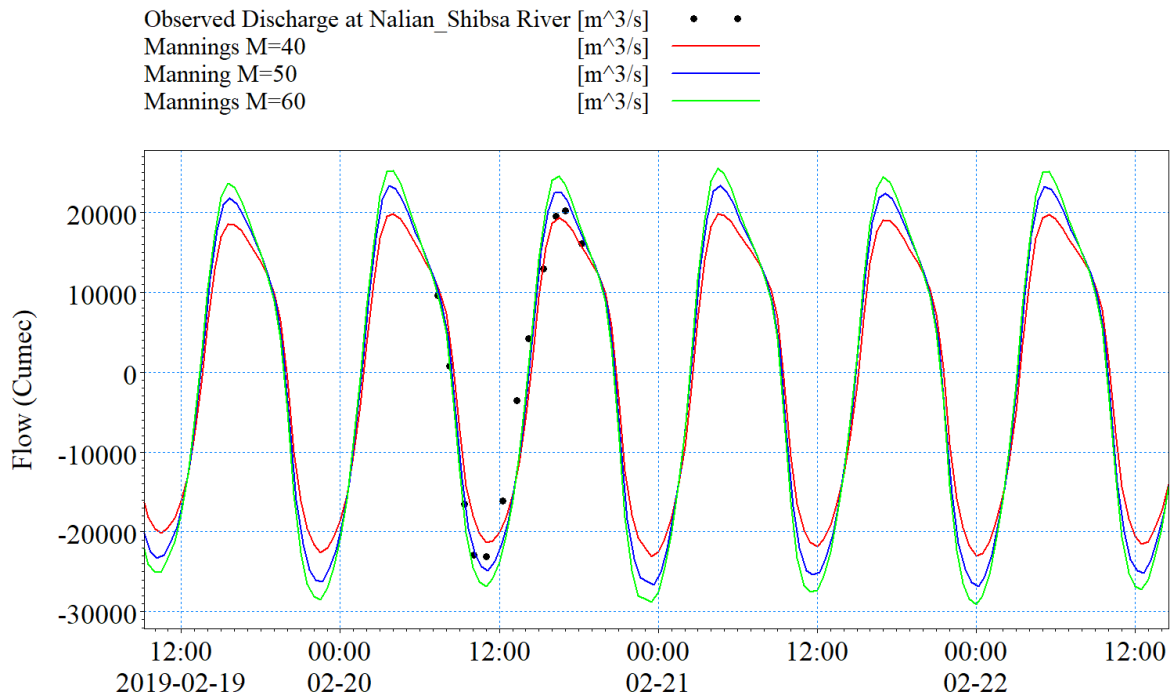


Figure 4-15: Optimization of manning's roughness with trial simulation of different bed resistance (at Sibsa River).

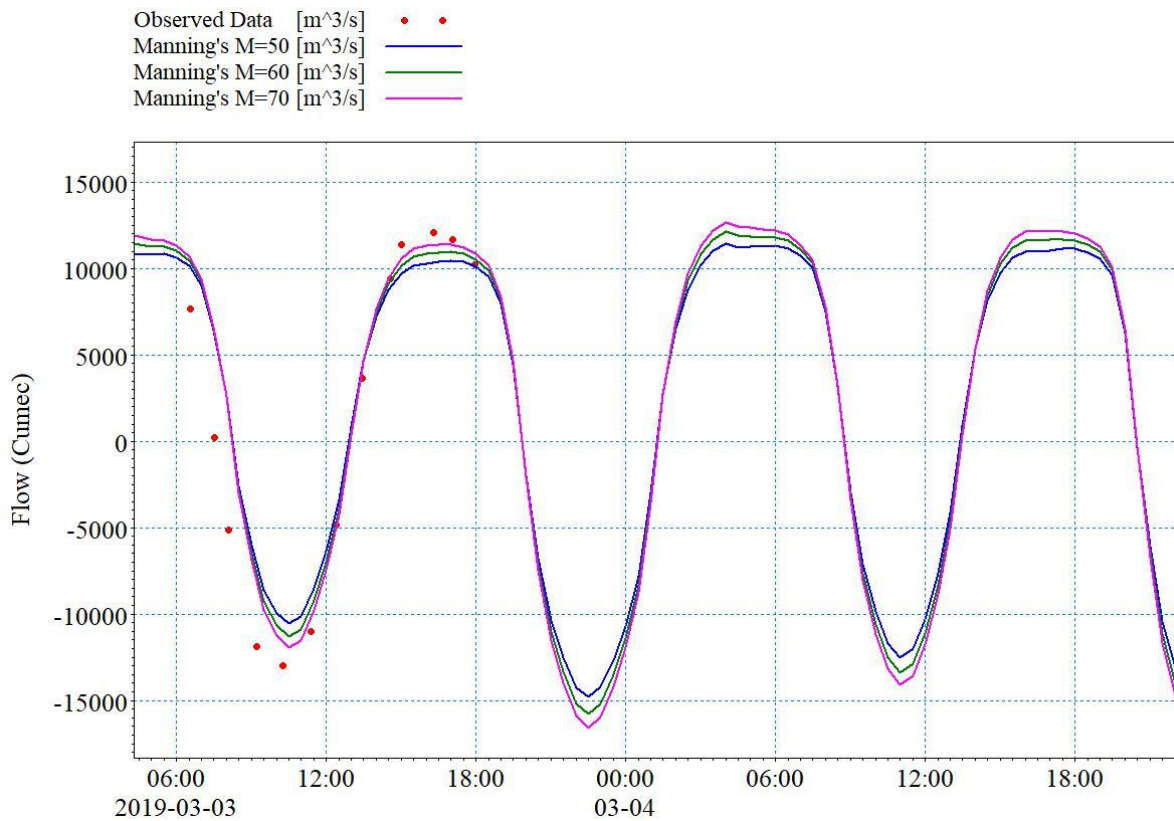


Figure 4-16: Optimization of Manning's roughness with trial simulation of different bed resistance (at Baleswar River).

4.3.5 Dispersion co-efficient used in the 1D mathematical model (SWRM)

Value of dispersion co-efficient at estuaries is a key calibration parameter for salinity intrusion modelling. Dispersion co-efficient is also an important calibration factor for one dimensional advection dispersion model. Value of dispersion co-efficient in the major river system of south west region is show in **Table 4-3**.

Table 4-3: Dispersion co-efficient used in the major river systems

Name of the Major River in South West Region	Dispersion co-efficient (m ² /s)
ANDHARMANIK	400
ARPANGASIA	300
BALESWAR	150
BISHKHALI	100
BURISWAR	200
HARINGHATA	100
KHAPRABHANGA	400
MALANCHA	500
PUSSUR	500
SIBSHA	200
RUPSA	300
TENTULIA	600

4.3.6 Sensitivity of Dispersion co-efficient observed from SWRM

Similar to determination of Manning’s roughness number, the dispersion co-efficient is also determined with trial-and-error simulation. For example, **Figure 4-17** shows the times series salinity simulation result for dispersion co-efficient (100 m²/s, 200 m²/s, 300 m²/s and 400m²/s respectively) for Rupsha river. And it is found that, value 300 m²/s is the optimum value for advection dispersion simulation.

Similarly, sensitivity of dispersion co-efficient for Baleswar, Buriswar and Sibsar river system is shown in **Figure 4-18** to **Figure 4-20**.

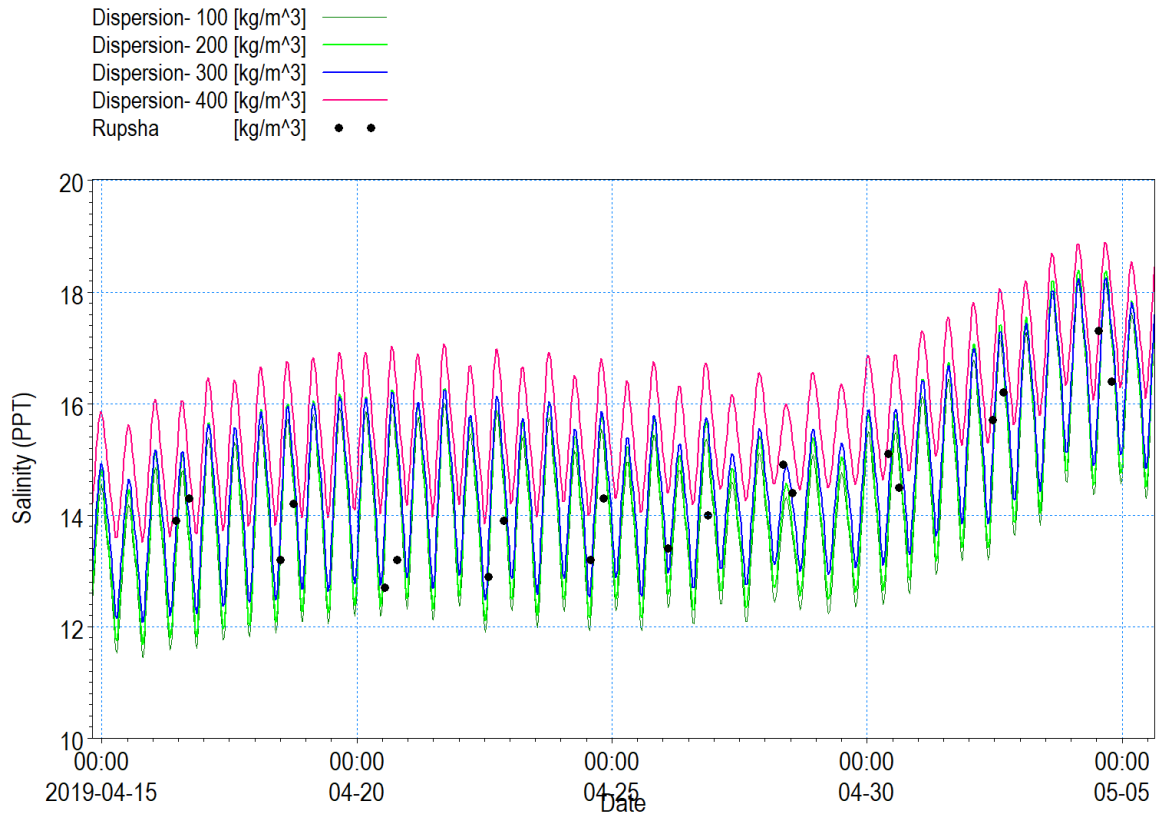


Figure 4-17: Optimization of dispersion co-efficient with trial simulation (for Rupsha River).

