Chickahominy River Salinity Impact Evaluation of Proposed Raw Water Supply Withdrawal and Brine Concentrate Discharge Memorandum

James City Service Authority

Date: December 2016

CDM Smith

Memorandum

To: *Michael D. Vergakis, P.E.*

From: *Frances Bui, Karina Hull, Richard Wagner*
Jian Shen, PhD (VIMS)

Date: *December 12, 2016*

Subject: *James City Service Authority (JCSA)*
Chickahominy River Salinity Impact Evaluation of Proposed Raw Water Supply Withdrawal and Brine Concentrate Discharge

1.0 Purpose and Background

This technical memorandum summarizes the results of the modeling efforts conducted to determine the effect of a proposed raw water intake withdrawal and brine concentrate discharge on the salinity gradient of the Chickahominy River at two potential sites: Brickyard Landing and Chickahominy Riverfront Park. The location of Brickyard Landing and Chickahominy Riverfront Park is shown in **Figure 1**.

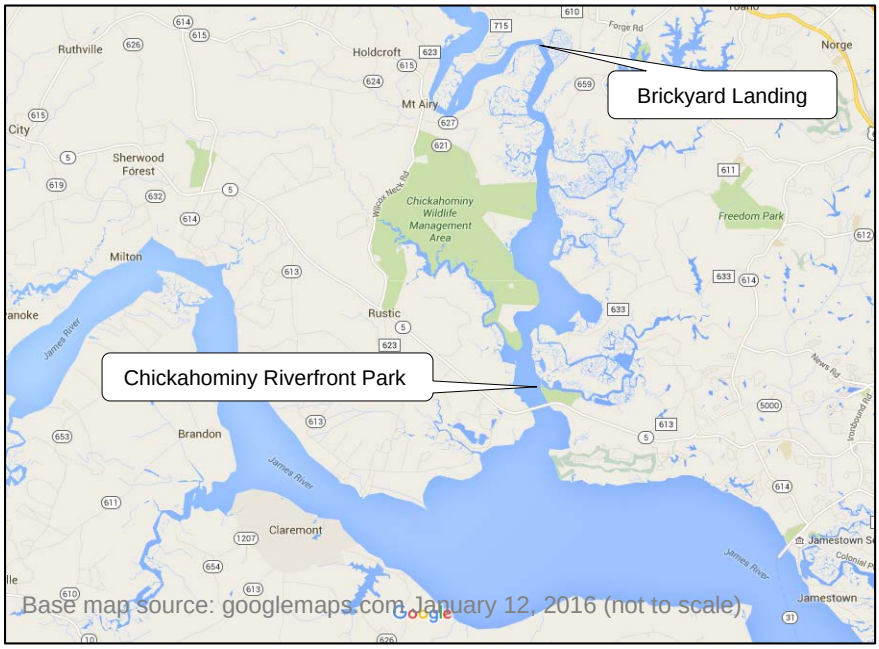

Figure 1
Location Map

The Chickahominy Riverfront Park intake location was identified in the *Water Supply Study Final Draft Report* prepared by CDM Smith, dated April 2015; the Joint Permit Application (JPA) for this property was submitted to the Virginia Marine Resources Commission (VMRC) on October 7, 2016. The Brickyard Landing intake location was identified in the *Chickahominy River Brickyard Landing Raw Water Supply Feasibility Study Final Report* completed by CDM Smith in March 2016.

JCSA had a pre-application meeting with regulatory agencies that was coordinated by the Virginia Department of Environmental Quality (DEQ) in August 2015 on the proposed Chickahominy Riverfront Park intake. The pre-application panel provided comments. The Virginia Department of Game and Inland Fisheries (DGIF) requested that results of spatio/temporal modeling of the salinity changes resulting from the proposed intake be provided to help them assess the impact on instream habitat and resident aquatic species. JCSA, CDM Smith, DEQ, and the Virginia Institute of Marine Science (VIMS) met on March 11, 2016 to discuss the flow determination approach for the JPA application. VIMS requested that modeling be conducted to determine the potential impact of the withdrawal and brine concentrate discharge on the salinity gradient and that the results be included in the JPA application. VIMS indicated that they have an Environment Fluid Dynamics Code (EFDC) three-dimensional (3D) model and a MARINA model of the river.

Based on discussions with DEQ, VIMS, and CDM Smith on May 19, 2016, all parties agreed that the best approach is to use the mixing zone model CORMIX in conjunction with the EFDC model for the evaluation. The use of both models provides the ability to evaluate the potential initial dilution immediately near the brine discharge location (i.e., the near-field region via CORMIX) and the impact of the salinity discharge on a scale of the ambient waterbody (i.e., the far-field region via the EFDC model). Based on comments received from DEQ Office of Water Supply on June 1, 2016 and DEQ-Office of Virginia Pollutant Discharge Elimination System (VPDES) Permits on June 24, 2016, it was determined that VIMS would need to refine the model grid prior to the analysis to meet the project's objectives.

This memorandum summarizes the results of the CORMIX modeling work conducted by CDM Smith and the EFDC modeling work performed by VIMS; the detailed reports for each model are included in Attachments A and B, respectively.

2.0 Proposed Water Treatment Facility Capacity, Withdrawal, and Discharge Flows

The proposed water treatment facility on the Chickahominy River requires reverse osmosis treatment for both sites. The required capacity for the treatment facility is highly dependent on the DEQ permitted groundwater withdrawal and the projected water demands. For the purpose of this evaluation, 4-, 8-, and 12-million-gallon-per-day (mgd) finished water plant capacities were considered. The flow requirements for each plant capacity are summarized in **Table 1**. The raw water withdrawal required for the facility includes the finished water plant capacity as well as the process water required for treatment. The majority of the process water is brine concentrate from the reverse osmosis treatment units. The brine concentrate will be discharged back into the Chickahominy River, downstream of the intake.

Table 1 Reverse-Osmosis Water Treatment Facility Estimated Flows[1,2]

Finished Water Plant Capacity (mgd)	Raw Water Withdrawal (mgd)[3]	Brine Concentrate Discharge (mgd)
4	6	1.3
8	12	2.7
12	18	4.0

Notes:

1. CDM Smith. 2015. *Water Supply Study Final Draft Report* for the James City Service Authority. Figures 9-2 and 9-3.
2. CDM Smith. 2016. *Chickahominy River Brickyard Landing Raw Water Supply Feasibility* Study for the James City Service Authority. Figures 2-4 and 2-5.
3. Raw water withdrawal includes finished water and process water, rounded up to the nearest million gallons per day.

3.0 Proposed Withdrawal and Discharge Location

CDM Smith met with JCSA to identify potential sites for the brine concentrate discharge. The brine concentrate must be discharged at a location that is a sufficient distance downstream of the intake to avoid recirculation. As a preliminary screening criterion, a minimum distance of 1,500 feet downstream of the intake was applied. A discussion of potential sites based on this criterion and available property identified by JCSA follows. A shoreline and an in-river discharge configuration were considered at each proposed discharge site.

3.1 Brickyard Landing

The proposed withdrawal location for Brickyard Landing is shown in **Figure 2**. Available property approximately 1,500 feet downstream of the proposed Brickyard Landing intake is located in a freshwater emergent wetland area; Hog Neck Creek flows through the wetland area. The impact of the brine concentrate discharge construction and operation would have significant impact to the wetlands, making it difficult to obtain regulatory approval for this site. Hence, this discharge site was eliminated from consideration.

Property for the Brickyard Landing brine concentrate discharge is also available approximately 6,000 feet downstream of the proposed intake at the end of Uncles Nick Road. This location was selected for the proposed discharge. It is estimated that approximately 16,000 feet of discharge main installed in existing road right-of-way will be required from the treatment facility to the discharge point. The shoreline and in-river discharge locations that were evaluated for this discharge area are shown on Figure 2.

3.2 Chickahominy Riverfront Park

The proposed withdrawal location for the Chickahominy Riverfront Park water treatment facility is shown in **Figure 3**. The County owns an easement under the Route 5 bridge; this property is approximately 1,500 feet downstream of the intake. The shoreline and in-river discharge locations that were evaluated for this discharge area are shown in Figure 3.

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Salinity Memorandum
Withdrawl and Discharge Locations

Figure 2
Brickyard Landing Water Treatment Facility
Raw Water Withdrawal and
Brine Concentrate Discharge

Date: 11/4/2016

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Salinity Memorandum
Withdrawl and Discharge Locations

Figure 3
Chickahominy Riverfront Park
Water Treatment Facility Raw Water
Withdrawal and Brine Concentrate Discharge

Date: 11/4/2016

Property is also available approximately 5,000 feet downstream of the intake; however, this area is in a shallow embayment. Hence, the mixing potential is questionable. This discharge location was eliminated from further consideration.

4.0 Virginia DEQ Mixing Zone Regulations

The discharge of the brine concentrate will be regulated by the VPDES permit requirements. In 9VAC25-260-20, the Virginia State Water Control Board states that they may use mixing zone concepts in evaluating limitations for the VPDES permit based on the following description:[1]

1. *"Mixing zones evaluated or established by the board in open ocean, estuarine, and transition zone waters shall not:*

    a. *Prevent movement of or cause lethality to passing and drifting aquatic organisms through the water body in question;*

    b. *Extend more than five times in any direction the average depth along a line extending 1/3 of the way across the receiving water from the discharge point to the opposite shore.*

2. *A subsurface diffuser shall be required for any new or expanded freshwater discharge greater than or equal to 0.5 MGD to open ocean, estuarine and transition zone waters and the acute and chronic criteria shall be met at the edge of the zone of initial mixing. The zone of initial mixing is the area where mixing of ambient water and effluent is driven by the jet effect and/or momentum of the effluent. Beyond this zone, the mixing is driven by ambient turbulence."*

5.0 Existing Model Description and Refinement

VIMS assisted the United States Geological Survey (USGS) in evaluating the impact of sea-level rise on drinking water in the Chickahominy River in 2011.[2,3] VIMS has also assisted DEQ in assessing the Chlorophyll-a criteria in the James River. During these studies, VIMS developed the EFDC models for the James River and Chickahominy River to simulate salinity. The Chickahominy River model was developed to assess the impact of sea-level rise on a drinking water study. The model was calibrated based on field data.

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[1] http://www.deq.virginia.gov/portals/0/deq/water/waterqualitystandards/wqs_eff_6jan2011.pdf (Last accessed November 4, 2016)

[2] Rice, K.C., Bennett, M.R., Shen, J., 2011. *Simulated Changes in Salinity in the York and Chickahominy Rivers from Projected Sea-level Rise in Chesapeake Bay*. USGS Open-File Report 2011e1191, 31 p.

[3] Rice, K.C., Hong, B., and Shen, J. 2012. Assessment of salinity intrusion in the James and Chickahominy Rivers as a result of simulated sea-level rise in Chesapeake Bay, East Coast, USA. Journal of Environmental Management. 111, 61-69.

The calibrated EFDC model was used in this study to evaluate the salinity impact of the proposed water treatment facility on the Chickahominy River. Prior to conducting the analysis, VIMS increased the discretization of the EFDC model near the proposed raw water withdrawal and discharge locations (i.e., refined the grid with smaller grid cells) to improve model resolution. The refined grid is shown in **Figure 4** and has 8 vertical layers and 2,656 horizontal grid cells in comparison to the original model which had 1,158 horizontal grid cells. The model was recalibrated after the grid cells were refined based on 2006 to 2008 field data; the 2007 data generated the best calibration accuracy.

6.0 Ambient Conditions

The Virginia Estuarine and Coastal Observing System (VECOS) has a continuous monitoring station at Chickahominy Haven as located in **Figure 5;** the mean flow data from 1990 to 2013 for this station as compiled by VIMS is presented in **Figure 6**. VIMS indicated that 2007 is a dry-year with very low flow similar to 2002 and includes periods of high salinity as well as low salinity. Hence, 2007 was selected as the base year for the evaluation.

An initial long-term simulation of the EFDC model was conducted for 2007 to establish ambient conditions for the CORMIX model. Hourly temperature and salinity results for the 8 vertical model layers of the EFDC model, river current speed, water depth, and vertical density profiles were used to develop input data for the CORMIX model.

The vertical stratification in the ambient water body is important for the correct prediction of effluent discharge plume behavior. Profiles were tested in a series of CORMIX sensitivity simulations to identify and evaluate the stratification profiles most likely to produce the least effective mixing. All other model inputs, including ambient temperature, were held constant. The following stratification profiles were tested:

- Greatest difference between the surface and bottom salinities
- Highest river bottom salinities
- Highest river surface salinities
- Profiles that have the highest vertical average salinity.

It was determined from the sensitivity simulations that the stratification profiles that cause the least effective mixing are typically the profiles with the greatest difference between surface and bottom salinities and the profiles with the highest bottom salinity.

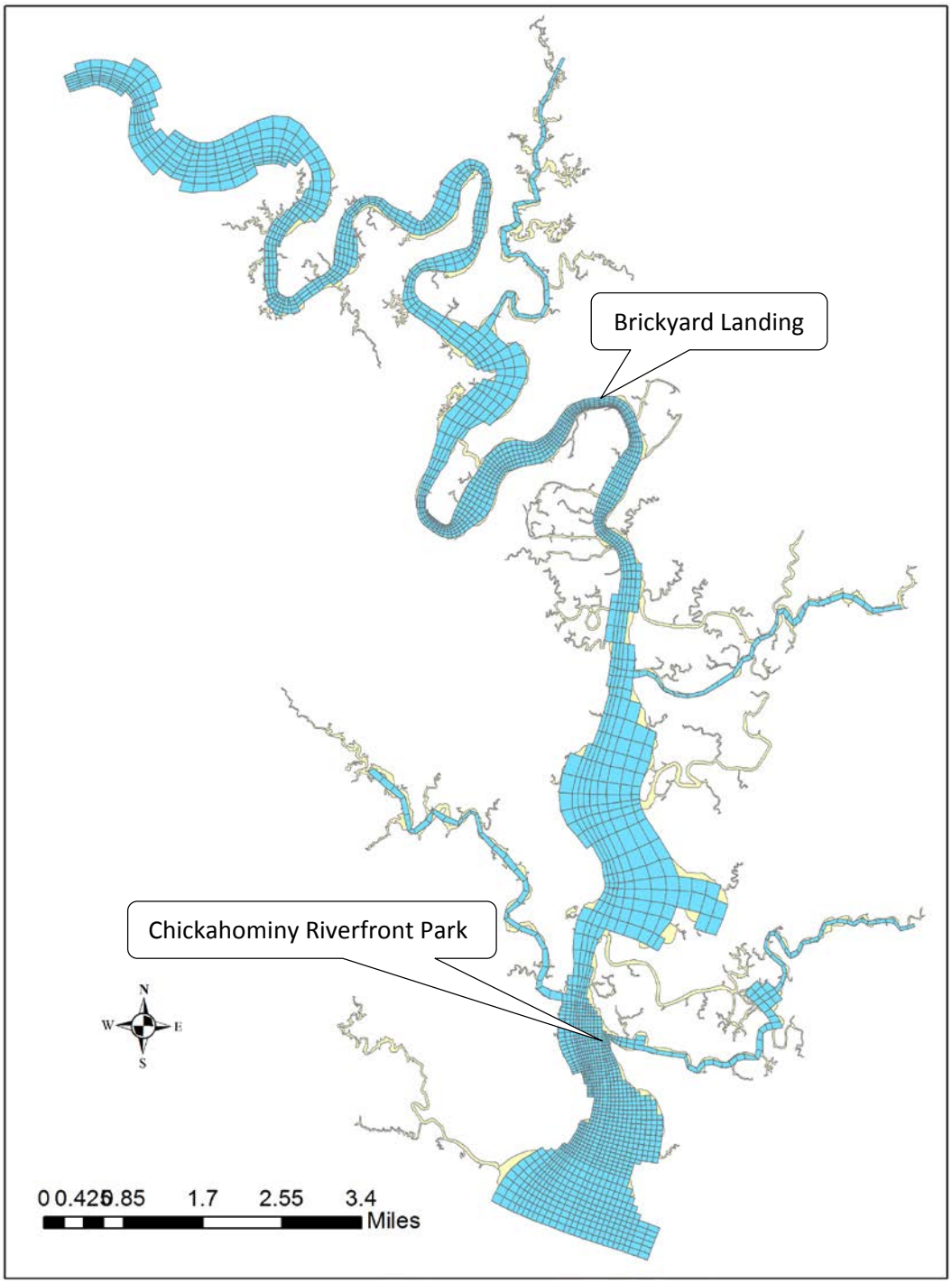


Figure 4
Refined EFDC Chickahominy River Model Grid

Figure 5
Chickahominy River VECOS Monitoring Station CHK015.12 Location

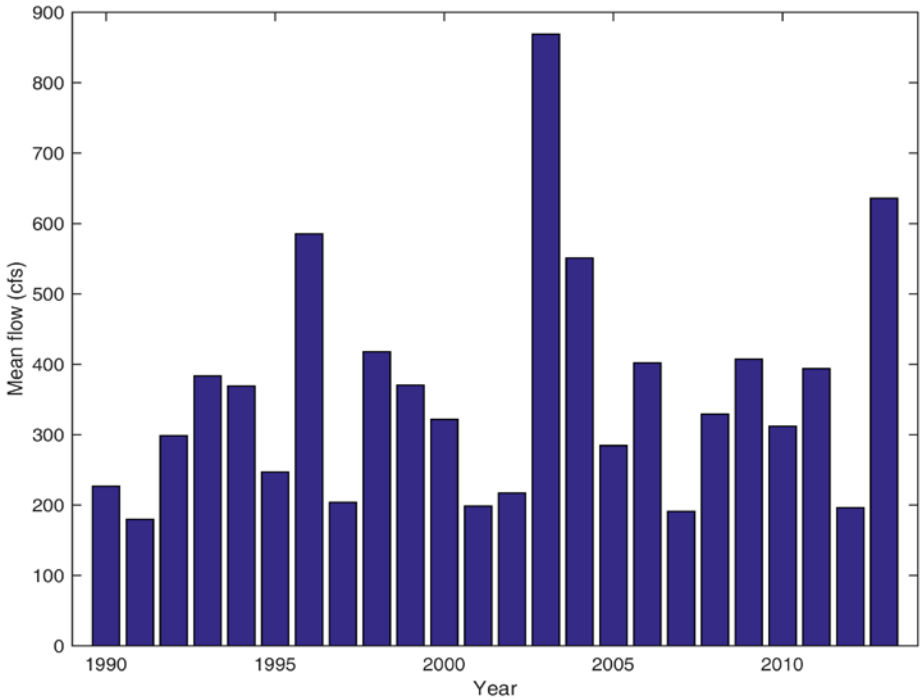


Figure 6
Mean flow of Chickahominy River VECOS Monitoring Station CHK015.12

7.0 Brine Concentrate Discharge Characteristics

7.1 Effluent Quality

Discharge salinity is a function of the withdrawal salinity and the reverse osmosis processes in the water treatment facility. The withdrawal salinity is assigned based on the ambient salinity at the depth in the river at which withdrawal occurs, which was assumed to be approximately 60 percent of the water depth from the river bottom. The corresponding salinity at this depth was established from the EFDC model ambient salinity profiles for the two stratification scenarios that cause the lowest dilution.

The conceptual design for the reverse-osmosis treatment facility is based on a system recovery of 75 percent; hence, the salinity concentration in the concentrate stream for this evaluation was estimated to be four times the concentration in the feed, i.e.

$$\frac{1}{(1-Y)} = \frac{1}{(1-0.75)} = 4$$

where Y = recovery rate as a decimal. To dilute the concentrate back to the feed concentration, a 4:1 dilution would be required.

Discharge water temperature was assumed to be equal to the average annual withdrawal ambient water temperature of 17°C (63 °F). Effluent density was calculated using the effluent salinity and temperature.

7.2 Discharge Configuration

For the outlet discharge, a pipe size is estimated based on the range of effluent flows and potential head loss within a reasonable range of exit velocities that promote mixing based on discharge momentum. For Brickyard Landing, the proposed water treatment facility is located approximately 3 miles (4.8 kilometers (km)) from the proposed discharge location (assuming the pipe is installed in existing road right-of-way) whereas for Chickahominy Riverfront Park, the facility is proposed to be generally co-located with the discharge location.

Based on an assumed acceptable headloss for each site, it is estimated that a 16-inch diameter pipe is sufficient to convey discharge flows for Brickyard Landing and a 12-inch diameter pipe is sufficient for Chickahominy Riverfront Park. It is also assumed that the effluent discharge may be pumped from the treatment plant to the outfall to maintain reasonable velocities. Refinement of the pipe size, optimization of pumping scenarios, and a hydraulic analysis for any given head constraint will be performed under future design efforts.

Two proposed discharge configurations were modeled in CORMIX:

- Single-port discharge (In-River) - CORMIX1 was the module used for the single-port discharge and required specification of the pipe size, vertical discharge angle, and horizontal

angle. The port was assumed to be located just above the river bottom and angled upward at 45 degrees to the river bottom to assist in breaking through the ambient stratification. The port was also configured to be perpendicular to the shoreline and thus perpendicular to the dominant direction of river flow or ambient velocity, which entrains flow to aid in dilution.

- Shoreline discharge - CORMIX3 was the module used for the surface or shoreline discharge and required specification of the pipe size, pipe invert, and depth of discharge. The pipe was configured to be perpendicular to the shoreline and thus perpendicular to the dominant direction of river flow or ambient velocity. Near-shore and far-shore bottom slopes and velocities are inputs. It is assumed that near-shore and far-shore velocities are the same; bottom slopes are estimated based on the detailed bathymetric data from the EFDC model.

8.0 CORMIX Results – Near-Field Salinity Impact of Discharge

Various scenarios were simulated using CORMIX for both sites with combinations of varying:

- Ambient conditions defining the river current, density, and water depth conditions at the outfall structure,
- Effluent characteristics including the density and discharge rate, and
- Discharge characteristics including the discharge orientation and dimensions.

Table 3 summarizes the variables for the twelve CORMIX simulations conducted for each in-river and shoreline discharge configuration.

Table 3 CORMIX Simulation Scenarios for Each Discharge Location and Configuration

River or Discharge Characteristic	Scenario											
	1	2	3	4	5	6	7	8	9	10	11	12
Discharge Flow = 1.3 mgd	●			●			●			●		
Discharge Flow = 2.7 mgd		●			●			●			●	
Discharge Flow = 4 mgd			●			●			●			●
10th Percentile Ambient Velocity	●	●	●	●	●	●						
90th Percentile Ambient Velocity							●	●	●	●	●	●
Maximum Vertical Salinity Difference	●	●	●				●	●	●			
Maximum Bottom Salinity				●	●	●				●	●	●

A detailed discussion of the CORMIX modeling approach and evaluation results is provided in Attachment A. A summary of the results follows.

8.1 In-River Single-Port Discharge

8.1.1 Brickyard Landing

For the in-river, single-port discharge scenarios, the CORMIX1 results indicating the distance at which a dilution of 4:1 is calculated are summarized in **Figure 7**. Case 1 to Case 6 represent dilution at low ambient velocities for two different ambient stratification profiles with incremental increases in effluent flow rate. This shows that the distance needed to achieve a dilution of 4:1 is greatest at low ambient velocity and high effluent flow, and that the difference in dilution based on varying the ambient stratification is marginal. Less distance to achieve target dilution is needed at high river current speeds as high river flows can induce more mixing.

