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

DHI Deltares Enabling Delta Life IWM Water Environment & Climate Columbia University

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Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone

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Memo No: CEIP/LTMRA/0921/130 20 September, 2021

Project Management Unit
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
House No.15, 4tn Floor, Road
No.24(CNW) Gulshan, Dhaka-1212

Attn: Mr. Syed Hasan Imam, Project Director

Dear Mr Imam,

Subject: Submission of Interim report on Salinity Modelling at current situation (Component 4D)

It is our pleasure to submit herewith five copies of the Modelling report on "***Component-4D**: The effect of climate change on water levels, salinity intrusion and storm surges: Interim report on Salinity Modelling Current Situation*".

This report contains 6 chapters. The report describe the procedure of salinity data collection, seasonal variation of salinity in the river system and estuary, stratification of surface water salinity in coastal river system of Bangladesh based on survey data and literature review, 1D and 2D mathematical modelling framework for salinity in the coastal zone, calibration of the model, Simulation of salinity intrusion model at base condition and it's post processing for base condition (preparation of Map of spatial variation of salinity at base for dry season) etc.

Thanking you,

Yours sincerely,

Dr Ranjit Galappatti
Team Leader

27/09/2021

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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.

As a start this report describes the problems caused by an increasing salinity intrusion, due to a lowering of transboundary flow. It is also illustrated how dredging int Ganges distributaries 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.

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 distributary of Ganges River. Moreover, there are other distributary rivers, such as Mathabhanga, Ichamoti and Baral (upper). However, almost all these distributaries 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 distributary 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.

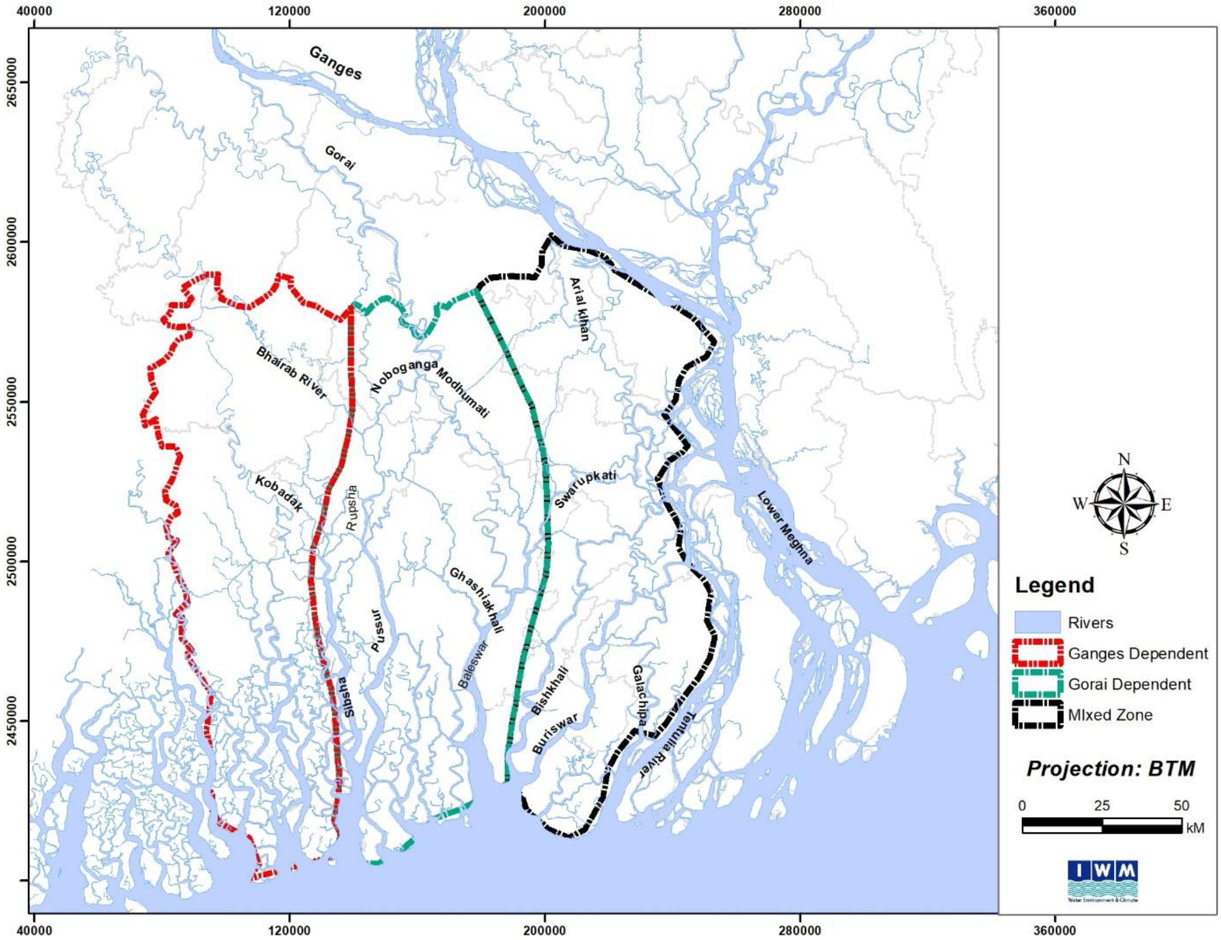


Figure 2-1: South west region is divided into three regions according to salinity level and availability of fresh water.

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.

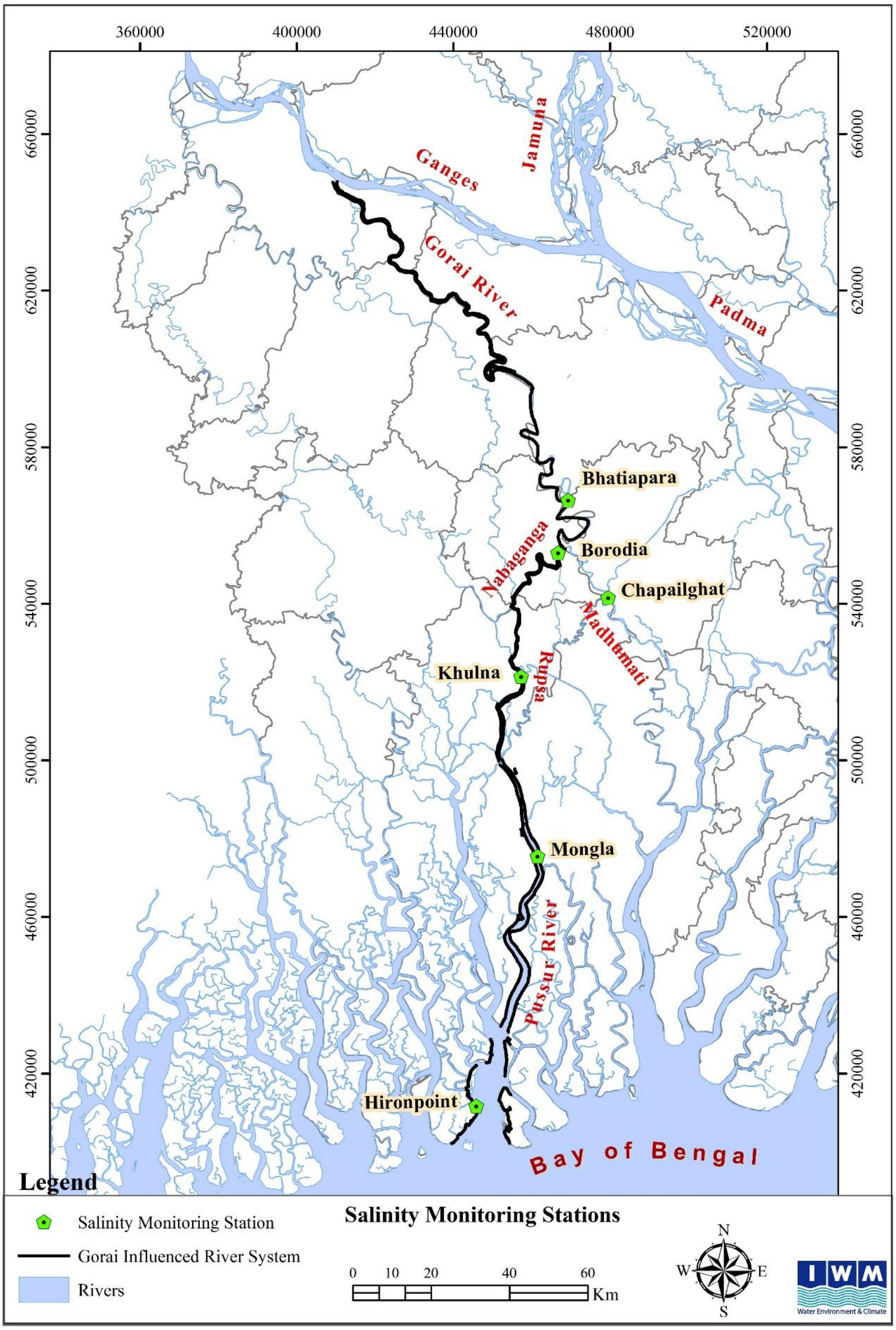


Figure 2-2: Schematics of Gorai- Nabaganga-Rupsha-Pussur river system.

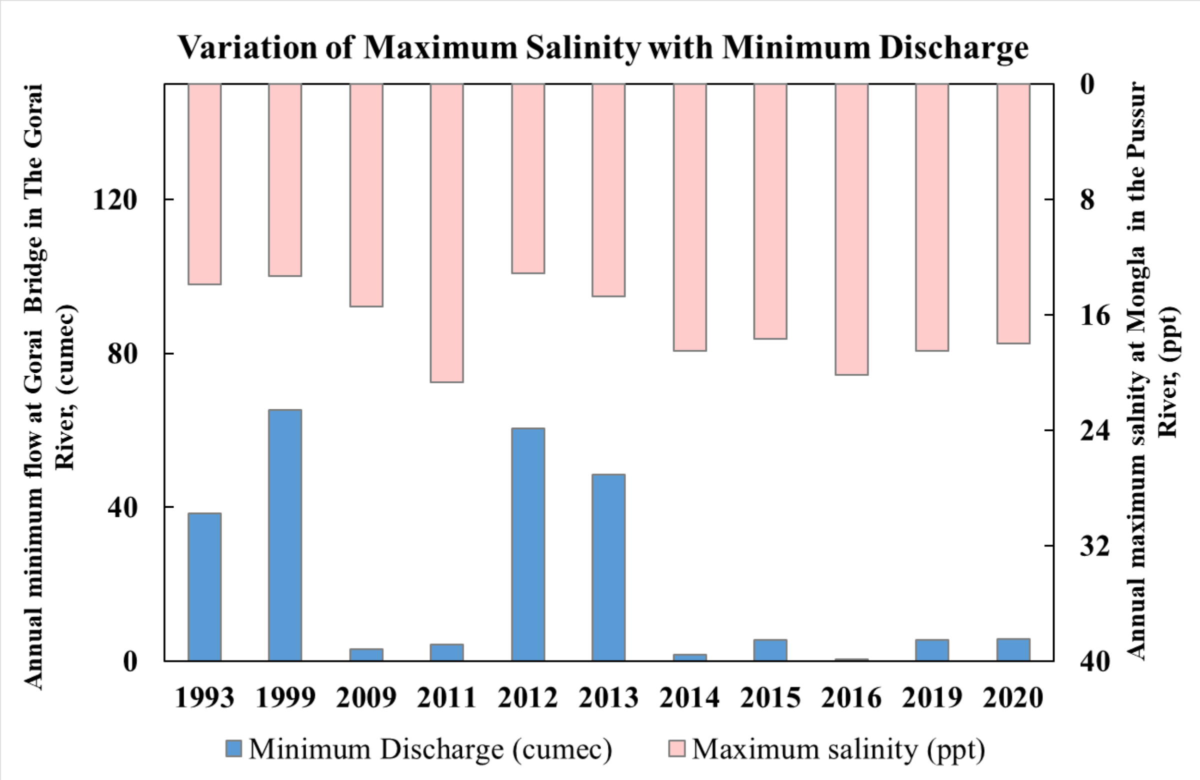


Figure 2-3: Change of salinity at Mongla in Pussur River with the flow of Gorai river.

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**).

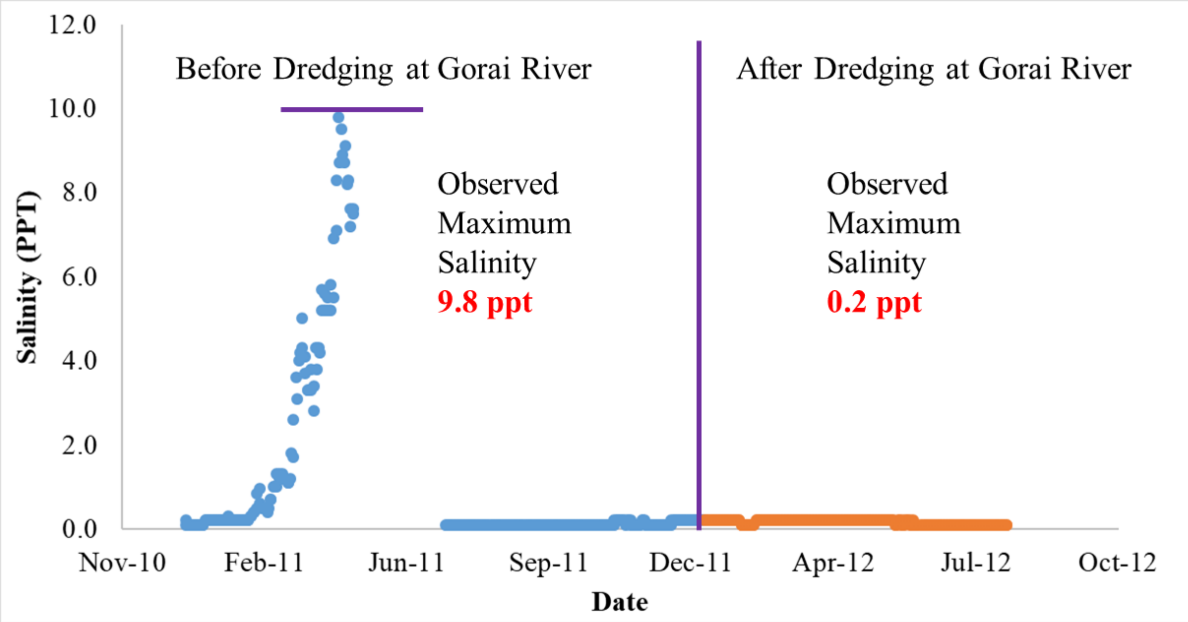


Figure 2-4: Salinity change at Nabaganga River (Bardia) for Dredging of the Gorai river

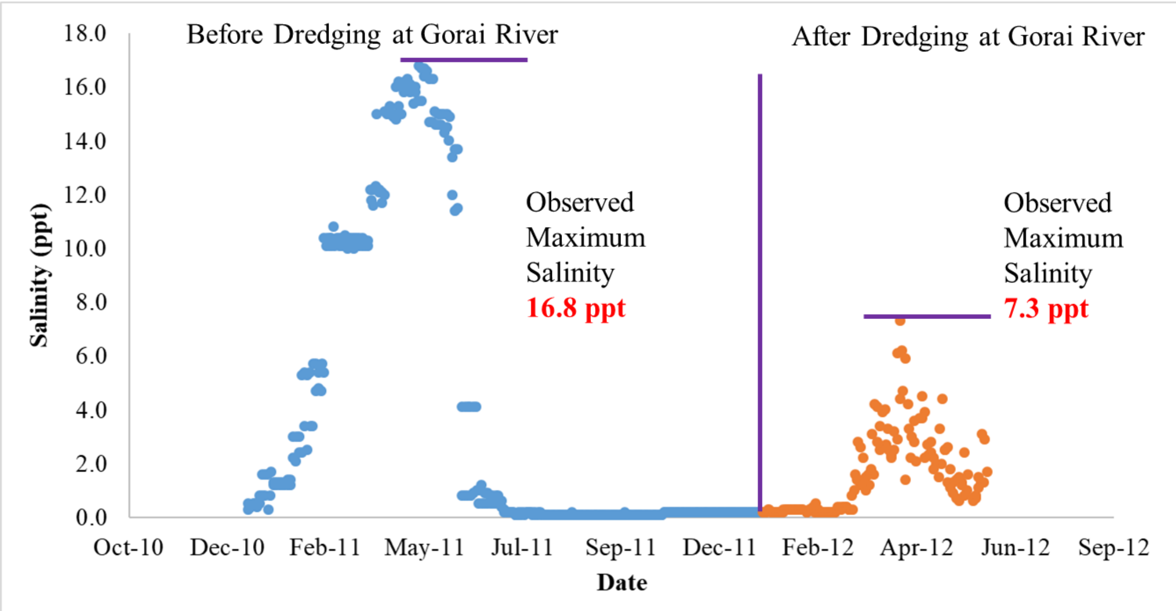


Figure 2-5: Salinity change at Rupsha River (Khulna) for Dredging of the Gorai river.

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)

<table>
<tr><th rowspan="3">River Name</th><th colspan="3">Flow diversion (m^3/s) for salinity control</th></tr>
<tr><th rowspan="2">No diversion (Base)</th><th colspan="2">With diversion</th></tr>
<tr><th>Option-1</th><th>Option-2</th></tr>
<tr><td>Gorai</td><td>0</td><td>150</td><td>150</td></tr>
<tr><td>Bhairab Upper</td><td>0</td><td>25</td><td>10</td></tr>
<tr><td>Mukteswari-Hari</td><td>--</td><td>0</td><td>15</td></tr>
<tr><td>Kobadak</td><td>0</td><td rowspan="2">50</td><td>25</td></tr>
<tr><td>Harihar</td><td>--</td><td>25</td></tr>
<tr><td>Betna</td><td>0</td><td>25</td><td>39</td></tr>
</table>

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.

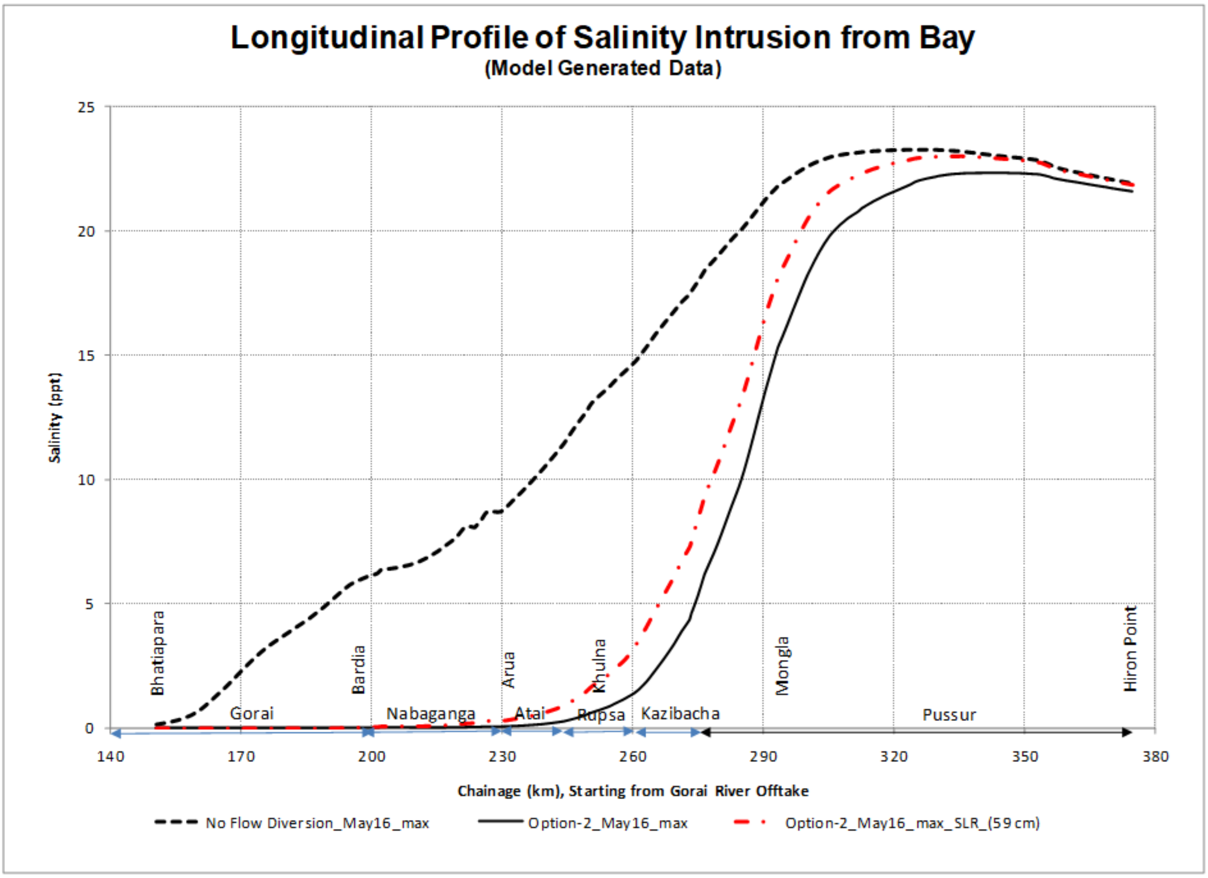


Figure 2-6: The longitudinal profile of saline intrusion from the Bay due to sea level rise (Without Ganges Barrage, with Ganges Barrage, with Ganges Barrage + 59 cm sea level rise) (Source: Ganges Barrage Study Project, 2012)

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.