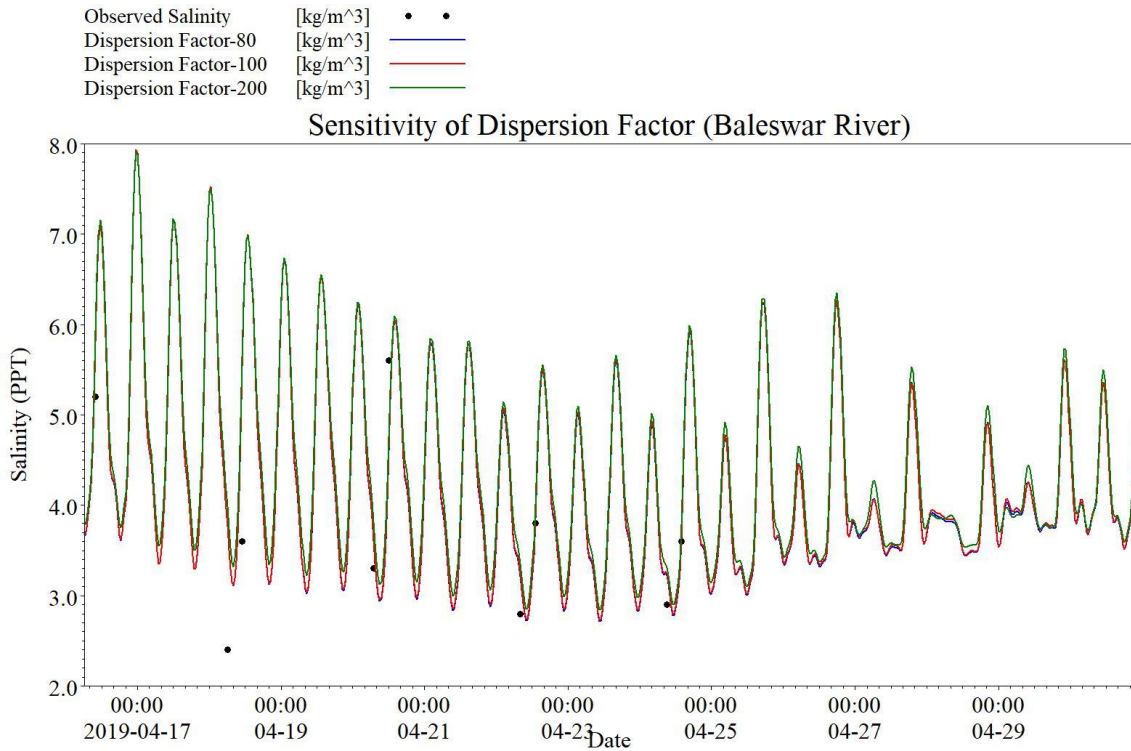


Figure 4-18: Optimization of dispersion co-efficient with trial simulation (for Baleswar River).

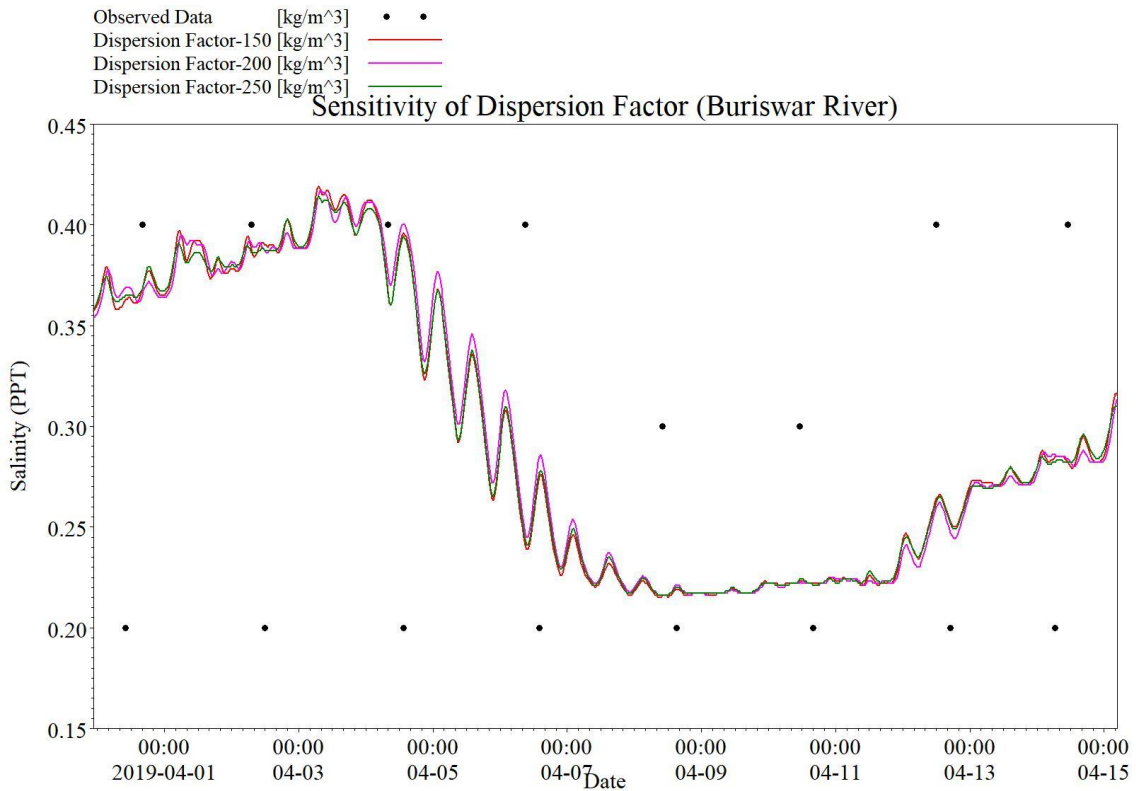


Figure 4-19: Optimization of dispersion co-efficient with trial simulation (for Buriswar River).

Observed Salinity [kg/m³] • •
 Dispersion Factor-200 [kg/m³] —
 Dispersion Factor-400 [kg/m³] —
 Dispersion Factor-600 [kg/m³] —

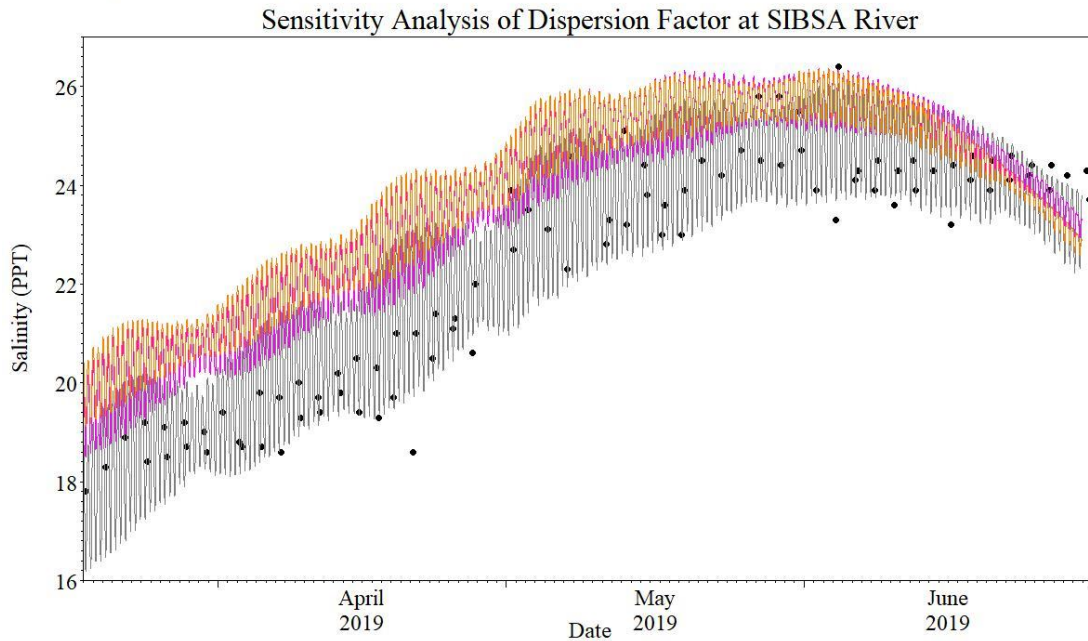


Figure 4-20: Optimization of dispersion co-efficient with trial simulation (for Sibsra River).

4.3.7 Calibration of Hydrodynamic & Advection Dispersion of SWRM

Calibration means adjustment of the model parameters so that simulated and observed data will match within the desired accuracy. This section discusses the performance of hydrodynamic and advection dispersion models. In order to get a good calibration of salinity, water flow calibration in the branches of the model is very important. Simulated flow and water level Water level, water flow and salinity are calibrated against measured data in different locations (shown in **Figure 4-21**) of the coastal region. Following figures shows some water flow calibration results.