Figure 8 presents the dilution at 10 m (33 feet) and 20 m (66 feet), respectively. For this CORMIX1 configuration, the x-direction is down river and the y-direction is cross-river. At low river current speeds, the dilution varies minimally at 10 m (33 feet), with a pattern emerging at 20 m (66 feet) with decreasing dilution as effluent flow increases. The results for low river current speeds are reported in the y- or cross-river direction. At high river current speeds, the dilution increases with an increase in effluent flow and is reported in the x- or down-river direction since high river current speeds generally induce more turbulent downstream mixing.

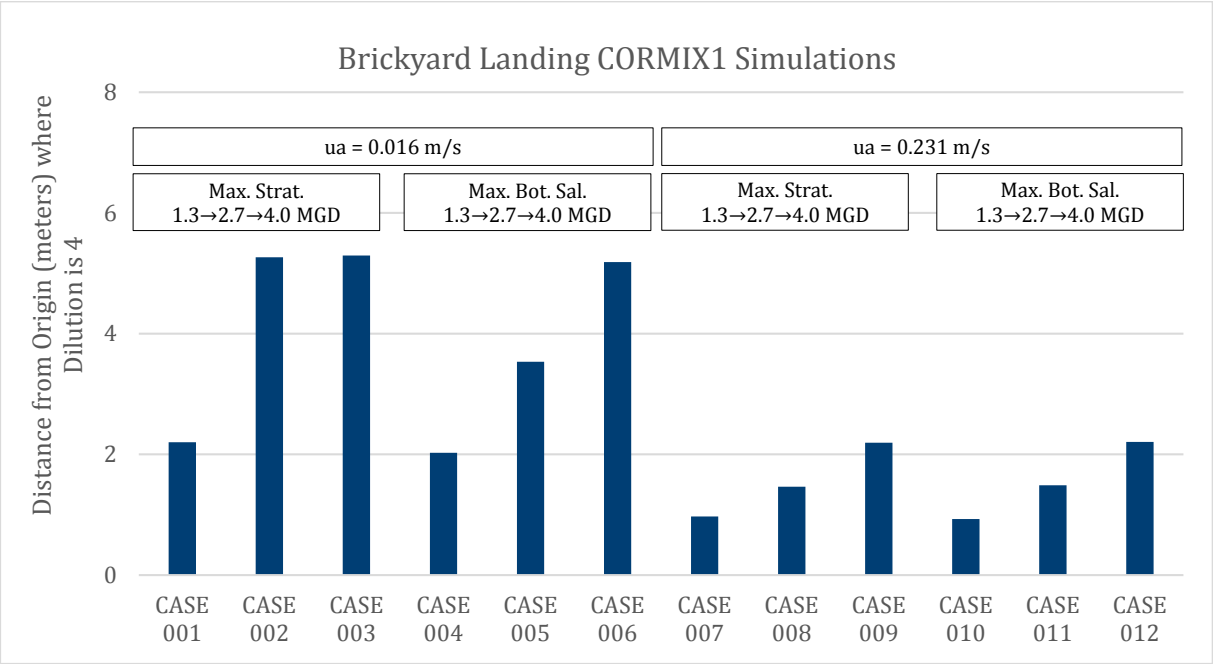


Figure 7
CORMIX1 Results for Brickyard Landing In-River Discharge – Distance from Origin (meters) where Dilution is 4 (1 m = 3.28 ft) (Distances are calculated from x-y coordinates where the dilution is 4:1)

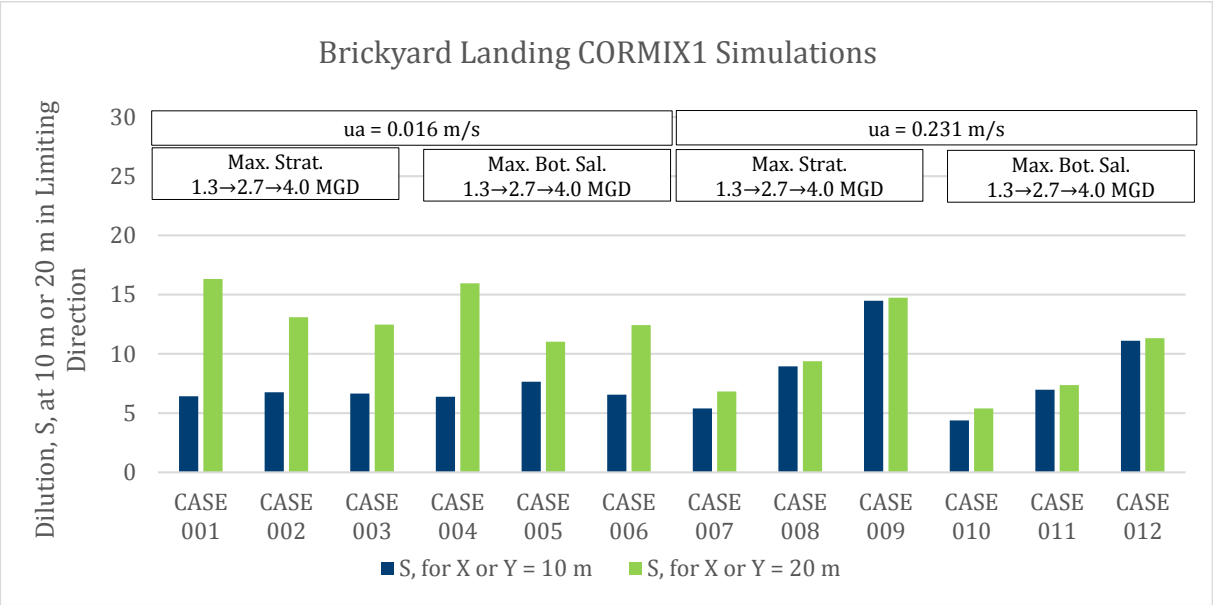


Figure 8
CORMIX1 Results for Brickyard Landing In-River Discharge – Dilution at 10 m (33 ft) or 20 m (66 ft) in Limiting Direction (Dilution is reported at 10 m and 20 m from the discharge location.)

8.1.2 Chickahominy Riverfront Park

For the in-river discharge at Chickahominy Riverfront Park, a similar pattern in dilution is observed. Low current speeds require more distance to dilute the same volume compared to high current speeds (**Figure 9**). An increase in effluent flow rates also require greater distance to dilute. The difference between the two ambient stratification scenarios are marginal, which is expected considering the similarities in ambient profile shapes. In general, compared to Brickyard Landing, Chickahominy Riverfront Park appears to have an advantage in requiring less distance to achieve the same dilution and a greater dilution potential at both 10 m (33 feet) and 20 m (66 feet) for the same cases (**Figure 10**). This is because of the available water depth and available diluting ambient volume that allows for greater dilution of the brine discharge.

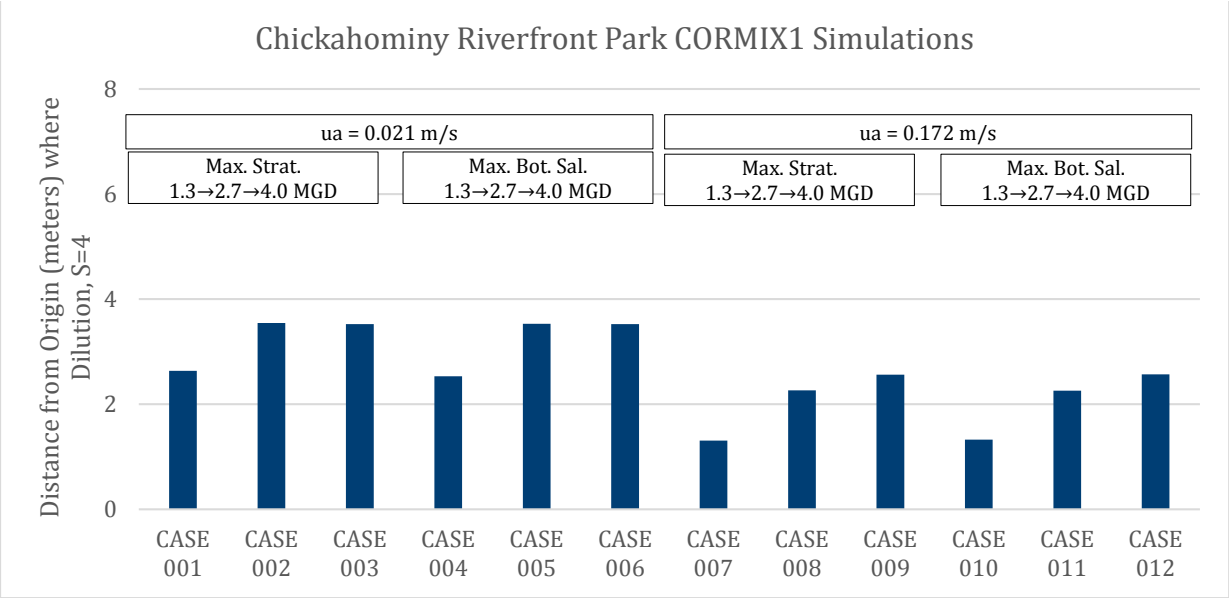


Figure 9
CORMIX1 Results for Chickahominy Riverfront Park In-River Discharge – Distance in Meters from Origin where Dilution is 4 (1 m = 3.28 ft) (Distances are calculated from x-y coordinates where the flux-averaged dilution is 4:1.)

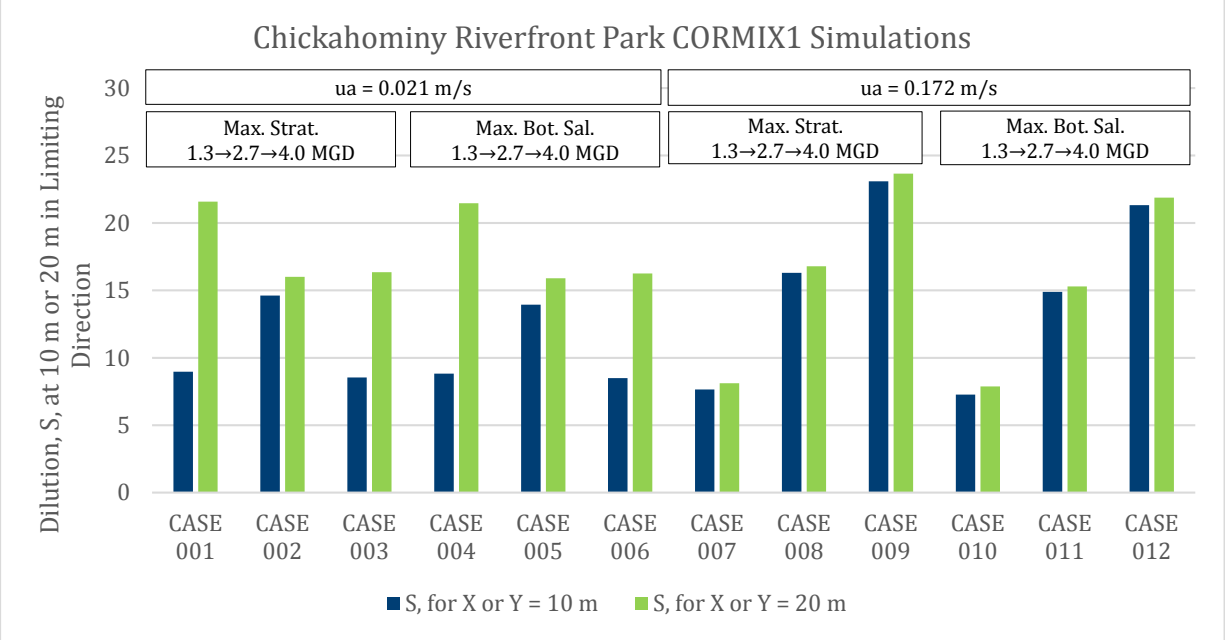


Figure 10
CORMIX1 Results for Chickahominy Riverfront Park In-River Discharge – Dilution at 10 m (33 ft) or 20 m (66 ft) in Limiting Direction (Dilution is reported at 10 m and 20 m from the discharge location.)

8.2 Shoreline Discharge

8.2.1 Brickyard Landing

For the shoreline, pipe discharge scenarios, the CORMIX3 results indicating the distance at which a dilution of 4:1 is calculated are summarized in **Figure 11**. Like the CORMIX1 in-river discharge simulations at this location, the distance required to achieve a 4:1 dilution increases with increasing effluent flows at low current speed. The distance needed to achieve a dilution of 4:1 is much greater for the shoreline simulations compared to the in-river simulations. This may be related to the location and depth of the in-river discharge compared to a shoreline discharge at shallower depths. In CORMIX1, the discharge is at-depth with the available water column to mix, whereas in CORMIX3, the discharge is limited to the local depth, determined by CORMIX based on the near-shore river slope, where dilution is dependent on mixing via buoyant spreading or density currents, and not dependent on momentum-driven mixing.

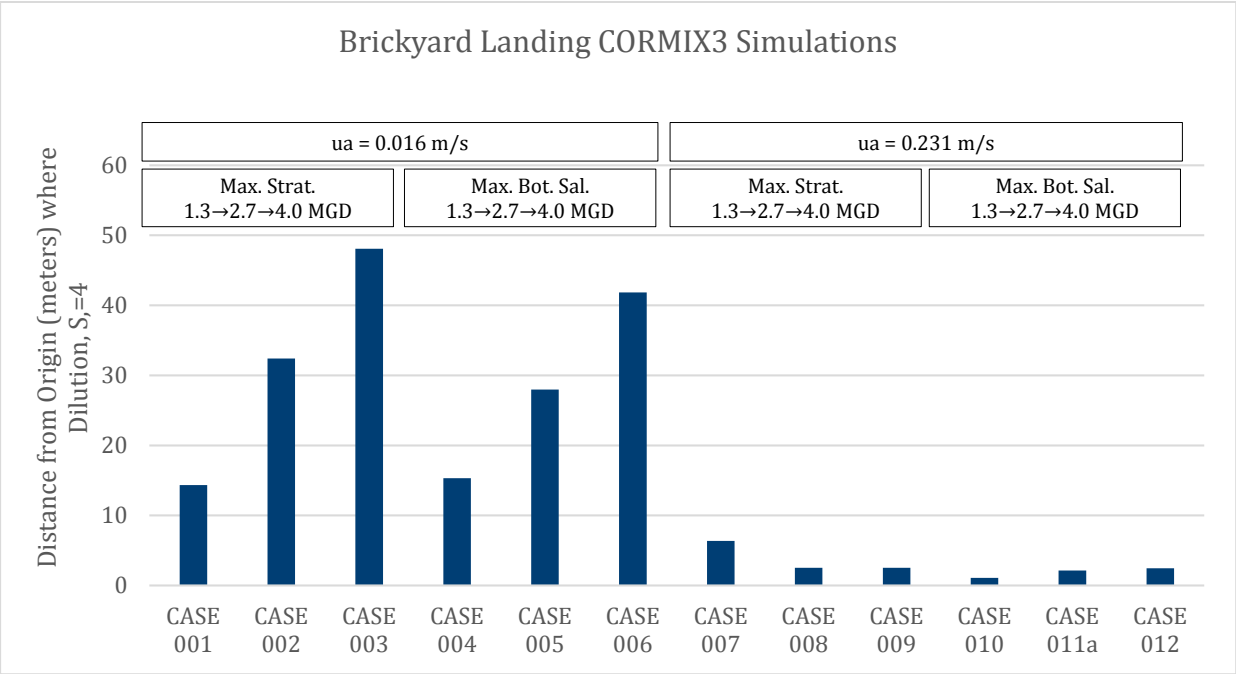


Figure 11
CORMIX3 Results for Brickyard Landing Shoreline Discharge – Distance from Origin where Dilution is 4 (Distances are calculated from x-y coordinates where the dilution is 4:1.) (1 m = 3.28 ft)

As shown in **Figure 12**, dilution decreases as effluent flow increases at low current speeds. At high current speeds, no apparent pattern emerges aside from the moderate effluent flow result being less than the low or high effluent flow scenarios. The comparison between possible dilutions for CORMIX1 and CORMIX3 demonstrate that an in-river discharge provides greater dilution potential

at depth than a shoreline discharge for what could be considered the critical case of low current speed and high effluent flow.

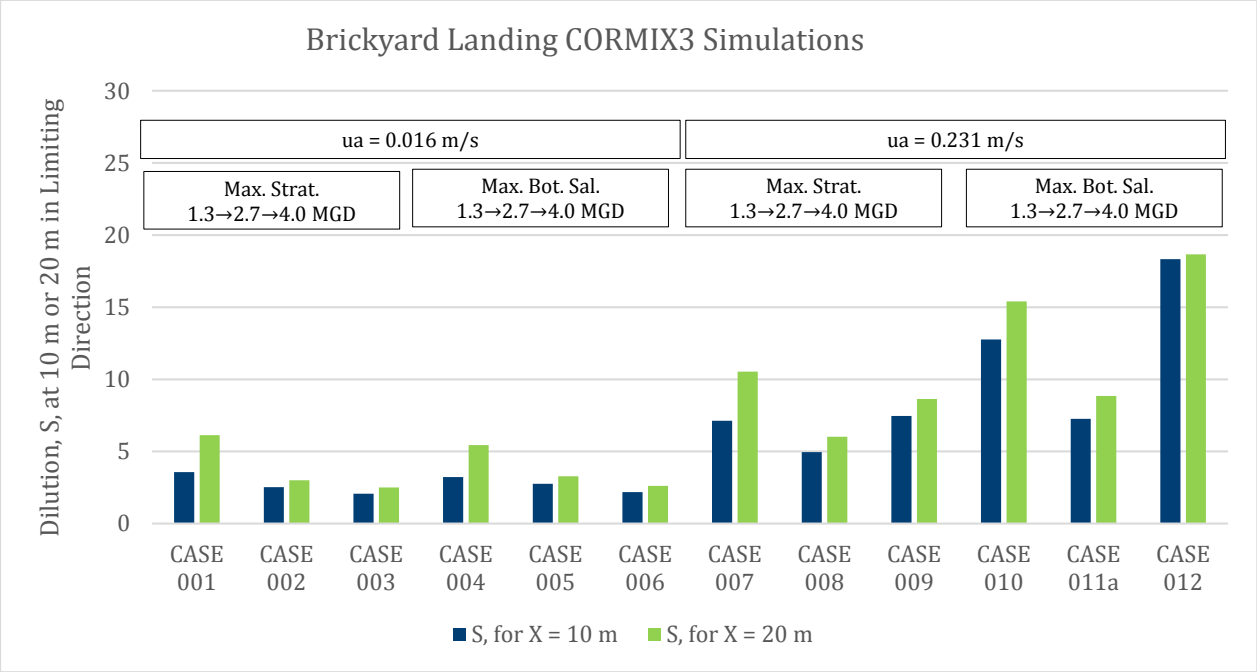


Figure 12
CORMIX3 Results for Brickyard Landing Shoreline Discharge – Dilution at 10 m (33 ft) or 20 m (66 ft) in Limiting Direction (Dilution is reported at 10 m and 20 m from the discharge location.) (1 m = 3.28 ft)

8.2.2 Chickahominy Riverfront Park

For the shoreline discharge at Chickahominy Riverfront Park, a similar pattern in dilution is observed as the Brickyard Landing shoreline discharge. Low current speeds require more distance to dilute the same effluent flow compared to high current speeds (**Figure 13**). Also, for a shoreline discharge at this location, dilution decreases as effluent flow increases (**Figure 14**).

Comparing an in-river (CORMIX1) versus a shoreline discharge (CORMIX3) at this location, greater dilution is achieved consistently for the in-river discharge, with the same reasoning as for Brickyard Landing. The discharge is at-depth with the available water column to mix, whereas the shoreline discharge is limited to the local depth, where dilution is dependent on mixing via buoyant spreading or density currents.

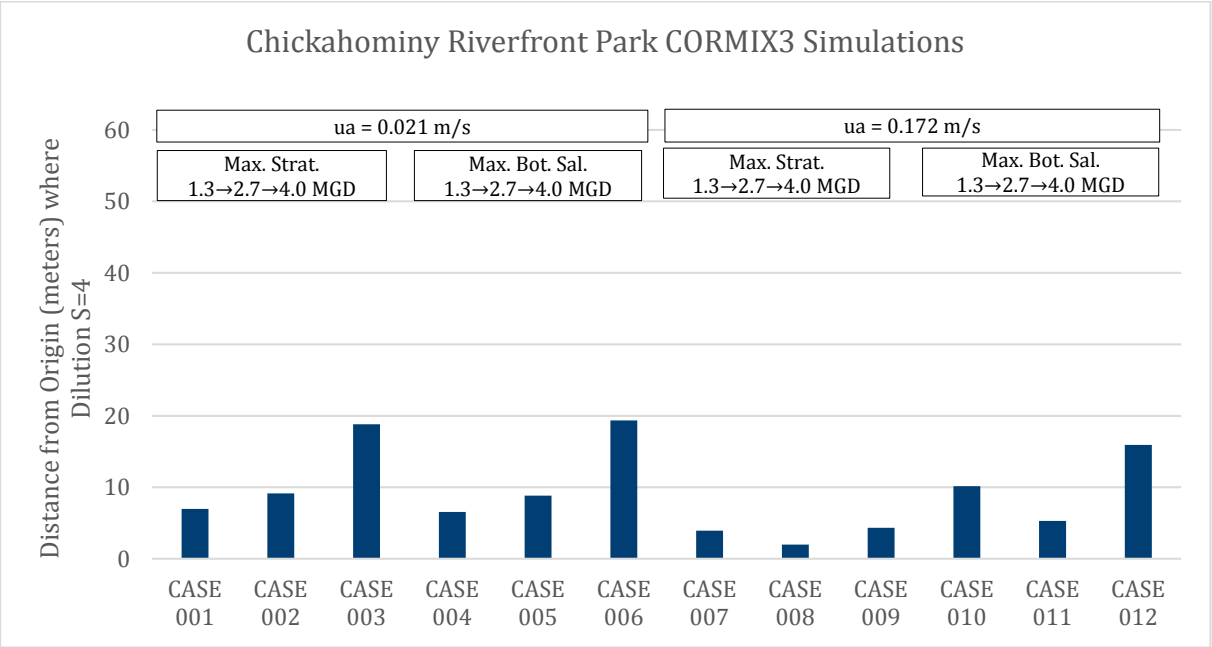


Figure 13
CORMIX3 Results for Chickahominy Riverfront Park Shoreline Discharge – Distance from Origin where Dilution is 4 (1 m = 3.28 ft) (Distances are calculated from x-y coordinates where the dilution is 4:1.)