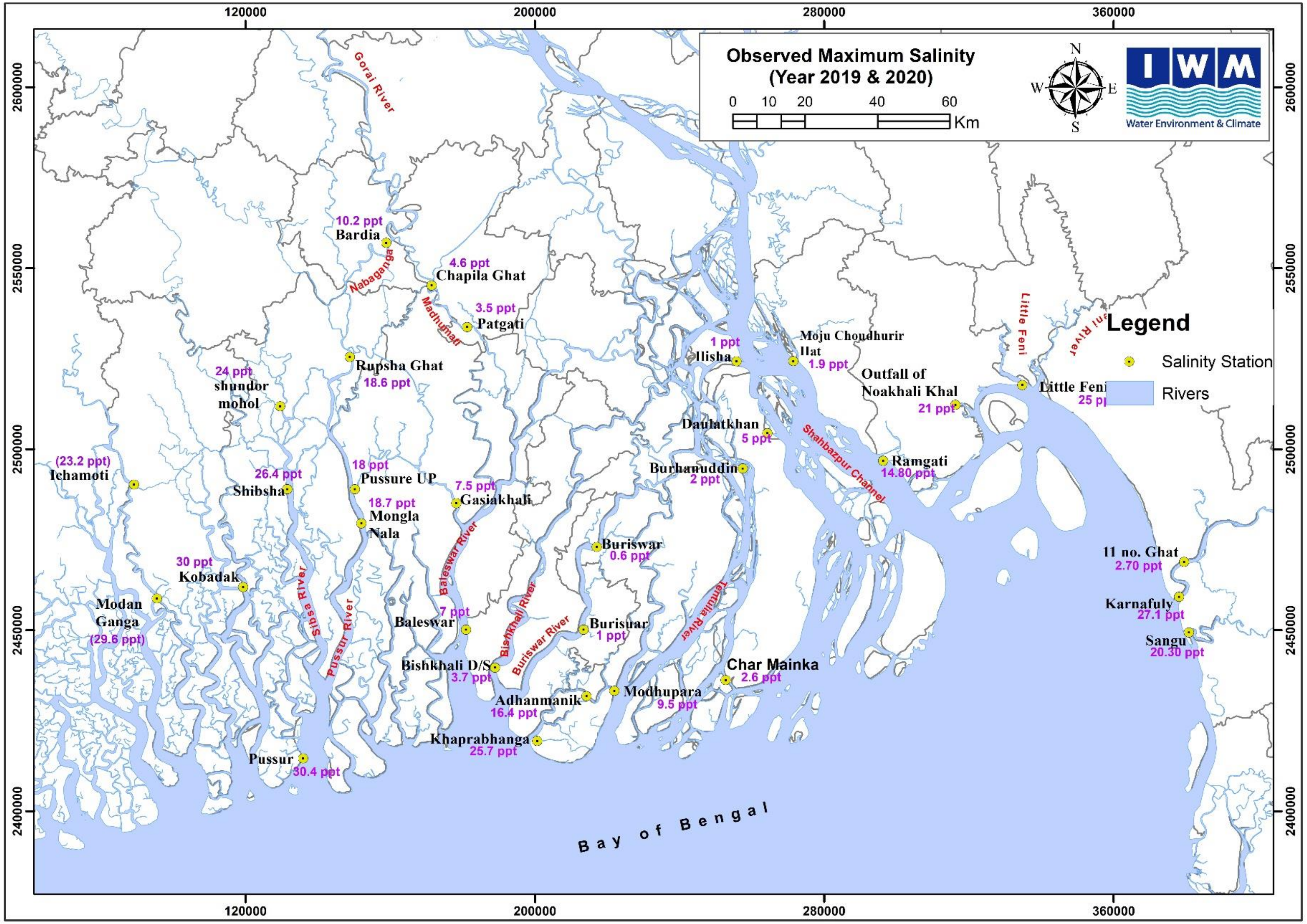


Figure 3-1: Salinity Monitoring stations.

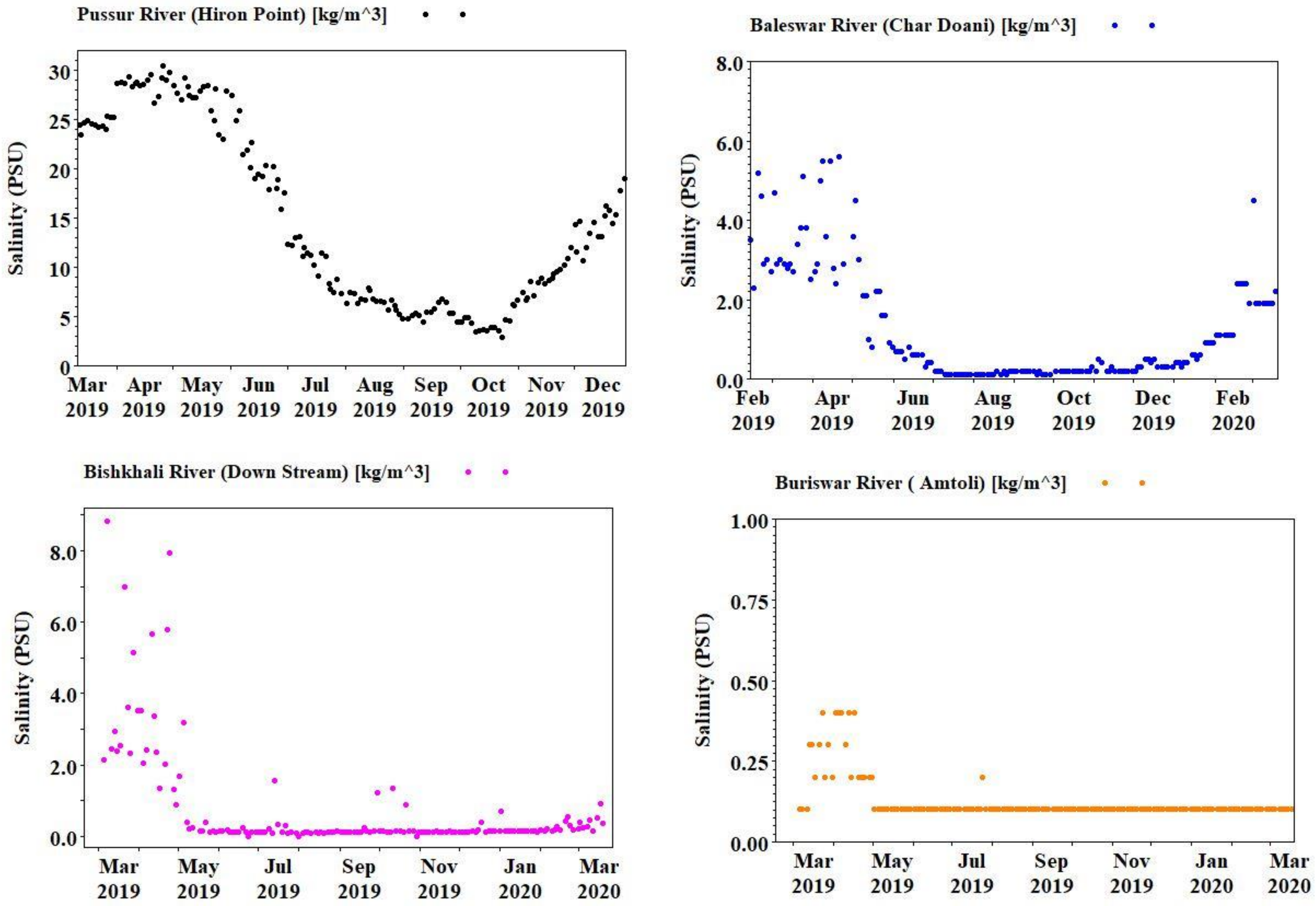


Figure 3-2: Seasonal variation of surface water salinity at Pussur River (Hironpoint), Baleswar river (Char Doani), Bishkhali river (downstream), Buriswar River (Amtali)

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 Sibsa 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.

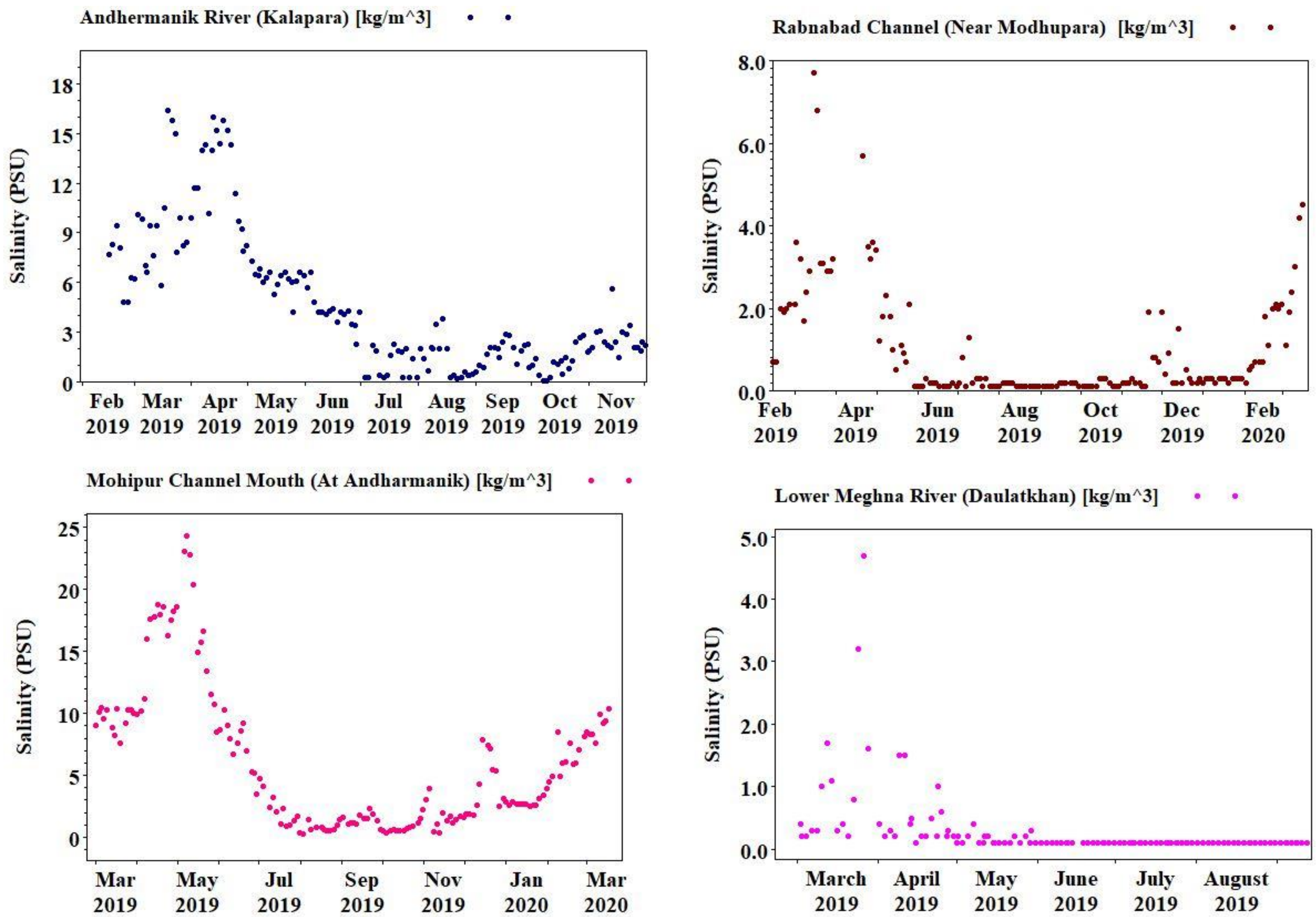
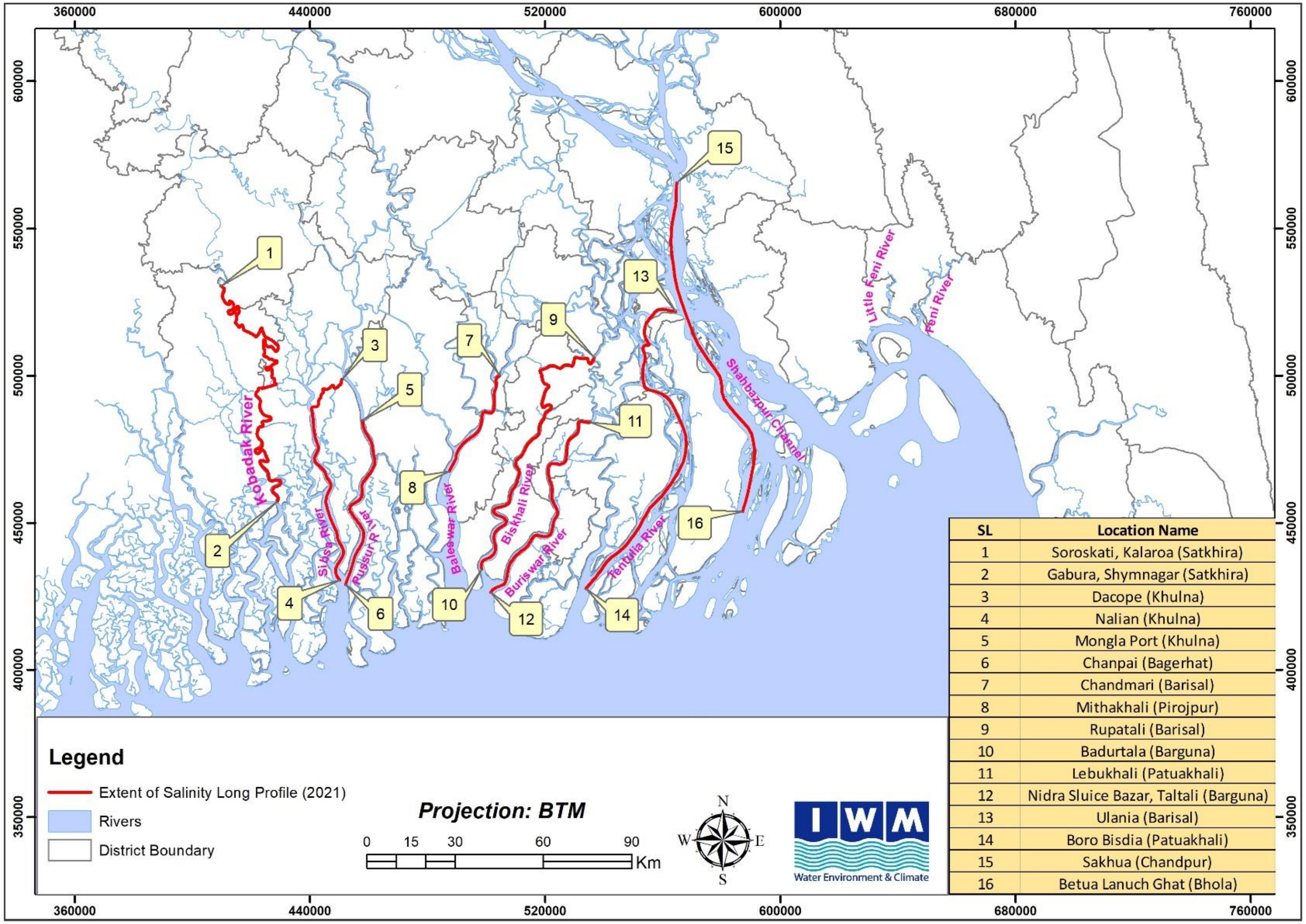


Figure 3-3: Seasonal variation of surface water salinity at Andharmanik River (Kalapara), Rabnabad Channel (Modhupara), Mohipur channel and Lower Meghna River (Daulatkhan).

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.

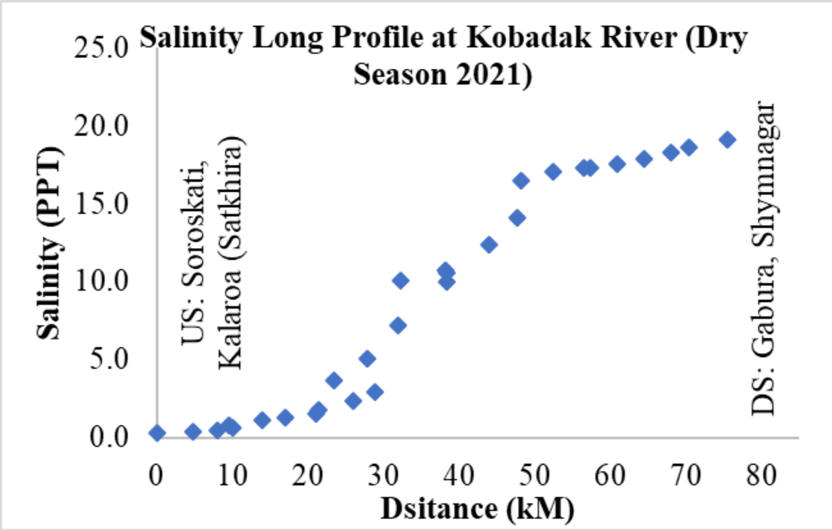
3.2 Salinity long Profile variation along the River

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.

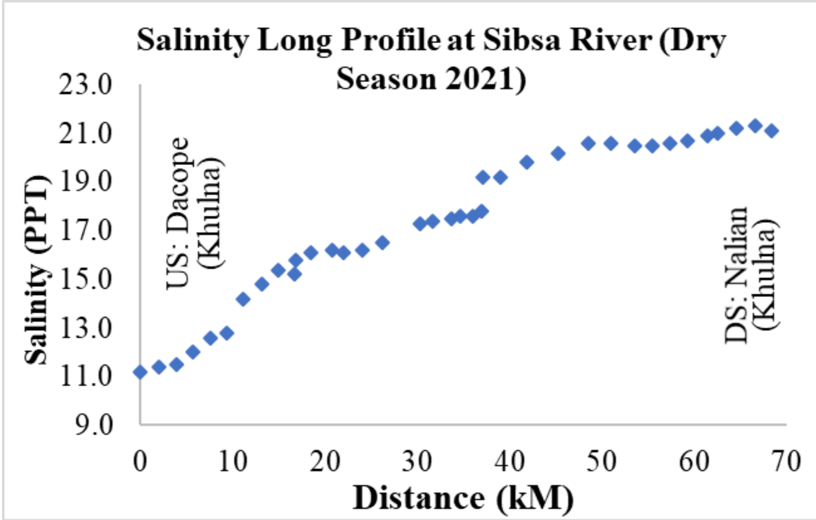


SL	Location Name
1	Soroskati, Kalaroa (Satkhira)
2	Gabura, Shymnagar (Satkhira)
3	Dacope (Khulna)
4	Nalian (Khulna)
5	Mongla Port (Khulna)
6	Chanpai (Bagerhat)
7	Chandmari (Barisal)
8	Mithakhali (Pirojpur)
9	Rupatali (Barisal)
10	Badurtala (Barguna)
11	Lebukhali (Patuakhali)
12	Nidra Sluice Bazar, Taltali (Barguna)
13	Ulania (Barisal)
14	Boro Bisdia (Patuakhali)
15	Sakhua (Chandpur)
16	Betua Lanuch Ghat (Bhola)

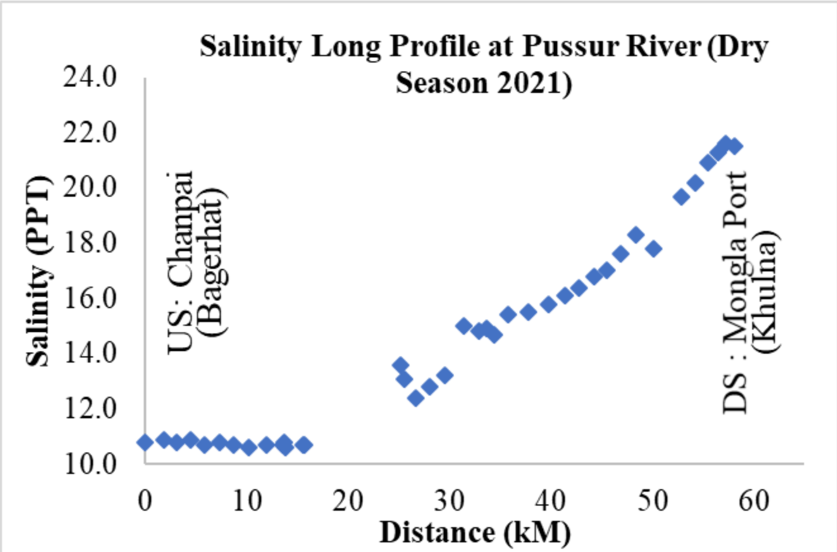
Figure 3-4: Long profile salinity measurement along the highlighted channel.