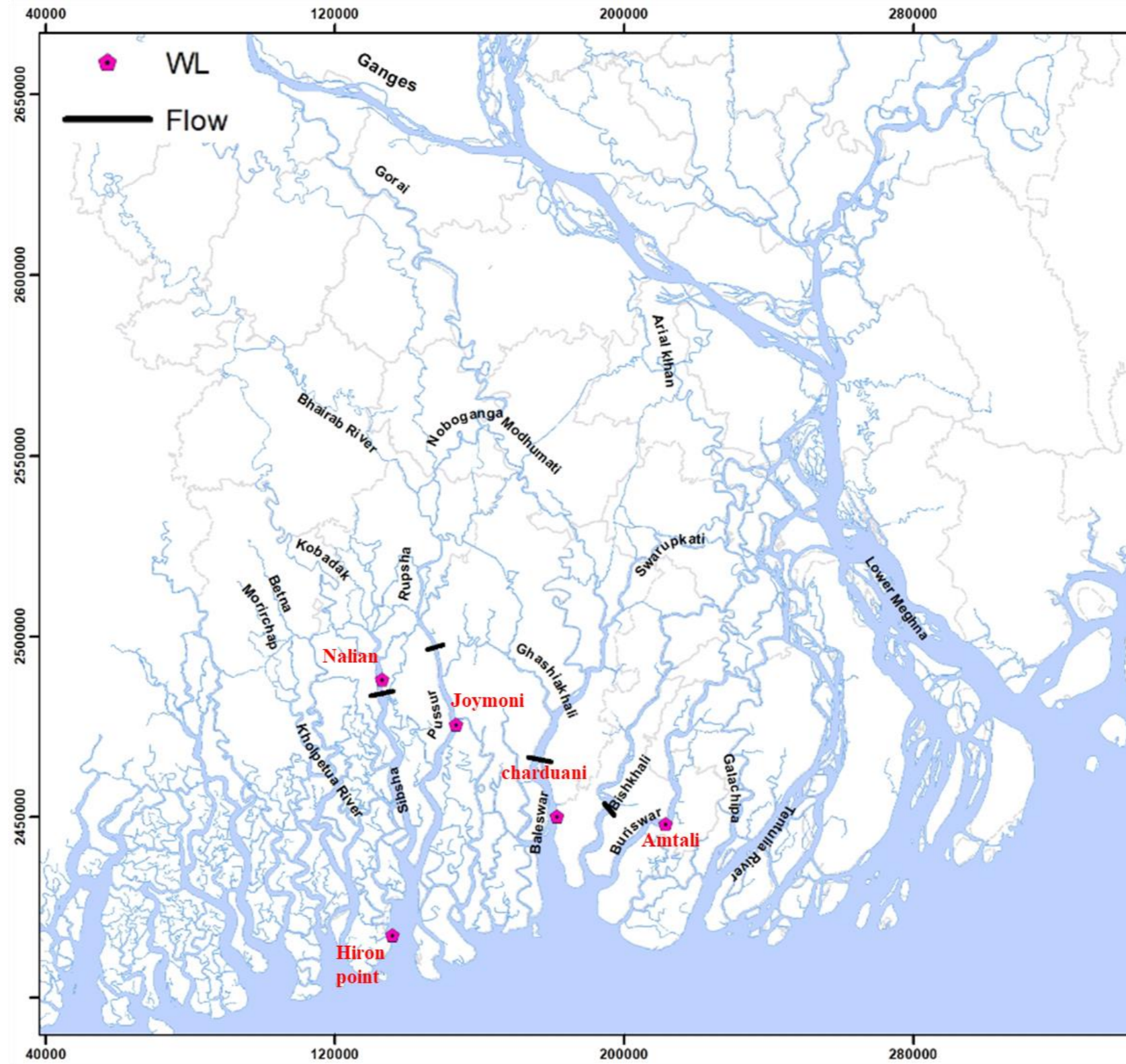


Figure 4-21: Water level and flow calibration location.

Calibration of Discharge

Figure 4-22 shows the graphical comparison between observed and simulated discharge in Bishkhali and Pussur river. Table 4-4 shows the comparison of maximum observed and simulated ebb and flood discharge.

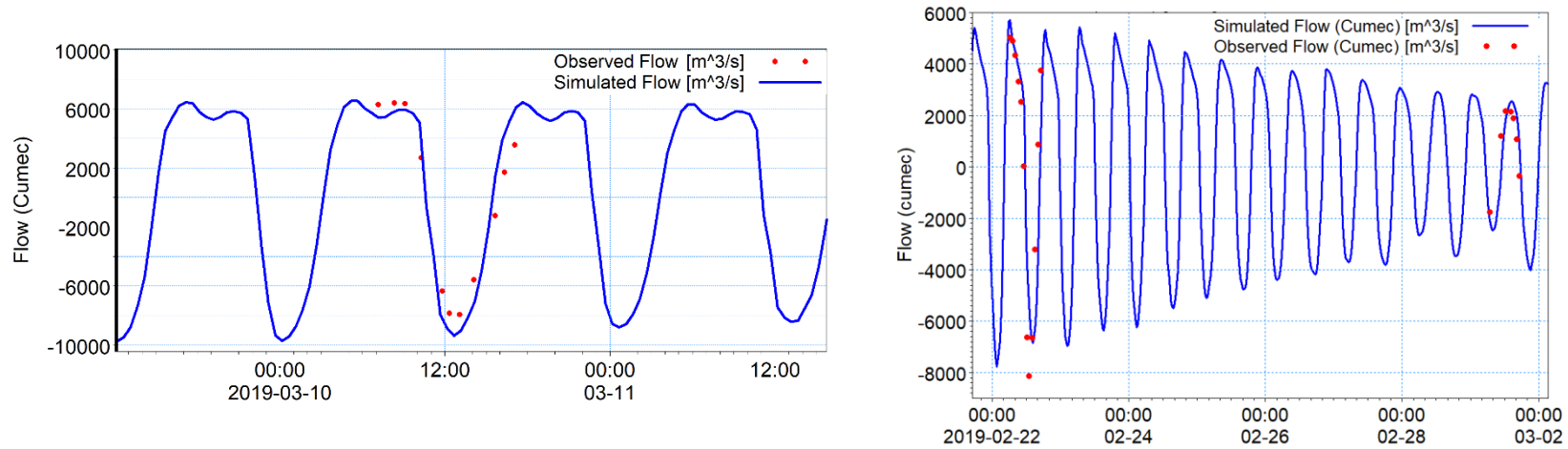


Figure 4-22: Calibration plot of Dry season flow at Bishkhali (left) and Pussur (right)

Table 4-4: Comparison of simulated and observed maximum ebb flow and flood flow

Location		Observed	Simulated
Bishkhali	Maximum Ebb flow (cumec)	6390	6539
	Maximum Flood flow (cumec)	-7933	-9717
Pussur	Maximum Ebb flow (cumec)	5031	5710
	Maximum Flood flow (cumec)	-8140	-7766

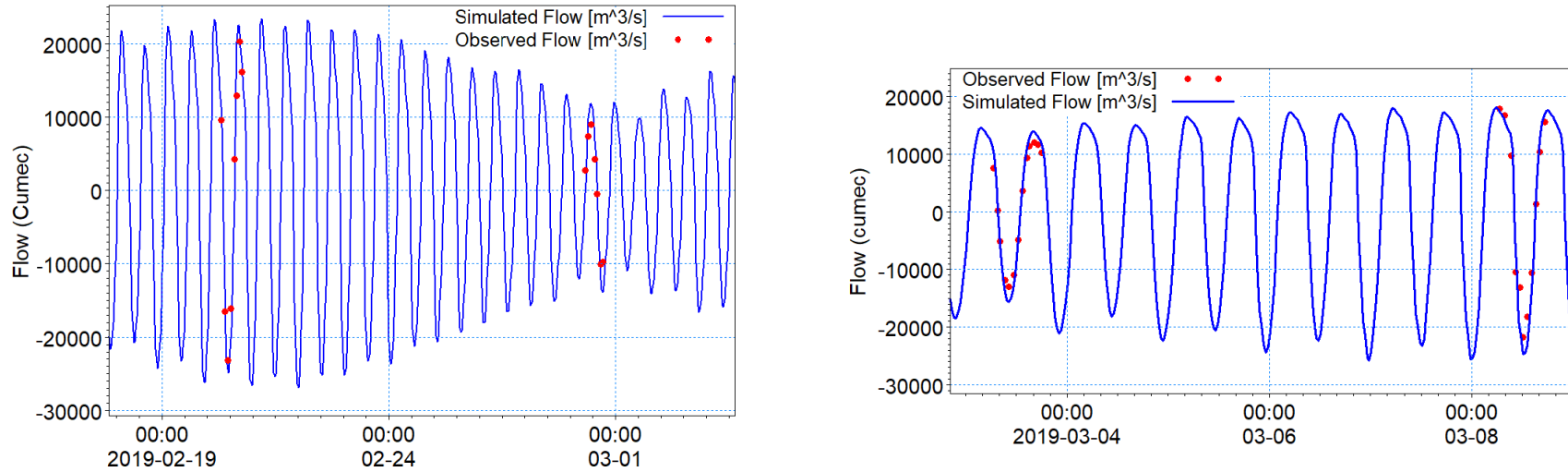


Figure 4-23: Calibration plot of Dry season flow at Sibsa (left) and Baleswar (right)

Figure 4-23 shows the graphical comparison between observed and simulated discharge in Sibsa and Baleswar River. **Table 4-5** shows the comparison of maximum observed and simulated ebb and flood discharge.