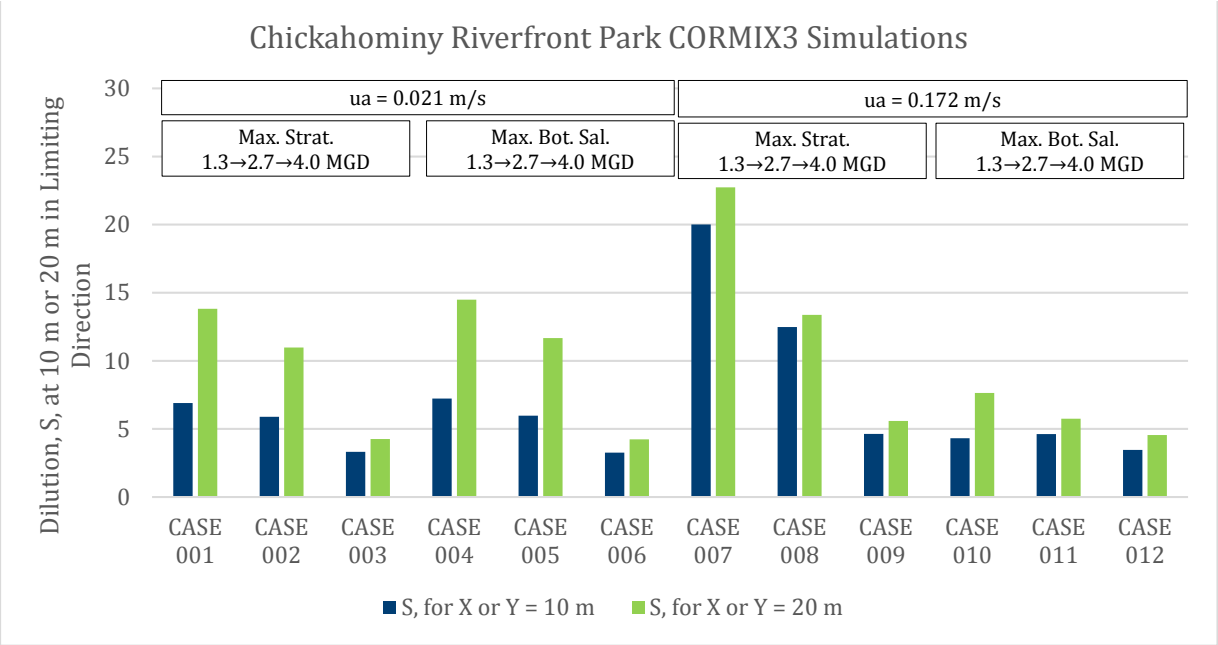
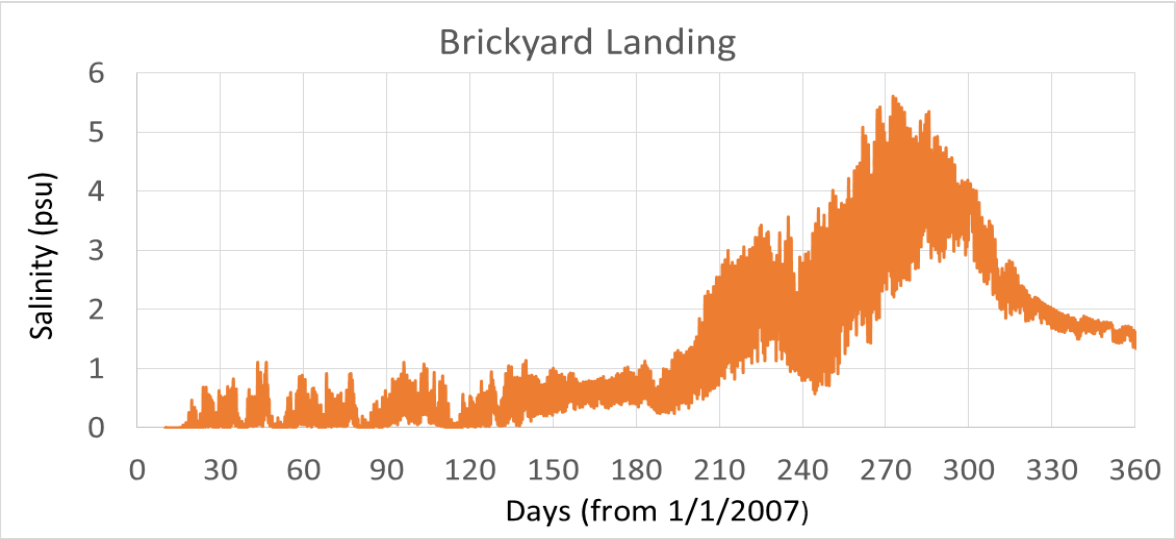


Figure 14
CORMIX3 Results for Chickahominy Riverfront Park Shoreline Discharge – Dilution at 10 m (33 ft) or 20 m (66 ft) in Limiting Direction (Dilution is reported at 10 m and 20 m from the discharge location.)

9.0 EFDC Model Results (Far-Field Salinity Impact of Withdrawal and Discharge)

In contrast to the CORMIX model which provides steady-state results of the near-field conditions, the EFDC model simulates time-varying far-field conditions that consider tidal effects. The impact of the withdrawal and the discharge was simulated simultaneously by the EFDC model. The salinity concentration at the withdrawal location for 2007 is shown in **Figure 15**. The salinity ranges from 0 to 6 practical salinity units (psu) at Brickyard Landing and 0 to 8 psu at Chickahominy Riverfront Park.



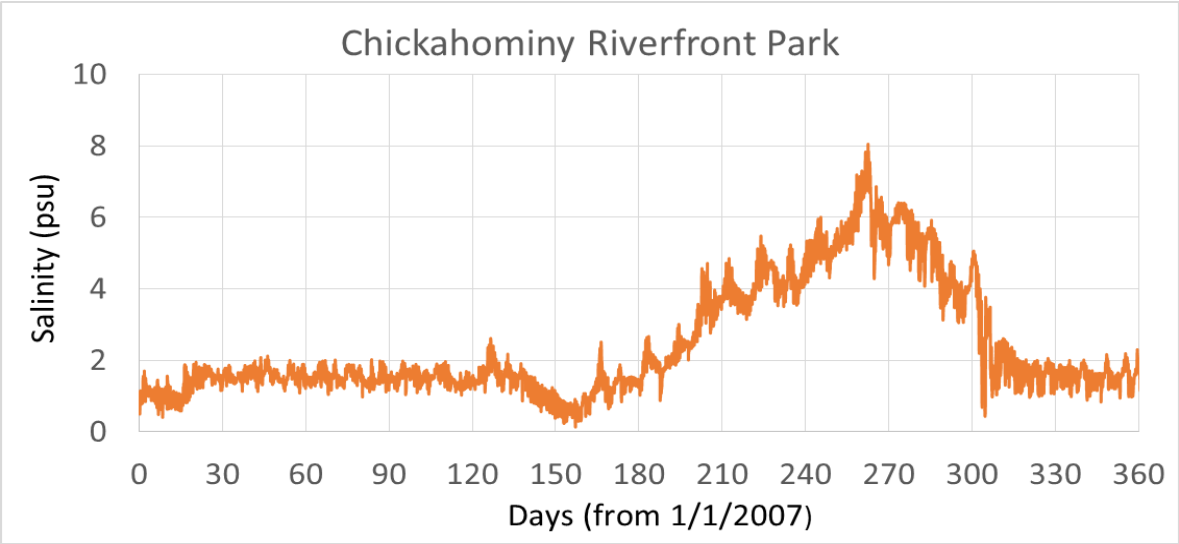


Figure 15
Salinity Concentration at Withdrawal Location (psu = practical salinity unit)

For conservative purposes, the EFDC model focused on the shoreline discharge since the CORMIX results indicate an in-river discharge provides more dilution than a shoreline discharge,

VIMS indicated that the initial simulations show that the lowest withdrawal (6 mgd) and discharge (1.3 mgd) scenario resulted in minor salinity changes; hence, the results were presented for the 12-mgd withdrawal (2.7-mgd discharge) and 18-mgd withdrawal (4-mgd discharge) scenarios. A detailed discussion of the EFDC modeling approach and evaluation results is provided in Attachment B. A summary of the results follows.

9.1 Brickyard Landing

The EFDC model simulation results of the Brickyard Landing withdrawal site for the 12-mgd withdrawal and 2.7 mgd discharge scenario indicate that the largest difference in salinity near the withdrawal location is less than 0.3 psu in comparison to the 6.0 psu variation in salinity for 2007. Water that is pumped out of the river is quickly replaced by upstream or downstream water, depending on the tide. The salinity can increase during flood tide and decrease during ebb tide. A slight increase in salinity was observed for most of the simulation period.

The EFDC model simulation results at the discharge site for the 12-mgd withdrawal and 2.7 mgd discharge scenario indicate that salinity increased approximately 1.2 psu which is about 19 percent of the maximum salinity. Since the discharge flow is approximately 22 percent of the withdrawal, the increase in salinity is not very significant due to the strong tidal effect at this location. Dilution caused by the tide reduces the impact of the brine concentrate discharge.

For the high flow, low salinity simulation, the EFDC model simulation results indicate that the salinity increases slightly during flood tide, but decreases during ebb tide; there is a slight migration upstream at different phases of the tide. In a low flow, high salinity simulation, the salinity intrusion upstream of the withdrawal decreases, but increases slightly at the discharge site at the bottom. As briny water is removed from the channel during the low flow period, the density changes and a rebalance of the pressure gradient results in a decrease of upstream salt water intrusion.

The results for the highest flow case scenario (18-mgd withdrawal and 4.0-mgd discharge) are similar to the 12-mgd withdrawal (2.7-mgd discharge) scenario and are included in Attachment B. The salinity increase at the withdrawal location is approximately 0.4 psu. The maximum salinity at the discharge site is approximately 1.7 psu which is approximately 28 percent of the maximum salinity during the low flow period.

9.2 Chickahominy Riverfront Park

The EFDC model simulation results of the Chickahominy Riverfront Park withdrawal site for the 12-mgd withdrawal and 2.7 mgd discharge scenario indicate that the largest difference in salinity near the withdrawal location is approximately 0.3 psu in comparison to the 8.0 psu variation in salinity for 2007. The salinity increases approximately 1.6 psu at the discharge site at the bottom during a

low flow period which is about 18 percent of the maximum salinity. The salinity distribution change is larger during low flow periods than high flow periods and is dependent on the tide. Because of the large water volume in the lower estuary and large tide mixing, the changes in salinity are insignificant.

The results for the highest flow case scenario (18-mgd withdrawal and 4.0-mgd discharge) are similar to the 12-mgd withdrawal (2.7-mgd discharge) scenario and are included in Attachment B. The salinity increase at the withdrawal location is approximately 0.3 psu. The maximum salinity change at the discharge location is approximately 2.03 psu.

10.0 Summary of Conclusions

10.1 CORMIX Model Results (Near-Field)

The CORMIX model results demonstrate that an in-river discharge provides more potential dilution at the critical case (low current speed, high effluent flow) compared to a shoreline discharge. For other similar comparison cases during high current speed and high effluent flow, the difference between the two configurations are less drastic. In comparison of the two sites for an in-river discharge, it appears that the Chickahominy Riverfront Park will allow for greater dilution at some distance from the discharge compared to the Brickyard Landing site. This is likely because of the greater depth and width of the Chickahominy River at the Chickahominy Riverfront Park site, allowing for more volume to dilute the effluent.

The CORMIX modeling effort is a preliminary evaluation based on a conceptual design, therefore, the results herein are preliminary based on the assumptions. In addition, it is likely that a multi-port diffuser will be required to discharge the effluent into the river based on the DEQ regulations. As such, additional analysis and initial dilution modeling may be required during the preliminary and final design phase of the water treatment facility.

10.2 EFDC Model Results (Far-Field)

Based on historical data, the salinity ranges from 0 to 6 psu at Brickyard Landing and 0 to 8 psu at Chickahominy Riverfront Park. The EFDC model results indicate that the largest difference in salinity is less than 0.4 psu for the Brickyard Landing withdrawal which is minor in comparison to the 6-psu historical salinity variation. The Chickahominy Riverfront Park withdrawal resulted in a maximum salinity change of 0.3 psu which is also minor in comparison to the 8-psu historical salinity variation.

The EFDC model results indicate that the Brickyard Landing 2.7 and 4.0-mgd discharge increased the salinity about 1.2 and 1.7 psu, respectively. The Chickahominy Riverfront Park discharge increased the bottom salinity approximately 1.6 psu for the 2.7-mgd discharge (about 18 percent of the maximum salinity) and about 2.0 psu for the 4.0-mgd discharge (about 23 percent of the maximum salinity). Dilution caused by the tide reduces the impact of discharge of briny water.

The EFDC salinity contour results show minor changes in the salinity distribution gradient with salinity changes dependent on the tide. Salinity increases slightly during flood tide, but decreases during ebb tide.

Attachments

Attachment A – Chickahominy River Salinity Impact CORMIX Model Evaluation Results
Attachment B – Chickahominy River Salinity Impact EFDC Model Evaluation Results

Attachment A
CORMIX
Model Results

CORMIX Model Results for Brickyard Landing and Chickahominy Riverfront Park Reverse-Osmosis Water Treatment Facility Brine Concentrate Discharge

James City Service Authority

Date: November 2016

CDM Smith

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Section 1
Introduction

1.1 Purpose

The Virginia Department of Game and Inland Fisheries (DGIF) requested spatial and temporal modeling of the salinity changes resulting from the proposed raw water intake and reverse osmosis (RO) brine discharge to help assess the potential for the impact on instream habitat and resident aquatic species. Based on discussion between the James City Service Authority (JCSA), CDM Smith, the Virginia Department of Environmental Quality (DEQ), and the Virginia Institute of Marine Science (VIMS), a two-part approach is being used to determine the potential impact of the withdrawal and brine discharge on the salinity gradient:

1. An initial mixing zone model, Cornell Mixing Zone Expert System (CORMIX), is used to determine the characteristics of near-field mixing of the brine discharge with the receiving water.

2. An existing three-dimensional (3D) hydrodynamic model, Environmental Fluid Dynamics Code (EFDC), of the Chickahominy and James Rivers is used both to provide inputs on existing conditions to the CORMIX model and to examine far-field effects of the changes in salinity due to both the withdrawal and the discharge.

Findings from both models will be included in the Joint Permit Application (JPA) for the Chickahominy River raw water intake. This draft report presents the preliminary initial dilution modeling using CORMIX of a conceptual RO brine concentrate at two candidate discharge locations in the Chickahominy River: Brickyard Landing and Chickahominy Riverfront Park. The intent of these simulations is to provide an initial understanding of the dilution potential in the river and to allow for a comparison of the alternative discharge locations and configurations. A refined hydraulic design and discharge configuration of the outlet will occur in a future design stage.

1.2 Project Background

The conceptual raw water intake withdrawal and brine concentrate discharge are located in the Chickahominy River at two alternative sites: Brickyard Landing and Chickahominy Riverfront Park (**Figure 1**). The Chickahominy River is a tidal tributary to the James River and Chesapeake Bay. The upstream tidal effect on the Chickahominy River extends to Walker's Dam, a low-head impoundment of Chickahominy River, located 22 river miles upstream of the confluence of the Chickahominy and James Rivers.

The Chickahominy Riverfront Park intake location was identified in the *Water Supply Study Final Draft Report* prepared by CDM Smith dated April 2015. The Brickyard Landing intake location was identified in the *Chickahominy River Brickyard Landing Raw Water Supply Feasibility Study Report* prepared by CDM Smith dated March 2016. For both intake locations in the Chickahominy River, two discharge configurations are simulated and evaluated: an in-river discharge at depth and a surface discharge at the shoreline.

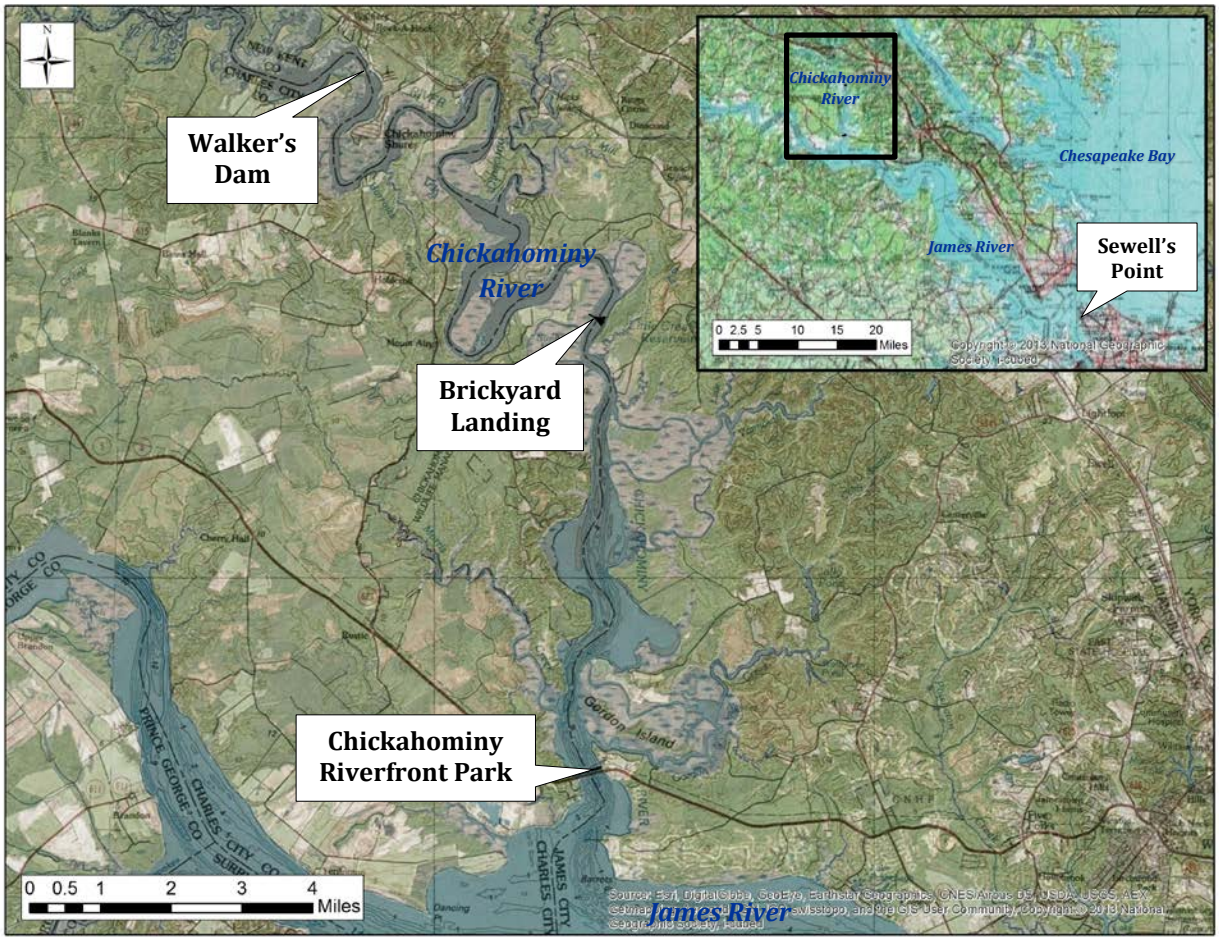

Figure 1 – Site Location Map.

1.3 Virginia DEQ Mixing Zone Regulations

The current DEQ regulations for mixing zones state the following:

The board may use mixing zone concepts in evaluating limitations for Virginia Pollutant Discharge Elimination System permits.

1. *Mixing zones evaluated or established by the board in open ocean, estuarine, and transition zone waters shall not:*

    a. *Prevent movement of or cause lethality to passing and drifting aquatic organisms through the water body in question.*

    b. *Extend more than five times in any direction the average depth along a line extending 1/3 of the way across the receiving water from the discharge point to the opposite shore.*

2. *A subsurface diffuser shall be required for any new or expanded freshwater discharge greater than or equal to 0.5 MGD to open ocean, estuarine and transition zone waters and the acute*

and chronic criteria shall be met at the edge of the zone of initial mixing. The zone of initial mixing is the area where mixing of ambient water and effluent is driven by the jet effect and/or momentum of the effluent. Beyond this zone, the mixing is driven by ambient turbulence.

1.4 Modeling Software

1.4.1 EFDC Model provides Inputs for CORMIX

Recently, VIMS developed a 3D hydrodynamic model in EFDC that simulates water surface elevation, current speed and direction, water salinity, and temperature for the Chickahominy and James rivers. The Chickahominy River model was developed to determine the impact of sea level rise on drinking water supplies and has 1,158 horizontal grid cells with eight vertical layers.

An initial long-term simulation of the EFDC model was conducted for 2007, a year with relatively low mean flow upstream of the Chickahominy River. Hourly temperature, salinity, and ambient velocity results for the eight vertical model layers of the EFDC model are used to develop inputs for the CORMIX model.

1.4.2 CORMIX Model

The U.S. Environmental Protection Agency (USEPA) program, CORMIX, is a software system used for the analysis, prediction, and design of discharges into diverse water bodies. Use of the program helps to determine the dilution that can be expected from a given outfall configuration, discharge characteristics, and receiving water characteristics. CORMIX offers different computational modules for various discharge configurations. In this study, CORMIX1 is used to analyze the submerged single-port, single-pipe discharge, and CORMIX3 is used to analyze the surface/shoreline discharge module. CORMIX can simulate brine discharges, which are expected to have discharge densities greater than the ambient environments into which they discharge. For surface/shoreline discharges, dense discharge sources must always be specified as a brine effluent type. CORMIX typically standardizes inputs and outputs using the SI system, consequently discussion herein will be reported in metric units.

1.5 Model Input Assumptions

The CORMIX simulations provide an initial understanding of the dilution potential in the river and to compare alternative discharge locations and configurations. A total of 48 CORMIX model scenarios are simulated to characterize the dilution potential for a range of ambient and discharge conditions at two sites with two discharge configurations for four receiving water scenarios and three discharge rates.

As part of the raw water supply feasibility study, pre-application meeting, and additional coordination, the conceptual design was based on the following assumptions:

- Three raw water intake scenarios are evaluated with withdrawal flow rates of 6, 12, and 18 mgd (0.26, 0.53, 0.79 m^3/s) and corresponding concentrate discharges of 1.3, 2.7, and 4 mgd (0.06, 0.12, 0.18 m^3/s), respectively.
- Based on the flow ratio of the withdrawal to the discharge, the brine concentrate is discharged at four times the salinity concentration of the ambient withdrawal.

- The discharge water temperature is equal to the withdrawal temperature.
- For the in-river configuration, a submerged single pipe is directed towards the center of the river with a port pointing upward at an angle from the river bottom. For the shoreline configuration, a single pipe outfall is fully submerged and discharged from the shoreline.

The CORMIX model inputs are discussed in the following sections:

- **Ambient conditions (Section 2)** defining the river current speed, water depth, and vertical density profile at the outfall structure
- **Effluent characteristics (Section 3),** including the discharge density and discharge rate
- **Discharge characteristics (Section 4),** including the outfall dimensions and orientation

The model results from CORMIX are discussed in **Section 5**.