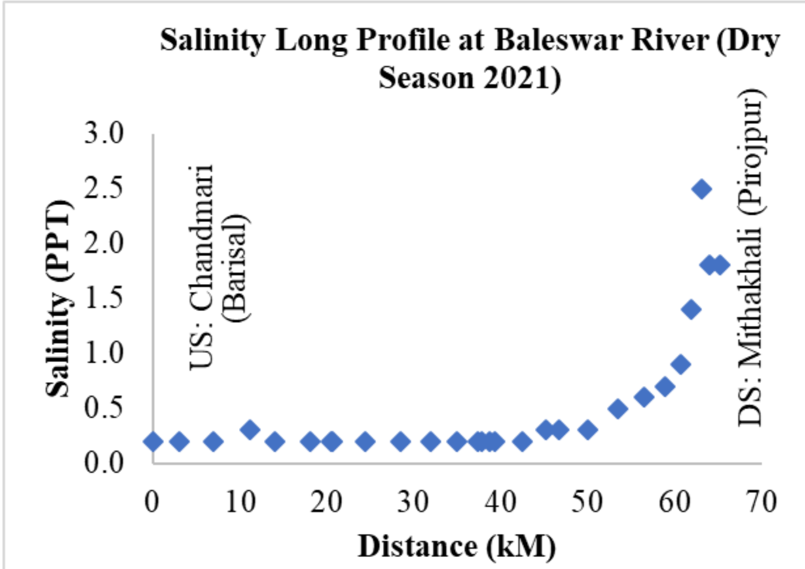
Salinity Long Profile at Kobadak River (Dry Season 2021)
Salinity (PPT)
Dsitance (kM)
US: Soroskati, Kalaroa (Satkhira)
DS: Gabura, Shymnagar
25.0
20.0
15.0
10.0
5.0
0.0
0 10 20 30 40 50 60 70 80



Salinity Long Profile at Sibsa River (Dry Season 2021)
Salinity (PPT)
Distance (kM)
US: Dacope (Khulna)
DS: Nalian (Khulna)
23.0
21.0
19.0
17.0
15.0
13.0
11.0
9.0
0 10 20 30 40 50 60 70



Salinity Long Profile at Pussur River (Dry Season 2021)
Salinity (PPT)
Distance (kM)
US: Champai (Bagerhat)
DS : Mongla Port (Khulna)
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
0 10 20 30 40 50 60



Salinity Long Profile at Baleswar River (Dry Season 2021)
Salinity (PPT)
Distance (kM)
US: Chandmari (Barisal)
DS: Mithakhali (Pirojpur)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 10 20 30 40 50 60 70

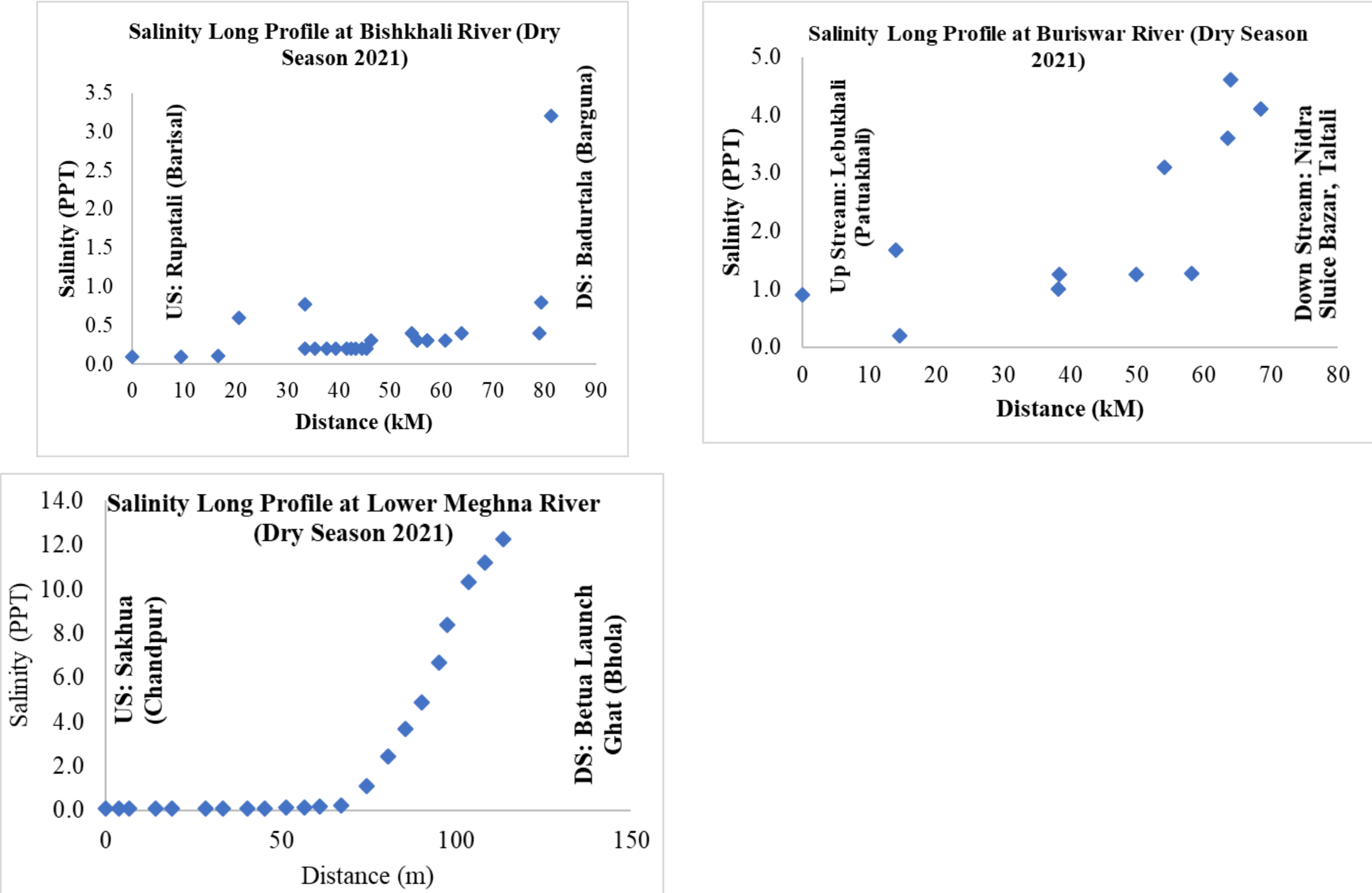


Figure 3-5: Salinity variation along the length of river shown in Figure 3-4

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.

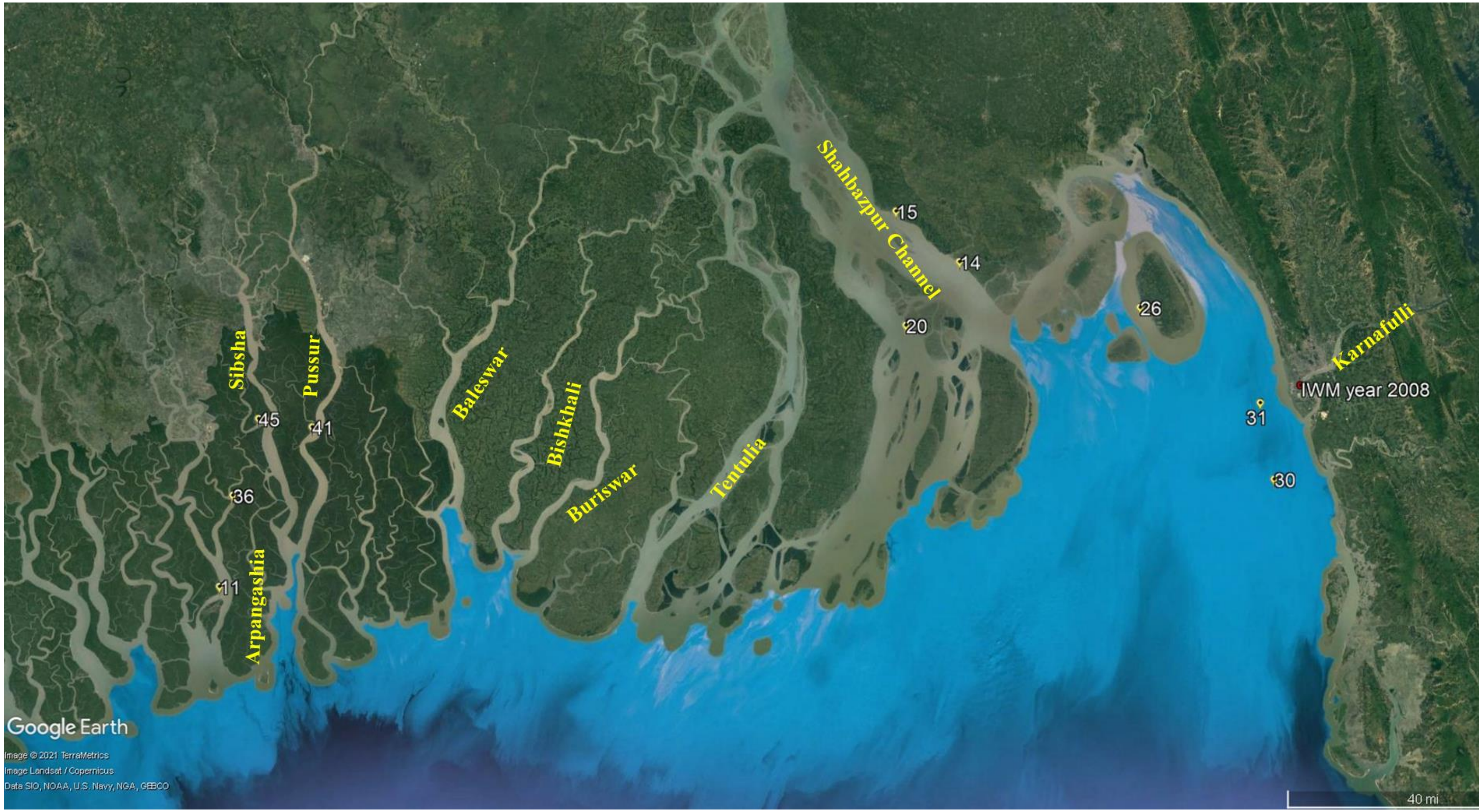


Figure 3-6: Location of salinity measurement (vertical profiling)

Vertical Temperature and Salinity Profile at Southwest Region (Sundarban)

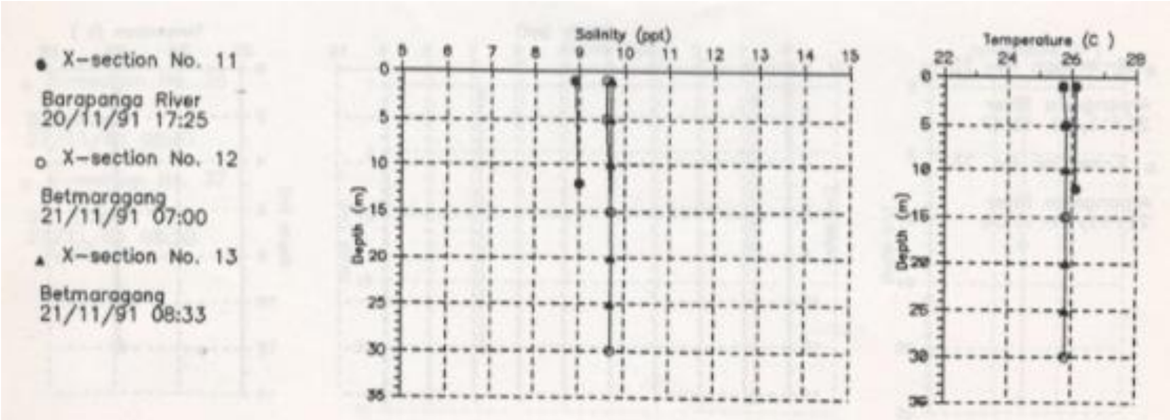


Figure 3-7: Vertical Salinity and Temperature Profile at Betmargang River. (Date of measurement: 20th November, 1991) (Source: SWMC, 1993)

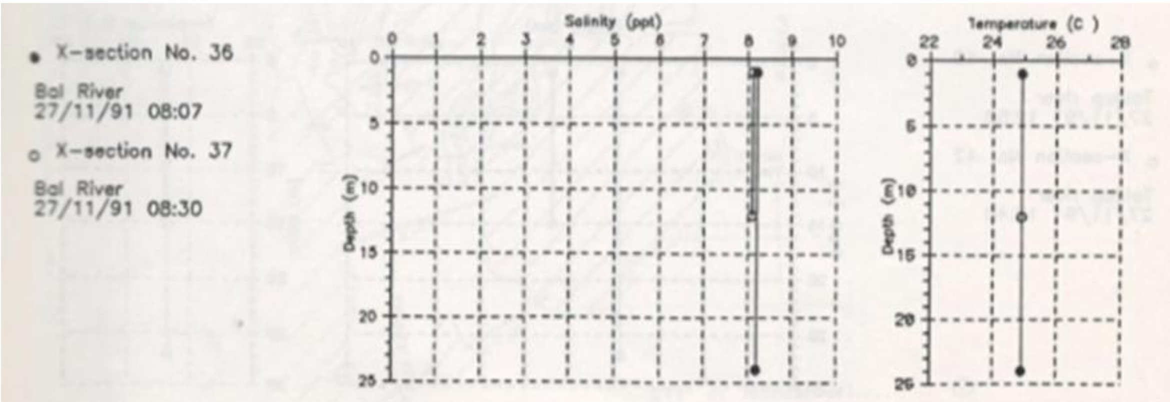


Figure 3-8: Vertical Salinity and Temperature Profile at Arpangashia River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

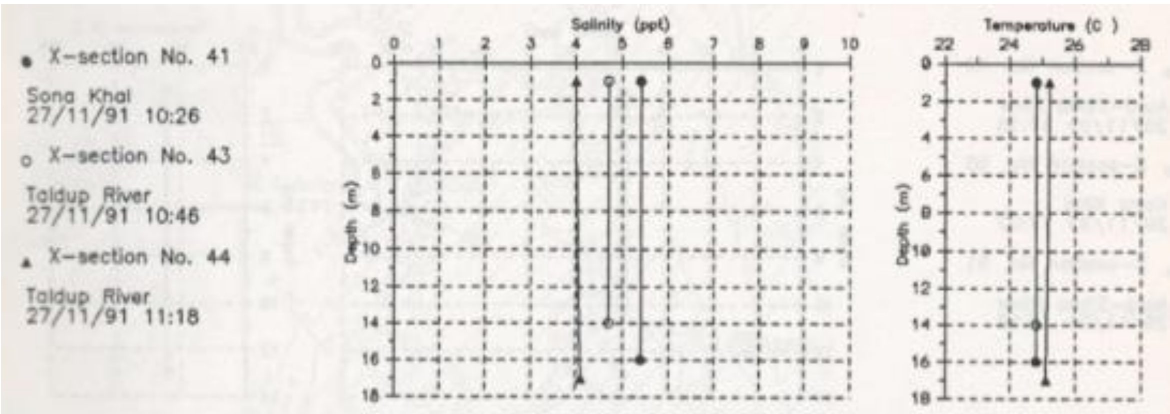


Figure 3-9: Vertical Salinity and Temperature Profile at Pussur River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

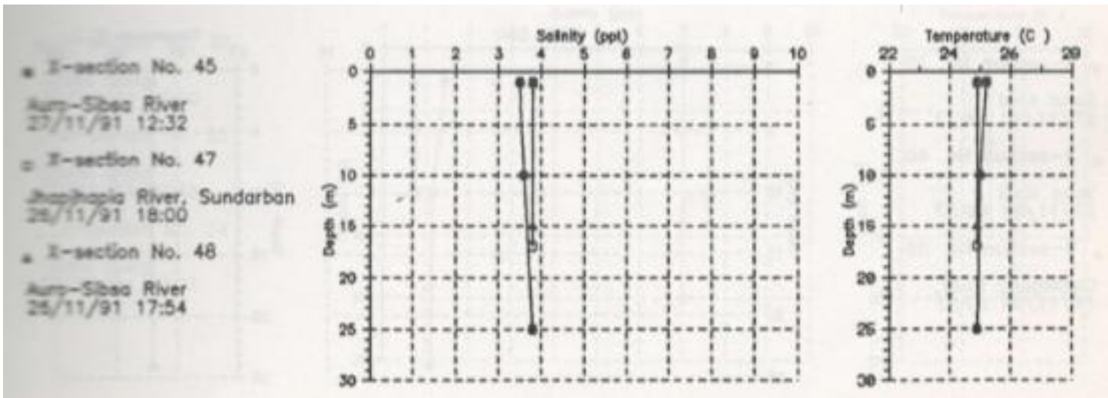


Figure 3-10: Vertical Salinity and Temperature Profile at Sibsa River. (Date of measurement: 27th November, 1991) (Source: SWMC, 1993)

Vertical Temperature and Salinity Profile at Meghna Estuary

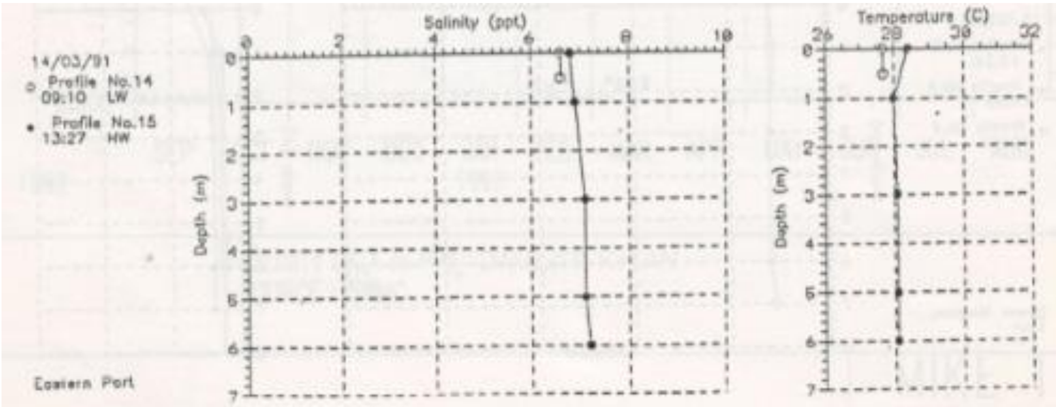


Figure 3-11: Vertical Salinity and Temperature Profile at Lower Meghna River. (Date of measurement: 14th March, 1991) (Source: SWMC, 1993)

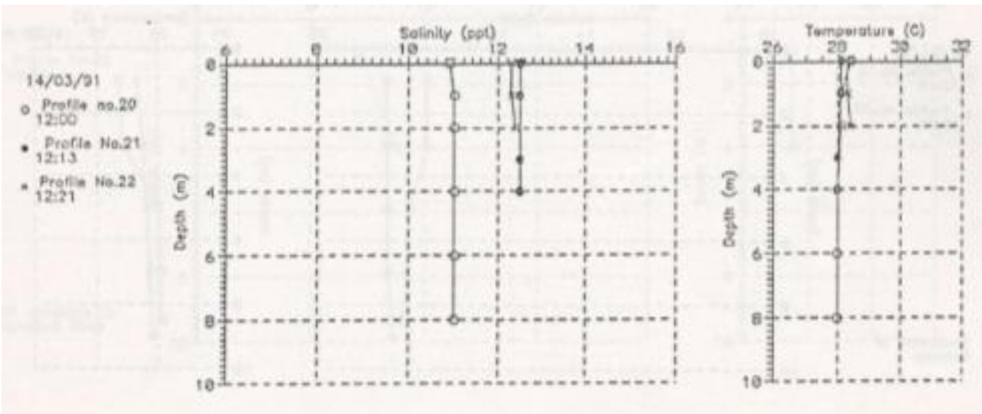


Figure 3-12: Vertical Salinity and Temperature Profile at Char Zahiruddin (Lower Meghna River). (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

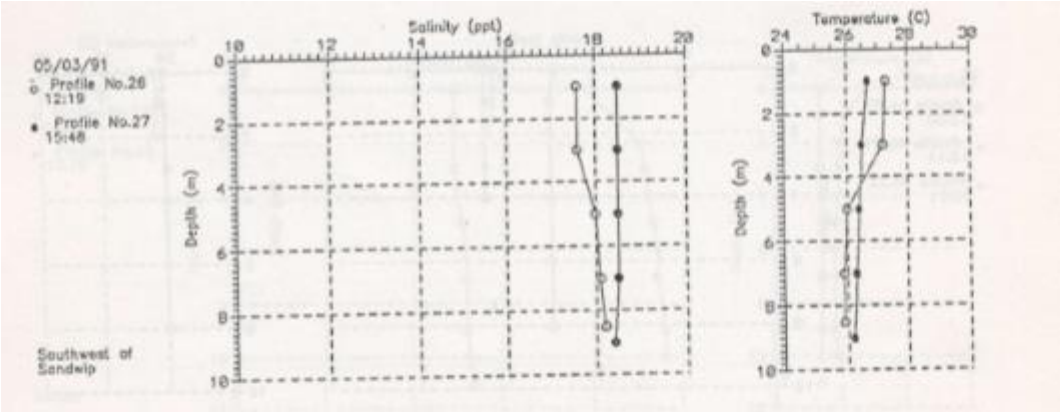


Figure 3-13: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

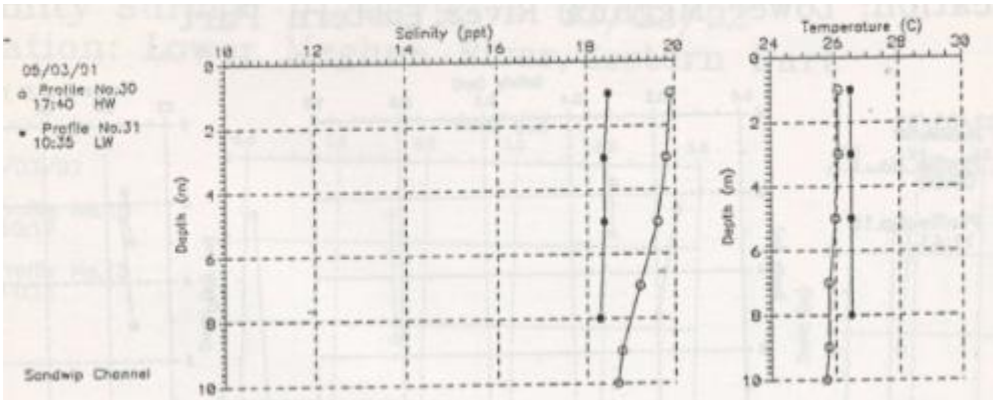


Figure 3-14: Vertical Salinity and Temperature Profile at Sandwip Channel. (Date of measurement: 5th March, 1991) (Source: SWMC, 1993)

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**.

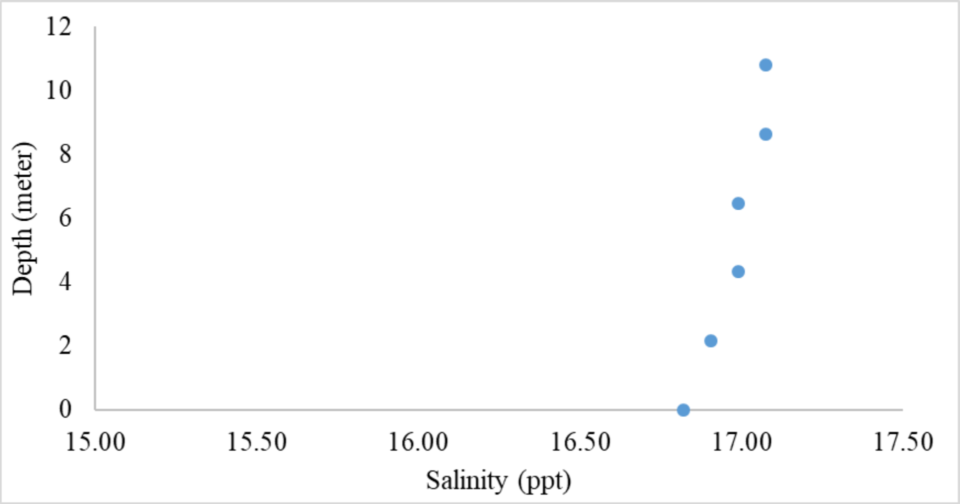


Figure 3-15: Across depth salinity variation at Karnaphuli

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 hydrodynamic 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**.