Table 4-5: Comparison of simulated and observed maximum ebb flow and flood flow

Location		Observed	Simulated
Sibsa	Maximum Ebb flow (cumec)	20221	23378
	Maximum Flood flow (cumec)	-23115	-26224
Baleswar	Maximum Ebb flow (cumec)	17938	18200
	Maximum Flood flow (cumec)	-21795	-24668

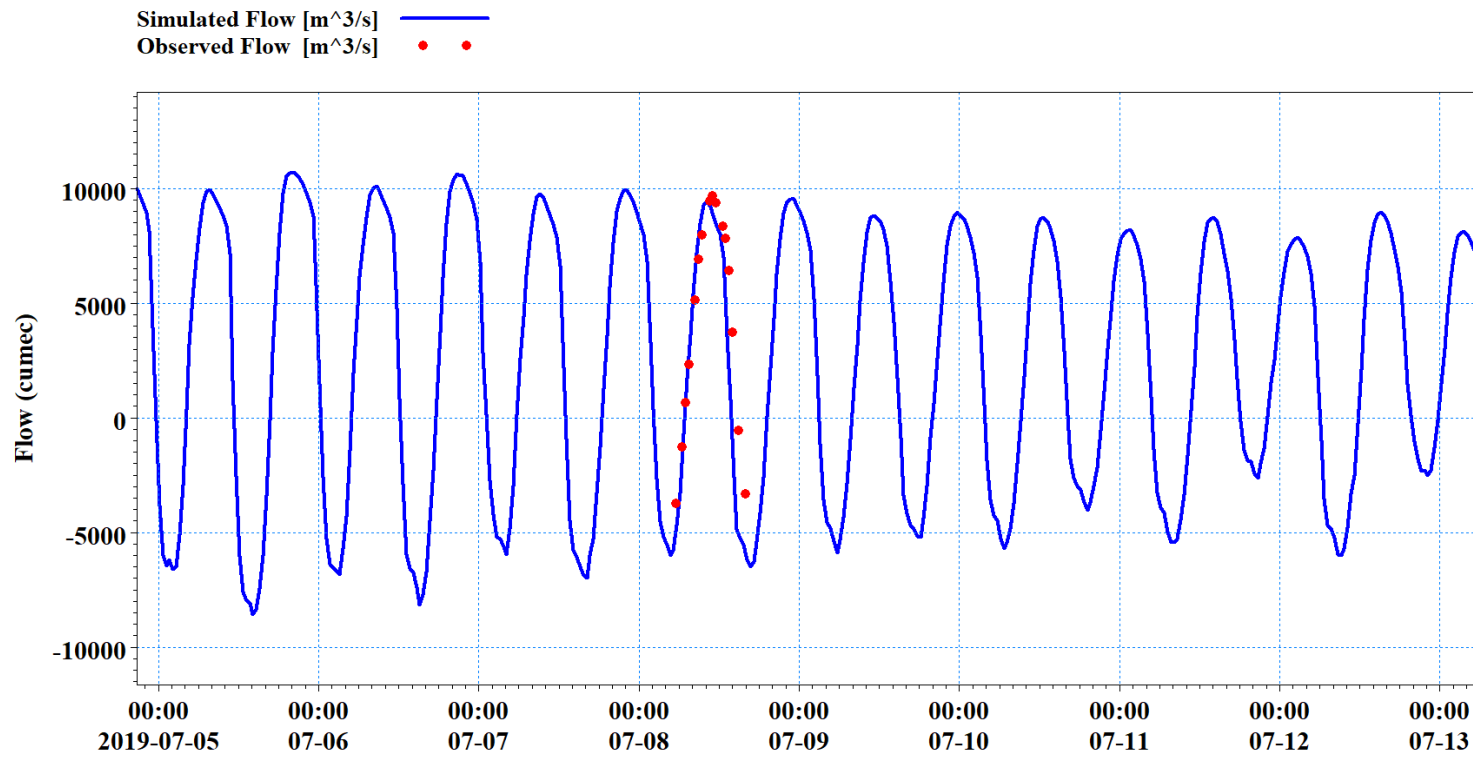


Figure 4-24: Calibration plot of Monsoon season flow at

Calibration of water level

Figure 4-25 shows the graphical comparison between observed and simulated water level in Buriswar river at Amtali and in Pussur river at Joymoni. Table 4-6 shows the comparison of water level statistics for observed and simulated data.

Table 4-6: Comparison for statistics of water level for simulated and observed data

	Buriswar River		Pussur River	
	Observed	Simulated	Observed	Simulated
Max Water Level (mPWD)	2.36	2.53	3.12	2.94
Min Water Level (mPWD)	-1.00	-0.76	-1.72	-1.89
Tidal Range (m)	3.36	3.28	4.84	4.83

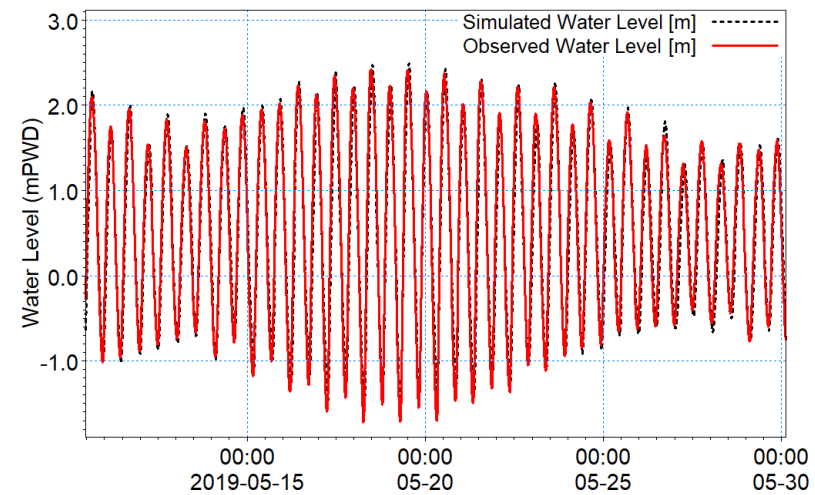
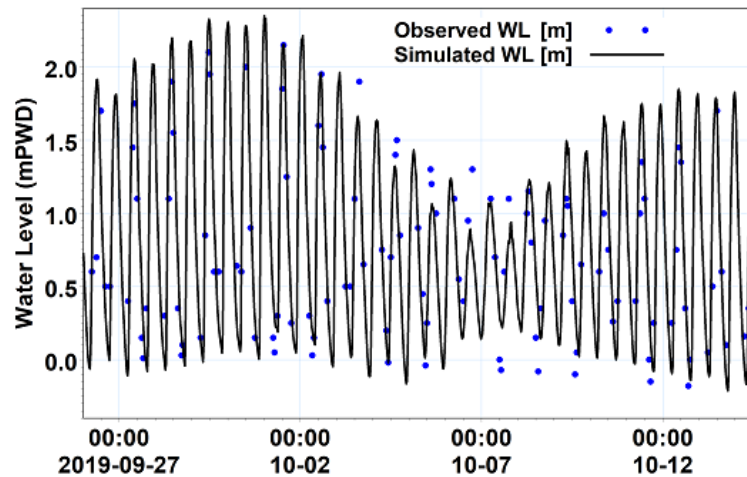


Figure 4-25: Calibration plot of Water level data in Buriswar river at Amtali (left) and in Pussur river at Joymoni (Right)

Figure 4-26 shows the graphical comparison between observed and simulated water level in Sibsa river at Nalian and in Baleswar river at Charduani. Table 4-7 shows the comparison of water level statistics for observed and simulated data.

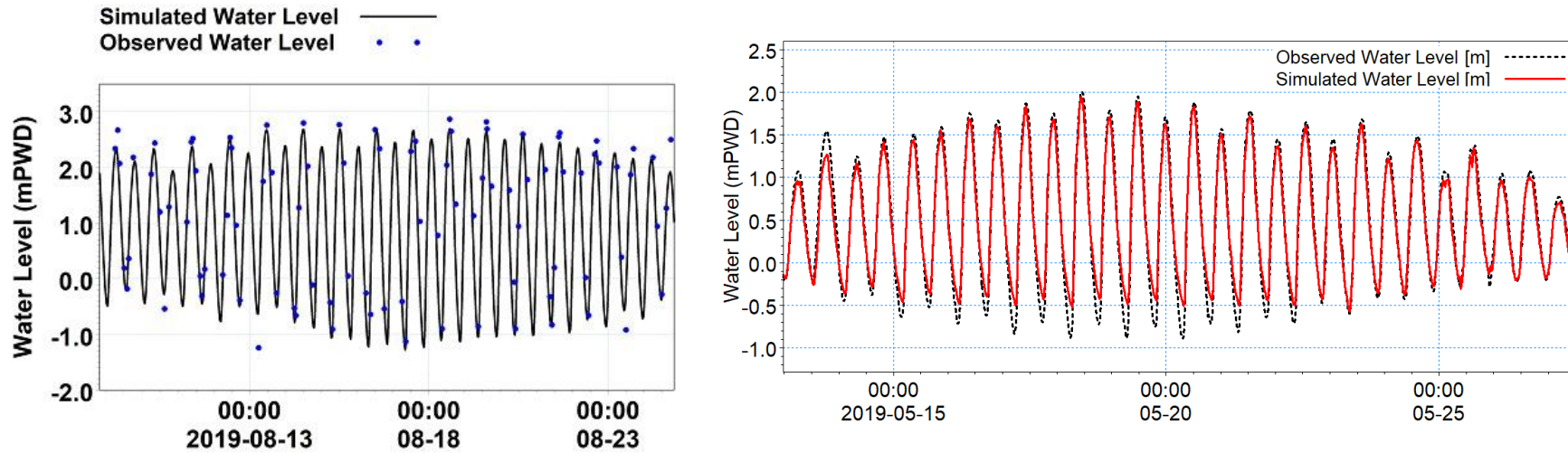


Figure 4-26: Calibration plot of Water level data in Sibsa river at Nalian (left) and in Baleswar river at Charduani (Right)

Table 4-7: Comparison for statistics of water level for simulated and observed data

	Sibsa River		Baleswar River	
	Observed	Simulated	Observed	Simulated
Max Water Level (mPWD)	3.89	2.93	2.43	2.60
Min Water Level (mPWD)	-1.66	-2.16	-1.28	-0.77
Tidal Range (m)	5.54	5.09	3.71	3.37

Calibration of 1D salinity Model

Advection dispersion module was incorporated after calibration of the hydrodynamic model. Advection dispersion model is simulated for the year 2019. Thereafter, measured salinity was compared with simulated salinity. **Figure 4-27** to **Figure 4-35** shows the calibration plot of salinity at Charduani (Baleswar river), Amtali (Buriswar river), Ghashikahli river, Rupsha ghat (Rupsha river), Bardia (Nabaganga river), Nalian (Sibsa river) and Sundormohol (Gangril river). Location of calibration point is depicted in **Figure 3-1**.