Section 2

Ambient Conditions in the Chickahominy River

Candidate intake and discharge locations are located on the Chickahominy River. Ambient river conditions that affect the mixing zone analysis include river current speed, salinity and water temperature, vertical density profile, and water depth. The current speed and density data influence the mixing and movement of the discharge plume in the river.

2.1 River Current Speed

Simulated depth-averaged, maximum daily ambient velocity during ebb and flood tides are obtained from EFDC model simulations at locations near Brickyard Landing and Chickahominy Riverfront Park. A representative timeseries of the model results are shown in **Figure 2**. The observed water level at the long-term National Oceanic and Atmospheric Administration (NOAA) tide gage at Sewell's Point (shown in Figure 1) is shown to demonstrate how the EFDC model represents current speed relative to tidal stage. Different ambient current velocities reflecting different parts of the tidal cycle are evaluated in the CORMIX simulations. Summary statistics of ambient velocity for 2007 are summarized in **Table 2-1**.

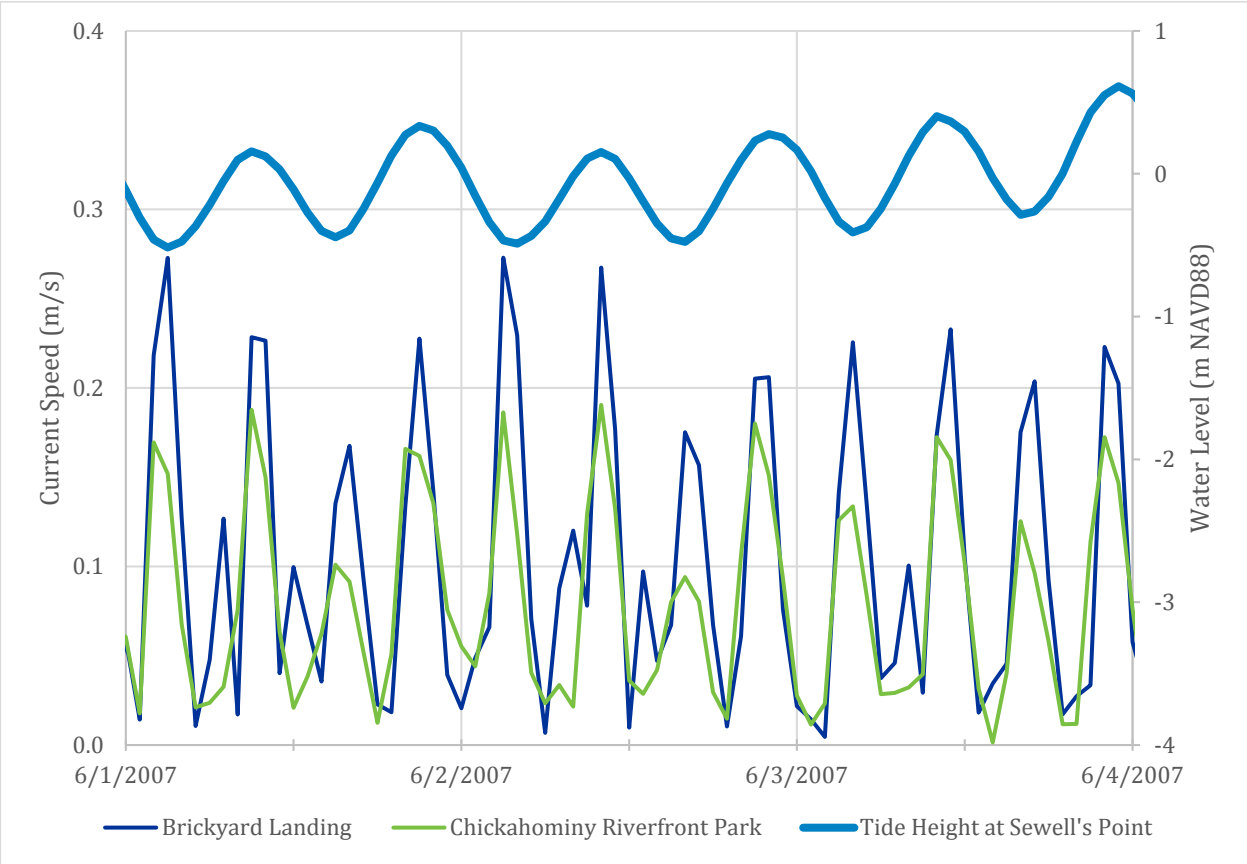

Figure 2 – Simulated current speed at the proposed sites from EFDC and observed water levels from the NOAA tide gage at Sewell's Point.

Table 2-1 Summary of Current Speed Statistics

EFDC Model Node/Site	Minimum Current Speed (m/s)	10th Percentile Current Speed (m/s)	Mean Current Speed (m/s)	90th Percentile Current Speed (m/s)	Maximum Current Speed (m/s)
Node 18 Brickyard Landing	0.0	0.016	0.104	0.231	0.365
Node 23 Chickahominy Riverfront Park	0.0	0.021	0.085	0.172	0.271

The lower 10th percentile and higher 90th percentile current speed represent a reasonable range of low and high ambient velocities; these are used as inputs to CORMIX. Low current speeds typically yield a more critical dilution scenario than higher current speeds.

2.2 River Geometry

Bathymetry data were obtained from two sources:

- **Brickyard Landing** - The water depth from the EFDC model for the Chickahominy River was provided by VIMS and is based on a vertical datum of mean sea level. The average spacing between the bathymetry data points is coarse at approximately 75 m, therefore, a digital raster elevation dataset was interpolated at 10 m spacing for Brickyard Landing in both plan and profile view (**Figure 3**). The approximate width of the Chickahominy River at this location is 390 m with a maximum water depth of approximately 5.3 m.

- **Chickahominy Riverfront Park** - Because bathymetric data from the EFDC model are limited at Chickahominy Riverfront Park, a single Chesapeake Bay bathymetric dataset was obtained from the Chesapeake Community Modeling Program (using different sources of bathymetric data from NOAA, the Maryland Geological Survey, and Old Dominion University) referenced to a vertical datum of mean sea level. The data are converted to a raster dataset and resampled to develop a detailed depth profile at 10 m spacing (**Figure 4**). The approximate width of the Chickahominy River at this location is 660 m with a maximum water depth of approximately 10.2 m.

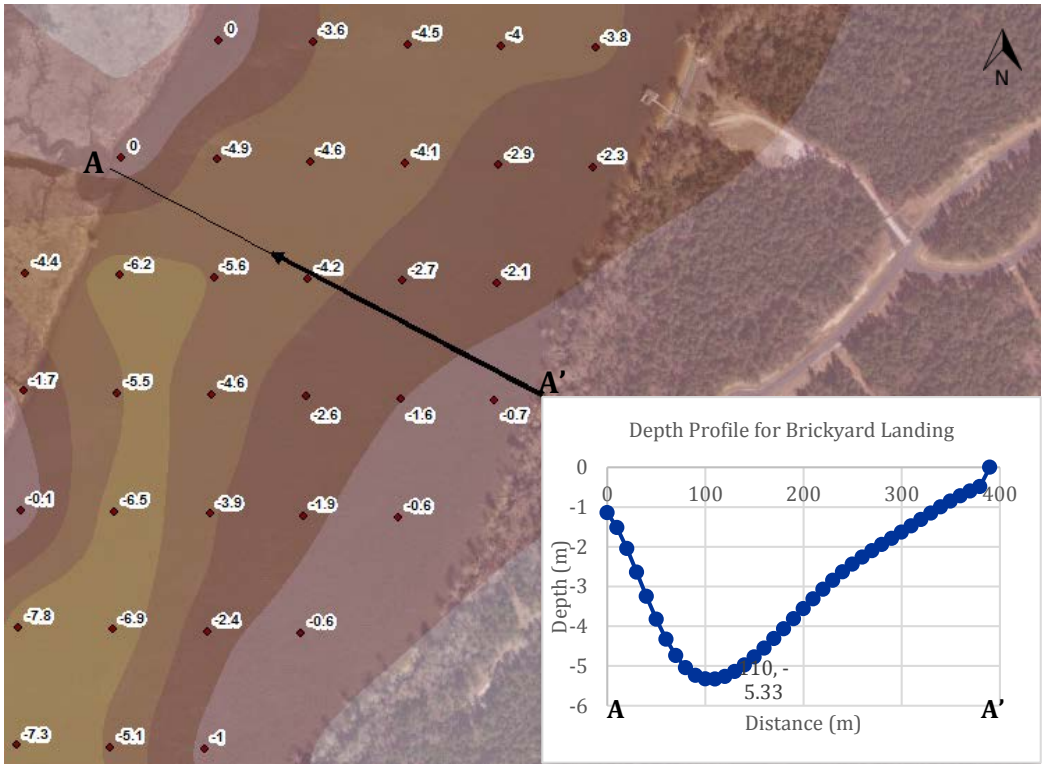

Figure 3 – Bathymetric data at Brickyard Landing. The discharge location (black arrow) is approximate for this stage of preliminary conceptual design.

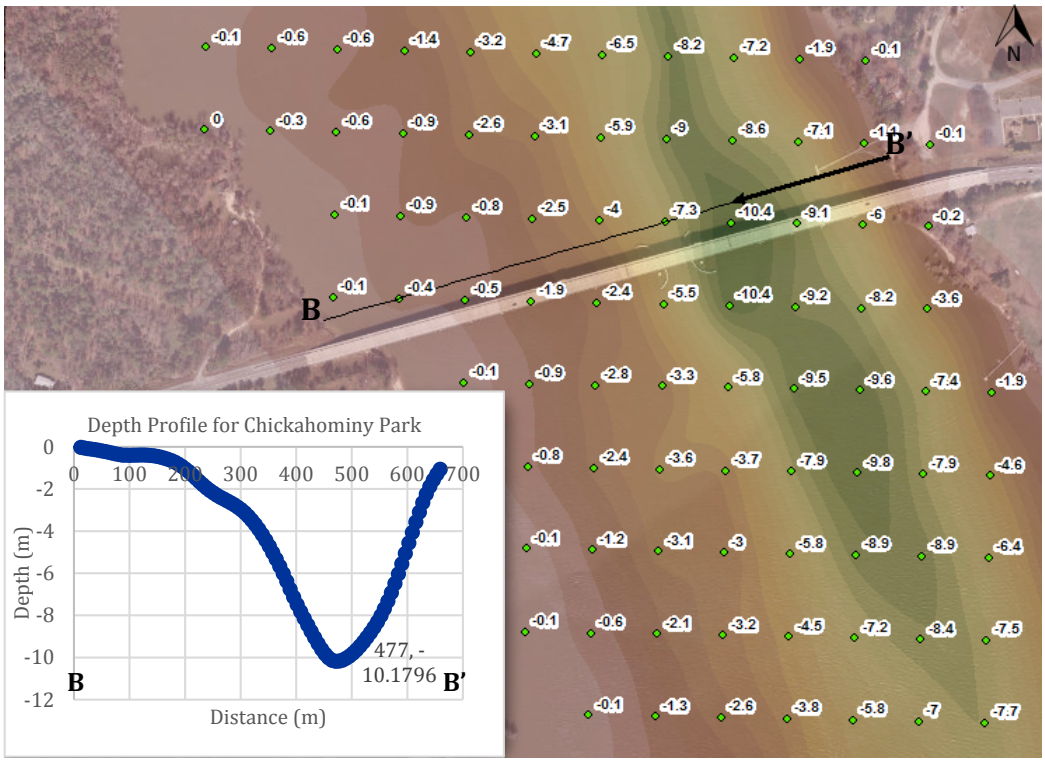

Figure 4 - Bathymetric data for Chickahominy Riverfront Park. The discharge location (black arrow) is approximate for this stage of preliminary conceptual design.

2.3 Ambient Water Temperature

Simulated daily ambient water temperature for all vertical layers is obtained from the EFDC model near Brickyard Landing and Chickahominy Riverfront Park. An example timeseries of ambient surface and bottom layer temperatures at both locations is shown in **Figure 5**; the figure shows the seasonal variation in temperature and marginal differences between surface and bottom layers. The maximum vertical difference between the surface and bottom layer temperature is quite small, at only 0.9 and 1.5°C for Chickahominy Riverfront Park and Brickyard Landing, respectively. Since vertical differences in salinity dominate the difference in ambient density, an average temperature of 17°C is used at both sites for CORMIX simulations.

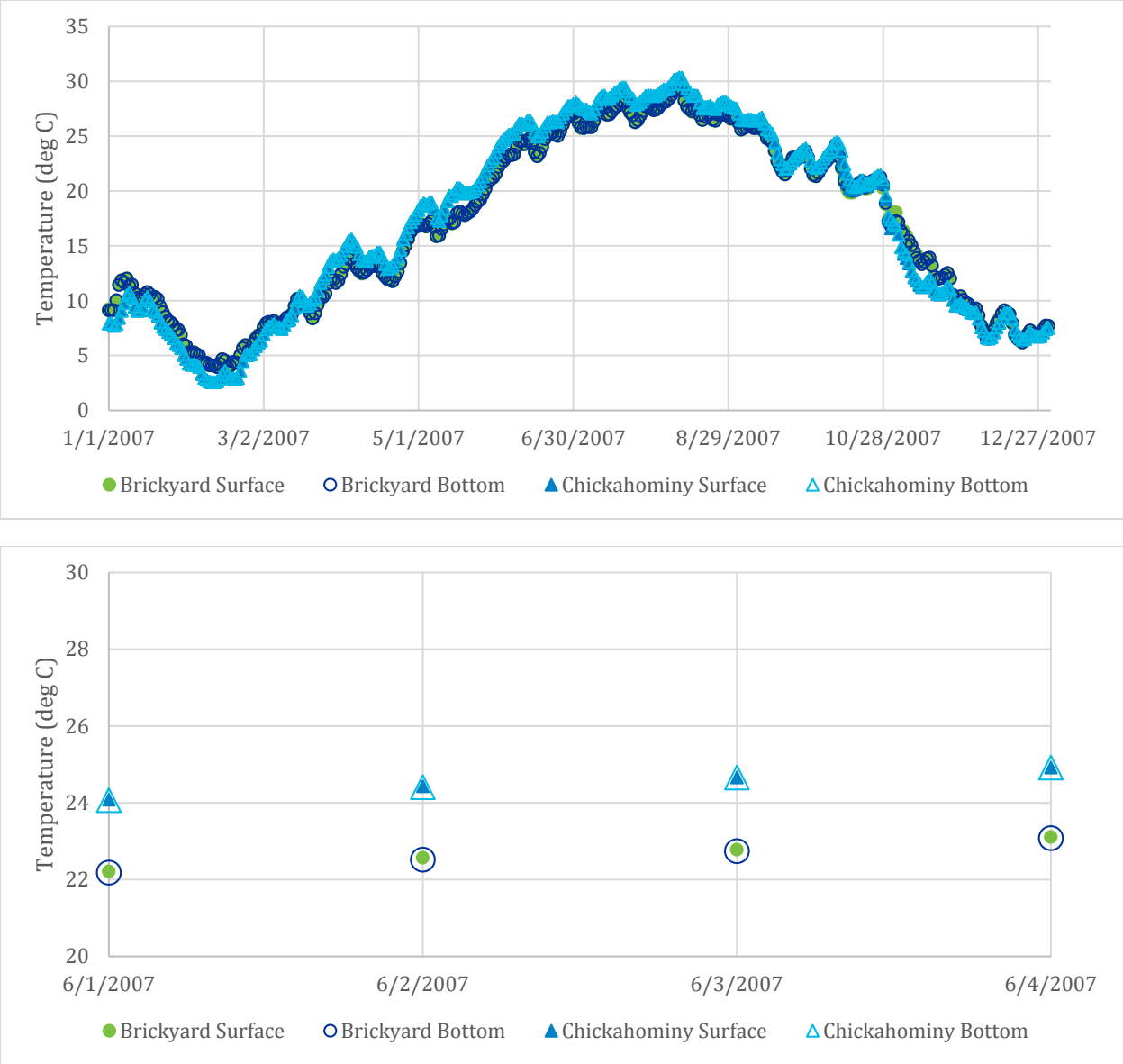

Figure 5 - Simulated surface and bottom temperatures from EFDC at Brickyard Landing and Chickahominy Riverfront Park for 2007 (top) and a representative time period (bottom). Small differences between the surface and bottom temperature are observed.

2.4 Ambient Salinity

Simulated hourly ambient salinity for all vertical layers is obtained from the EFDC model near Brickyard Landing and Chickahominy Riverfront Park. An example timeseries of simulated ambient surface and bottom layer salinities is shown in **Figure 6** for Brickyard Landing to demonstrate the difference in seasonal salinity signal and magnitude for 2007, a year with relatively low mean flow upstream of the Chickahominy River representing high salinities in autumn. Similar patterns in salinity were simulated at the Chickahominy Riverfront Park. During the early summer months, an increase in salinity is observed at a continuous monitoring station (CHK015.12) at Chickahominy Haven[1] located approximately 4 miles upstream of Brickyard Landing (**Figure 7**). The measurements are part of the VIMS Virginia Estuarine and Coastal Observing System (VECOS). This is caused by a seasonal decrease in runoff in the Chickahominy River and thus allows for the salinity wedge to intrude upstream past Brickyard Landing. As shown in Figure 7 for 2007, there were relatively high salinities observed because of the relatively low autumn flows.

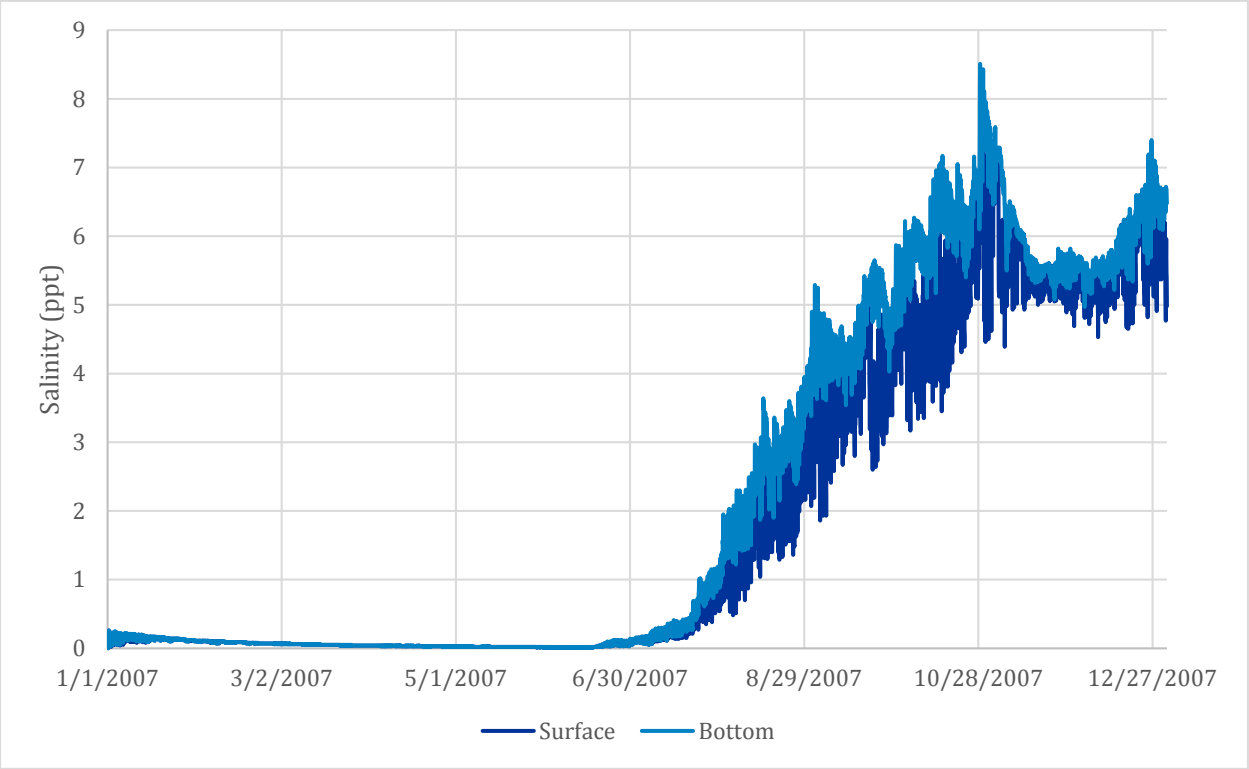

Figure 6 - Simulated surface and bottom salinities at Brickyard Landing from EFDC for simulation year 2007

[1] http://web2.vims.edu/vecos/StationDetail.aspx?param=CHK015.12&program=CMON

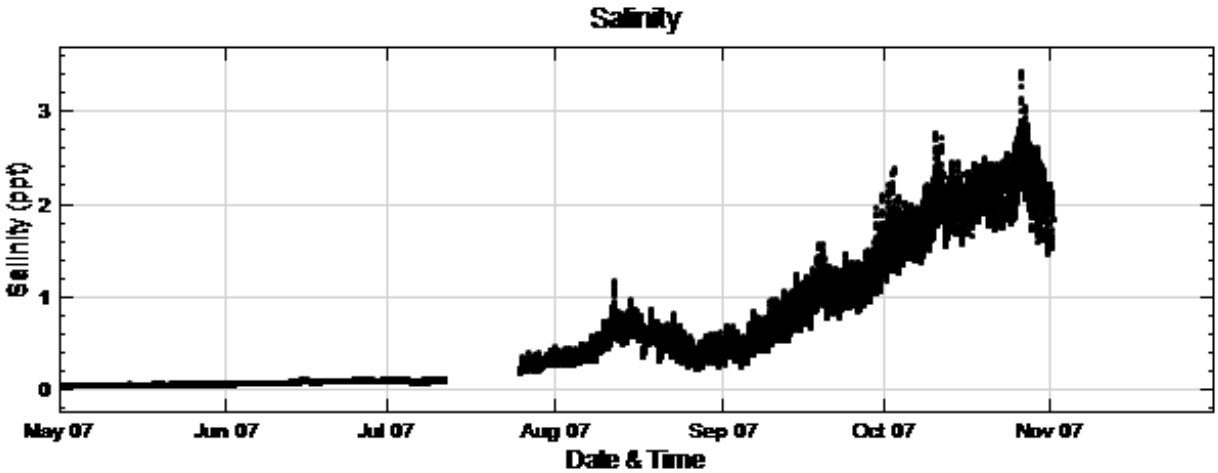

Figure 7 – Observed salinity at the Chickahominy Haven continuous monitoring station between May-November 2007 (VIMS VECOS, 2007). Chickahominy Haven is located 4 miles upstream of Brickyard Landing.