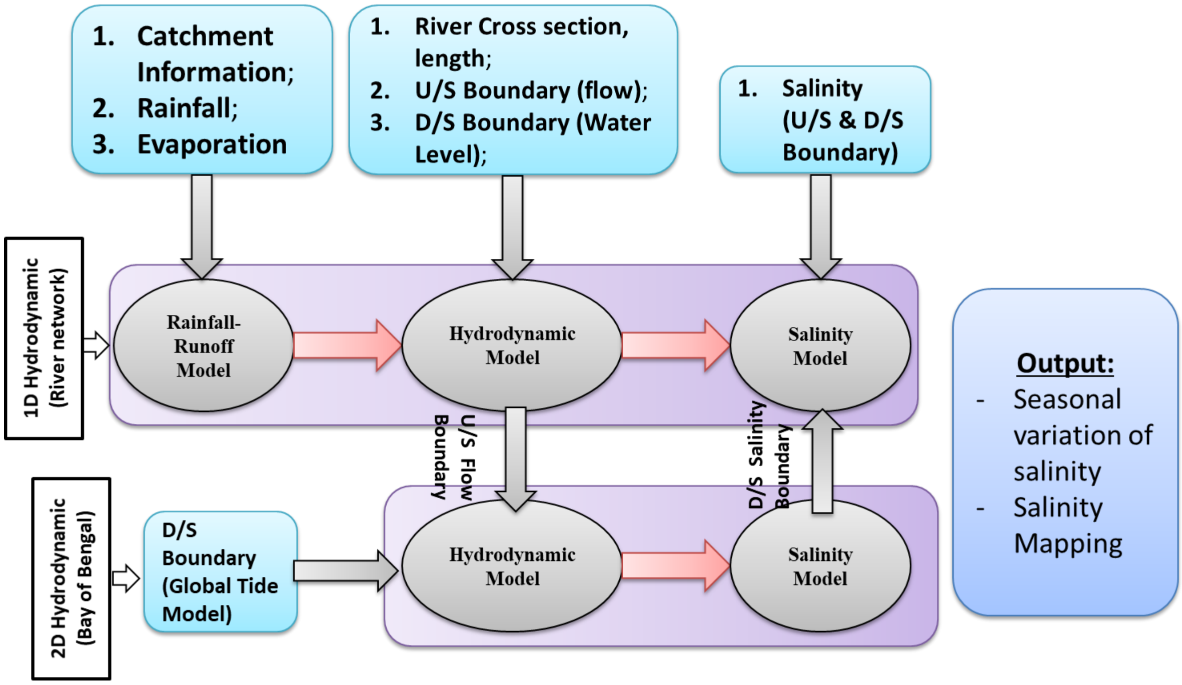


Figure 4-1: Flow chart of salinity model

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.

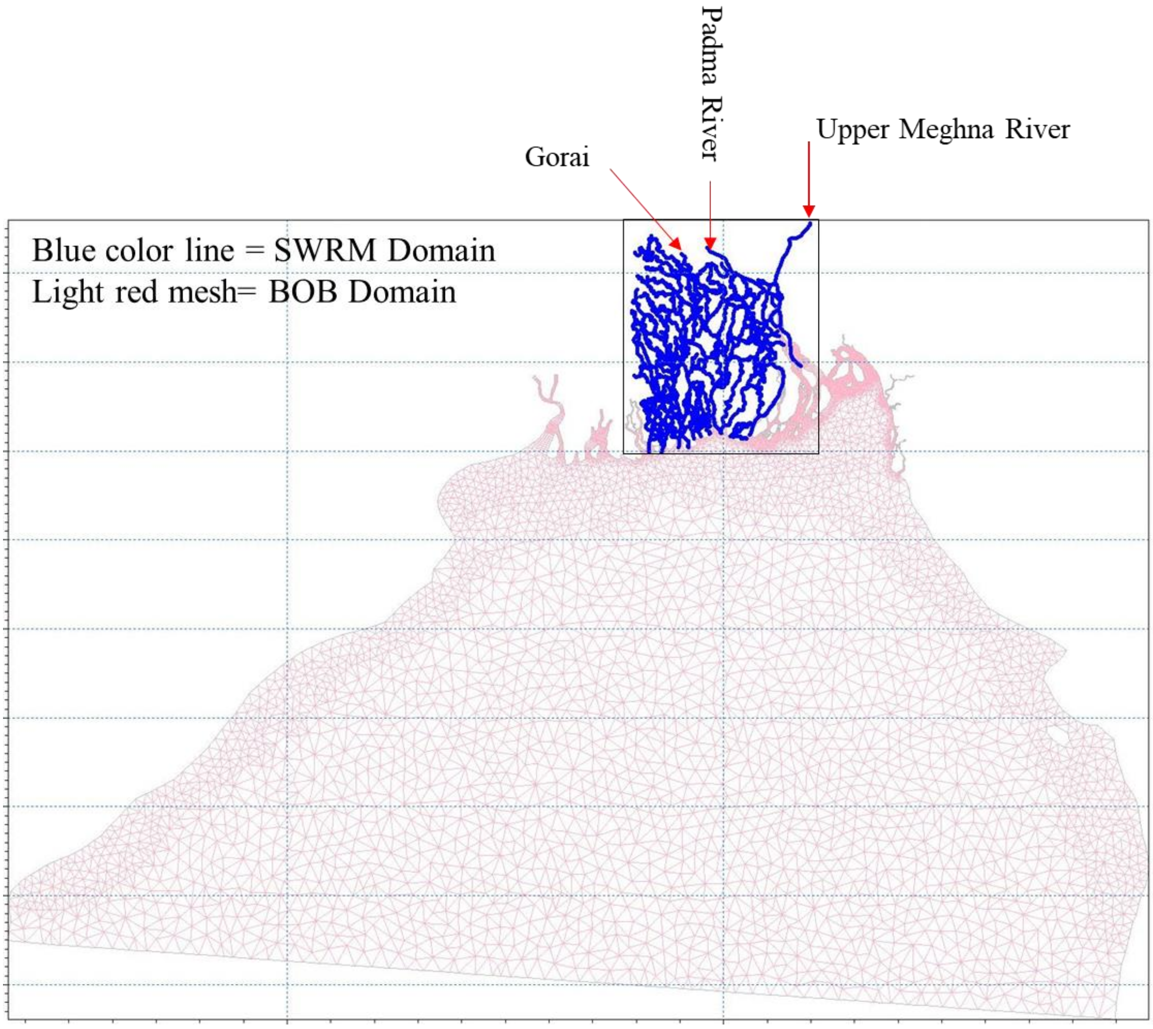


Figure 4-2: Superposition of SWRM model domain onto BoB model domain.

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.

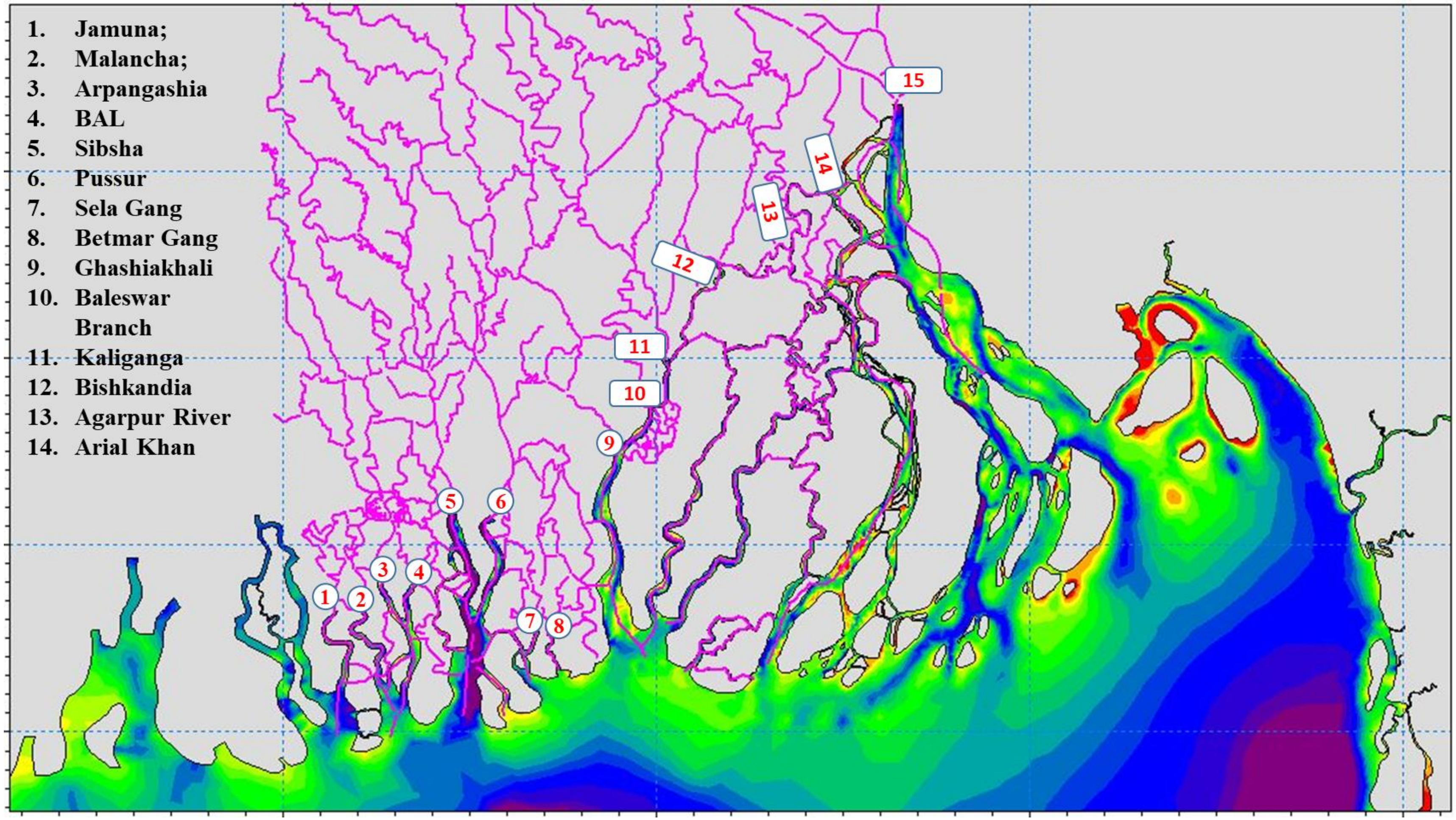


Figure 4-3: Boundary generation obtain from SWRM for upstream flow of Bay of Bengal

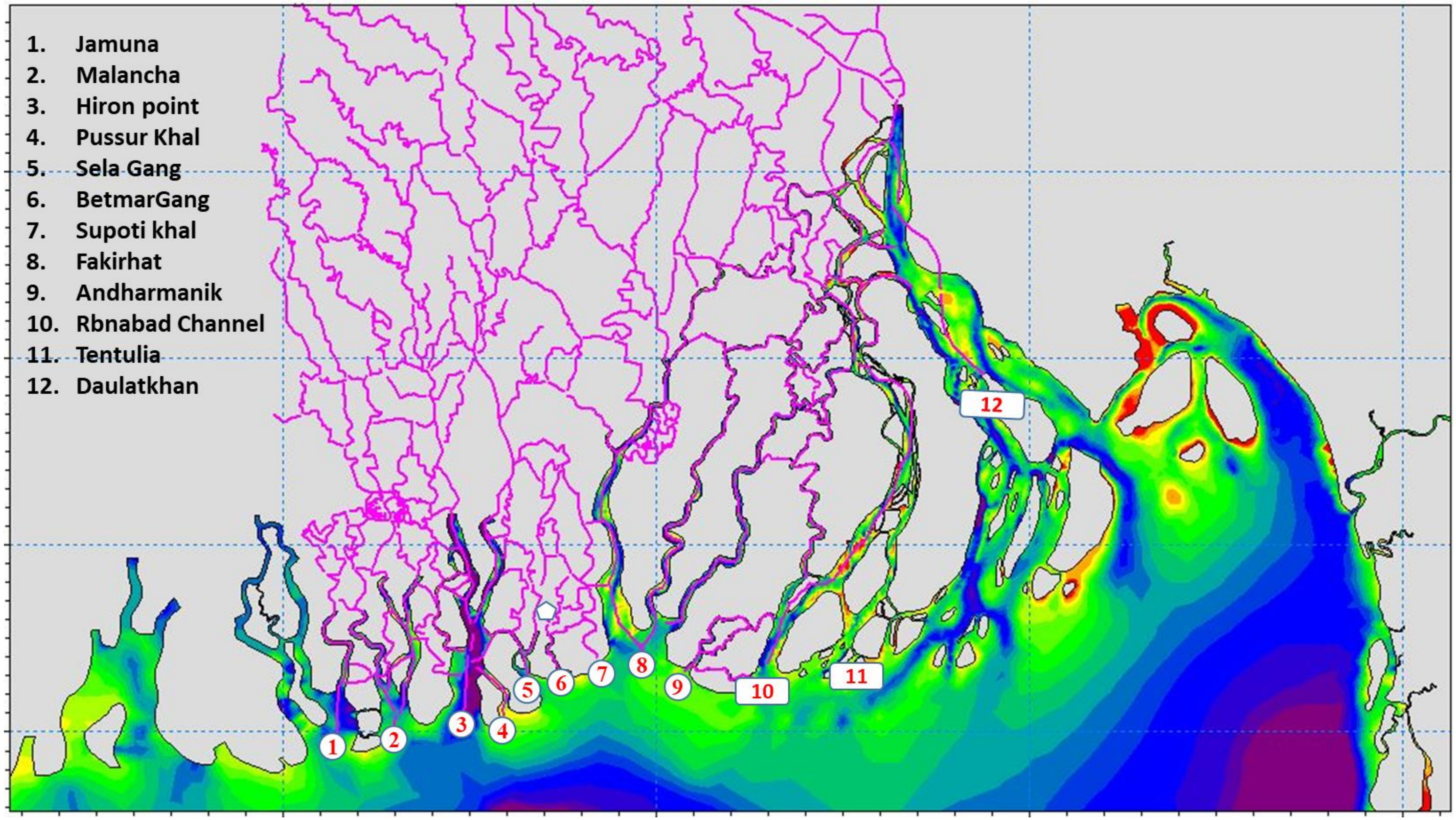


Figure 4-4: Down Stream boundaries of SWRM One dimensional model

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.

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 4-3**). 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 4-4**). If usable observed data is available, then it is used instead of simulated data.

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). 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 4-3**). After simulation, downstream salinity boundary is extracted from result of 2d boundary and is used in **Step-4** (as shown in **Figure 4-4**).

4.2 Description of Two-Dimensional Hydrodynamic & Advection Dispersion 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 4-5.**

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 4-3**.

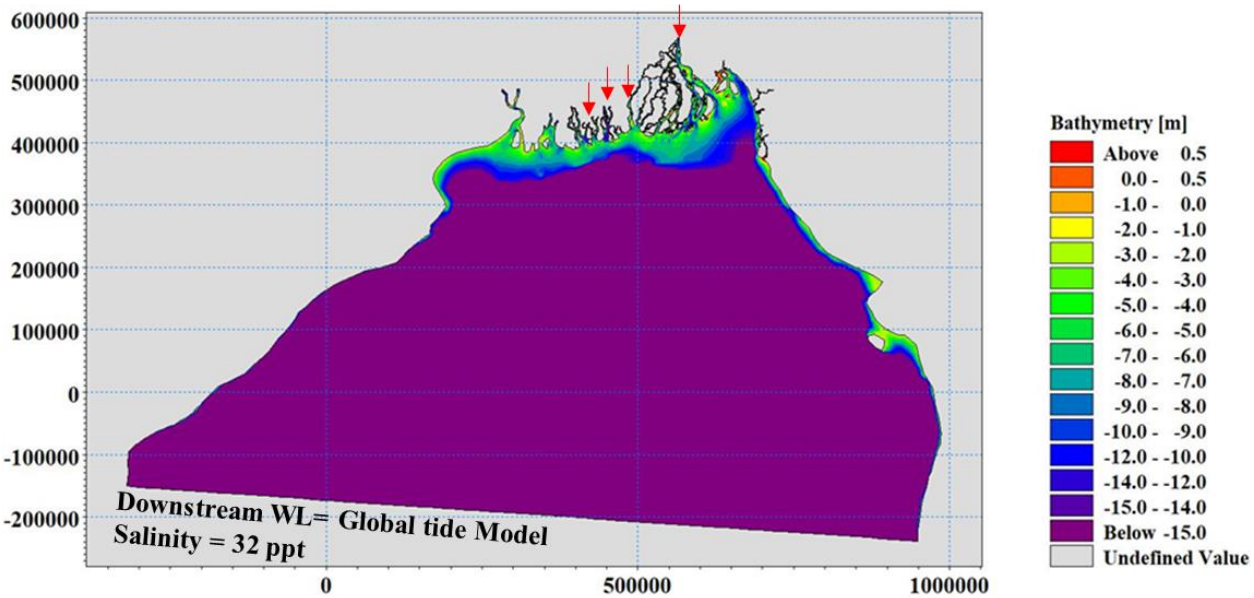


Figure 4-5: Bay of Bengal Model Boundary

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 constituent 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:

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

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 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 (m2/s)
Pussur – Sibsa Estuary	400
Buriswar- Bleswar -Bishkhali Esturay	200
Tentulia and Meghna Estuary	1200

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

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 4-6** and **Figure 4-7** show the water level calibration. **Figure 4-8** and **Figure 4-9** show the comparison of observed salinity and simulated salinity for the year 2019.

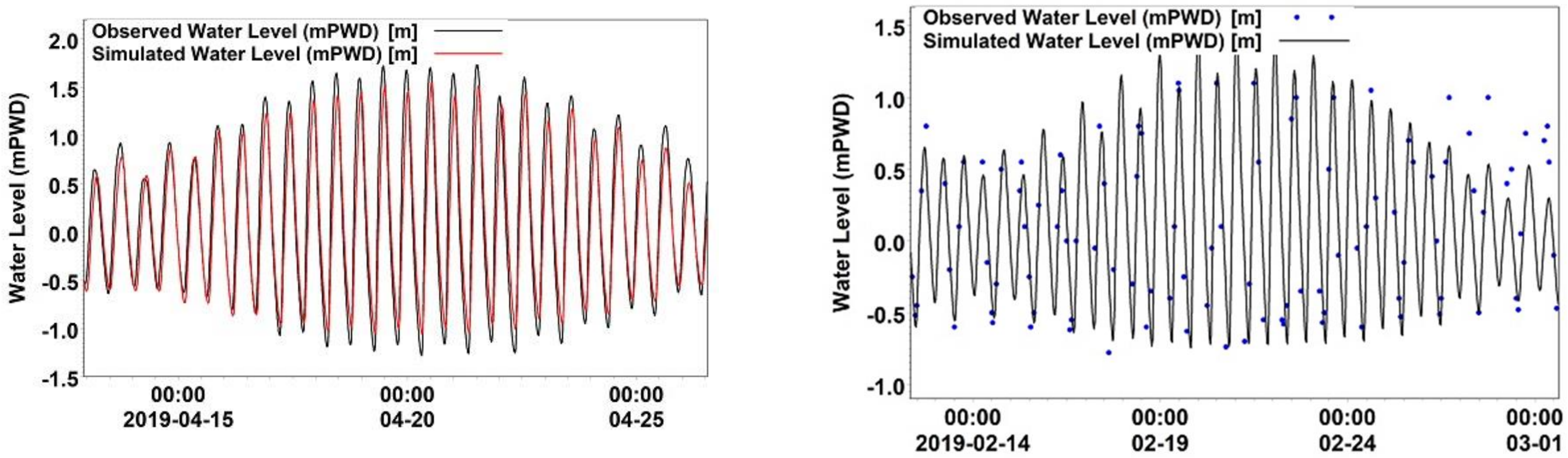


Figure 4-6: Comparison of Observed and Simulated Water Level at Charduani (Baleswar River) (left) and Amtali (Buriswar River) (right)

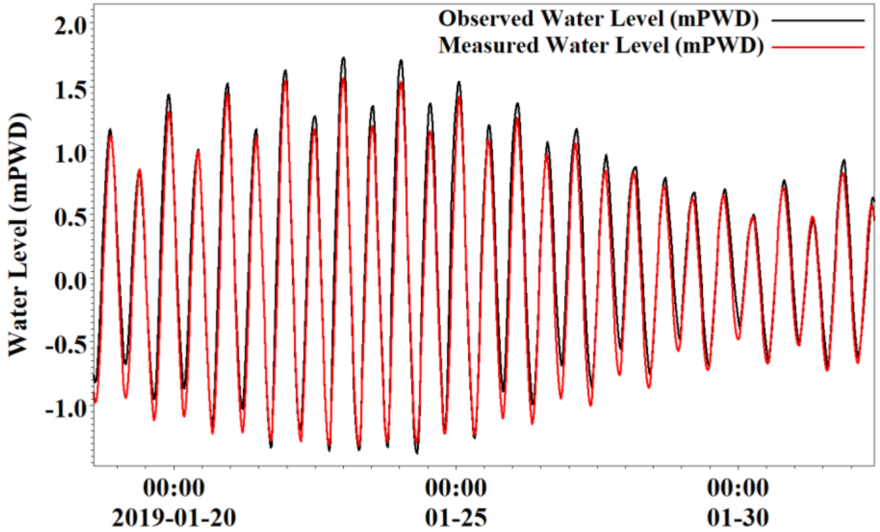


Figure 4-7: Comparison of Observed and Simulated water level at Hironpoint (Pussur River) (left)