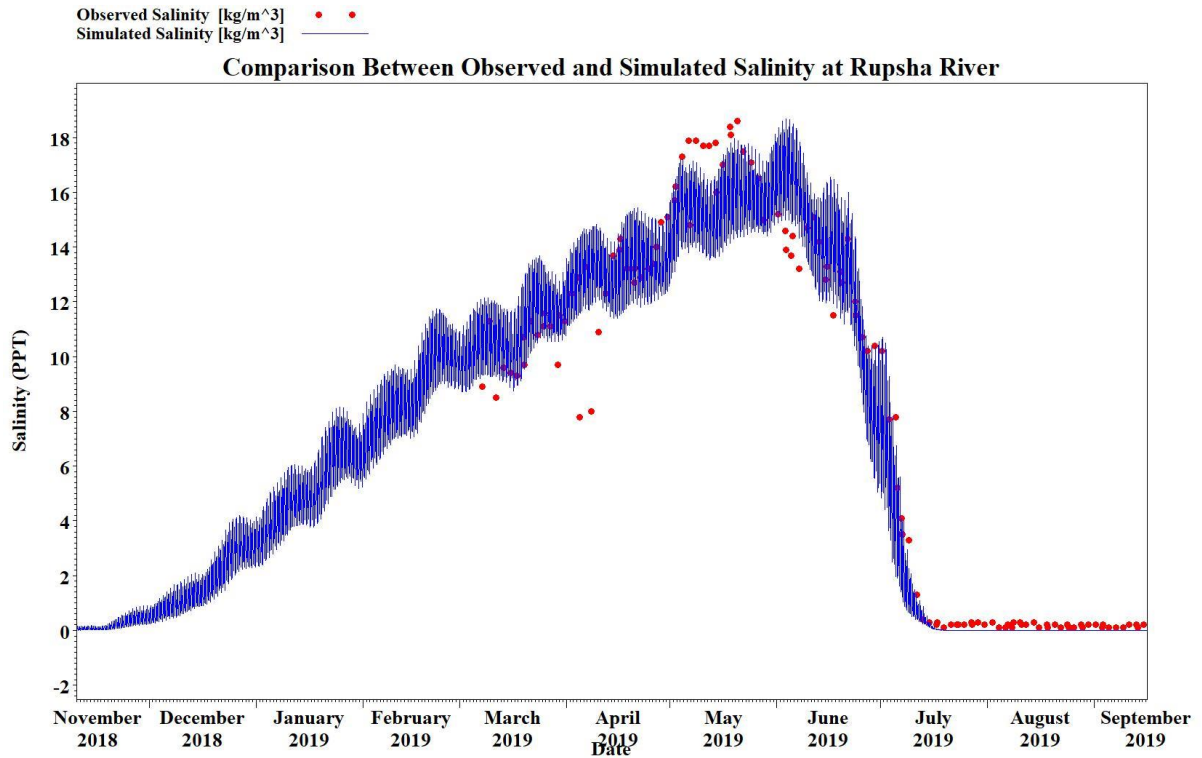


Figure 4-27: Salinity calibration plot at Rupsha River

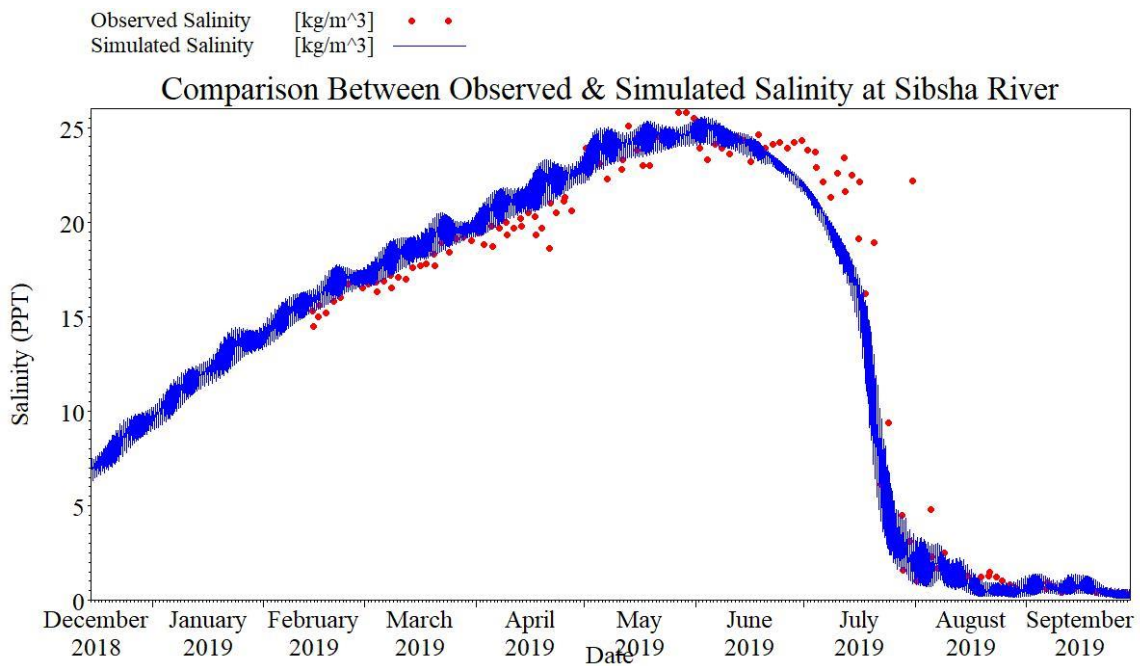


Figure 4-28: Salinity calibration plot at Sibsha River

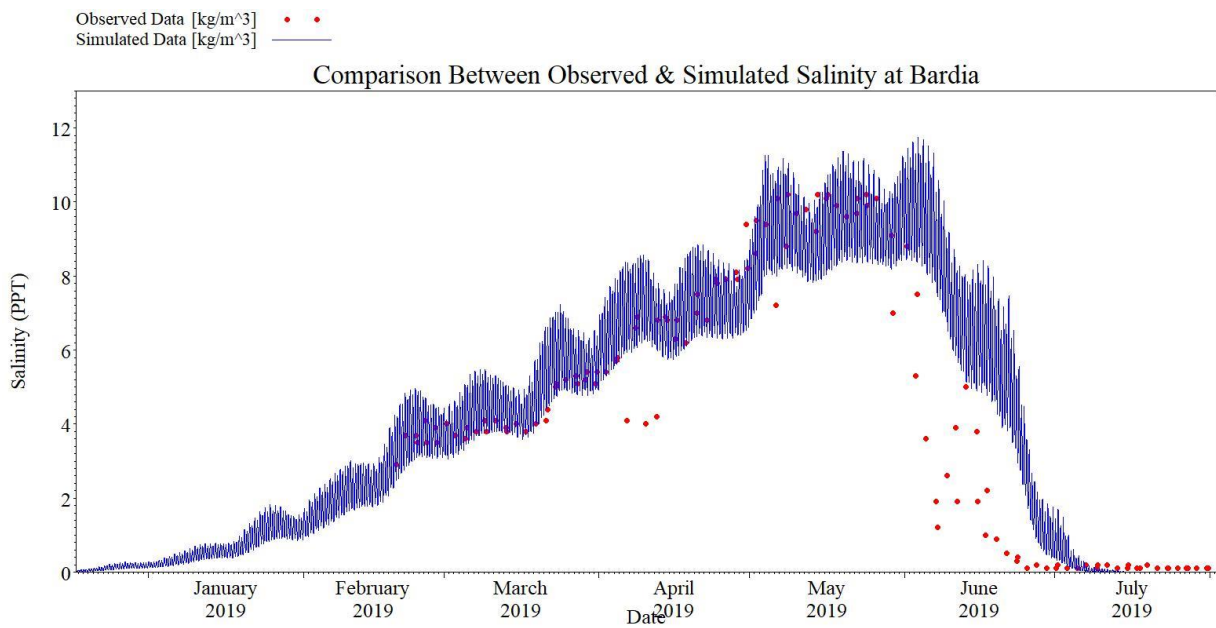


Figure 4-29: Salinity calibration plot at Sibsha River

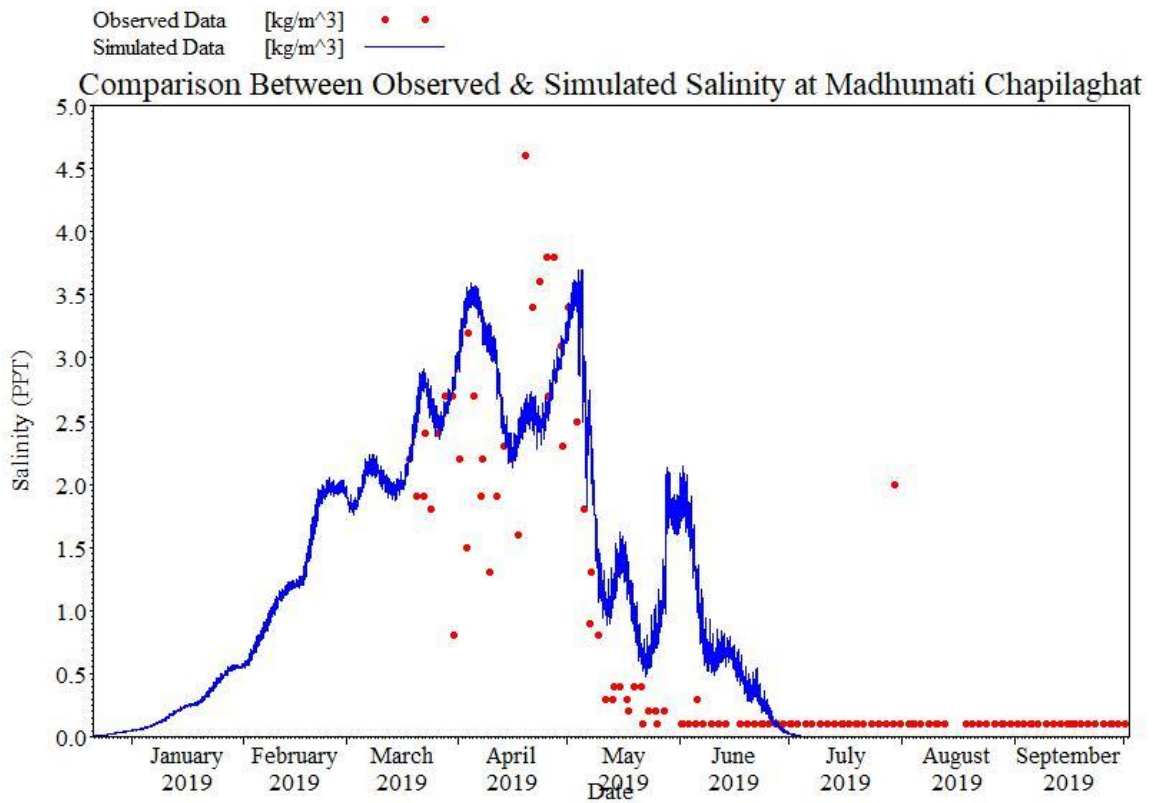


Figure 4-30: Salinity calibration plot at Chapilaghat (Madhumati River)