The vertical stratification in the ambient water body is important for prediction of effluent discharge plume behavior. A subset of the simulated hourly vertical salinity profiles from the EFDC model are plotted in **Figure 8** and is shown only for demonstration at Brickyard Landing. Profiles were tested in a series of CORMIX sensitivity simulations to identify and evaluate the most likely stratification profile to produce a low dilution. All other model inputs, including ambient temperature, are held constant. The following stratification profiles were tested:

- Greatest difference between the surface and bottom salinities
- Highest river bottom salinities
- Highest river surface salinities
- Profiles that have the highest vertically-averaged salinity

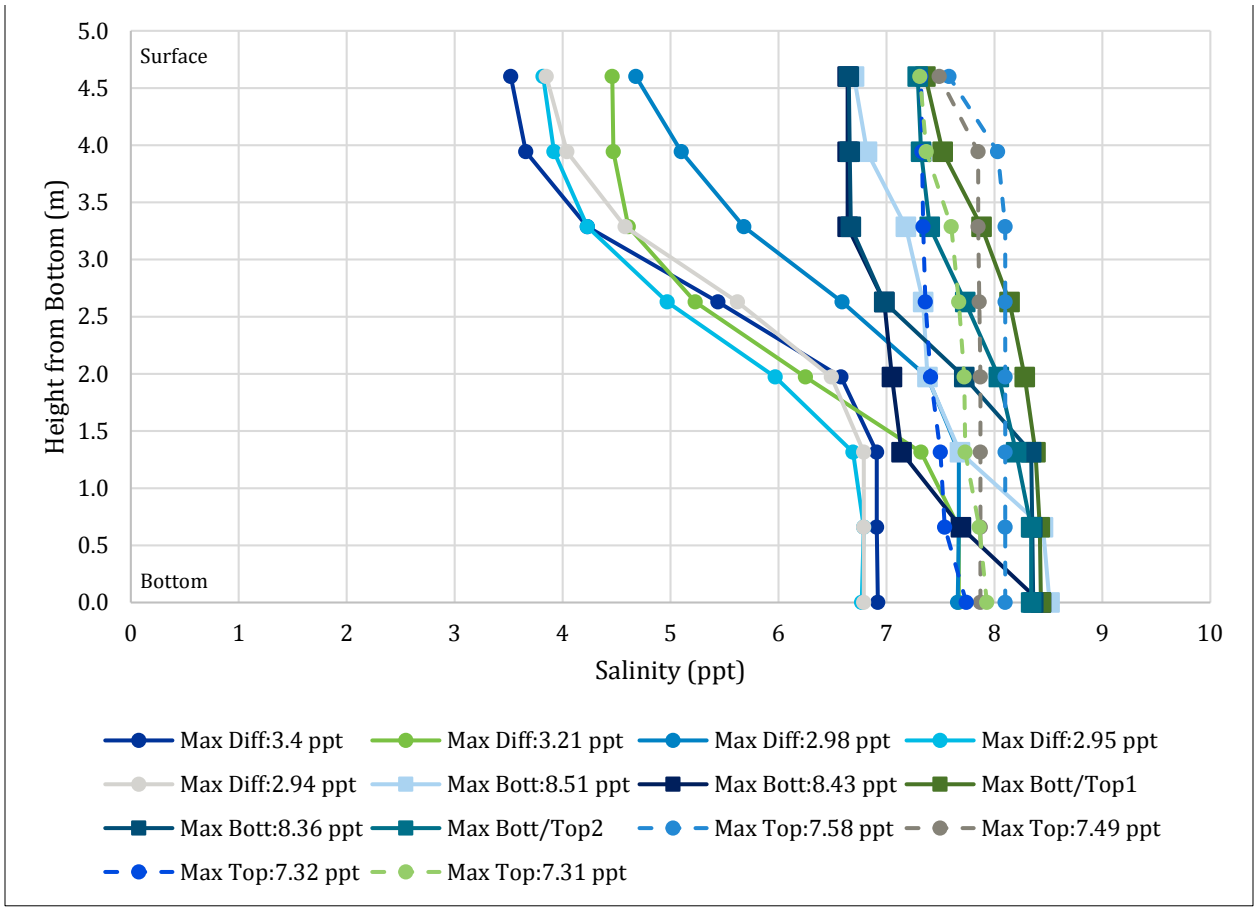

Figure 8 – Subset of EFDC salinity stratification profiles at Brickyard Landing

It was determined from the sensitivity simulations that the stratification profiles that cause the lowest dilutions are typically the profiles with the greatest difference between surface and bottom salinities and the profiles with the highest bottom salinity.

Ambient stratification can be approximated in CORMIX by using a three-layer density profile appropriate for coastal brine effluent types as shown in **Figure 9** and **Figure 10** for Brickyard Landing and Chickahominy Riverfront Park, respectively.

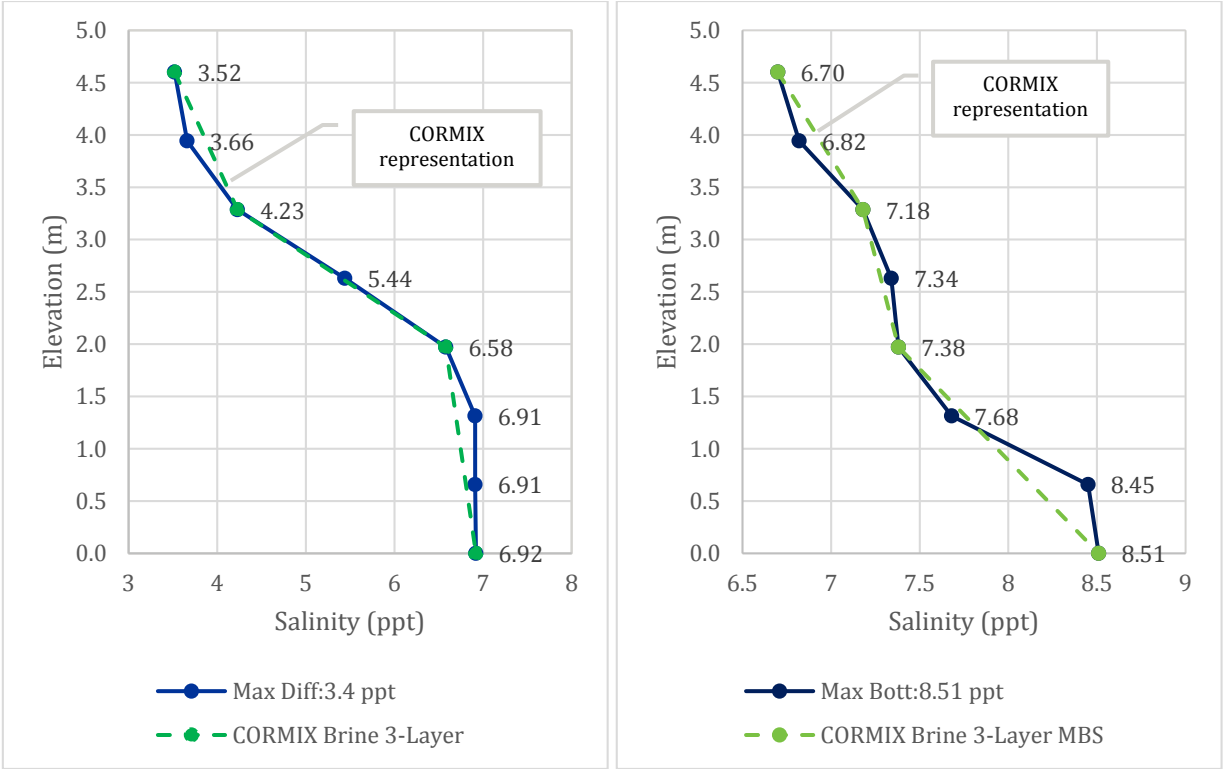

Figure 9 – The ambient stratification profiles for Brickyard Landing representing the maximum difference between top and bottom salinities (left) and maximum bottom salinity (right). Dashed lines are the CORMIX representations.

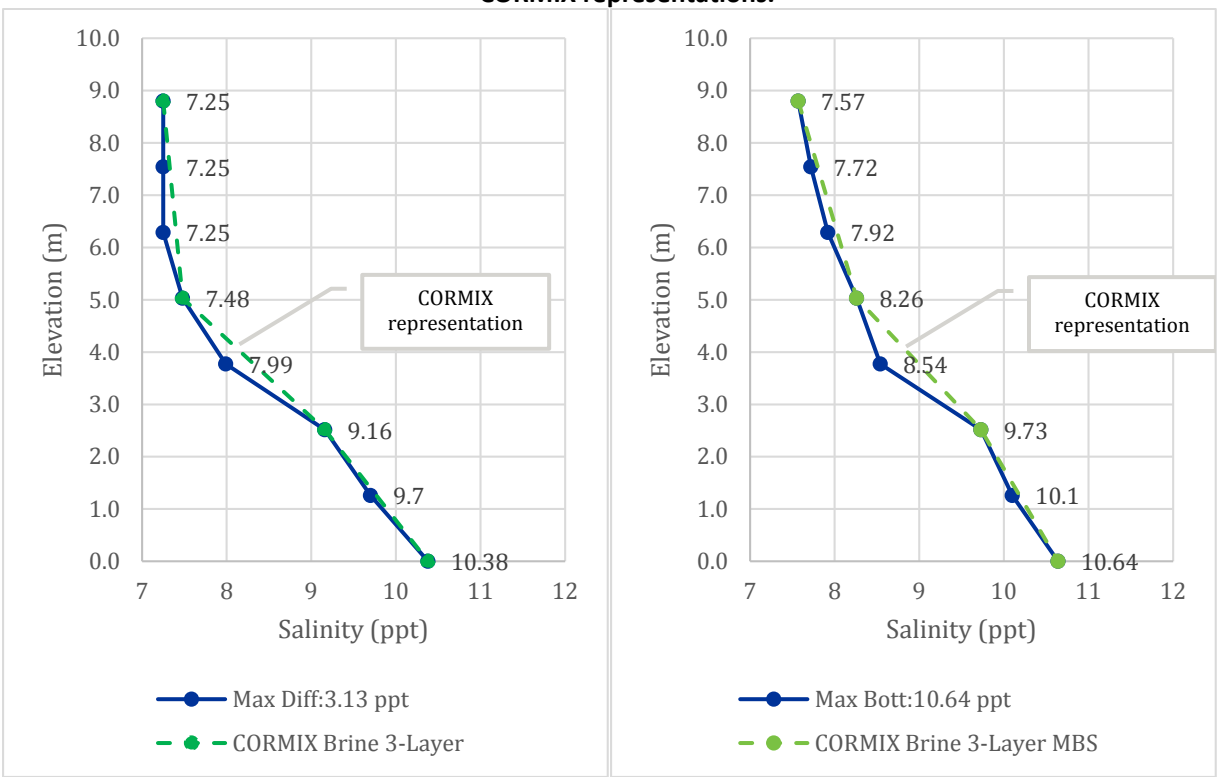

Figure 10 – The ambient stratification profiles for Chickahominy Riverfront Park representing the maximum difference between top and bottom salinities (left) and maximum bottom salinity (right).

2.5 Ambient Input Summary

The ambient inputs for CORMIX are summarized in **Table 2-2**. Depending on the configuration, CORMIX checks and applies limits to certain parameters, such as ambient depth, slope, and width, to ensure computational consistency. Thus, some parameters are adjusted to satisfy the computational rules and are discussed below. Since the brine discharge module calculations in CORMIX assume an unbounded river section, the user must also audit CORMIX results to determine their validity within the physical width and depth of the ambient water body.

Table 2-2 Summary of CORMIX Ambient Inputs

Parameter	Brickyard Landing	Chickahominy Riverfront Park	Comment
10th percentile river current speed	0.016 m/s	0.021 m/s	From EFDC model results of hourly simulated river current speed
90th percentile river current speed	0.231 m/s	0.172 m/s	From EFDC model results of hourly simulated river current speed
Salinity	Maximum vertical difference: 3.4 ppt Maximum bottom salinity: 8.51 ppt	Maximum vertical difference: 3.13 ppt Maximum bottom salinity: 10.64 ppt	Two different profiles per site. see Figures 9 and 10
Temperature	17 °C	17 °C	Average of hourly simulated temperature across all vertical layers
Density	Maximum vertical difference: 1001.48 to 1004.07 kg/m^3 Maximum bottom salinity: 1003.9 to 1005.28 kg/m^3	Maximum vertical difference: 1004.32 to 1006.71 kg/m^3 Maximum bottom salinity: 1004.57 to 1006.91 kg/m^3	Based on salinity and temperature, calculated from *One Atmosphere International Equation of State of Seawater* (UNESCO, 1980)
Depth at discharge	4.6 m	8.8 m	Adjusted to satisfy ambient slope and shoreline width estimates. The limit of CORMIX results is evaluated at the estimated depth in **Section 2.2**.
Wind speed	2 m/s	2 m/s	Default CORMIX value
Ambient cross-section definition	Unbounded	Unbounded	To simulate a brine discharge, CORMIX requires an unbounded cross-section.
Bottom friction factor	0.0805	0.0805	Darcy-Weisbach factor for channel roughness
Bottom slope	2.9 %	7.0 %	Used for CORMIX1
Near shore bottom slope	1.5 %	6.0 %	Used for CORMIX3
Distance from shoreline to slope break	130 m	50 m	Used for CORMIX3
Far shore bottom slope	2.1 %	6.3 %	Used for CORMIX3

Notes:

[1]m/s = meters per second; 1 meter = 3.28 feet

[2]ppt = parts per thousand

[3]°F (degrees Fahrenheit) = °C (degrees Celsius) × 9/5 + 32

[4]CORMIX1 = CORMIX module for a single-port discharge (in-river)

[5]CORMIX3 = CORMIX module for a surface or shoreline discharge

Section 3

Effluent Characteristics

The conceptual design of the RO water treatment facility is in the preliminary stage, thus certain assumptions are made to evaluate and compare different configurations and discharge conditions. Effluent discharge conditions that affect mixing zone analysis include effluent salinity (density), temperature, flow rate, and the physical configuration of the outfall structure.

3.1 Effluent Flow Rate

Three raw water intake scenarios were considered with withdrawal flows of 6, 12, and 18 mgd (0.26, 0.53, 0.79 m^3/s) and corresponding concentrate discharges of 1.3, 2.7, and 4 mgd (0.06, 0.12, 0.18 m^3/s), respectively. The first phase of the water treatment facility involves the construction of an 18 mgd (0.79 m^3/s) raw water intake and pump station with a finished water capacity of 8 mgd (0.35 m^3/s) (expandable to 12 mgd [0.53 m^3/s]). The maximum annual withdrawal of 18 mgd (0.79 m^3/s) is a function of the average daily withdrawal and the number of days in a year. The maximum daily withdrawal is the most water the plant could withdraw on a given day (otherwise known as a peak day).

3.2 Withdrawal Intake and Discharge Configuration

A preliminary conceptual design of the raw water intake for Chickahominy Riverfront Park is shown in **Figure 11.** The proposed raw water intake has three 2.1-m (7 foot) diameter wedge-wire screens installed at the end of three, 0.91-m (3-foot) diameter mains that feed into the raw water pump station. The figure indicates that the raw water intake is approximately 4 meters (13 feet) below mean low water (based on the NOAA gauge at Sewell's Point) and approximately 6.4 meters (21 feet) above the existing river bottom, if the water depth shown at this cross-section is approximately 10.4 meters (34 feet). It is assumed that the proposed intake and discharge will occur at approximately the same depth ratio (4 m/6.4 m) at Brickyard Landing.

The discharge location is assumed to be into the deepest part of the river, and the discharge configuration, and angle of discharge into the Chickahominy River is approximate for this stage of the preliminary conceptual design.

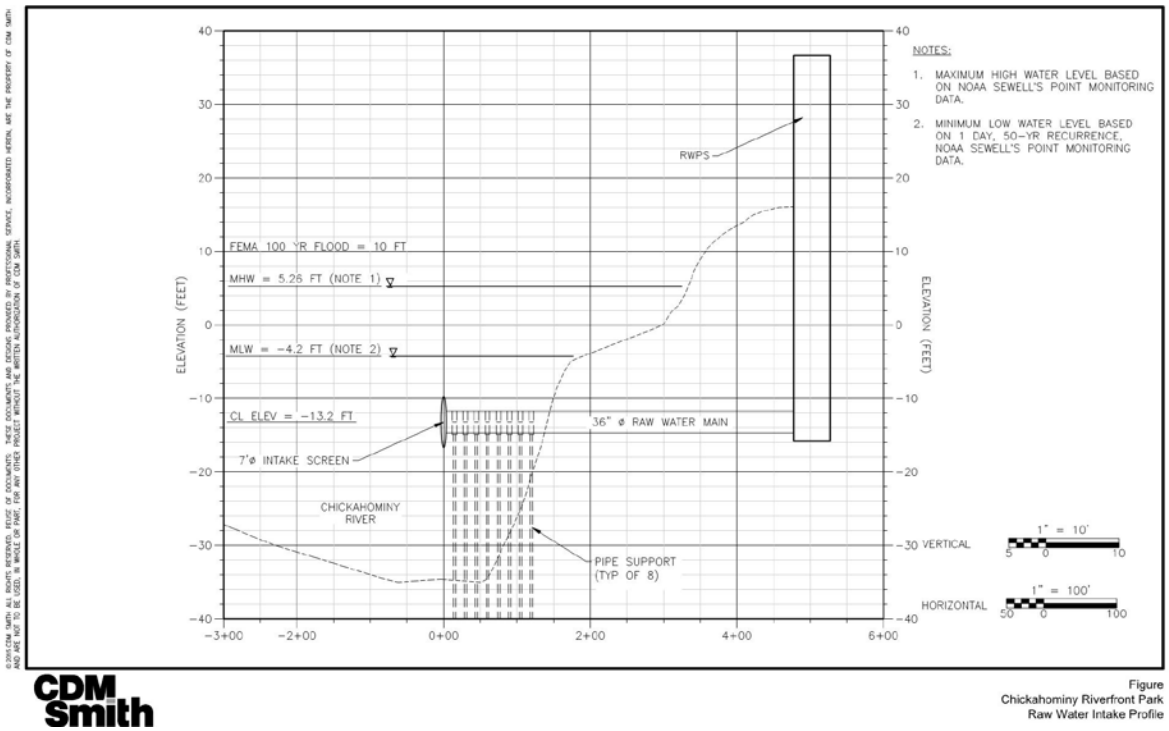

Figure 11 – Conceptual drawing of raw water intake for Chickahominy Riverfront Park

For the outlet discharge, a pipe size is estimated based on the range of effluent flows and potential head loss within a reasonable range of exit velocities that promote mixing based on discharge momentum. For Brickyard Landing, the proposed water treatment facility is located approximately 4.8 km (3 miles) from the proposed discharge location (assuming the pipe is installed in existing road right-of-way) whereas for Chickahominy Riverfront Park, the facility is proposed to be generally co-located with the discharge location.

Based on an assumed acceptable headloss for each site, it is estimated that a 0.41-m (16-inch) diameter pipe is sufficient to convey discharge flows for Brickyard Landing and a 0.30-m (12-inch) diameter pipe is sufficient for Chickahominy Riverfront Park. It is also currently assumed that the effluent discharge may be pumped from the treatment plant to the outfall to maintain reasonable velocities. Refinement of the pipe size, optimization of pumping scenarios, and a hydraulic analysis for any given head constraint will be performed for future design efforts. The discharge exit velocities for each of the effluent flow rate scenarios are summarized in **Table 3-1**.

Table 3-1 Discharge Exit Velocities in SI (left) and US Standard (right)

		Velocity (m/sec)				Velocity (ft/sec)		
Site	Diameter (m)	Q_{eff} = 0.057 m^3/sec	Q_{eff} = 0.118 m^3/sec	Q_{eff} = 0.175 m^3/sec	Diameter (inches)	Q_{eff} = 1.34 mgd	Q_{eff} = 2.67 mgd	Q_{eff} = 4.0 mgd
Brickyard Landing	0.41	0.44	0.91	1.35	16	1.5	3.0	4.4
Chickahominy Riverfront Park	0.30	0.78	1.62	2.40	12	2.6	5.3	7.9

Two proposed discharge configurations were modeled in CORMIX: a single-port discharge and a shoreline discharge. CORMIX can also simulate multi-port diffusers, which may be performed for future design efforts.

3.2.1 Single-Port Discharge

CORMIX1 is the module used for the single-port discharge and requires specification of the pipe size, vertical discharge angle, and horizontal angle and is shown in **Figure 12**. The port is located just above the river bottom and is angled upward at 45 degrees to assist in breaking through the ambient stratification. The port is also configured to be perpendicular to the shoreline and thus perpendicular to the dominant direction of river flow or ambient velocity (black u_a arrow in Figure 12), which entrains flow to aid in dilution.

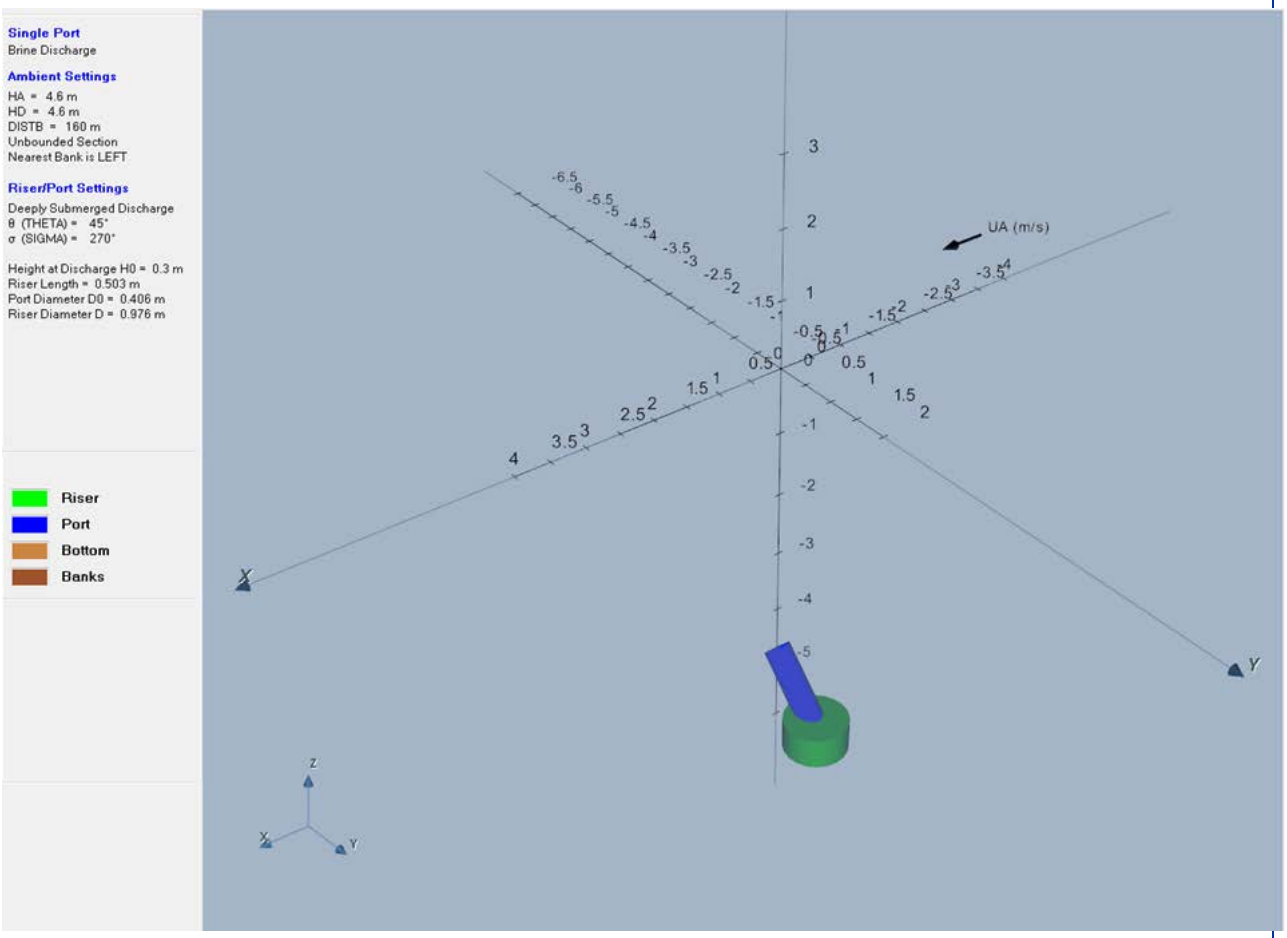

Figure 12 – CORMIX1 representation of a single-port discharge for Brickyard Landing.