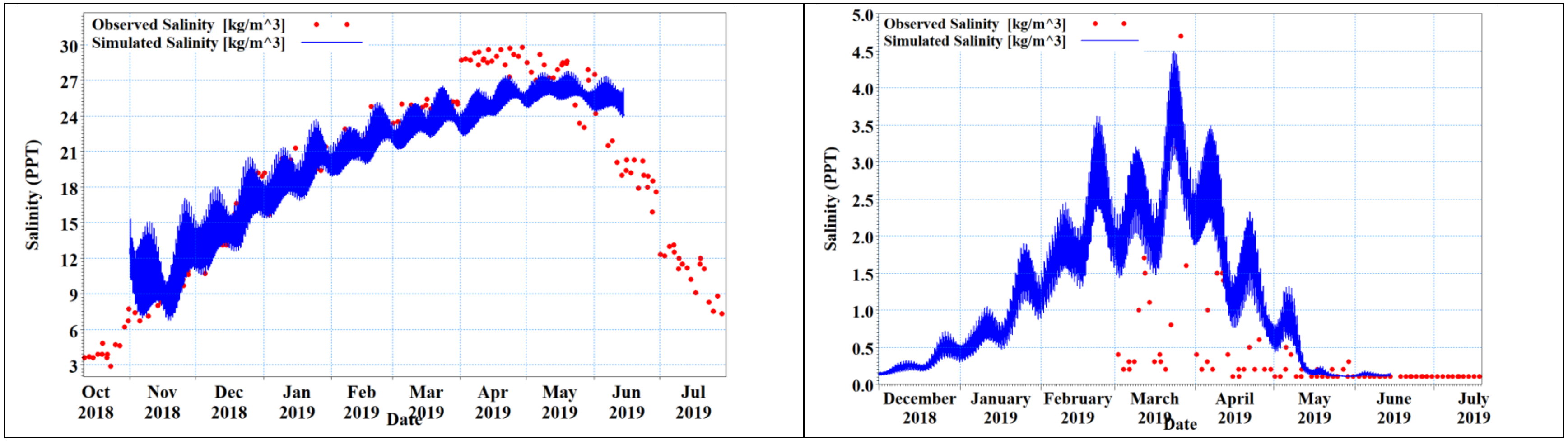


Figure 4-8: Comparison of Observed and Simulated Salinity at Hironpoint (Pussur River) (right) and Daulatkhan (Lower Meghna River) (left)

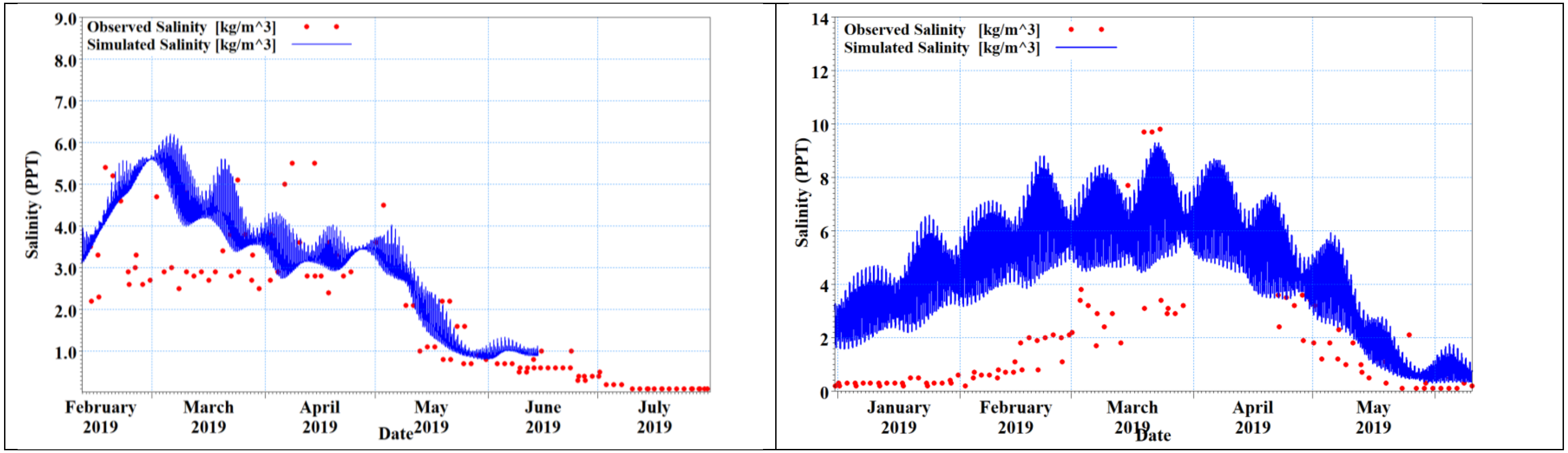


Figure 4-9: Comparison of Observed and Simulated Salinity at Charduani (Baleswar River) (right) and Modhupara (Andharmanik river) (left)

4.3 Description of 1D Hydrodynamic 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 4-10**.

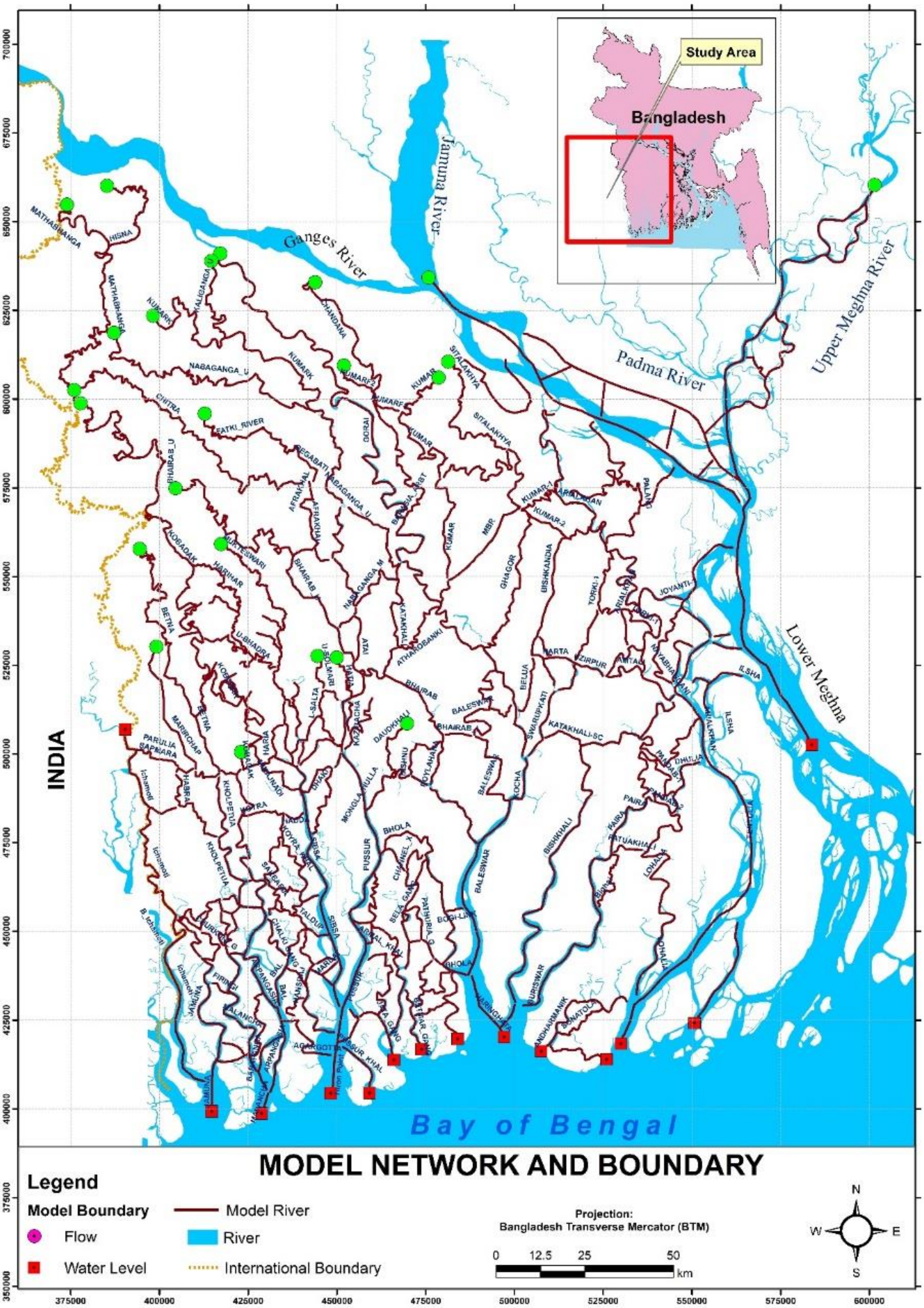


Figure 4-10: River network system & boundary condition in South west regional model

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

<table>
<tr><th>Boundary Type</th><th>River Name</th><th>Time series Boundary</th><th></th></tr>
<tr><td rowspan="4">Up Stream
Boundary</td><td>Gorai</td><td>Rated flow from measurement at Gorai Railway Bridge</td><td>Flow (Source: IWM & BWDB)</td></tr>
<tr><td>Padma</td><td>Rated flow from measurement at Baruria</td><td>Flow (Source: BWDB)</td></tr>
<tr><td>Upper Meghna</td><td>Simulated flow from North East Regional model. (To capture dry season tidal effect)</td><td>Flow (Source: North East regional Model)</td></tr>
<tr><td>ICHAMOTI</td><td>Measure water level from BWDB (at Basantipur)</td><td>WL
(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</td></tr>
<tr><td></td><td>Other rivers</td><td>From the runoff</td><td></td></tr>
<tr><td rowspan="13">Down Stream
Boundary</td><td>ANDHARMANIK</td><td rowspan="10">WL extracted from
Bay of Bengal model
WL extracted from
Bay of Bengal model
WL extracted from
Bay of Bengal model</td><td rowspan="11">WL</td></tr>
<tr><td>BETMAR GANG</td></tr>
<tr><td>JAMUNA SW</td></tr>
<tr><td>MALANCHA</td></tr>
<tr><td>PUSSUR KHAL</td></tr>
<tr><td>SELA GANG</td></tr>
<tr><td>SUPOTI KHAL</td></tr>
<tr><td>HARINGHATA
(outfall of Buriswar, Bishkhali & Baleswar River)</td></tr>
<tr><td>TENTULIA EAST</td></tr>
<tr><td>KHAPRABHANGA</td></tr>
<tr><td>TENTULIA</td><td>Water level measurement at Kawar Char</td></tr>
<tr><td>SHAHABAZ-1</td><td>Measured Water level at Daulatkhan</td><td></td></tr>
<tr><td>PUSSUR</td><td>Measure water level at Hiron Point</td><td></td></tr>
</table>

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)

Figure 4-11 to **Figure 4-14** 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 4-13** to **Figure 4-14**.

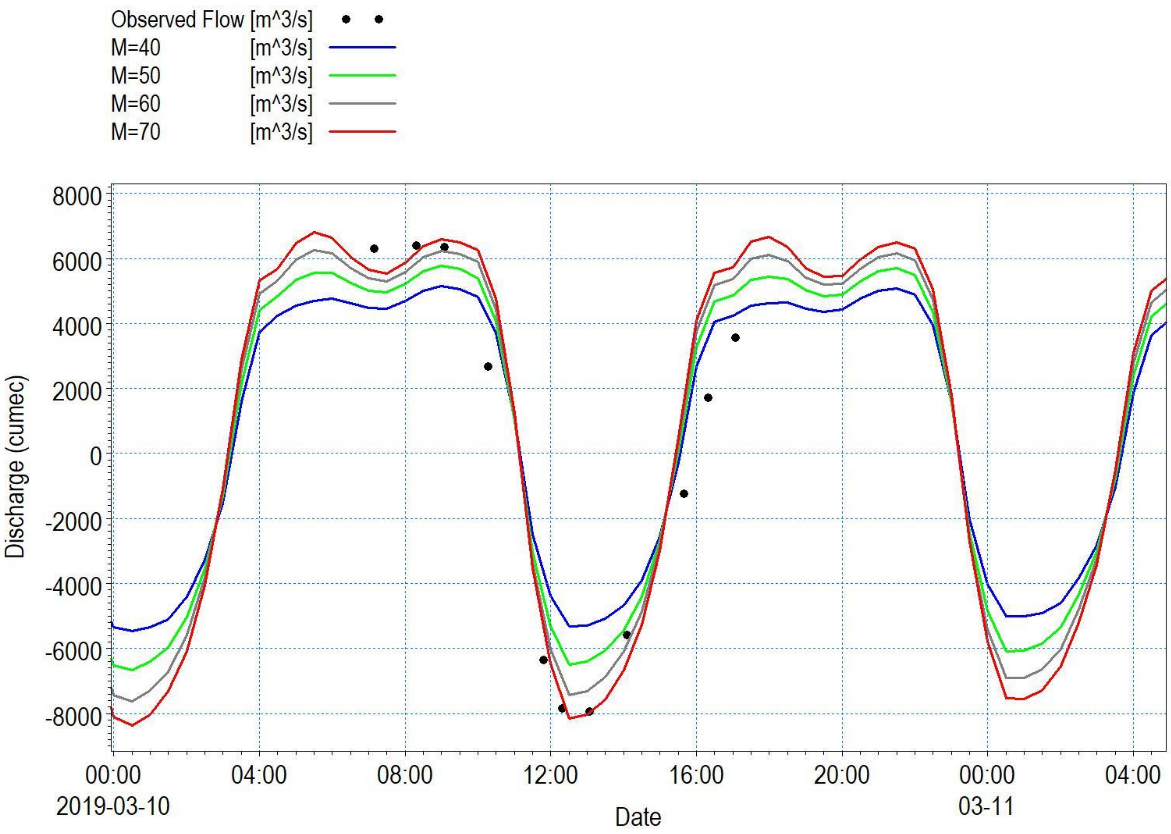


Figure 4-11: Optimization of manning's roughness with trial simulation of different bed resistance (at Bishkhali River).

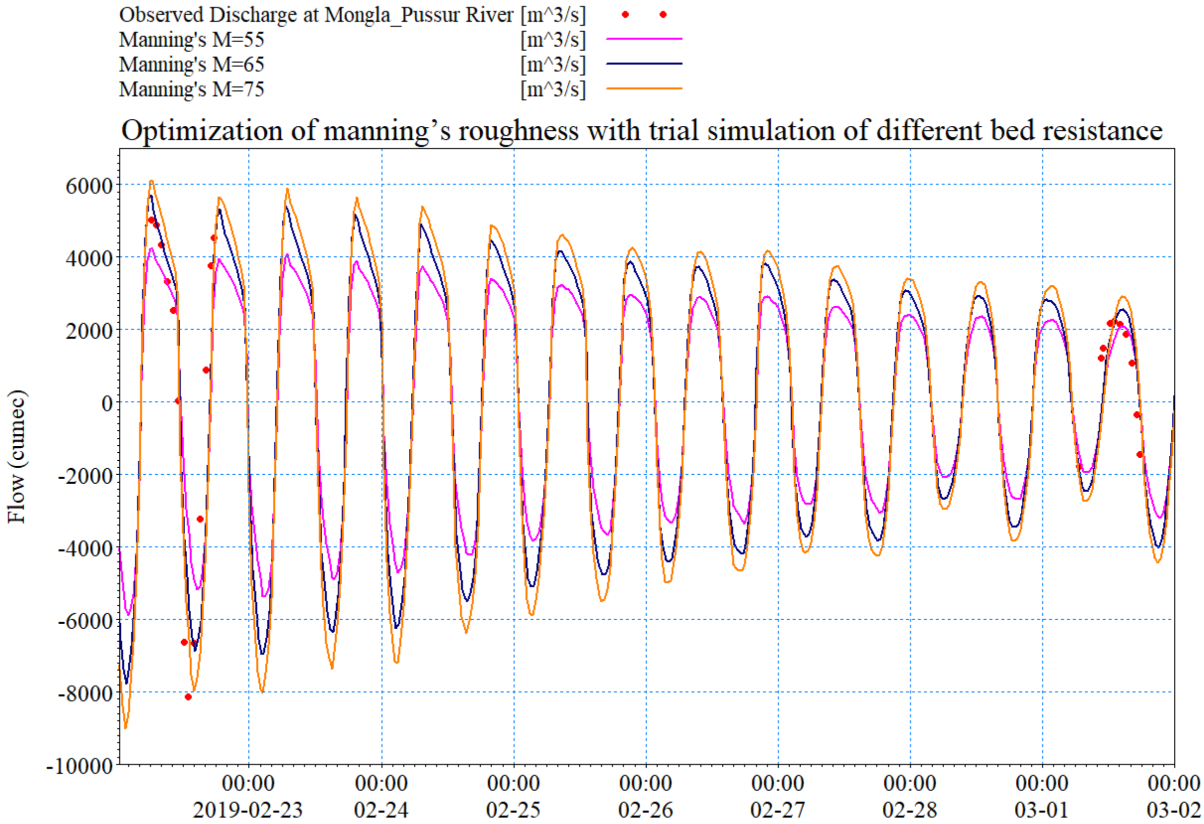


Figure 4-12: Optimization of manning's roughness with trial simulation of different bed resistance (at Pussur River).

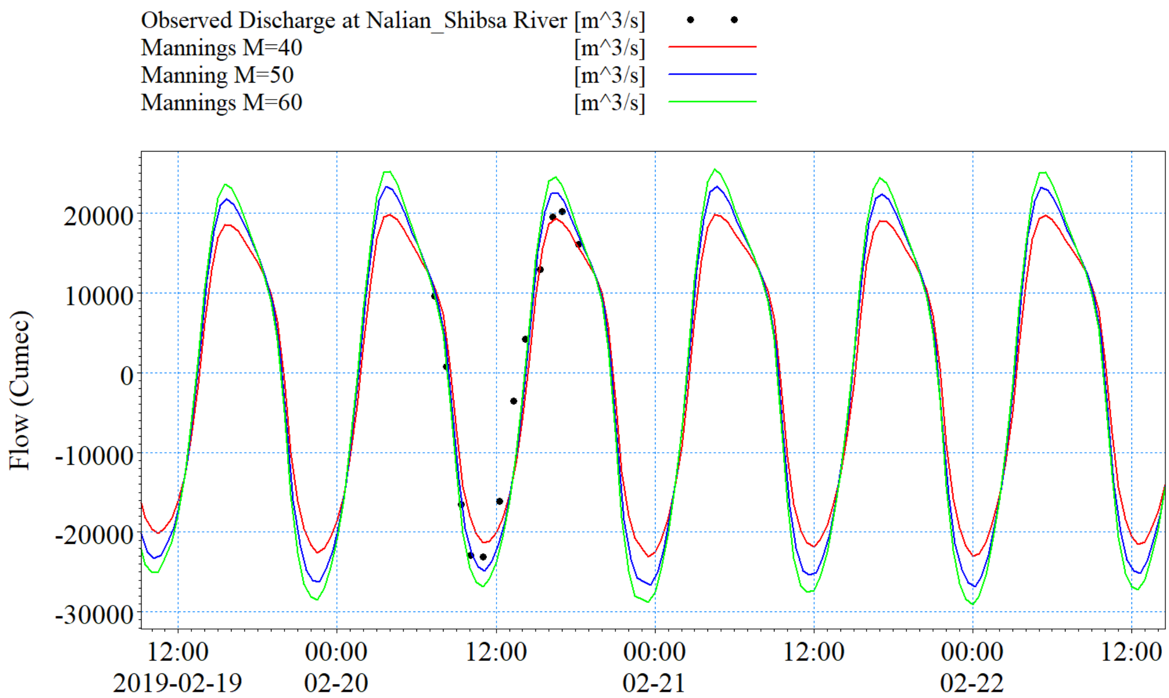


Figure 4-13: Optimization of manning's roughness with trial simulation of different bed resistance (at Sibsa River).

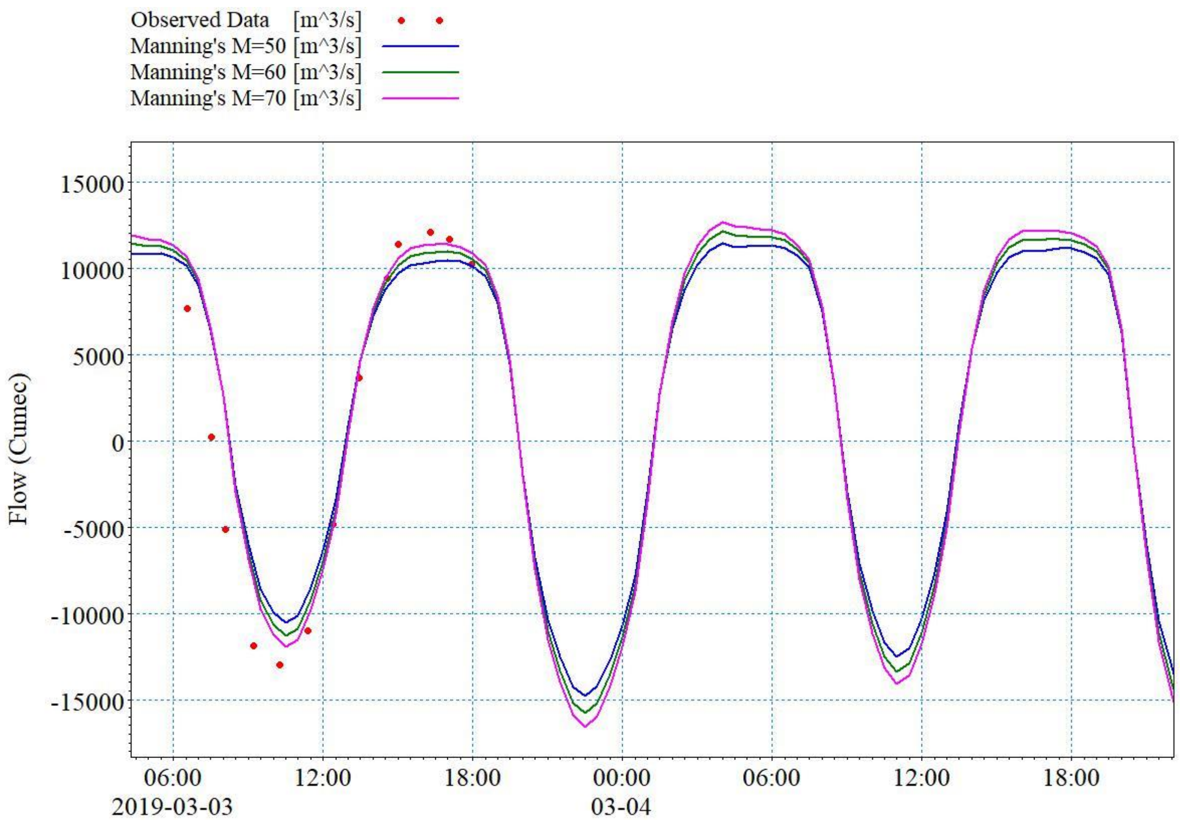


Figure 4-14: Optimization of manning's roughness with trial simulation of different bed resistance (at Baleswar River).