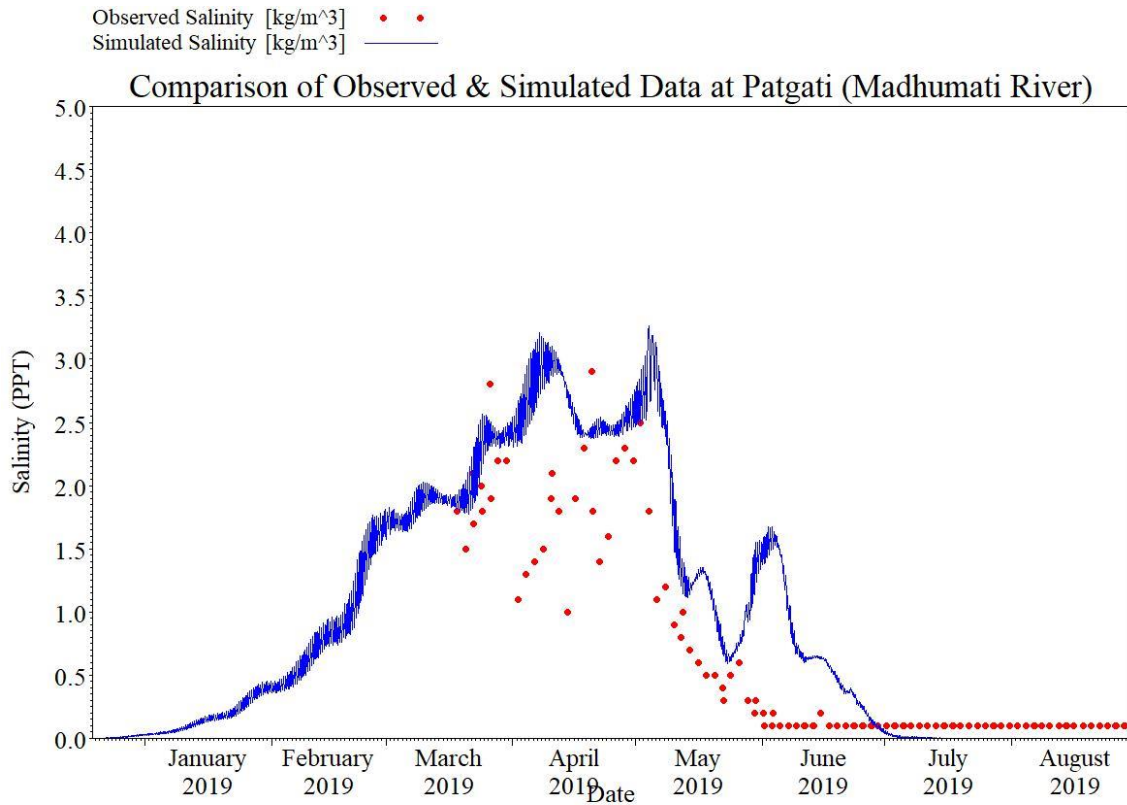


Figure 4-31: Salinity calibration plot at Patgati (Madhumati River)

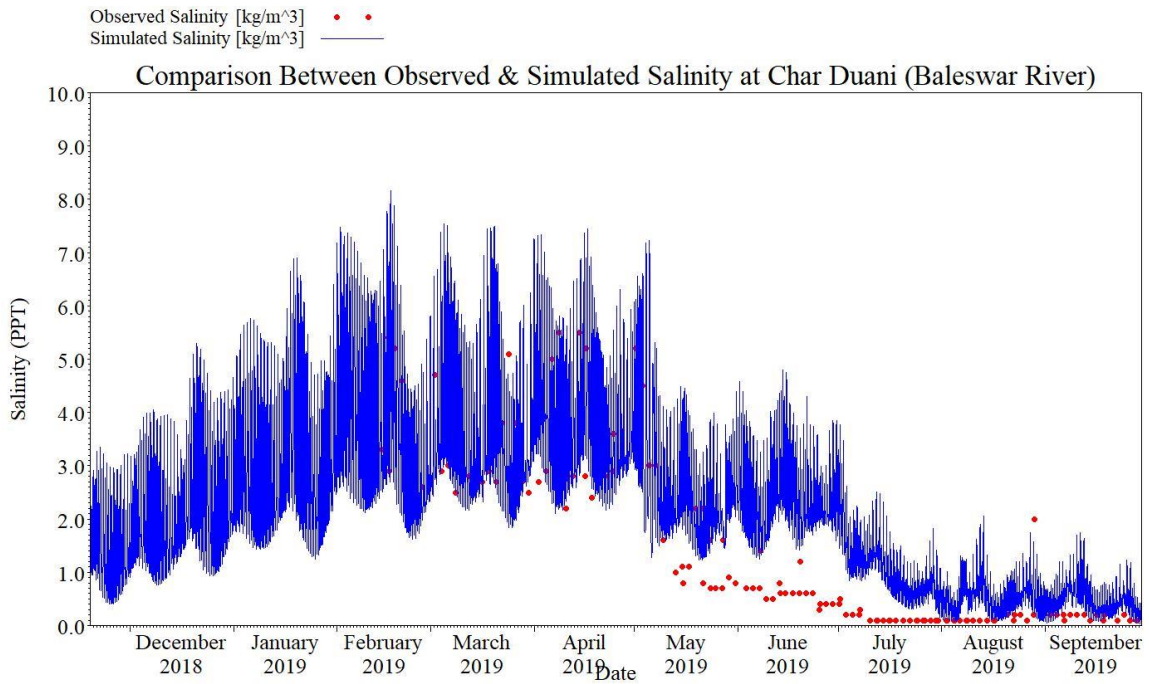


Figure 4-32: Salinity calibration plot at Amtali (Buriswar River)

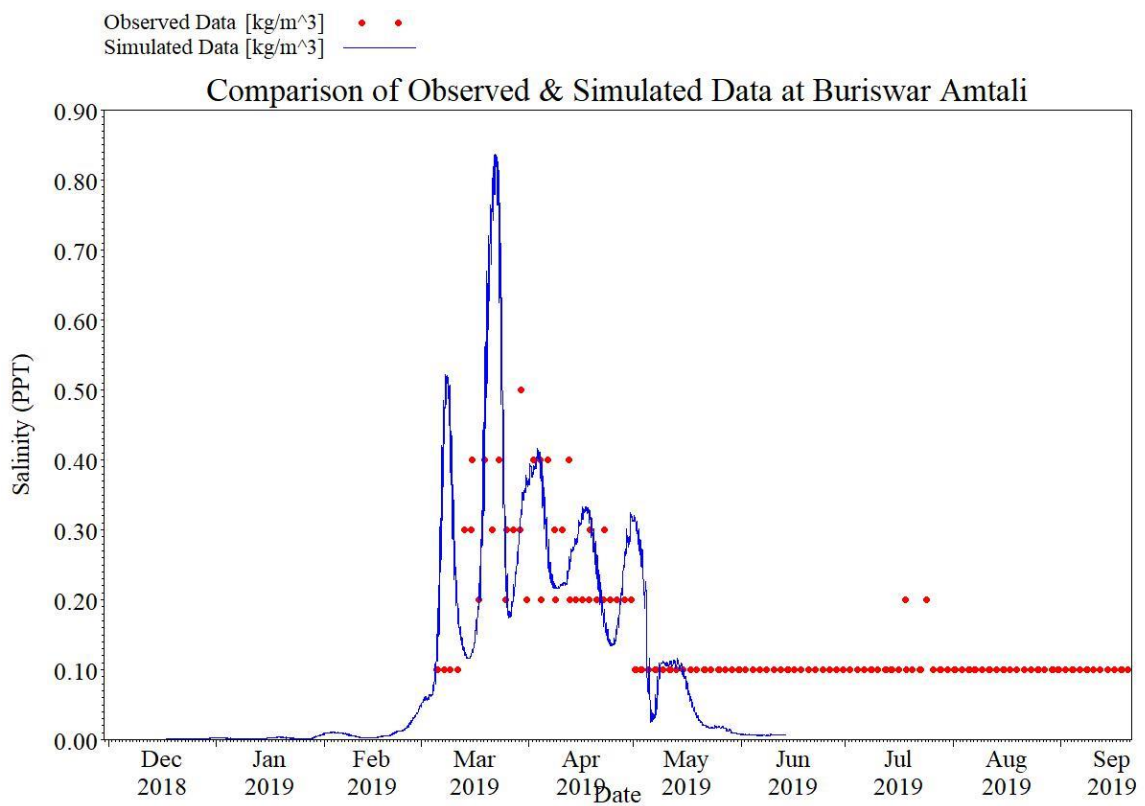


Figure 4-33: Salinity calibration plot at Amtali (Buriswar River)