3.2.2 Shoreline Discharge

CORMIX3 is the module used for the surface or shoreline discharge and requires specification of the pipe size, pipe invert, and depth of discharge and is shown in **Figure 13**Figure 12. The pipe is shown at the shoreline and is configured to be perpendicular to the shoreline and thus perpendicular to the dominant direction of river flow or ambient velocity (black u_a arrow in Figure 13). Near-shore and far-shore bottom slopes and velocities are inputs. It is assumed that near-shore

and far-shore velocities are the same, but bottom slopes are estimated based on the detailed bathymetric data discussed in **Section 2.2**.

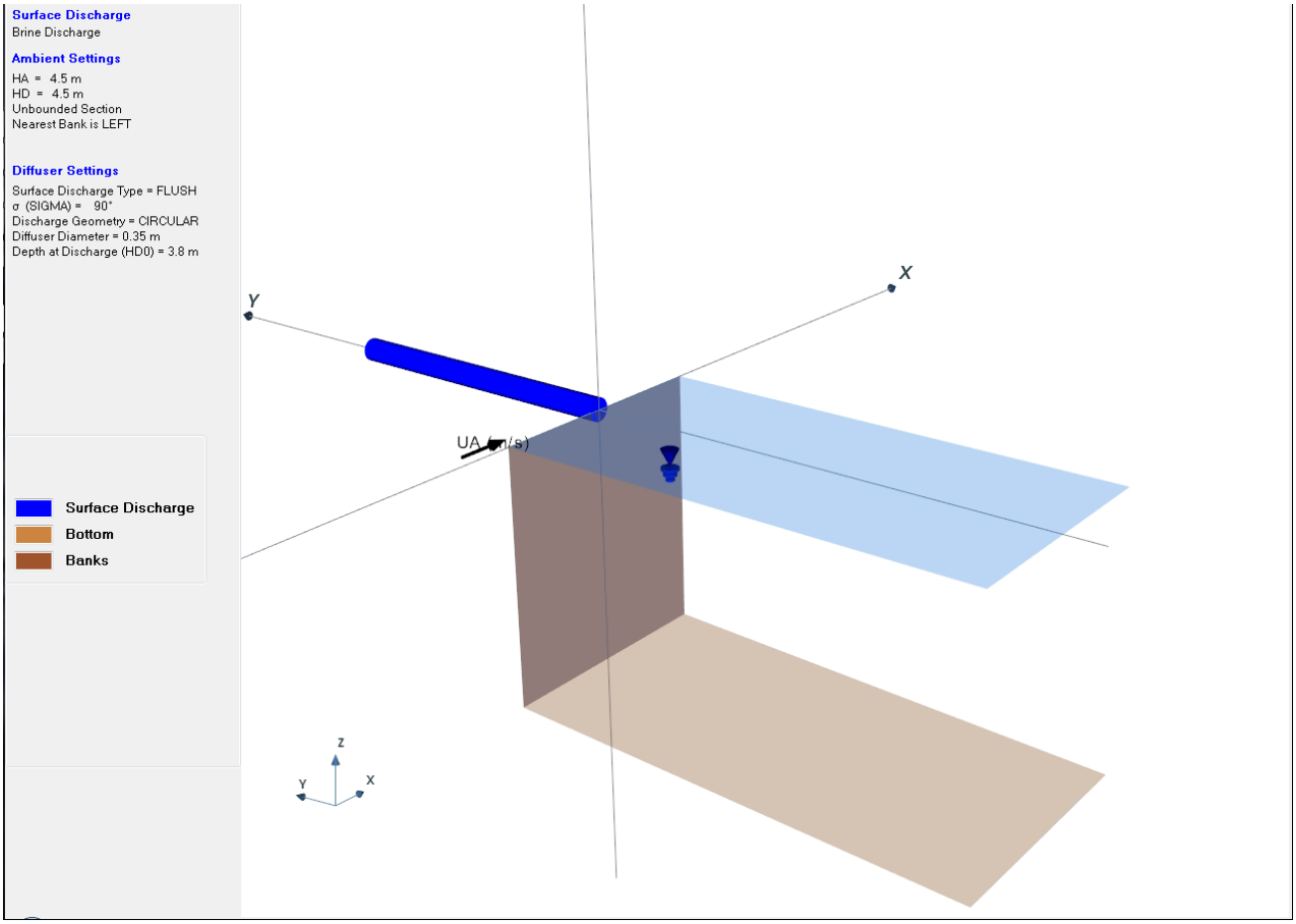

Figure 13 – CORMIX3 representation of a shoreline discharge for Brickyard Landing.

3.3 Effluent Density

Discharge salinity is a function of the withdrawal salinity and the RO processes in the water treatment facility. The withdrawal salinity is assumed to be ambient salinity at the depth in the river at which withdrawal occurs as described in **Section 3.3**, approximately 60 percent of the water depth from the river bottom. The corresponding salinity at this depth is established from the ambient salinity profiles for the two stratification scenarios as described in **Section 2.5**.

Based on the estimates as part of the RO system recovery discussed in *Water Supply Study Final Draft Report*, it is possible to have a system recovery of up to 75 percent, thus approximately four times as much salinity is possible in the brine discharge compared to the ambient salinity. For these preliminary simulations, discharge water temperature is assumed to be equal to the withdrawal ambient water temperature of 17 °C. Effluent density is calculated using ambient salinity and ambient temperature.

3.4 Effluent Input Summary

The effluent inputs for CORMIX are summarized in **Table 3-2**. CORMIX1 (single-port discharges) and CORMIX3 (shoreline discharges) require different inputs for their respective configurations and are noted below.

Table 3-2 Summary of CORMIX Effluent Inputs

Parameter	Brickyard Landing	Chickahominy Riverfront Park	Comment
Effluent flow rate	0.057 m^3/s, 0.118 m^3/s, 0.175 m^3/s	0.057 m^3/s, 0.118 m^3/s, 0.175 m^3/s	Effluent flow rates as defined by withdrawal scenarios for 1.3, 2.7, 4.0 mgd
Effluent salinity	Maximum vertical difference: 20.39 ppt Maximum bottom salinity: 29.86 ppt	Maximum vertical difference: 30.33 ppt Maximum bottom salinity: 33.27 ppt	Estimated to be four times the ambient salinity queried at the proposed withdrawal depth
Effluent temperature	17 °C	17 °C	Assumed to be the same as ambient temperature
Effluent density	Maximum vertical difference: 1014.34 kg/m^3 Maximum bottom salinity: 1021.57 kg/m^3	Maximum vertical difference: 1021.93 kg/m^3 Maximum bottom salinity: 1024.19 kg/m^3	Based on salinity and temperature, calculated from *One Atmosphere International Equation of State of Seawater* (UNESCO, 1980)
Port/pipe diameter	0.41 m	0.30 m	See **Section 3.1** for discussion.
Vertical angle of port, theta	45 degrees	45 degrees	Used for CORMIX1
Horizontal angle of port, sigma	270 degrees	270 degrees	Used for CORMIX1
Port height above the channel bottom	0.3 m	0.3 m	Used for CORMIX1, height for the discharge port center above bottom
Type of shoreline discharge	Flush discharge	Flush discharge	Used for CORMIX3
Local depth at discharge outlet	0.5 m	0.5 m	Used for CORMIX3, local water depth in front of discharge outlet
Bottom invert depth	0.41 m	0.30 m	Used for CORMIX3, depth below water surface assuming the shoreline/surface discharge is submerged
Horizontal angle of discharge, sigma	90 degrees	90 degrees	Used for CORMIX3

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Section 4

Mixing Zone Analysis

4.1 CORMIX Model Run Summary

CORMIX is simulated for various scenarios for both sites with combinations of varying:

- Ambient conditions defining the river current, density, and water depth conditions at the outfall structure
- Effluent characteristics including the density and discharge rate
- Discharge characteristics including the discharge orientation and dimensions

A total of 24 simulations are performed for each site as shown in **Figure 14** to evaluate the dilution of a proposed RO brine concentrate discharge in the Chickahominy River at Brickyard Landing and Chickahominy Riverfront Park. The results in this section are discussed by configuration (single-port vs. shoreline). The intent of these simulations is to provide an initial understanding of the dilution potential in the river and to allow for a comparison of the proposed discharge locations and configurations. A refined hydraulic design and discharge configuration of the outlet will occur in a future design stage.

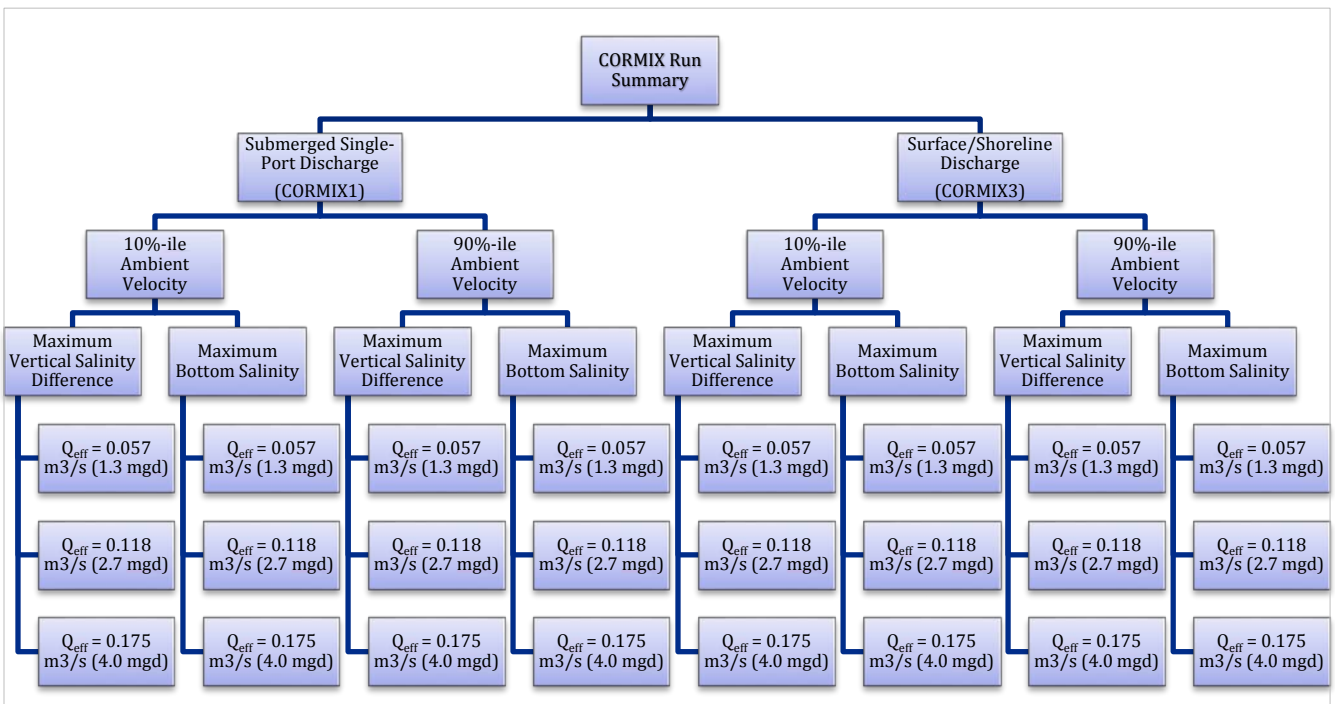

Figure 14 – CORMIX simulation scenarios for a total of 24 simulations per site.

4.2 Various Locations of CORMIX Results

Dilution (*S*) given by CORMIX for submerged jet or plume regions is typically reported as minimum centerline dilution. According to the CORMIX manual, the ratio of flux-average to minimum centerline dilution is 1.7 for single-port discharges. For this effort, the distance where a necessary flux-averaged 4 to 1 dilution (or an equivalent minimum centerline dilution of approximately 2.35 to 1) is tracked, which is based on where the brine discharge is diluted to a level at or near the original withdrawal concentration. An excerpt from a CORMIX result report within the near-field region is presented in **Figure 15**, showing the spatial coordinates of where centerline dilution is reported and the two lines that are interpolated. Depending on the classification schema in CORMIX, the location or dilution of interest can also be reported during control volume and buoyant spreading modules as a bulk dilution, which are equivalent to flux-averaged dilution for these regions.

```
BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION


 Zone of flow establishment:            THETAE=     45.00  SIGMAE=    270.59
  LE    =      1.49  XE    =      0.01  YE    =     -1.05  ZE    =     -3.25

 Profile definitions:
   B = Gaussian 1/e (37%) half-width, normal to trajectory
   S = hydrodynamic centerline dilution
   C = centerline concentration (includes reaction effects, if any)
  Uc = Local centerline excess velocity (above ambient)
  TT = Cumulative travel time

       X        Y        Z        S        C        B        Uc        TT
     0.00     0.00    -4.30      1.0 0.100E+03   0.20    0.910   .00000E+00
     0.01    -1.05    -3.25      1.0 0.100E+03   0.21    0.910   .14083E-01
     0.01    -1.32    -3.01      1.0 0.100E+03   0.25    0.910   .33364E+00
     0.01    -1.61    -2.81      1.1 0.932E+02   0.29    0.804   .71259E+00
     0.02    -1.94    -2.68      1.2 0.831E+02   0.34    0.645   .12102E+01
  Maximum jet height has been reached.
     0.03    -2.30    -2.66      1.3 0.745E+02   0.39    0.573   .17997E+01
     0.05    -2.64    -2.78      1.5 0.670E+02   0.40    0.586   .24130E+01
     0.06    -2.93    -3.00      1.7 0.600E+02   0.41    0.629   .29942E+01
     0.07    -3.17    -3.26      1.9 0.535E+02   0.42    0.667   .35385E+01
     0.09    -3.38    -3.56      2.1 0.476E+02   0.44    0.692   .40582E+01
     0.10    -3.56    -3.88      2.4 0.424E+02   0.46    0.704   .45647E+01
     0.11    -3.72    -4.22      2.6 0.378E+02   0.49    0.707   .50663E+01
 Cumulative travel time =           5.0663 sec  (    0.00 hrs)

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION
```

Figure 15 – Excerpt from a CORMIX result of the hydrodynamic, minimum centerline dilution (S), and the results that are interpolated to achieve S = 2.35 to determine the distance.

As described in **Section 1.3**, the initial dilution zone is defined as five times the average depth along a line extending 1/3 of the way across the receiving water from the discharge point to the opposite shore. Since the placement and configuration of the discharge is considered preliminary, modeled dilution at reasonable distances of 10 m and 20 m either cross-river or downstream from the discharge are also tracked to represent a range of dilution at a potential initial dilution zone. In addition, since the CORMIX simulations using brine discharge are schematized as "unbounded" but in reality are limited the by the river geometry, results are reported and are limited to the maximum depth and/or width of the river at both locations.

4.3 CORMIX1 Results

The results in the following sections are presented graphically by location and are also tabulated in **Section 4.5**.

4.3.1 Brickyard Landing

The CORMIX1 results from the in-river, single-port discharge scenarios are summarized in **Figure 16** which presents the distance at which a predicted flux-averaged dilution of 4:1 is calculated. Case 001 to Case 006 represent dilution at low ambient velocities for two different ambient stratification profiles with incremental increases in effluent flow rate. This shows that the distance needed to achieve a dilution of 4:1 is greatest at low velocities and high effluent flow, and that the difference in dilution based on varying the ambient stratification is marginal. Less distance to achieve target dilution is needed at high river current speeds as high river flows can induce more mixing. The figure also demonstrates the monotonic increase in distance as effluent flow increases, albeit the increase is marginal between Case 002 and Case 003. This is likely caused by the method or flow classification that CORMIX uses to characterize the relationship between effluent and ambient flow conditions and buoyancy and momentum driven mixing.

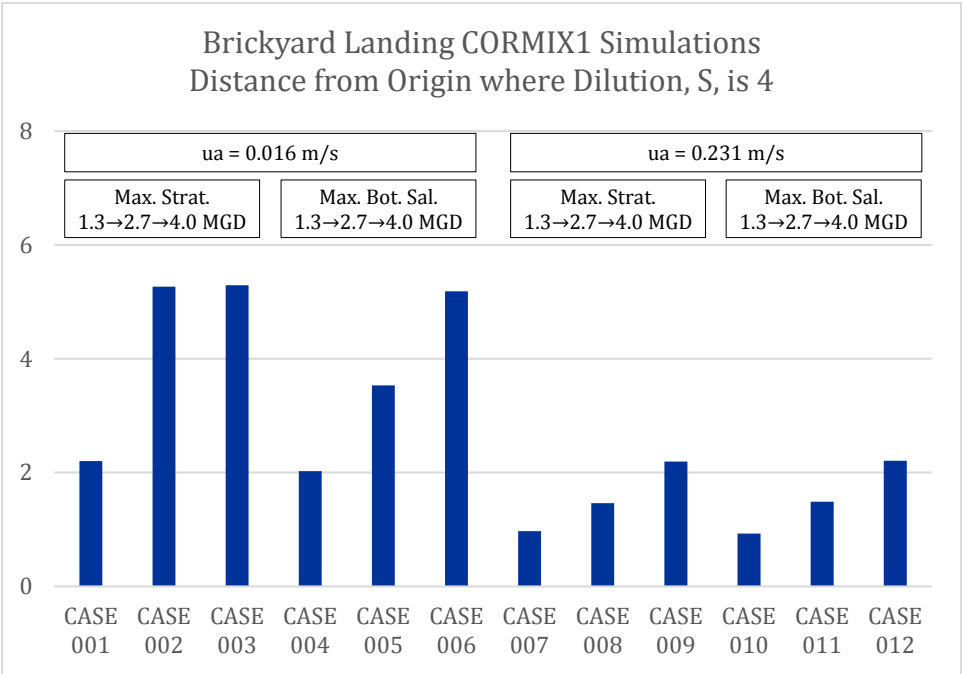

Figure 16 – CORMIX1 results at Brickyard Landing. Distances are calculated from x-y coordinates where the flux-averaged dilution is 4:1.

Figure 17 presents the dilution at 10 m and 20 m, respectively. For this CORMIX1 configuration, the x-direction is down river and the y-direction is cross-river. At low river current speeds, the dilution varies minimally at 10m, with a pattern emerging at 20 m with decreasing dilution as effluent flow increases. The results for low river current speeds are reported in the y- or cross-river direction. At high river current speeds, the dilution increases monotonically with an increase in effluent flow and reported in the x- or down-river direction since high river current speeds generally induce more turbulent downstream mixing.

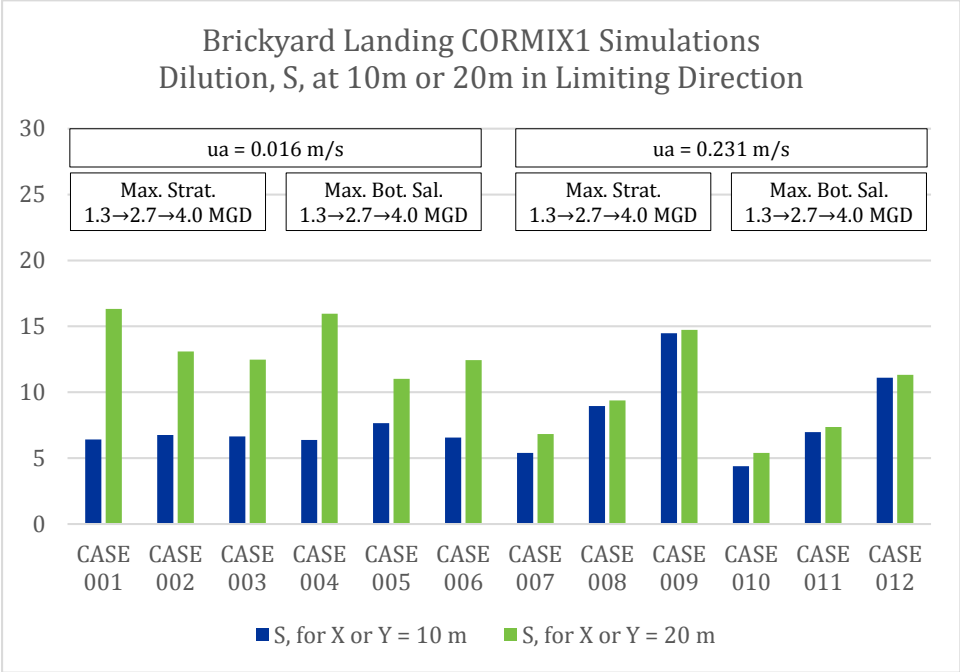

Figure 17 – CORMIX1 results at Brickyard Landing. Dilution is reported at 10 m and 20 m from the discharge location.

4.3.2 Chickahominy Riverfront Park

For the in-river discharge at Chickahominy Riverfront Park, a similar pattern in dilution is observed. Low current speeds require more distance to dilute the same volume compared to high current speeds (**Figure 18**). An increase in effluent flow rates also require greater distance to dilute. The difference between the two ambient stratification scenarios are marginal, which is expected considering the similarities in ambient profile shapes. In general, compared to Brickyard Landing, Chickahominy Riverfront Park appears to have an advantage in requiring less distance to achieve the same dilution and a greater dilution potential at both 10 m and 20 m for the same cases (**Figure 19**). This is because of the available water depth and available diluting ambient volume that allows for greater dilution of the original brine discharge.