4.3.5 Dispersion co-efficient used in the mathematical model

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

Similar to determination of Manning's roughness number, the dispersion co-efficient is also determined with trial-and-error simulation. For example, **Figure 4-15** shows the times series salinity simulation result for dispersion co-efficient (100 m^2/s, 200 m^2/s, 300 m^2/s and 400m^2/s respectively) for Rupsha river. And it is found that, value 300 m^2/s is the optimum value for advection dispersion simulation.

Similarly, sensitivity of dispersion co-efficient for Baleswar, Buriswar and Sibsa river system is shown in **Figure 4-16** to **Figure 4-18**.

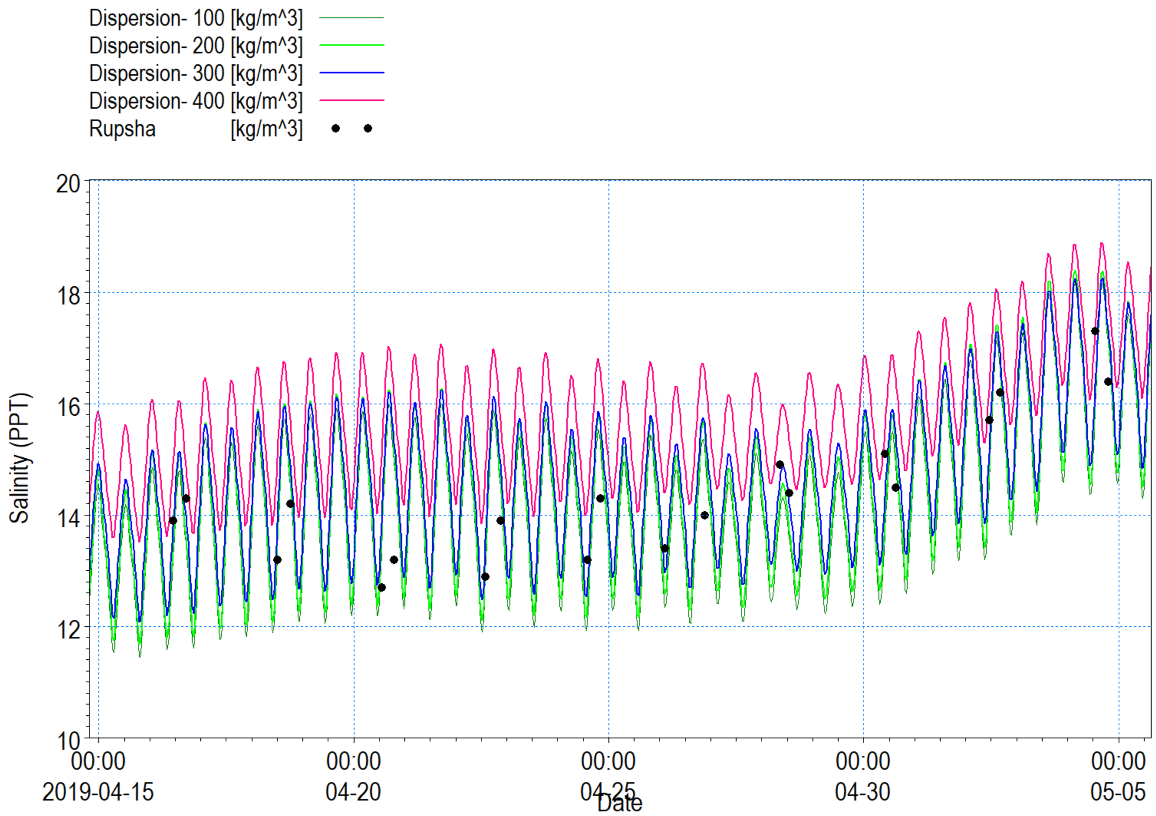


Figure 4-15: Optimization of dispersion co-efficient with trial simulation (for Rupsha River).

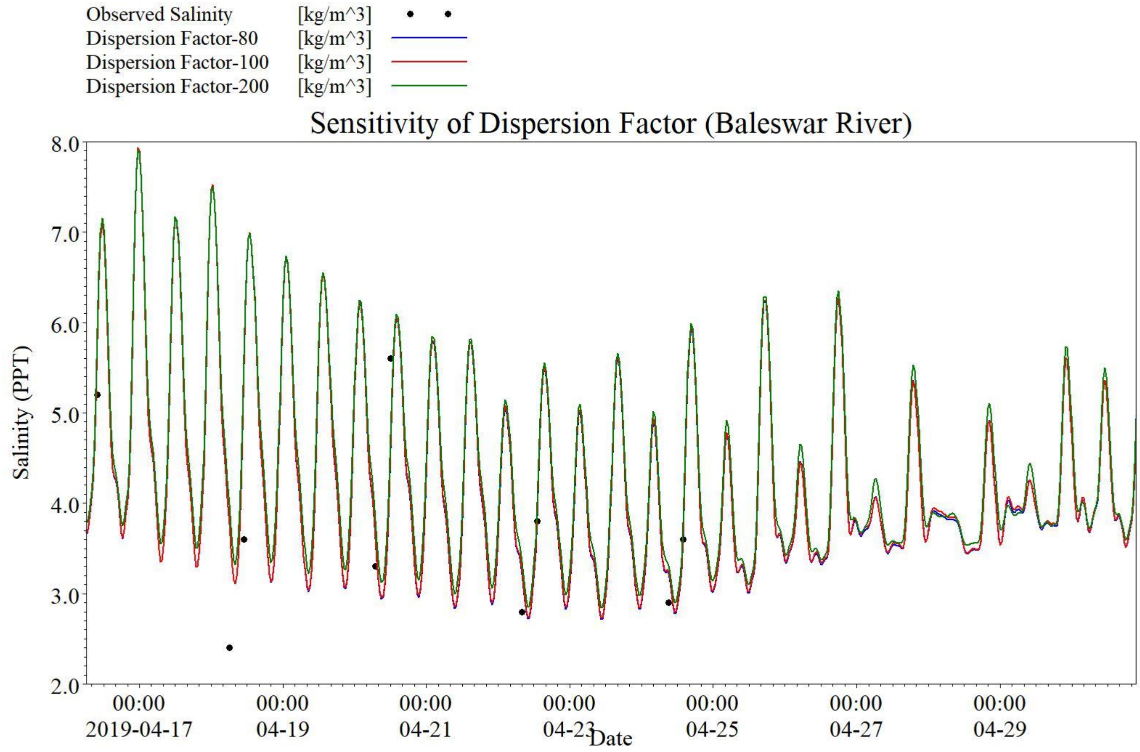


Figure 4-16: Optimization of dispersion co-efficient with trial simulation (for Baleswar River).

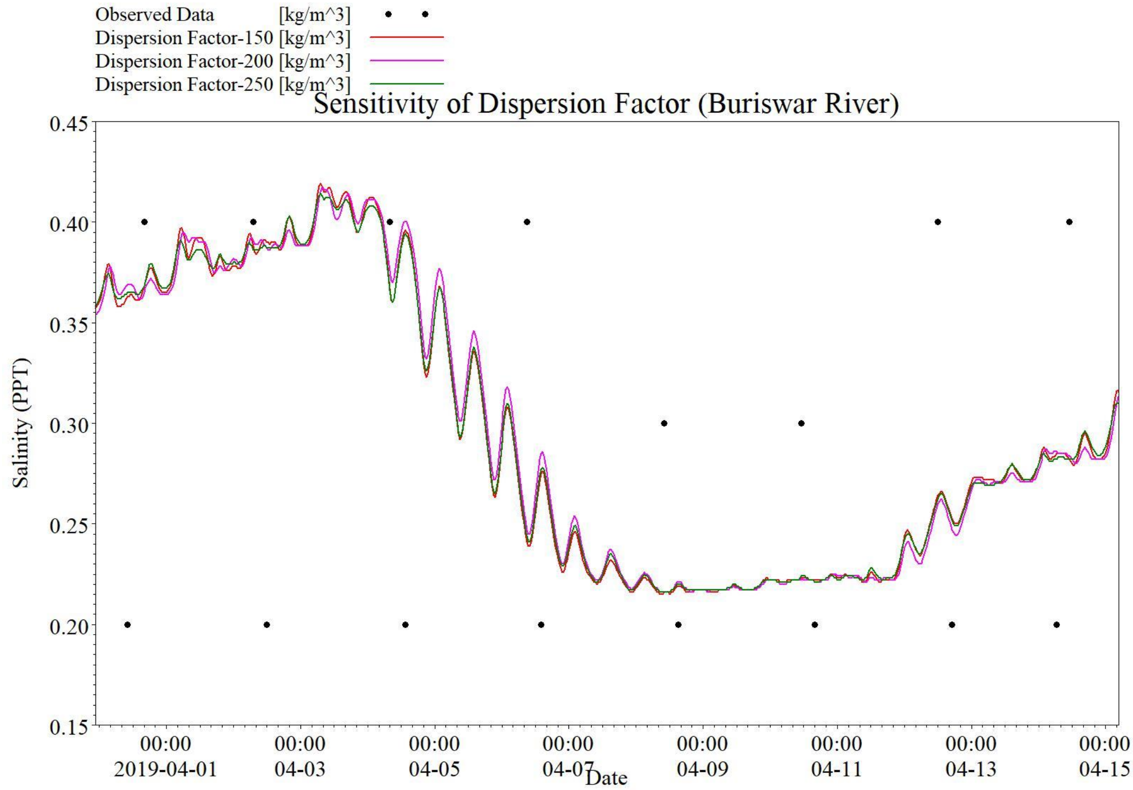


Figure 4-17: Optimization of dispersion co-efficient with trial simulation (for Buriswar River).

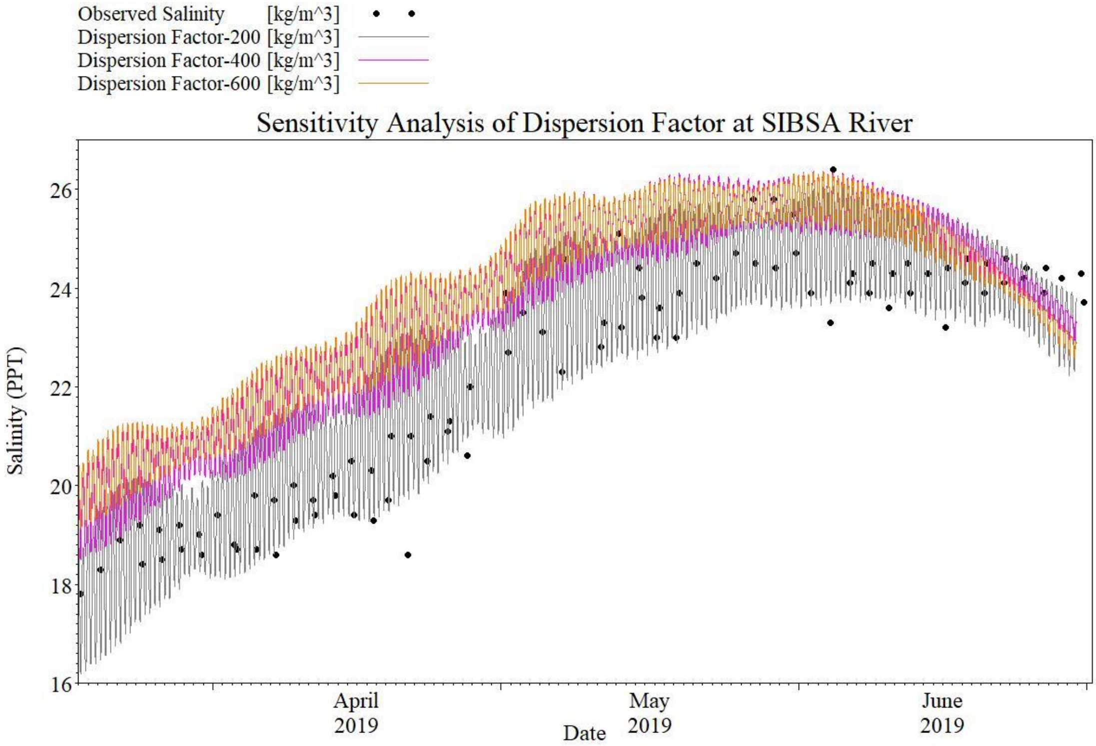


Figure 4-18: Optimization of dispersion co-efficient with trial simulation (for Sibsa River).

4.4 Calibration of Hydrodynamic & Advection Dispersion Model

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 4-19**) of the coastal region. Following figures shows some water flow calibration results.

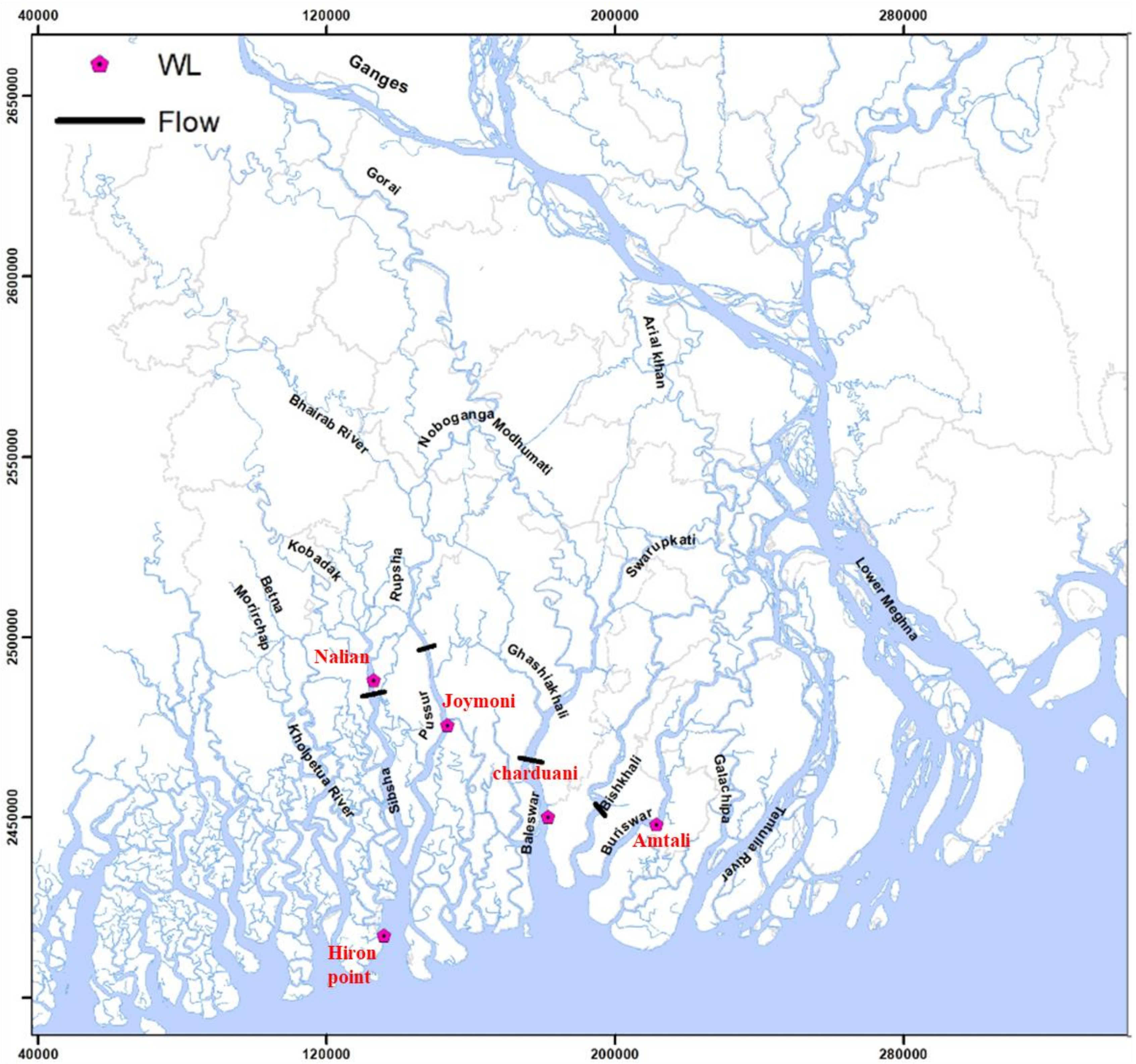


Figure 4-19: Water level and flow calibration location.

Calibration of Discharge

Figure 4-20 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.

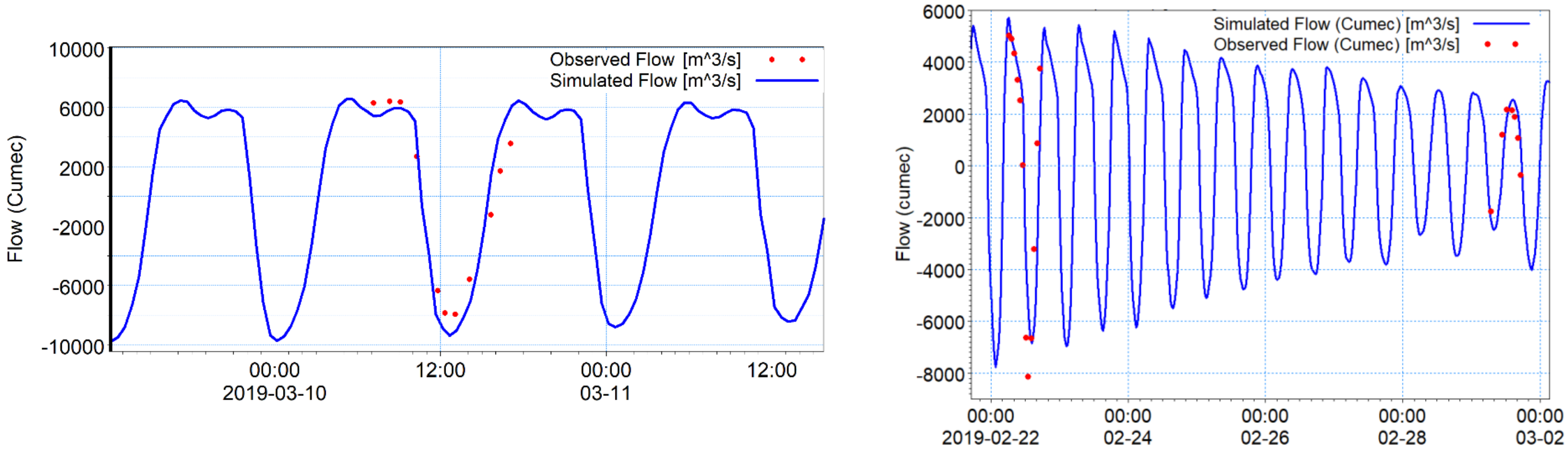
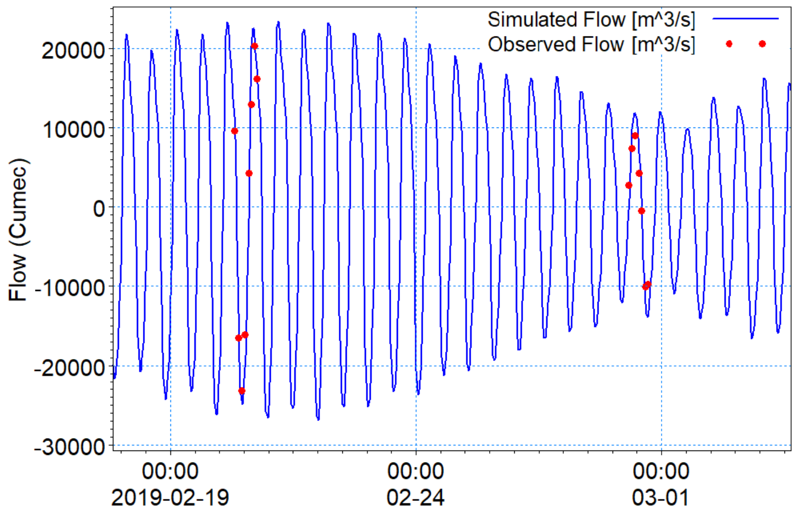


Figure 4-20: Calibration plot of Dry season flow at Bishkhali (left) and Pussur (right)

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



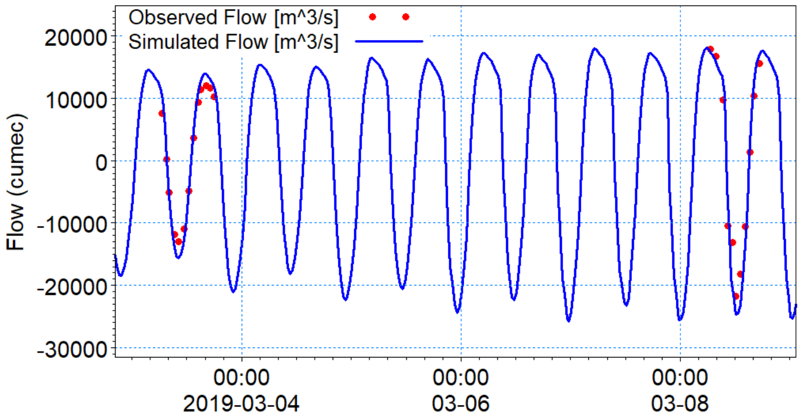


Figure 4-21: Calibration plot of Dry season flow at Sibsa (left) and Baleswar (right)