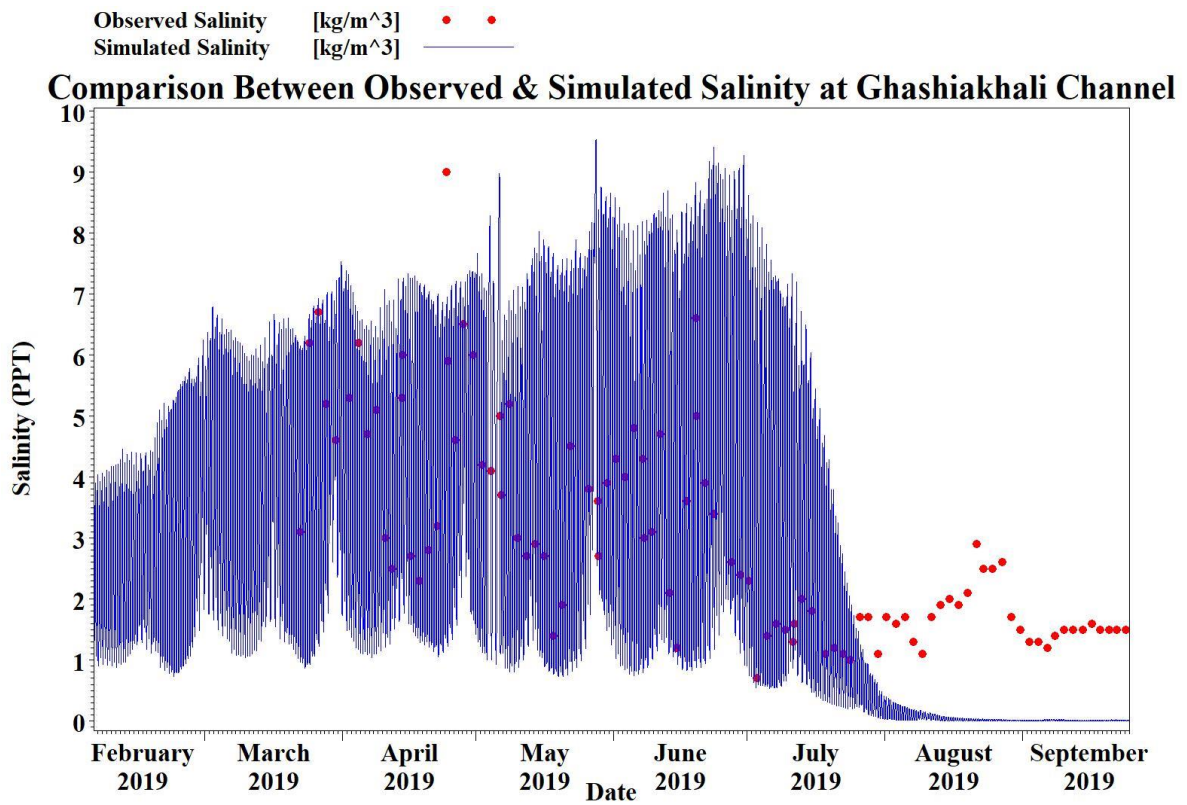


Figure 4-34: Salinity calibration plot at Ghashiakhali River

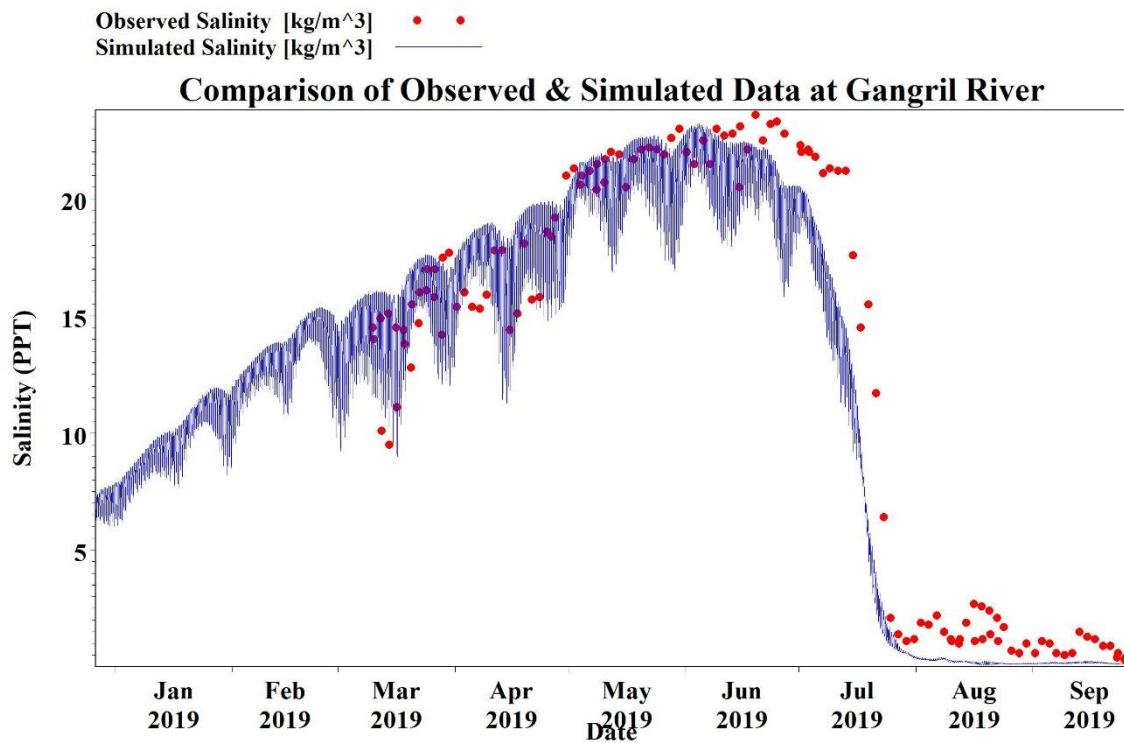


Figure 4-35: Salinity calibration plot at Gangril River.

5 Spatial Variation of Salinity

5.1 Methodology for Interpretation of Model result

From data analysis and model results it is observed that, salinity varied with time and distance along the rivers. Dry season is the most vulnerable for coastal zone of Bangladesh in perspective of salinity intrusion. Specifically, February, March, April and May are the most vulnerable month. However, firstly a threshold value needs to be defined to delineate boundary of vulnerable location. For drinking water purpose, **1ppt** salinity is the threshold value and for irrigation **2 ppt** salinity is the threshold value for irrigation for agricultural purposes.

Salinity spatial map is generated from the simulation data of 1D mathematical modelling result. 2D model does not contain all river system in the regional level but it does provide the boundary to 1D model and 1d model covers all the representative river system in the hydrological domain that's why ultimately 1D model is simulated to generate the result. However, Mathematical model simulation generates salinity value at the discretized nodes of each river within the model domain. Each discretized node in the river stores the value of time series. A simulation was carried out during dry season of 2019 (from December, 2018 to mid-June, 2019).

Methodology for Spatial Salinity Plot:

- a) From the simulation, co-ordinate of each discretized point is extracted;
- b) Maximum Salinity value at each discretized point is calculated for each month in the dry season;
- c) A three-column database is created for each month in the dry season. First two columns contain the x and y co-ordinate of the discretized point and third column contains the maximum salinity value in the particular month;
- d) This database is interpolated in Arc-GIS tool within the boundary of Southwest-Southcentral hydrologic region boundary.
- e) With the interpolation technique, geospatial maximum salinity contour is created;

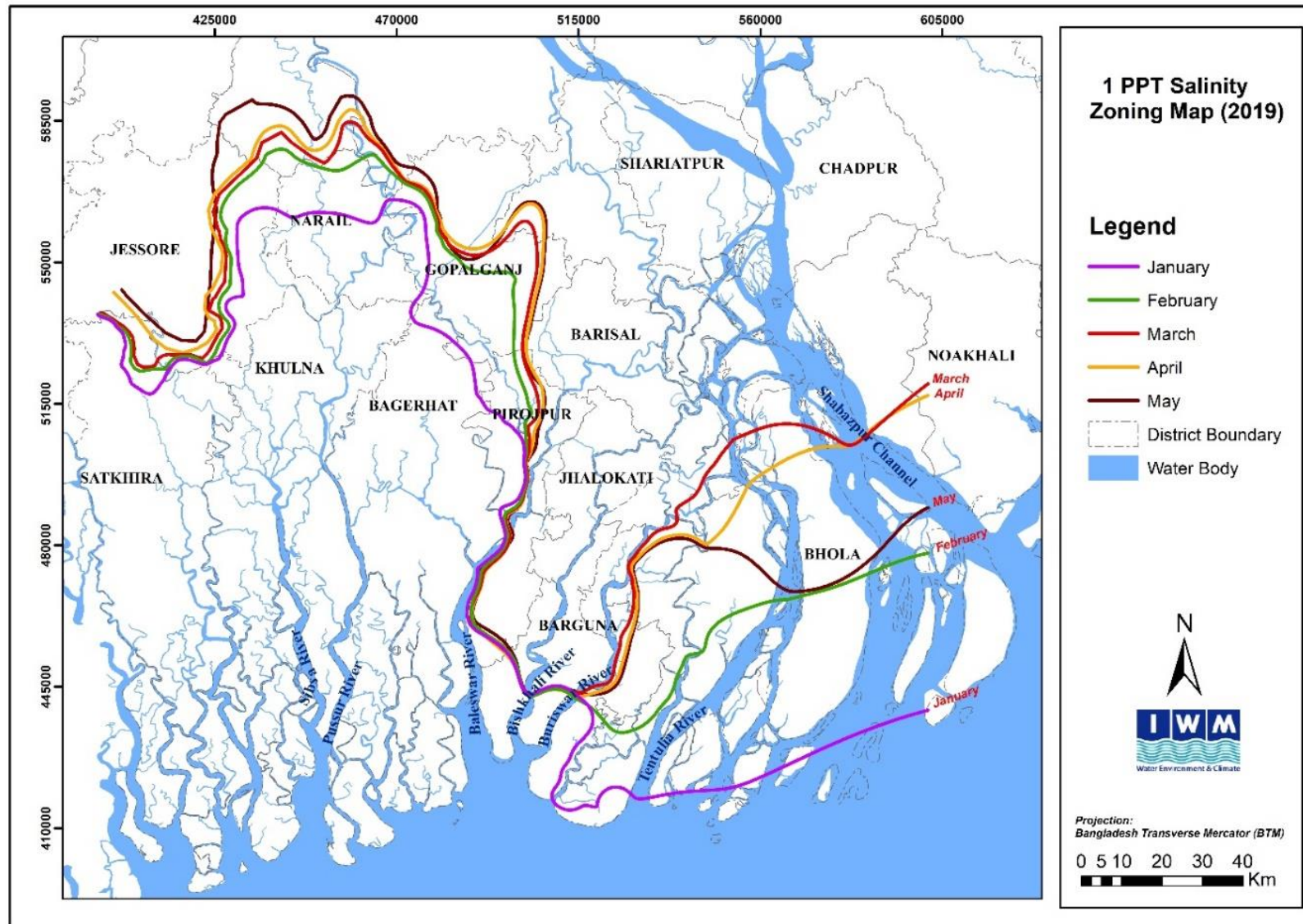


Figure 5-1: 1ppt salinity contour at Southwest regional model in dry season.