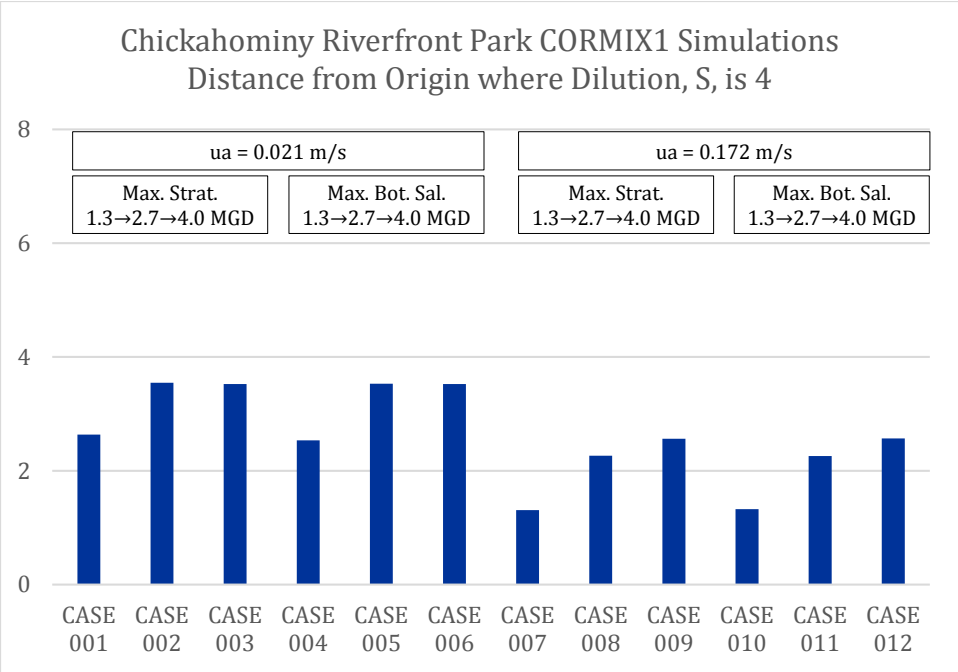

Figure 18 - CORMIX1 results at Chickahominy Riverfront Park. Distances are calculated from x-y coordinates where the flux-averaged dilution is 4:1.

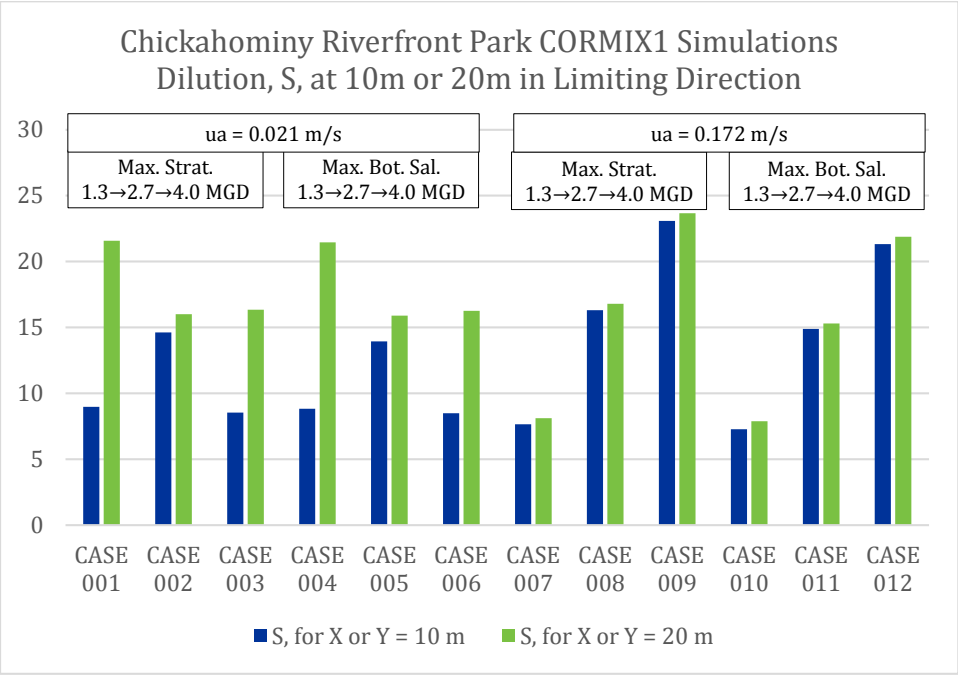

Figure 19 - CORMIX1 results at Chickahominy Riverfront Park. Dilution is reported at 10 m and 20 m from the discharge location.

4.4 CORMIX3 Results

CORMIX1 is used to evaluate dilution for an in-river discharge scenarios, while CORMIX3 is used to evaluate dilution for a shoreline discharge. Many of the inputs from CORMIX1 are used to inform CORMIX3 simulations, except for details associated with the depth at the discharge and distance to

the shoreline slope break. The results in the following sections are presented graphically by location and are also tabulated in **Section 4.5**.

4.4.1 Brickyard Landing

After review of an initial set of CORMIX3 simulations, it is noted that the results for Case 011 (with a maximum bottom salinity profile for an effluent flow of 0.118 m^3/s (2.7 mgd) at a current speed of 0.231 m/s) appeared inconsistent with the expected pattern of results within the same grouping. At times, CORMIX chooses a flow classification or calculation methodology based on ratios of input parameters, such as ambient or effluent flow. For Case 011, the ambient and effluent inputs are likely at a threshold value within a calculation subgroup that are different than the other cases in its grouping. The difference between the simulations within the same grouping was the process in which the plume became vertically mixed and then restratifies during the next timestep. Thus, an amended Case 011 was simulated using the same inputs except for a marginal increase in effluent flow of 0.001 m^3/s to 0.119 m^3/s. A comparison of the original Case 011 and the amended Case 011 (Case 011a) CORMIX3 text output are shown in **Figure 20**.

The CORMIX3 results from the shoreline, pipe discharge scenarios are summarized in **Figure 21** which presents the distance at which a predicted flux-averaged dilution of 4:1 is calculated. Like the CORMIX1 simulations at this location, there is a monotonic increase in distance required to achieve a 4:1 dilution with increasing effluent flows at low current speed, which is logical considering the needed ambient volume required to dilute greater effluent flows. The CORMIX output also reports different flow classification schema between the low and high current speeds (this is common) based on the model inputs, thus different equations are used to characterize the dilution and/or spreading at different current speeds.

The distance needed to achieve a dilution of 4:1 is much greater for the CORMIX3 simulations compared to the CORMIX1 simulations. For example, Case 001 in CORMIX1 required 2.2 m whereas the Case 001 in CORMIX3 required 14.3 m. This may be related to the location and depth at which the discharge is directed towards compared to a shoreline discharge at shallower depths. In CORMIX1, the discharge is at-depth with the available water column to mix, whereas in CORMIX3, the discharge is limited to the local depth, eventually reported using the near-shore river slope, where dilution is dependent on mixing via buoyant spreading or density currents, and not dependent on momentum-driven mixing.

As shown in **Figure 22**, dilution decreases as effluent flow increases at low current speeds. At high current speeds, no apparent pattern emerges aside from the moderate effluent flow result being less than the low or high effluent flow scenarios. The comparison between possible dilutions for CORMIX1 and CORMIX3 demonstrate that an in-river discharge provides potential greater dilution at depth than a shoreline discharge for what could be considered the critical case of low current speed and high effluent flow.

```
BEGIN CORDENS (MOD320): BOTTOM DENSITY CURRENT

 Density current in crossflow with weak buoyancy effects.

 Profile definitions:
   BV = top-hat thickness, measured vertically
   BH = top-hat half-width, measured horizontally in Y-direction
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S  = hydrodynamic average (bulk) dilution
   C  = average (bulk) concentration (includes reaction effects, if any)
   TT = Cumulative travel time

       X        Y       Z        S       C        BV       BH      ZU      ZL       TT
     0.06    -2.13    0.00      1.0 0.100E+03   0.19     0.53    0.00   -0.19 .23379E+01
   275.01   -20.06   -0.27     22.3 0.449E+01   0.43    19.93    0.00   -0.43 .91194E+03
   547.86   -57.60   -0.83     37.8 0.265E+01   0.48    31.23   -0.36   -0.83 .19420E+04
```

```
BEGIN CORDENS (MOD320): BOTTOM DENSITY CURRENT

 Density current in crossflow with weak buoyancy effects.

 Profile definitions:
   BV = top-hat thickness, measured vertically
   BH = top-hat half-width, measured horizontally in Y-direction
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S  = hydrodynamic average (bulk) dilution
   C  = average (bulk) concentration (includes reaction effects, if any)
   TT = Cumulative travel time

       X        Y       Z        S       C        BV       BH      ZU      ZL       TT
     0.06    -2.13    0.00      1.0 0.100E+03   0.19     0.53    0.00   -0.19 .23280E+01
 Jet/plume becomes VERTICALLY FULLY MIXED over the local ambient water depth.
    BV = water depth (vertically mixed)
     0.15    -2.14   -0.00      5.7 0.176E+02   0.76     2.26    0.00   -0.19 .23280E+01
    39.29    -2.93   -0.01     11.9 0.838E+01   0.54     3.61    0.00   -0.54 .10545E+03
 Jet/plume RESTRATIFIES at the above position.
    BV = Gaussian 1/e (37%) vertical thickness
   271.84   -45.33   -0.65     40.6 0.247E+01   0.83    24.74    0.00   -0.83 .15594E+04
   533.30  -131.48   -1.95     68.4 0.146E+01   0.79    38.00   -1.16   -1.95 .30352E+04
```

Figure 20 – CORMIX3 results at Brickyard Landing for Case 011 (top) and Case 011a (bottom) within the same CORMIX computational module. All other inputs are the same except for effluent flow where Case 011 is 0.118 m^3/sec and Case 011a is 0.119 m^3/sec.

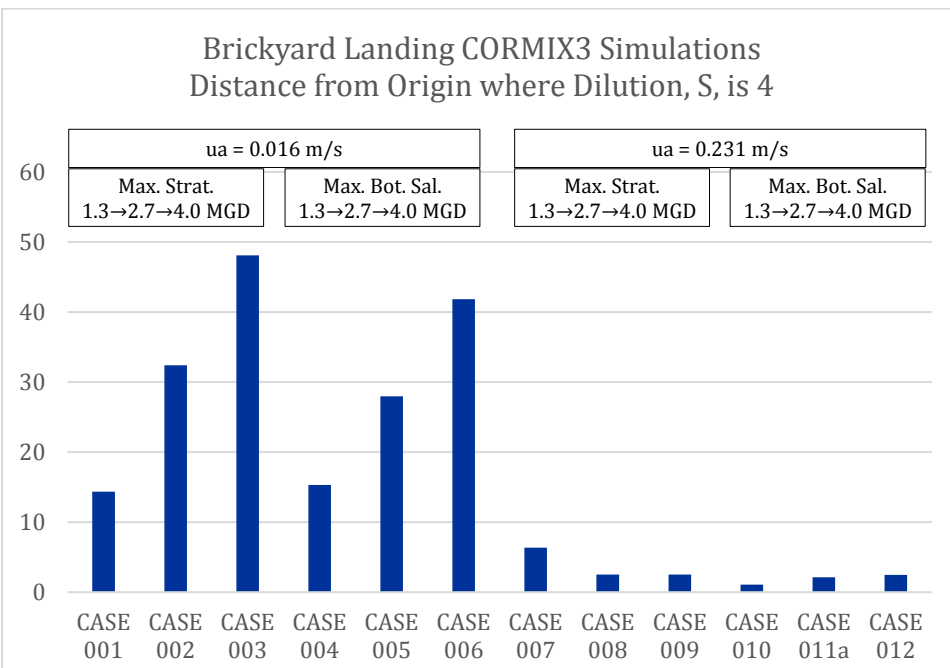

Figure 21 – CORMIX3 results at Brickyard Landing. Distances are calculated from x-y coordinates where the flux-averaged dilution is 4:1. These results include Case 011a, which has a marginal increase in effluent flow (0.001 m^3/s) to maintain calculation consistencies.

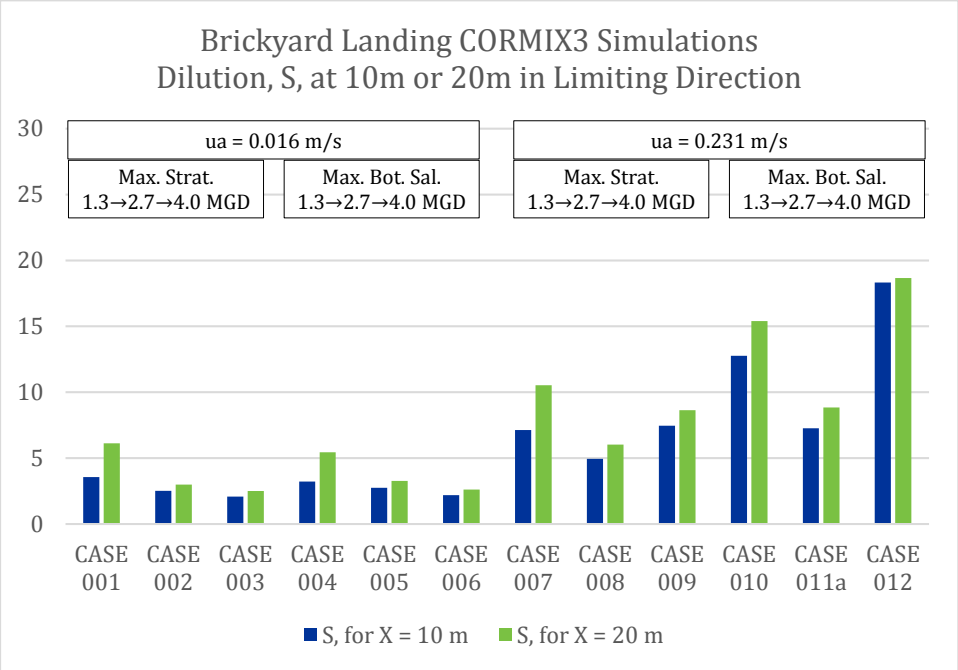

Figure 22 – CORMIX3 results at Brickyard Landing. Dilution is reported at 10 m and 20 m from the discharge location. These results include Case 011a, which has a marginal increase in effluent flow (0.001 m^3/s) to maintain calculation consistencies.

4.4.2 Chickahominy Riverfront Park

For the shoreline discharge at Chickahominy Riverfront Park, a similar pattern in dilution is observed as the Brickyard Landing shoreline discharge. Similar comparisons between locations and discharge configuration can be made for Chickahominy Riverfront Park. Low current speeds require more distance to dilute the same effluent flow compared to high current speeds (**Figure 23**). Also, for a shoreline discharge at this location, dilution decreases as effluent flow increases (**Figure 24**).

Comparing an in-river (CORMIX1) vs. shoreline discharge (CORMIX3) at this location, greater dilution is achieved consistently for the in-river discharge, with the same reasoning as for Brickyard Landing. The discharge is at-depth with the available water column to mix, whereas the shoreline discharge is limited to the local depth, where dilution is dependent on mixing via buoyant spreading or density currents.

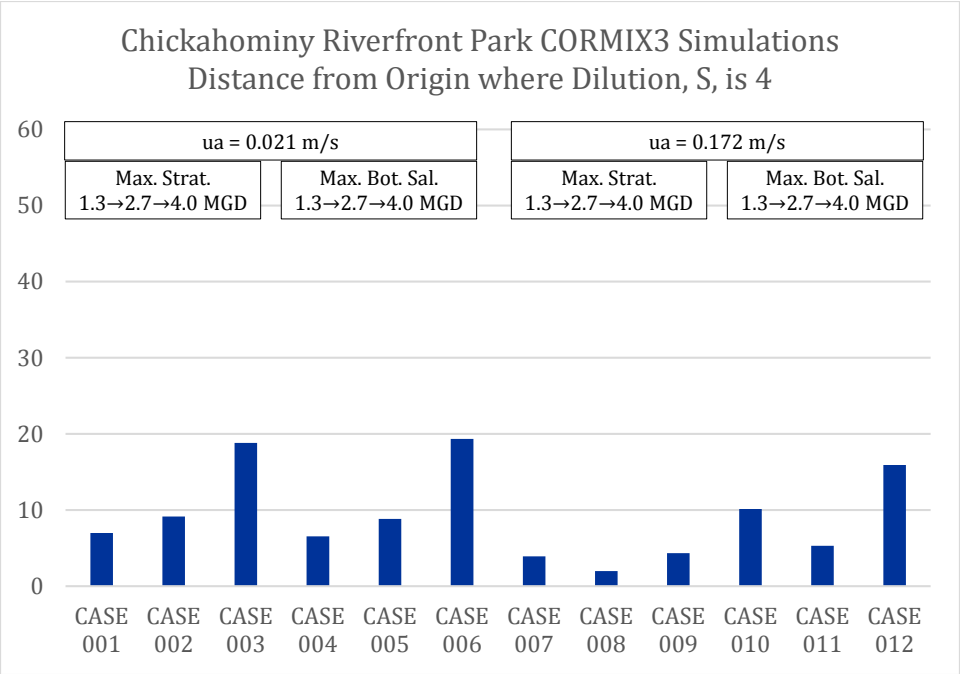

Figure 23 – CORMIX3 results at Chickahominy Riverfront Park. Distances are calculated from x-y coordinates where the flux-averaged dilution is 4:1.

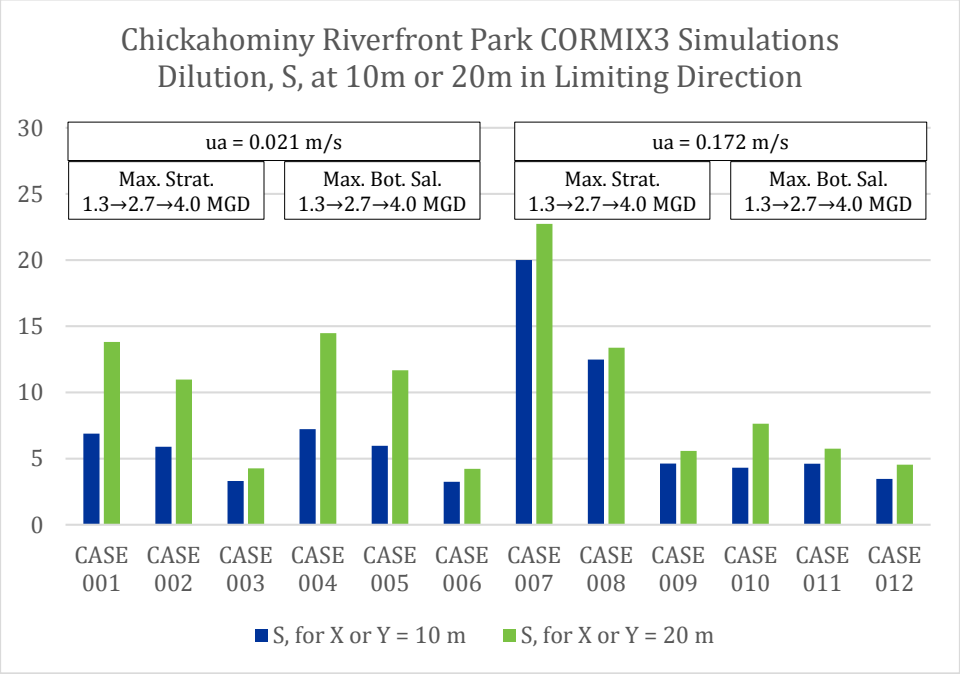

Figure 24 – CORMIX3 results at Chickahominy Riverfront Park. Dilution is reported at 10 m and 20 m from the discharge location.

4.5 CORMIX Output Summary

This section summarizes the CORMIX results for all 12 ambient condition scenarios at both location and for both discharge configurations. Dilution results at a distance are tracked and recorded at either the cross-river or down-river direction, depending on the current speed and the effluent flow. **Table 4-1** presents the summary of the CORMIX results.

Table 4-1 Summary of CORMIX Results

Scenario Number	Brickyard Landing CORMIX 1			Chickahominy Riverfront Park CORMIX 1			Brickyard Landing CORMIX 3			Chickahominy Riverfront Park CORMIX 3		
	Distance for S = 4	Dilution at 10 m	Dilution at 20 m	Distance for S = 4	Dilution at 10 m	Dilution at 20 m	Distance for S = 4	Dilution at 10 m	Dilution at 20 m	Distance for S = 4	Dilution at 10 m	Dilution at 20 m
CASE 001	2.2 m	6.4	16.3	2.6 m	9.0	21.6	14.3 m	3.6	6.1	7.0 m	6.9	13.8
CASE 002	5.3 m	6.8	13.1	3.5 m	14.6	16.0	32.4 m	2.5	3.0	9.1 m	5.9	11.0
CASE 003	5.3 m	6.6	12.5	3.5 m	8.5	16.3	48.1 m	2.1	2.5	18.8 m	3.3	4.3
CASE 004	2.0 m	6.4	16.0	2.5 m	8.8	21.5	15.3 m	3.2	5.4	6.5 m	7.2	14.5
CASE 005	3.5 m	7.7	11.0	3.5 m	13.9	15.9	28.0 m	2.8	3.3	8.8 m	6.0	11.7
CASE 006	5.2 m	6.6	12.4	3.5 m	8.5	16.3	41.8 m	2.2	2.6	19.3 m	3.3	4.2
CASE 007	1.0 m	5.4	6.8	1.3 m	7.7	8.1	6.4 m	7.1	10.5	3.9 m	20.0	22.7
CASE 008	1.5 m	9.0	9.4	2.3 m	16.3	16.8	2.5 m	5.0	6.0	2.0 m	12.5	13.4
CASE 009	2.2 m	14.5	14.7	2.6 m	23.1	23.7	2.5 m	7.5	8.6	4.3 m	4.6	5.6
CASE 010	0.9 m	4.4	5.4	1.3 m	7.3	7.9	1.1 m	12.8	15.4	10.1 m	4.3	7.6
CASE 011	1.5 m	7.0	7.4	2.3 m	14.9	15.3	2.1 m*	7.3*	8.8*	5.3 m	4.6	5.7
CASE 012	2.2 m	11.1	11.3	2.6 m	21.3	21.9	2.5 m	18.3	18.7	15.9 m	3.5	4.5

*Results are from amended Case 011a which had an effluent flow of 0.119 m^3/s.

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Section 5
Conclusion

This report presents the preliminary initial dilution modeling using CORMIX of a proposed RO brine concentrate discharge in the Chickahominy River at Brickyard Landing and Chickahominy Riverfront Park. The intent of these simulations is to provide an initial understanding of the dilution potential in the river and to allow for a comparison of the proposed discharge locations and configurations. The purpose of using both models is the ability to evaluate the potential initial dilution immediately near the brine discharge location (i.e., the near-field region via CORMIX) and the impact of the salinity discharge on a scale of the ambient waterbody (i.e., the far-field region via EFDC).

The CORMIX model is used to simulate 48 different scenarios for:

- Two different locations, Brickyard Landing and Chickahominy Riverfront Park, both of which have unique river geometry and depth characteristics
- Two different discharge configurations, an in-river discharge simulated by CORMIX1 and shoreline discharge simulated by CORMIX3
- Two different current speeds, representing the 10th percentile and 90th percentile velocities, unique to each location
- Three different brine discharge (effluent) flow rates based on preliminary conceptual design of a water treatment facility
- Two different ambient density profiles based on detailed salinity profiles exported from EFDC

The results in **Section 4.3** and **Section 4.4** demonstrate that an in-river discharge provides more potential dilution at the critical case (low current speed, high effluent flow) compared to a shoreline discharge. For other similar comparisons cases during high current speed and high effluent flow, the difference between the two configurations are less drastic. In comparison of the two sites for an in-river discharge, it appears as if the Chickahominy Riverfront Park will allow for greater dilution at some distance from the discharge compared to the Brickyard Landing site. This is likely because of the greater depth and width of the Chickahominy River at the Chickahominy Riverfront Park site, allowing for more volume to dilute the effluent.