Figure 4-21 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

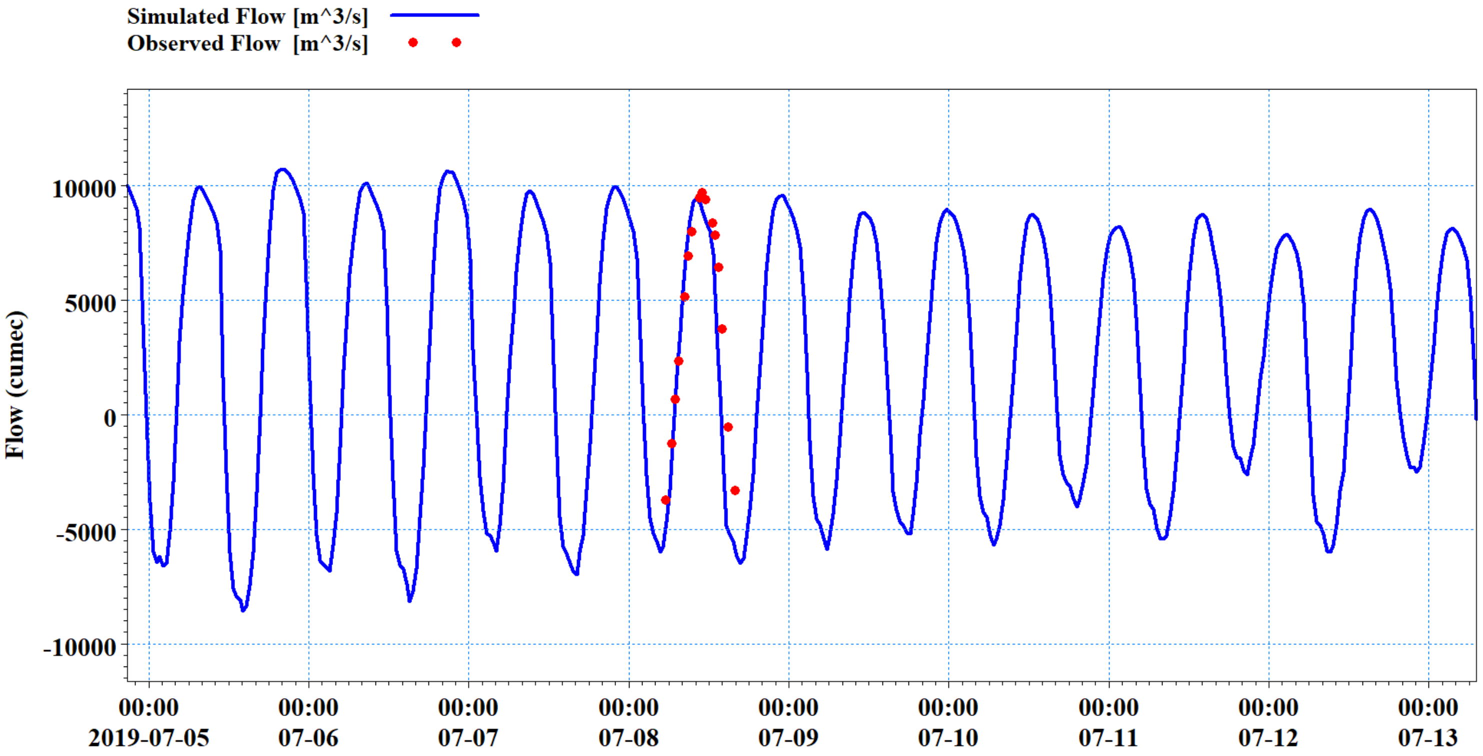


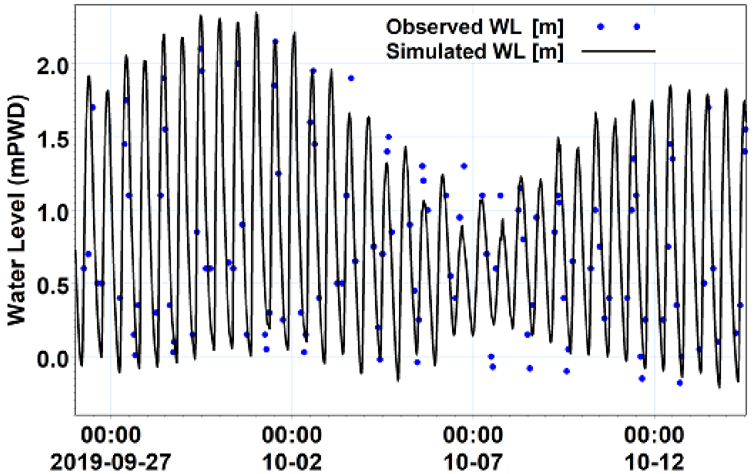
Figure 4-22: Calibration plot of Monsoon season flow at

Calibration of water level

Figure 4-23 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



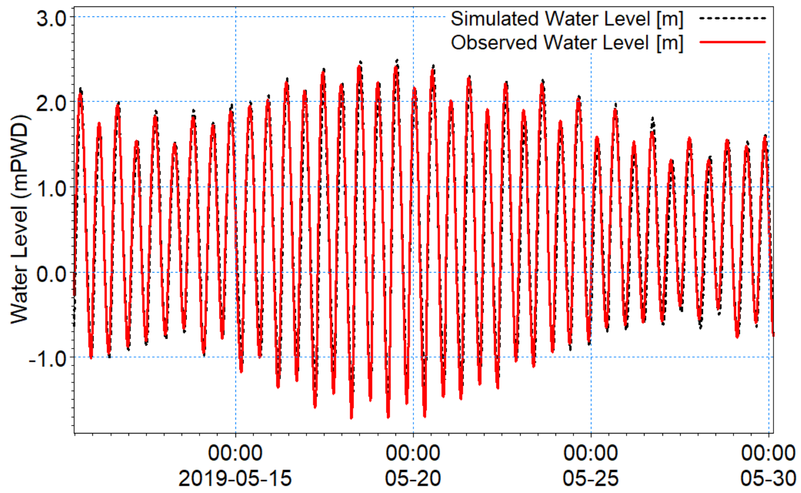


Figure 4-23: Calibration plot of Water level data in Buriswar river at Amtali (left) and in Pussur river at Joymoni (Right)

Figure 4-24 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.

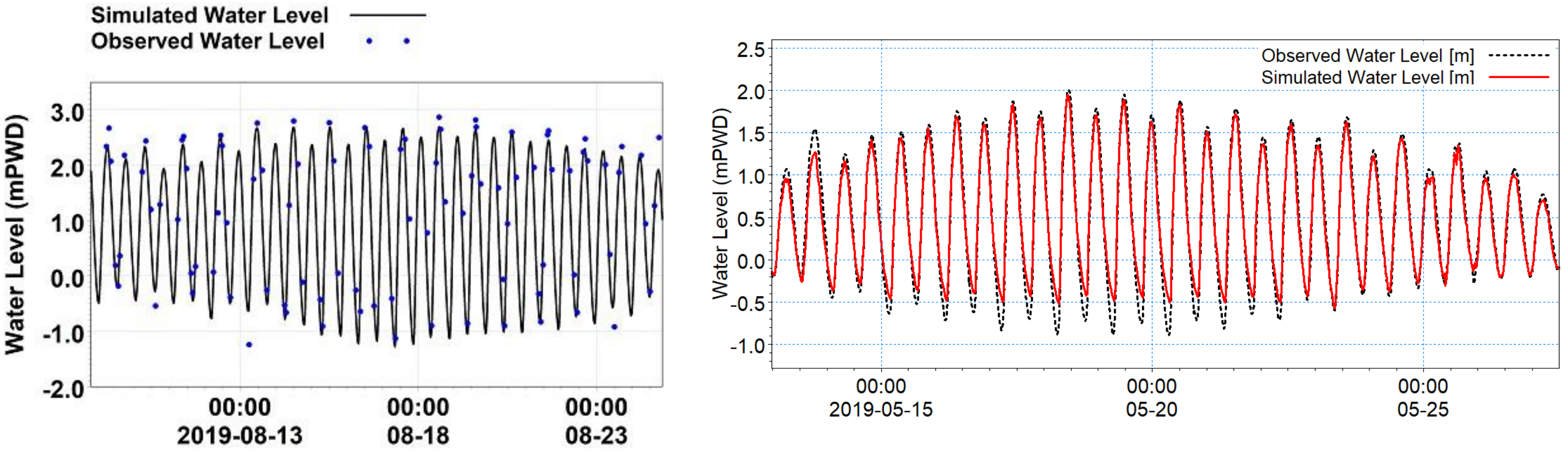


Figure 4-24: Calibration plot of Water level data in Sibsa river at Nalian (left) and in Baleswar river at Charduani (Right)

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 4-25** to **Figure 4-33** 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**.

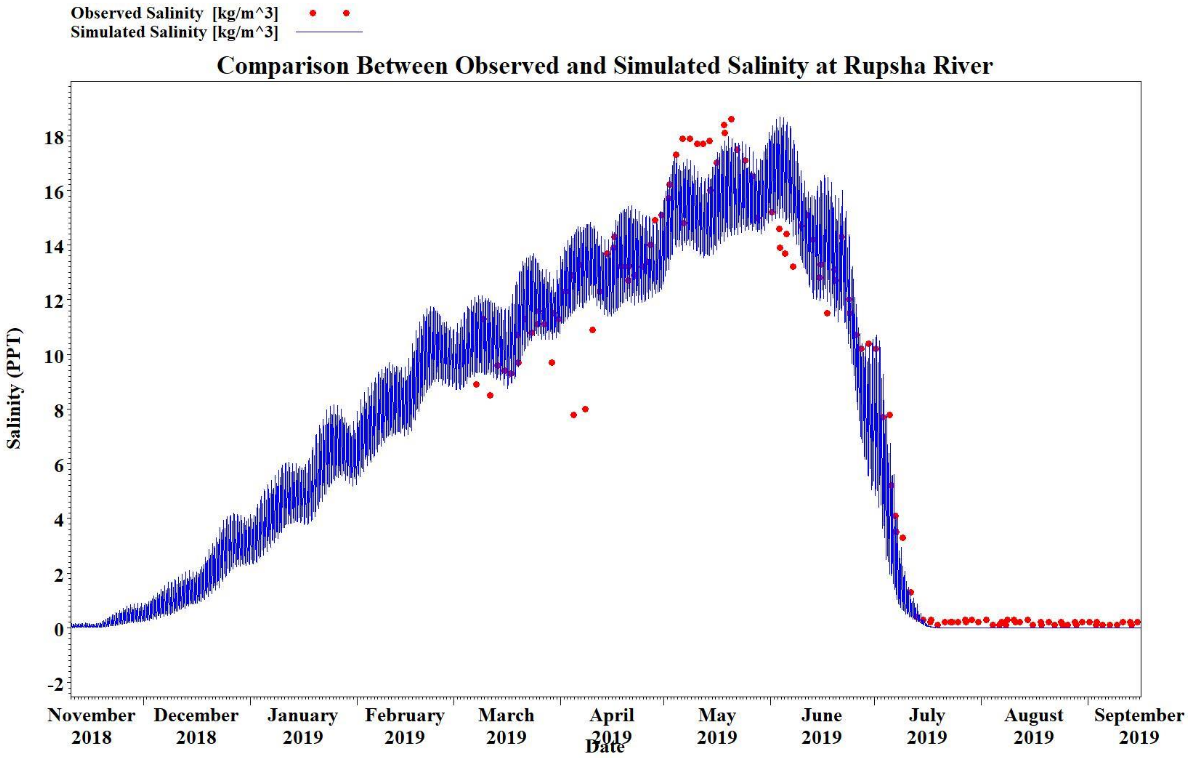


Figure 4-25: Salinity calibration plot at Rupsha River

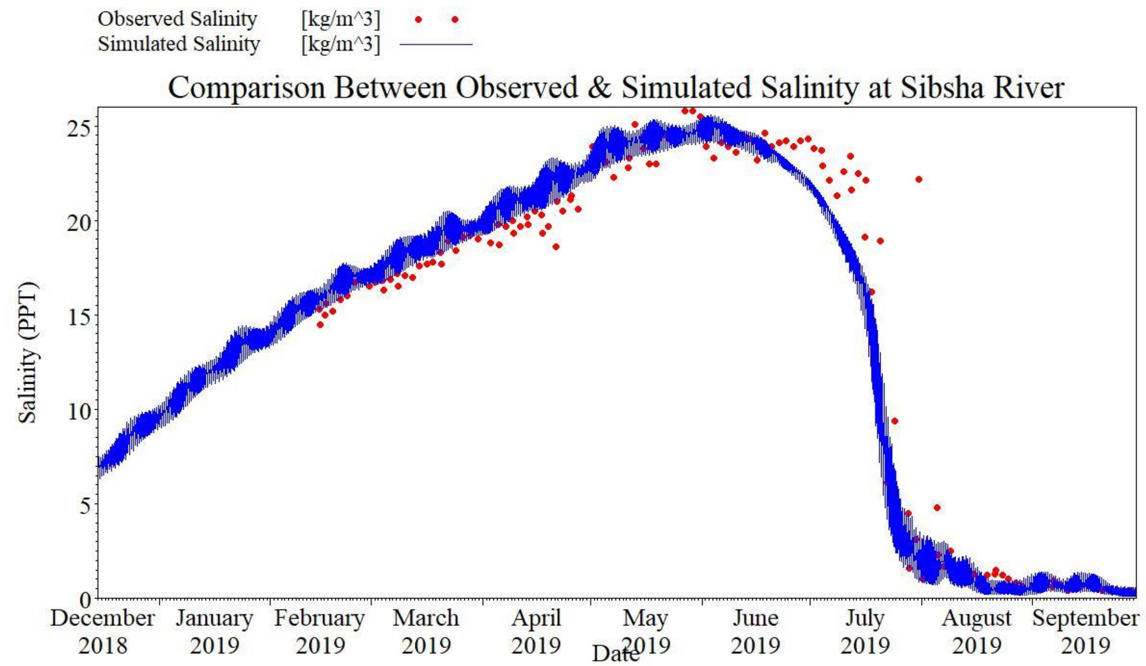


Figure 4-26: Salinity calibration plot at Sibsha River

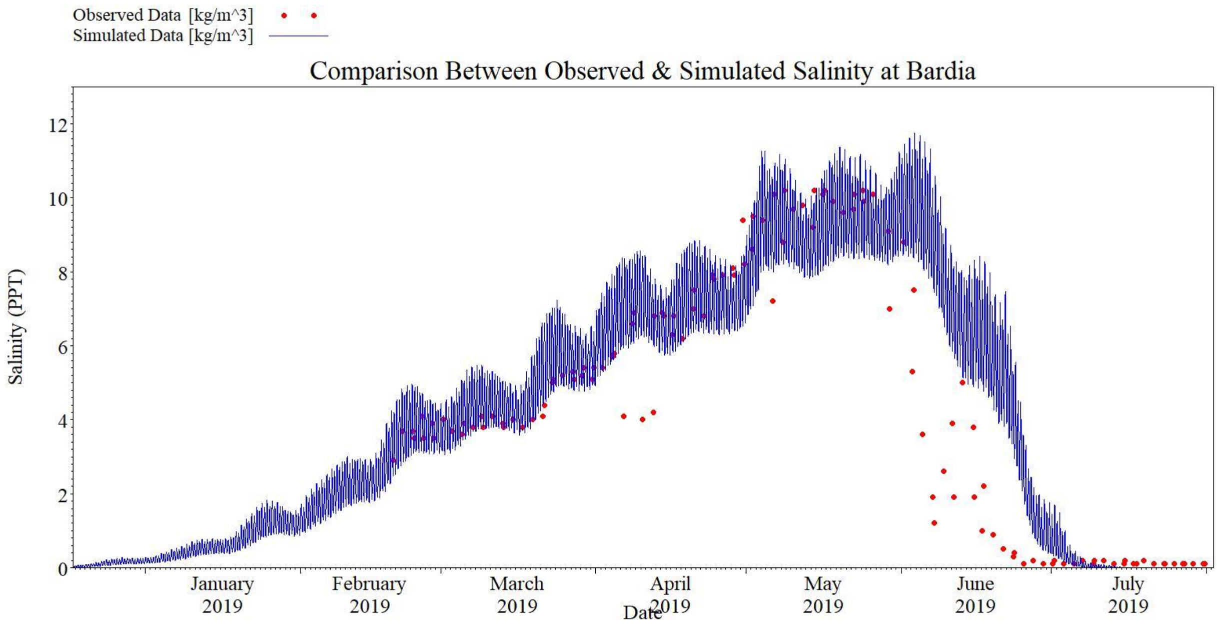


Figure 4-27: Salinity calibration plot at Sibsha River

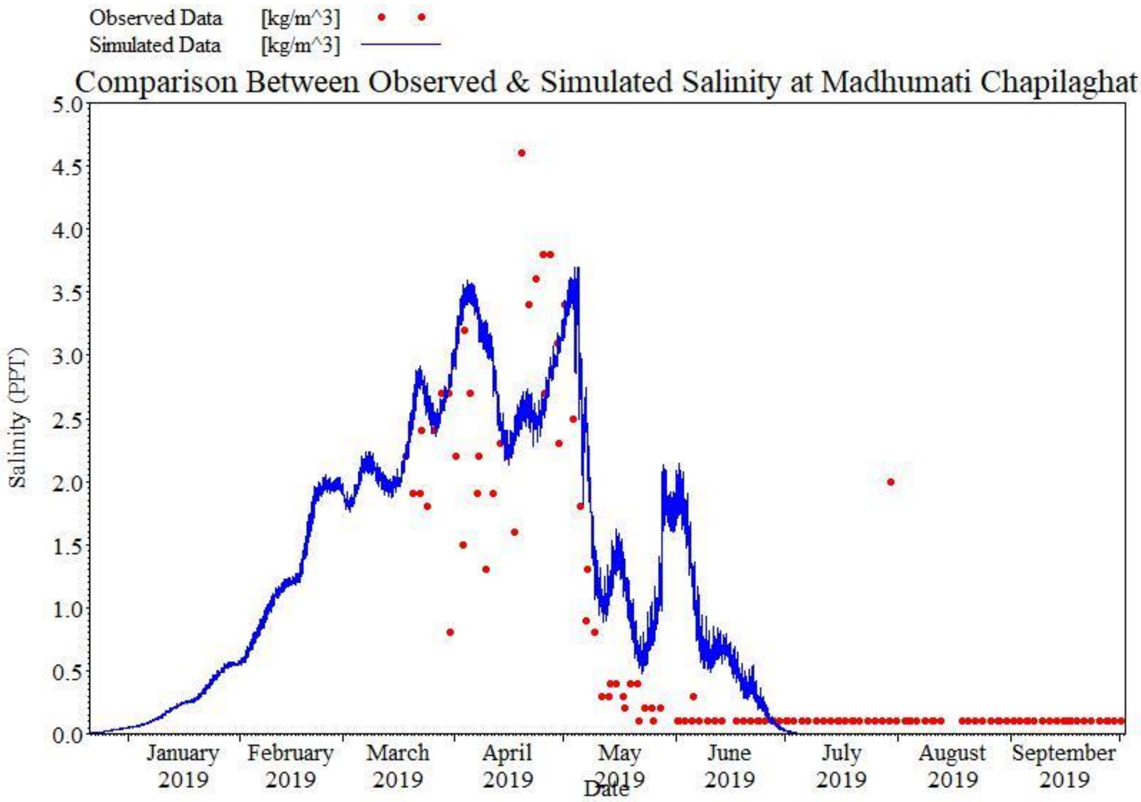


Figure 4-28: Salinity calibration plot at Chapilaghat (Madhumati River)

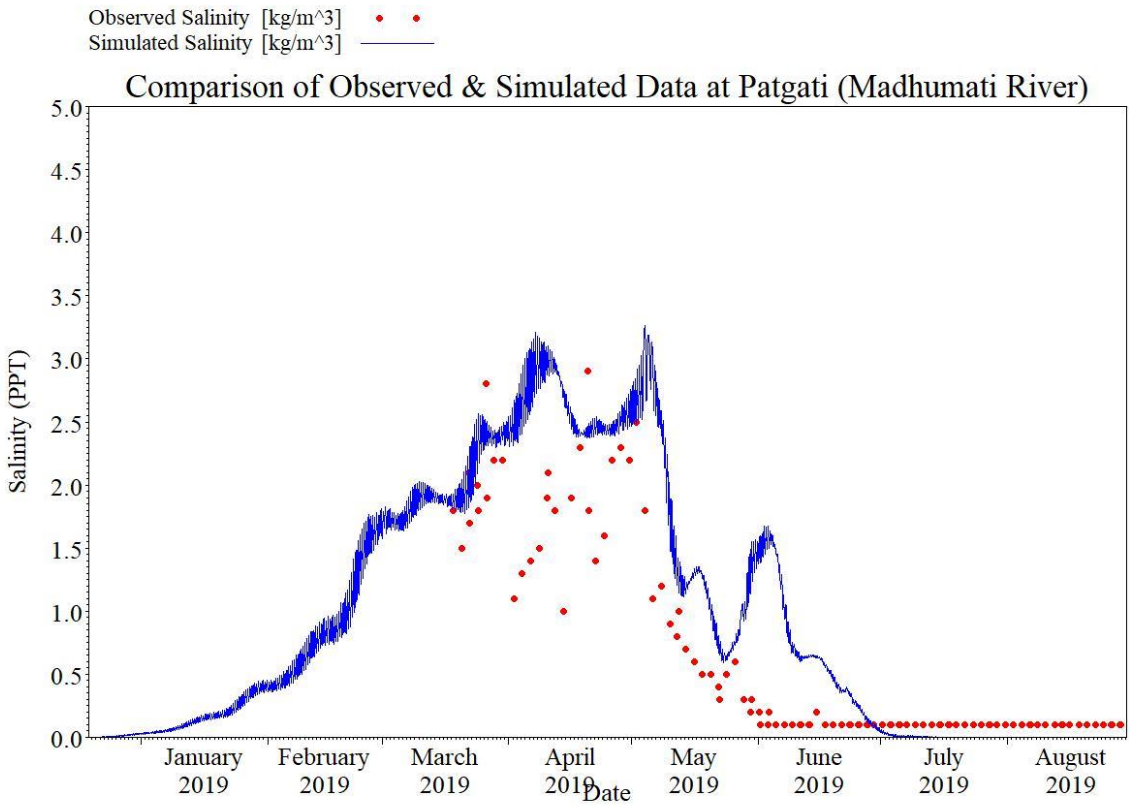


Figure 4-29: Salinity calibration plot at Patgati (Madhumati River)