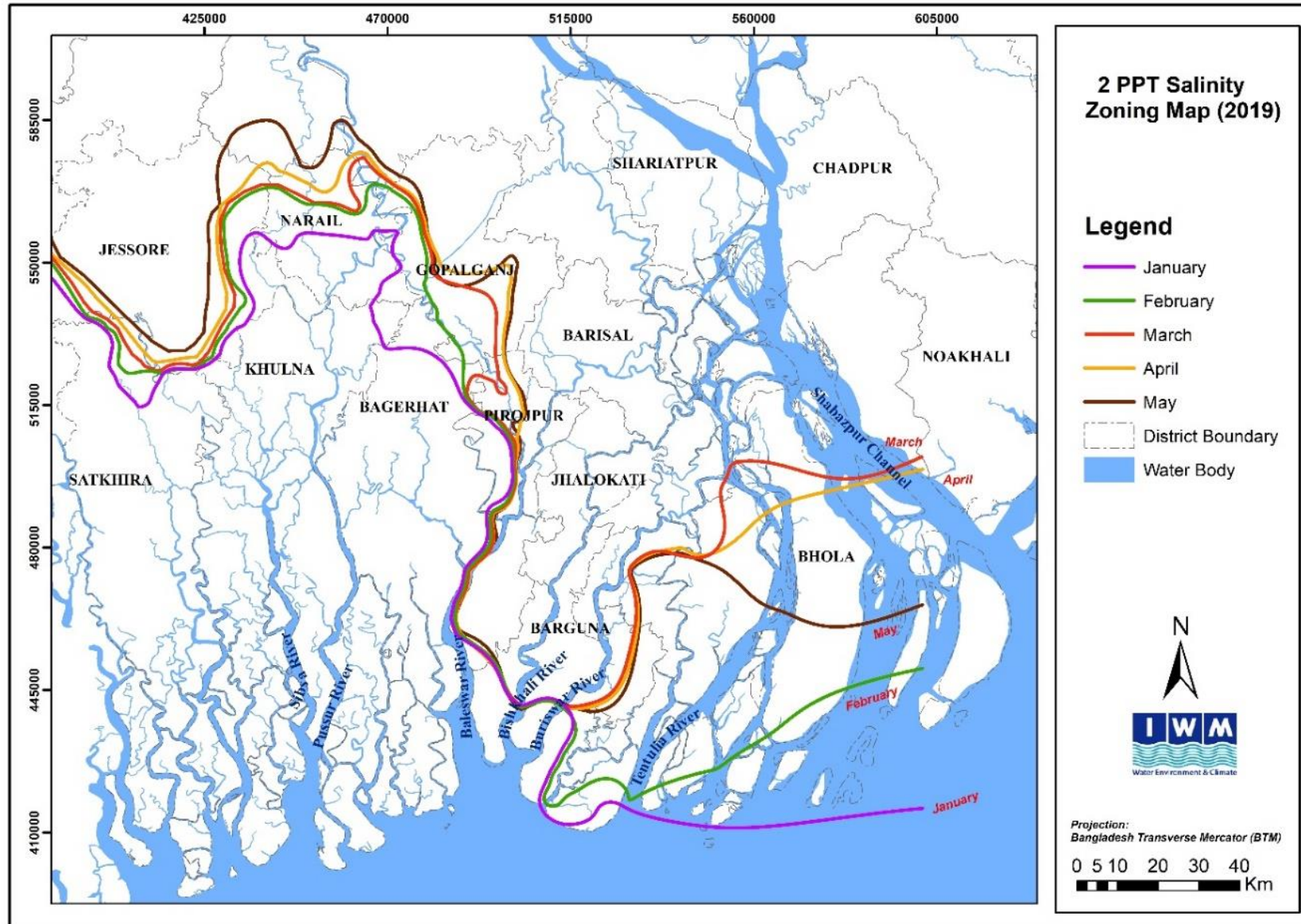


Figure 5-2: 2 ppt salinity contour at Southwest regional model in dry season

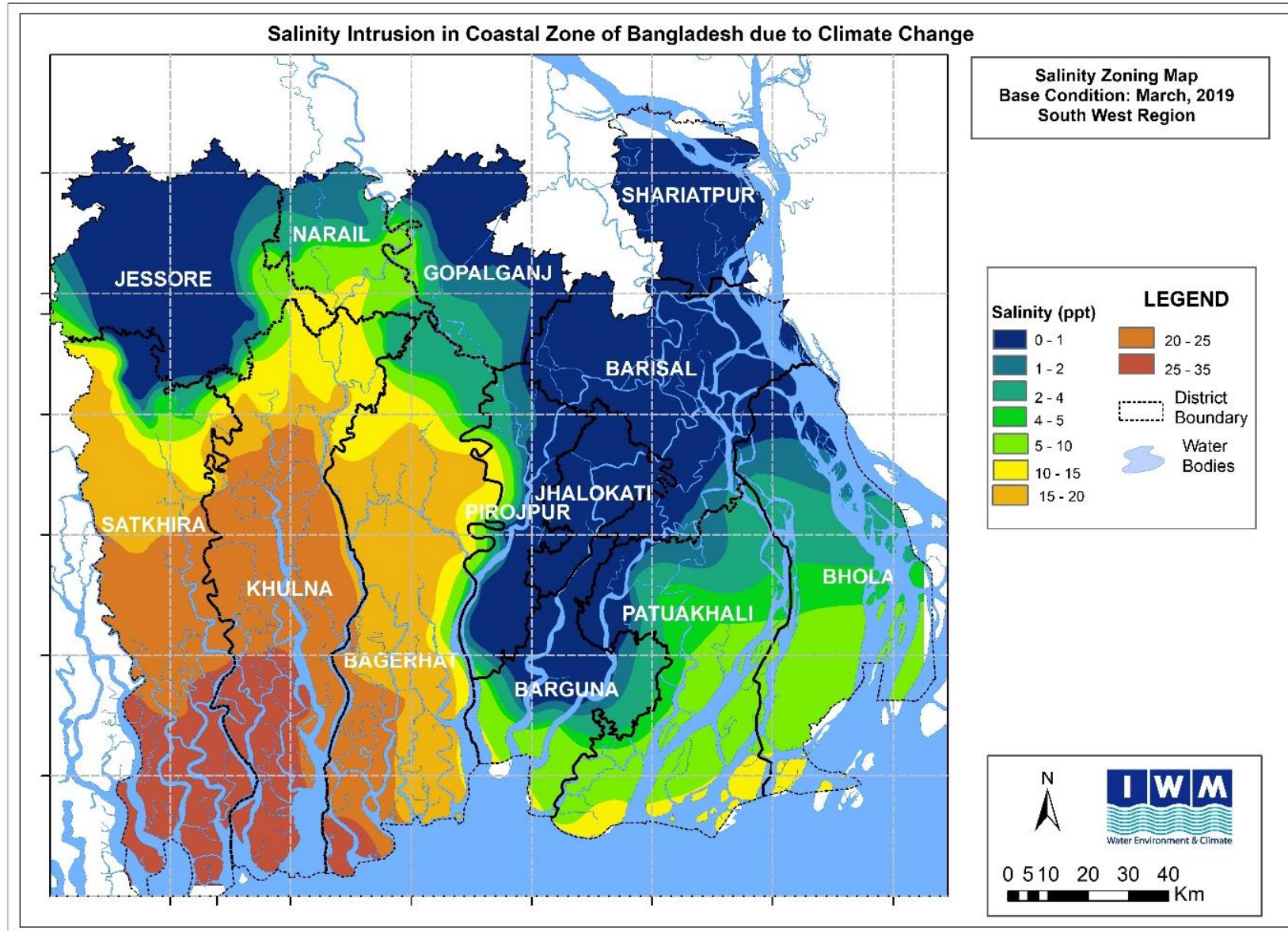


Figure 5-3: Salinity Raster during March, 2019



6 Future Work Plan

Future work plan of the project is mentioned following:

- a) Development of scenarios for climate change condition (change in rainfall, Sea level rise) and for in upstream withdrawal;
- b) Establishment of salinity iso-haline for different scenarios.



7 Reference

- /1/ *Salinity Modelling Report* (Surface Water Simulation Modelling Programme, Phase II). (1993). Danish Hydraulic Institute.
- /2/ Global Ocean Tide Model - DTU Space:
https://www.space.dtu.dk/english/research/scientific_data_and_models/global_ocean_tide_model
- /3/ Fischer, H., B., List, E., J., Koh, R., C., Y., Imerberger J., Brooks N., H., (1979). *Mixing in inland and coastal waters*, Academic Press, New York.
- /4/ Ganges Barrage Study Report: Vol. V. (2012). Ministry of Water Resources.