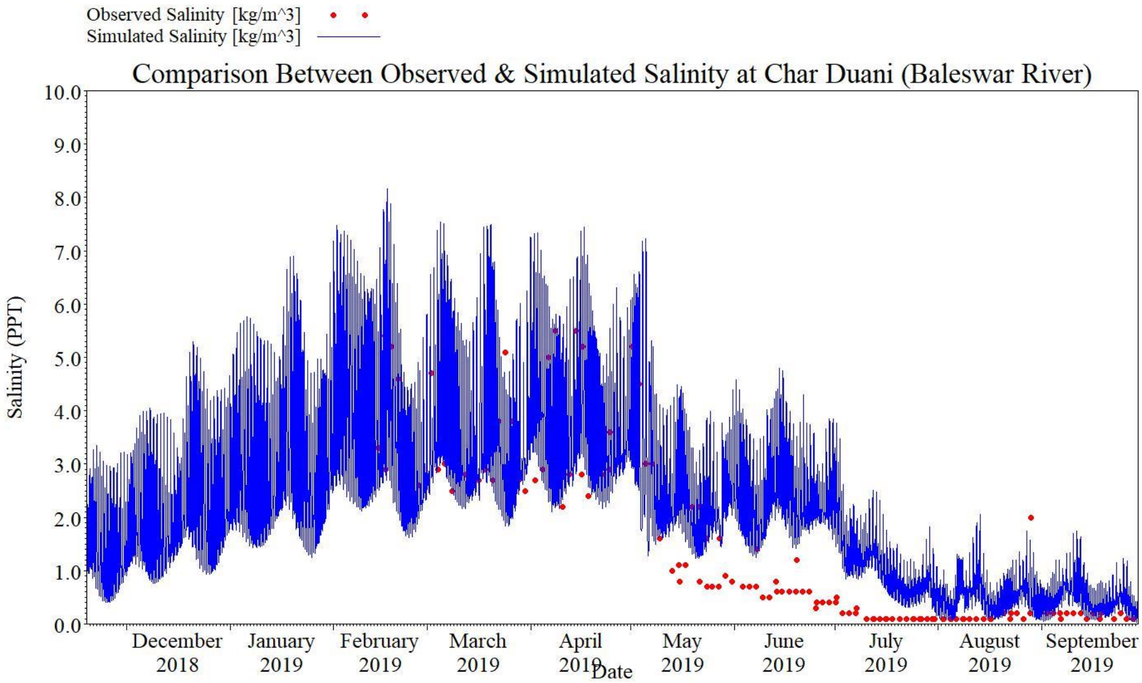


Figure 4-30: Salinity calibration plot at Amtali (Buriswar River)

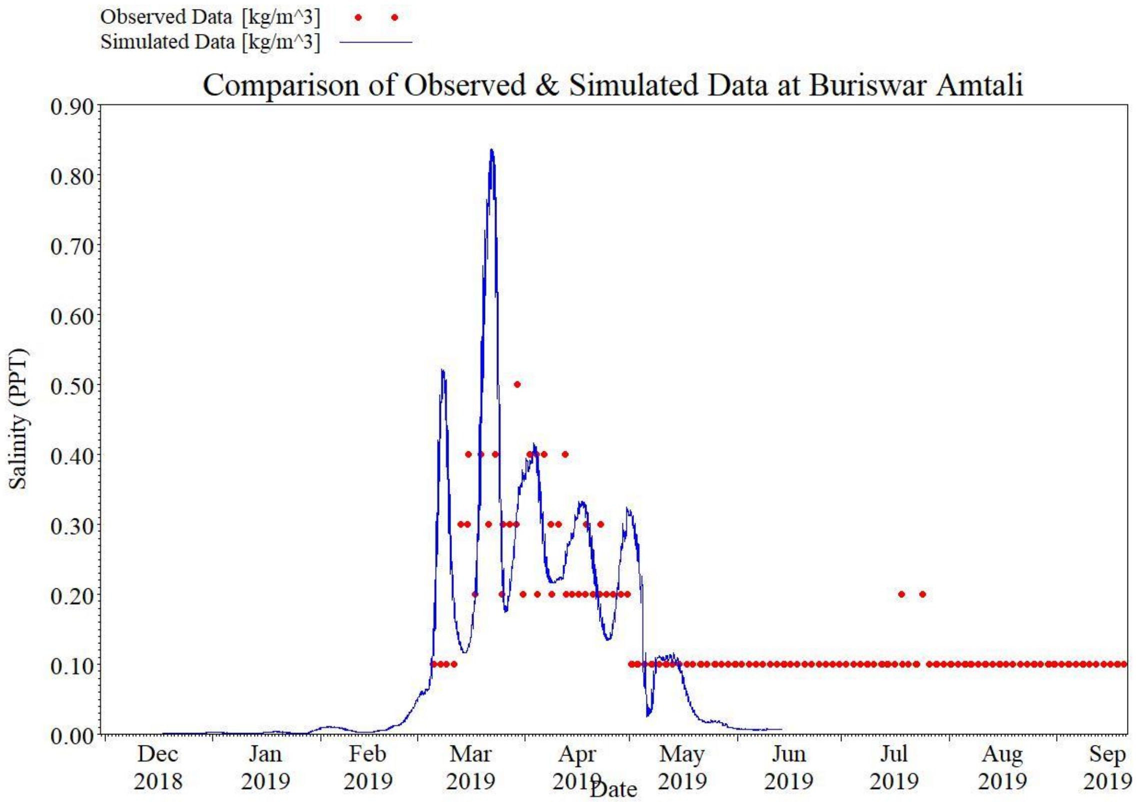


Figure 4-31: Salinity calibration plot at Amtali (Buriswar River)

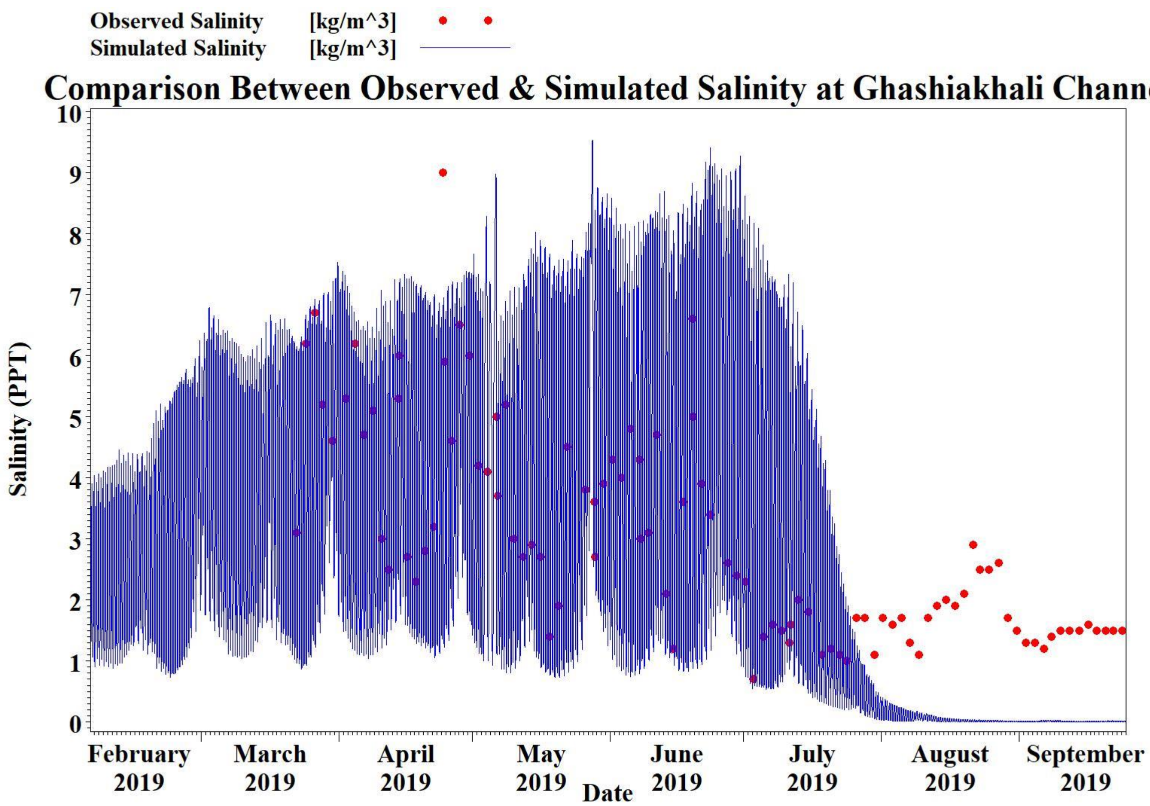


Figure 4-32: Salinity calibration plot at Ghashiakhali River

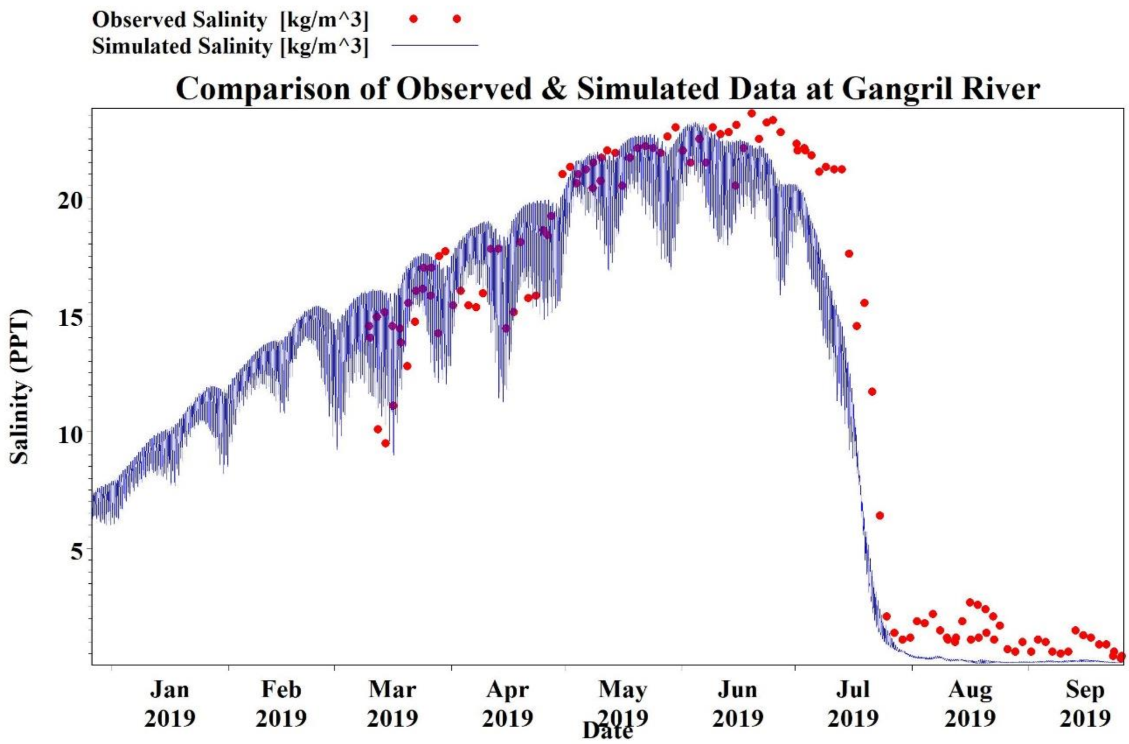


Figure 4-33: Salinity calibration plot at Gangril River

5 Spatial Variation of Salinity

5.1 Methodology for Interpolation 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 mathematical modelling. 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;

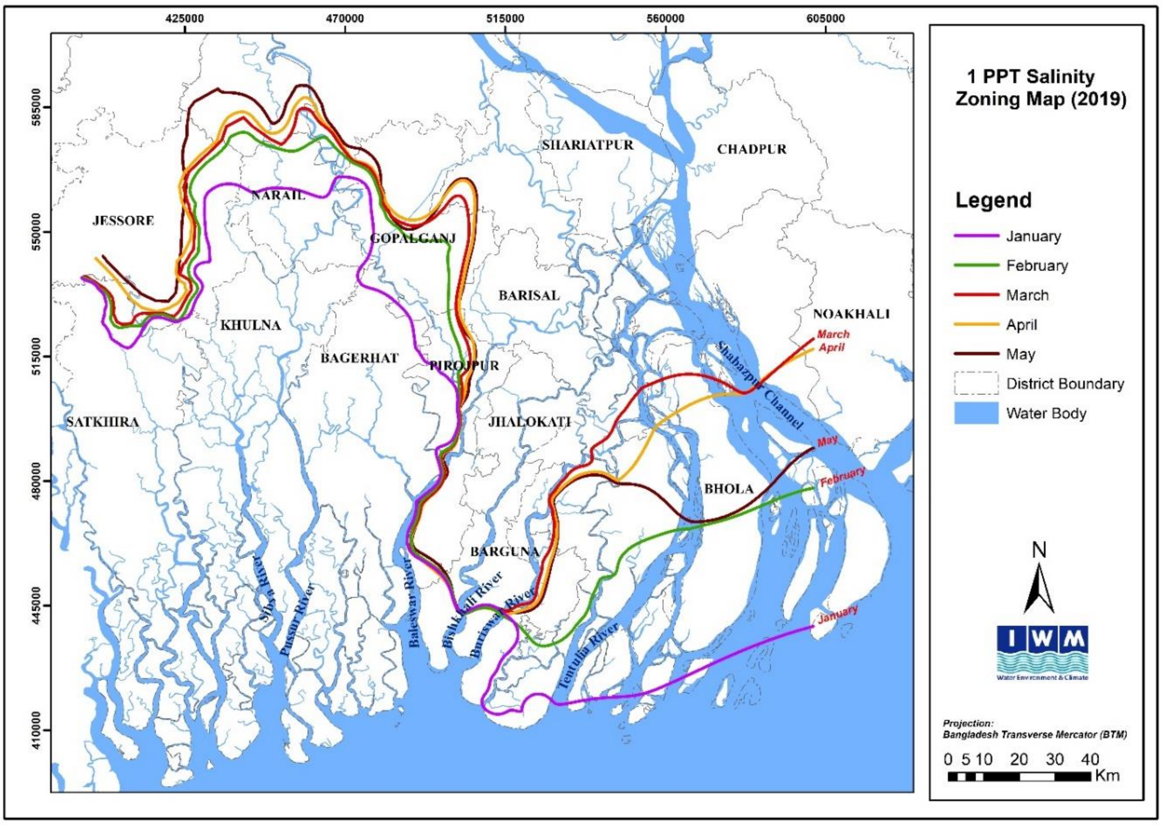


Figure 5-1: 1ppt salinity contour at Southwest regional model in dry season

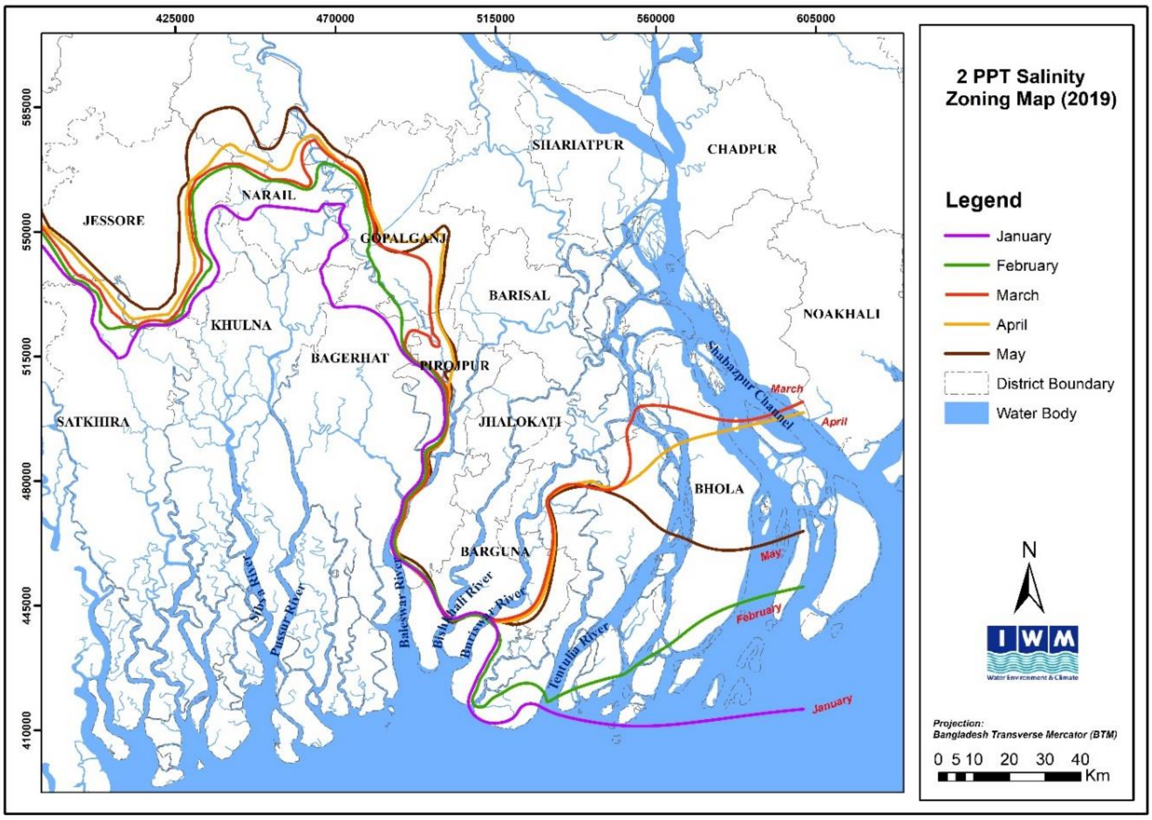


Figure 5-2: 2 ppt salinity contour at Southwest regional model in dry season

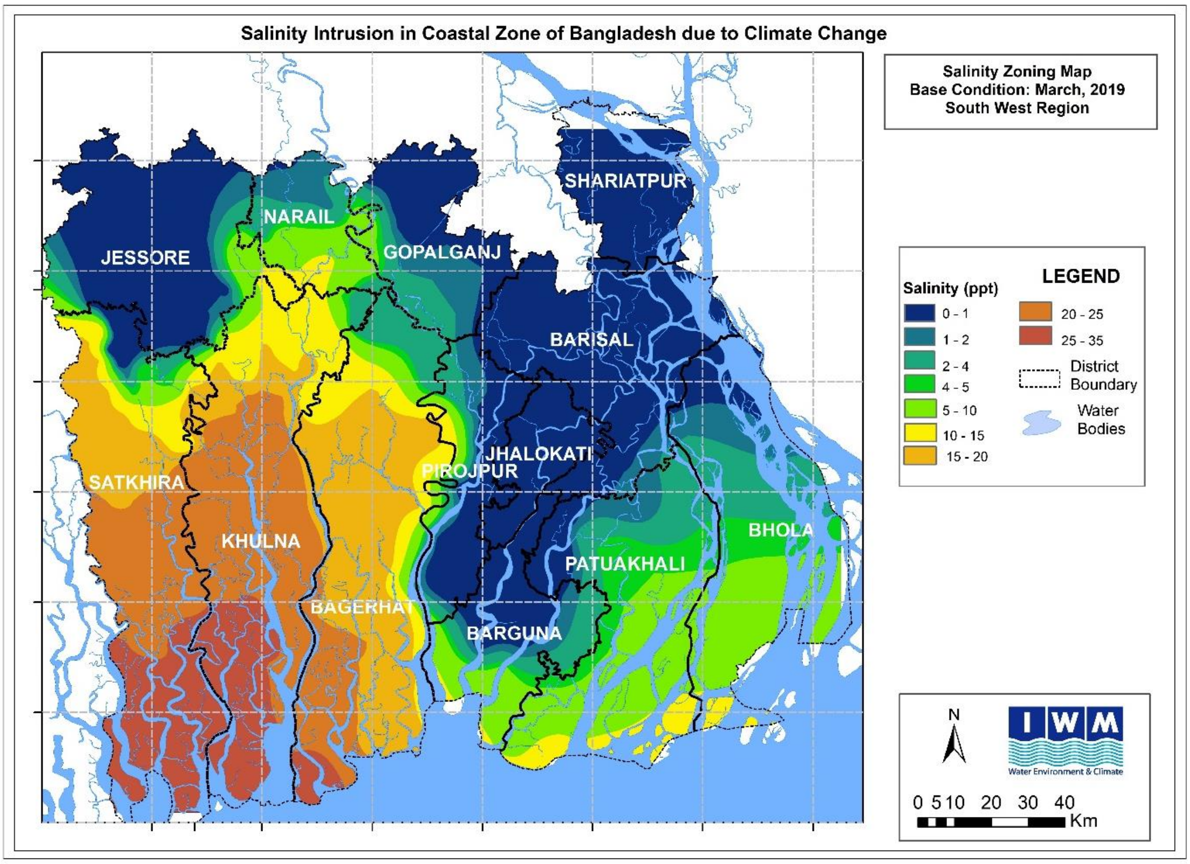


Figure 5-3: Salinity Raster during March, 2019

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.