This is a preliminary evaluation based on a conceptual design, therefore, the results herein are preliminary based on the assumptions described in **Section 1.5**. In addition, it is likely that a multi-port diffuser will be required to discharge the effluent into the river based on the regulations as described in **Section 1.3**. As such, additional analysis and initial dilution modeling may be required during the preliminary design of the plant and its infrastructure.

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Attachment B
EFDC Model Results

Evaluation of the Impact of Water Withdrawal on the Change of Salinity Intrusion in the Chickahominy River

Project Report submitted to

CDM Smith | 2104 West Laburnum Avenue, Suite 203 | Richmond, VA 23227

By

Jian Shen, Rico Wang, and Mac Sisson

Virginia Institute of Marine Science

December 2016

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1.0 Introduction

The withdrawal of water from the Chickahominy River has been proposed for a water treatment facility, which will use reverse osmosis (RO) technology to treat this water for a potable water supply. The maximum finished water capacity of the treatment facility is 12 million gallons per day (mgd) (18.6 cfs) with a raw water withdrawal of approximately 18 mgd (27.9 cfs). The additional raw water is necessary for the treatment process and will be discharged to the Chickahominy along with brine concentrate. If the amount of water withdrawn is large compared to the runoff of the River, it can affect the salinity gradient along the Chickahominy River, especially during a low flow period, which can have an impact on this aquatic environment. Besides, discharge back to the River with brine concentrate can alter the local salinity condition depending on the discharge location and concentration. To date, there has been no study of the potential impact on aquatic life and environment for this process in the Chickahominy River.

To assess the possible impacts of water withdrawal on salinity gradient and water discharge with brine concentration on the local condition, the numerical modeling group of Virginia Institute of Marine Science (VIMS) plans to use a hydrodynamic model to assist CDM Smith to conduct the evaluation.

2.0 Model Configuration

2.1 Model grid modification

The existing EFDC 3D model for the Chickahominy River does not have enough resolution. To improve the model simulation capability, we refined the model grid to increase model resolution near the locations of withdrawal and discharge. The refined model grid is shown in Figures 2-2-1 and 2-2-2. There are 2656 horizontal grid cells with eight vertical layers.

2.2 Model set-up

The model open boundary was forced by the large James River model output at the open boundary. The freshwater discharges from the upstream and adjacent watersheds are output from the watershed model developed for Virginia DEQ for the TMDL study in this estuary (VA-DEQ, 2016). There are a total of 19 sub-watersheds adjacent to the River. The daily discharge from the Chickahominy Lake is driven by outflow from Walkers Dam.

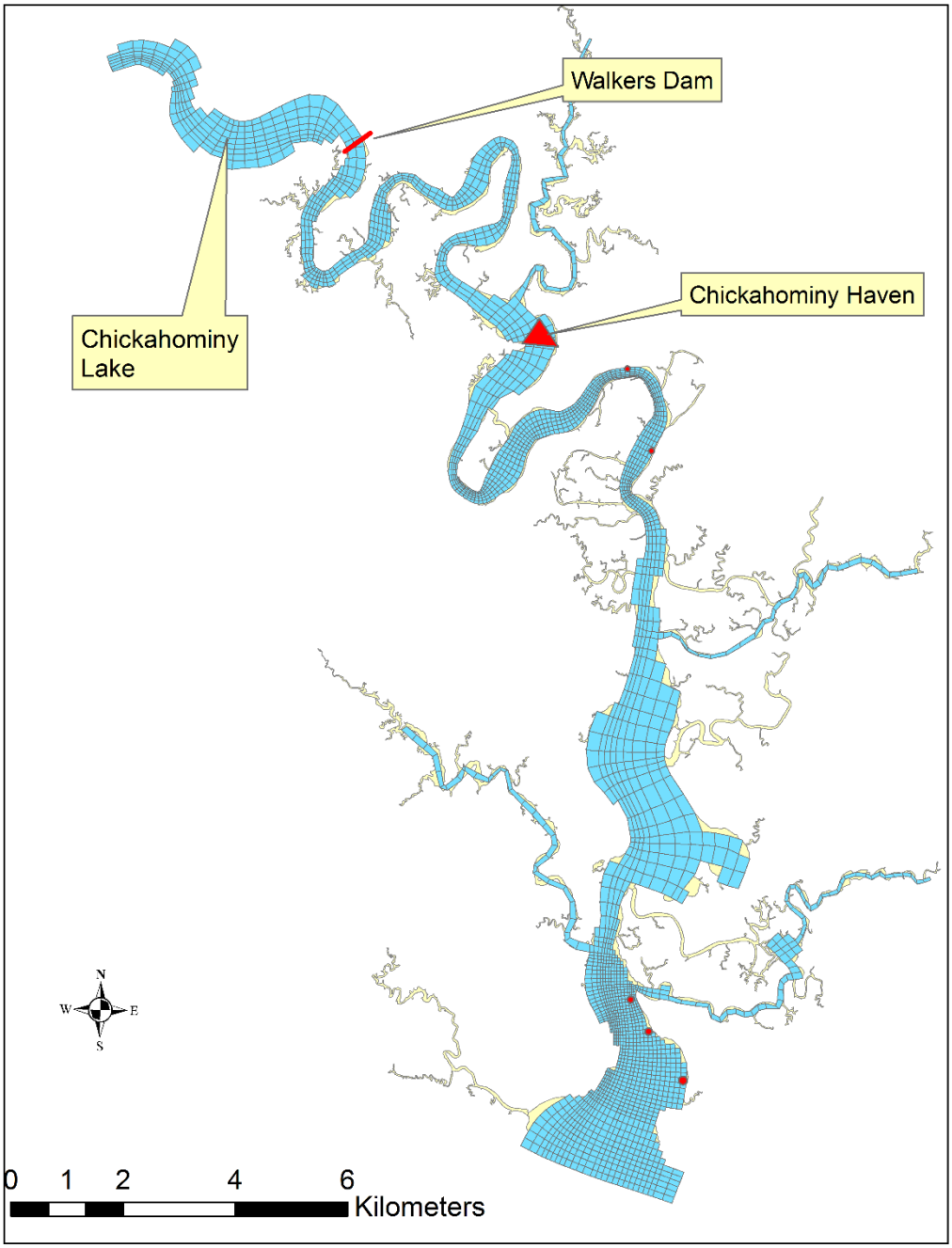


Figure 2-2-1. Refined model grid for the Chickahominy River (triangle is salinity observation station, red dots are withdrawal and discharge locations)

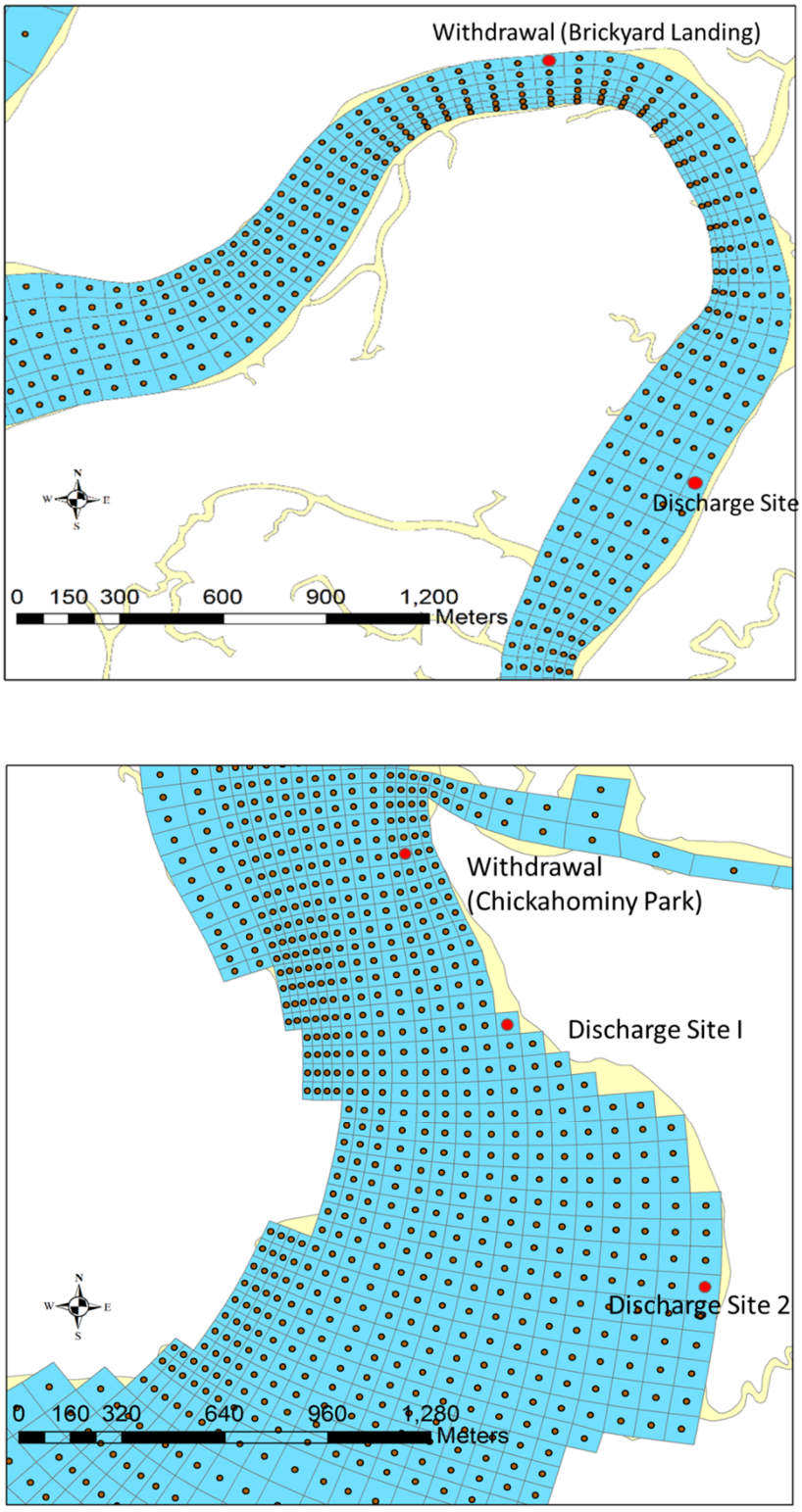


Figure 2-2-2. Model Grid (red dots are locations of withdrawals and discharges)

2.3 Model calibration

Although the previous coarse grid model was calibrated from the period from 2002-2003, the current observation data available for the Chickahominy River are from 2006-2008, which can be downloaded from VECOS (http://web2.vims.edu/vecos/). A continuous monitoring station is located at Chickahominy Haven (CH) (CHK015.12, Location: N 37º 22' 15.96" W 76º 53' 49.5"). The flow analysis shows that 2007 is a dry-year with very low flow, which is similar to the year 2002 (Fig. 2-3-1). Therefore, the period of 2006-2008 was used for the model calibration. The location of the observation station is shown in Figure 2-3-2. The model simulation of salinity is shown in Figures 2-3-3 to 2-3-5, respectively, for years 2006, 2007, and 2008. Observations are 15-minute data near the surface and model outputs are hourly near the surface. The accumulative distribution frequency curves are shown in Figures 2-3-6 to 2-3-8. Because the open boundary conditions of tide and salinity were extracted from a large domain model and the lateral flow were obtained from the watershed model simulation, some deviation from observations is expected, especially for 2006. It can be seen that the model simulation of salinity is satisfactory overall. The model performance is the best for the year 2007, which is a critical low-flow year.

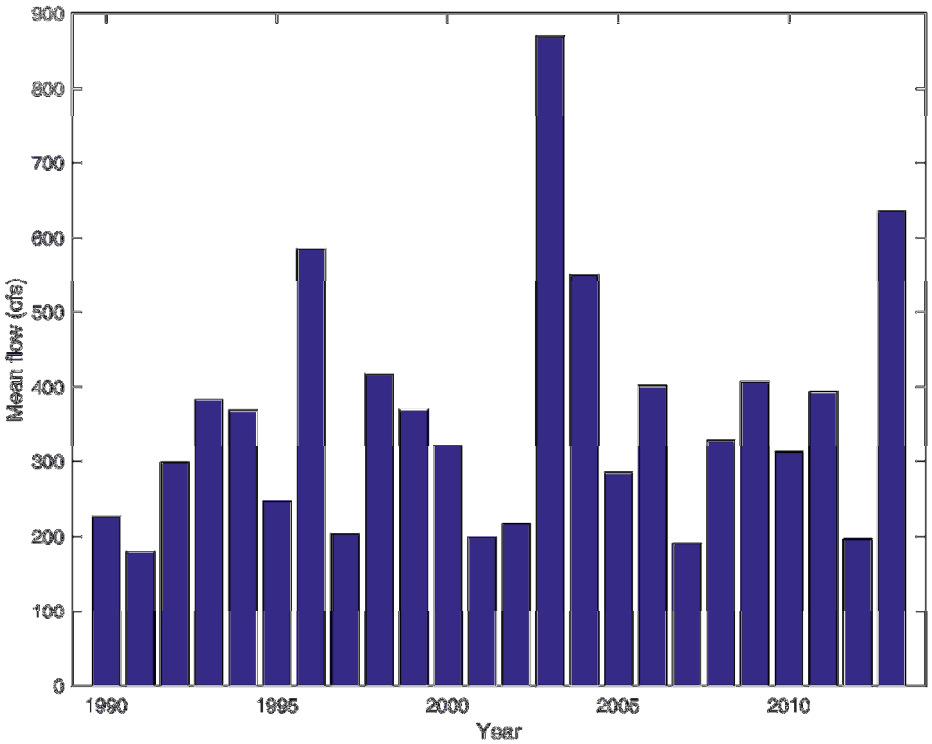


Figure 2-3-1. Mean flow from the upstream of the Chickahominy River.

Figure 2-3-2. Location of Observation Station of Chickahominy Haven.

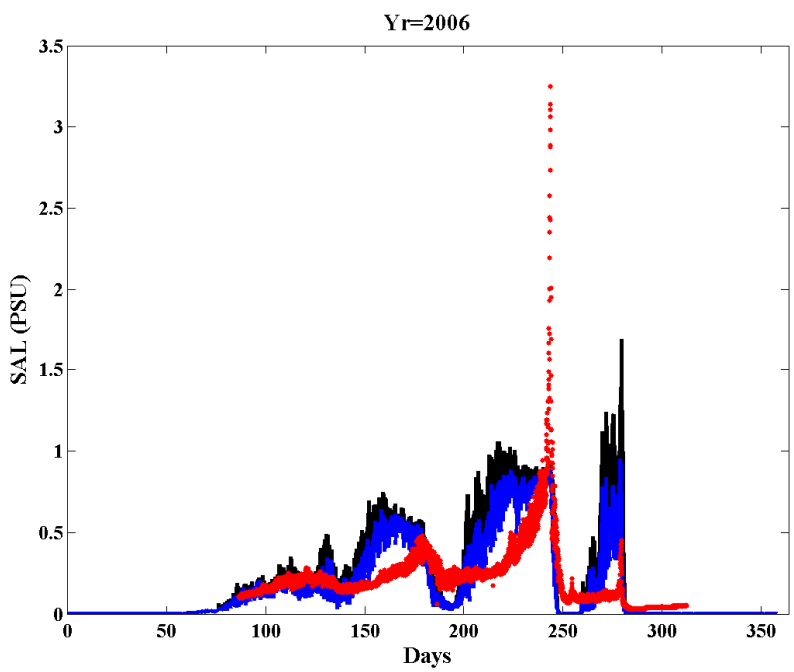


Figure 2-3-3. Model calibration results near the surface (Year 2006).

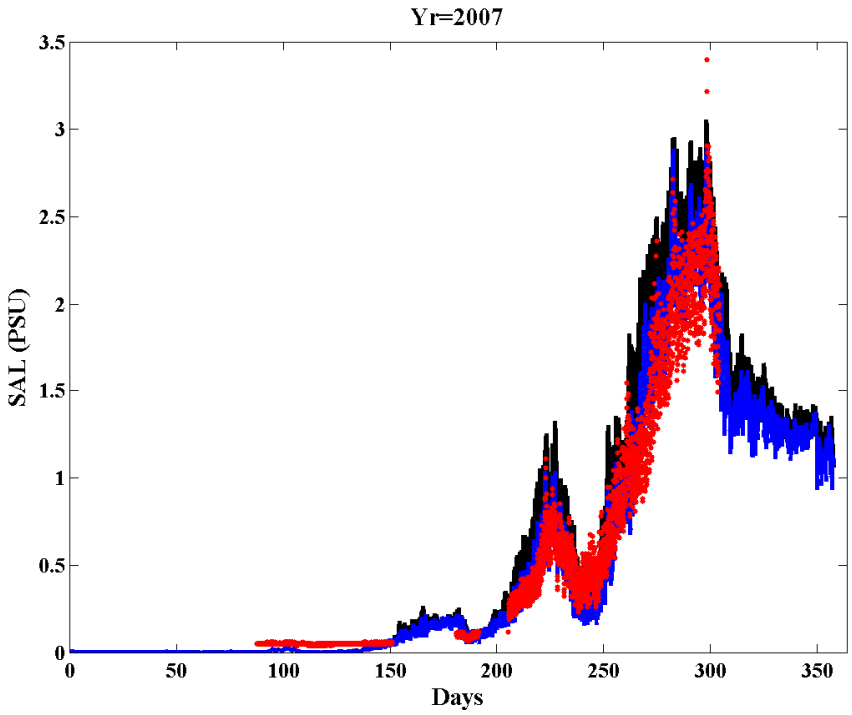


Figure 2-3-4. Model calibration results near the surface (Year 2007).

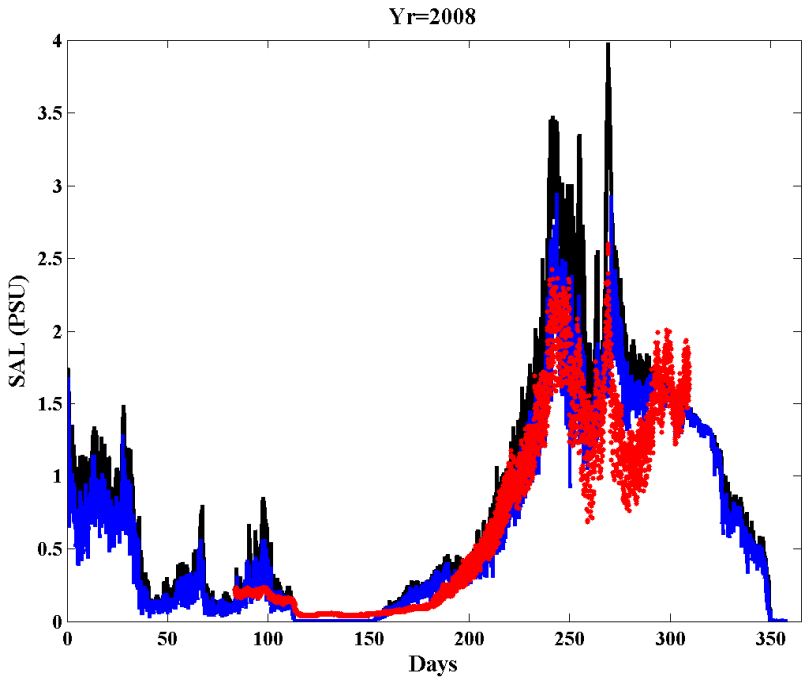


Figure 2-3-5. Model calibration results near the surface (Year 2008).

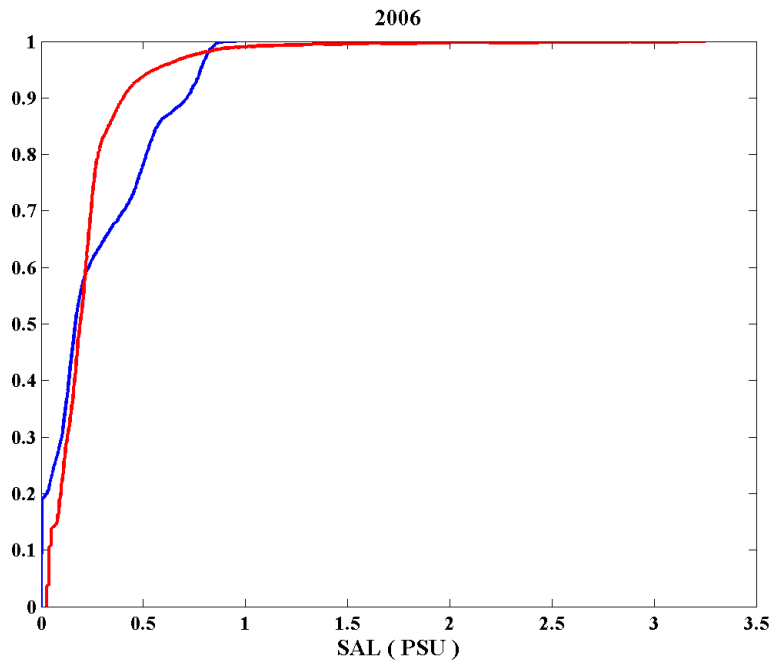


Figure 2-3-6. Comparison of accumulative distribution of model calibration results (Year 2006).

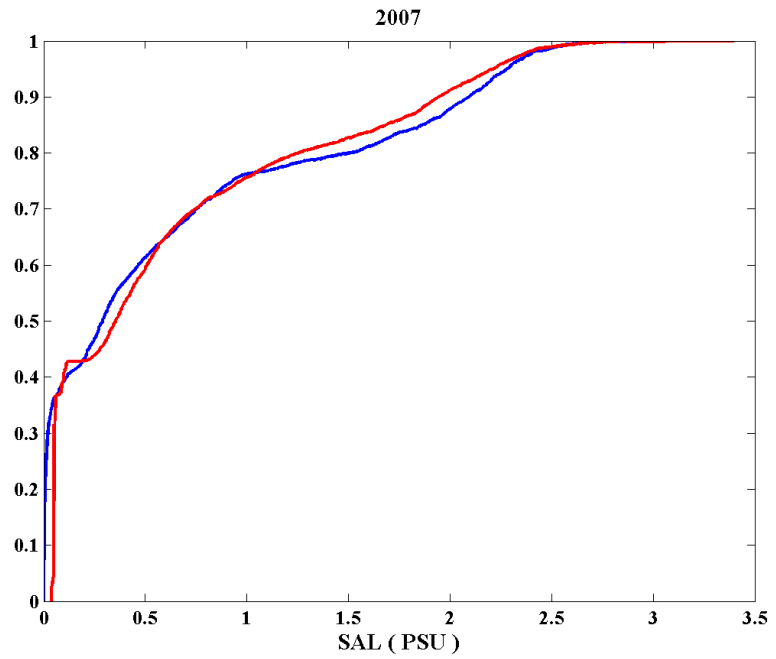


Figure 2-3-7. Comparison of accumulative distribution of model calibration results (Year 2007).

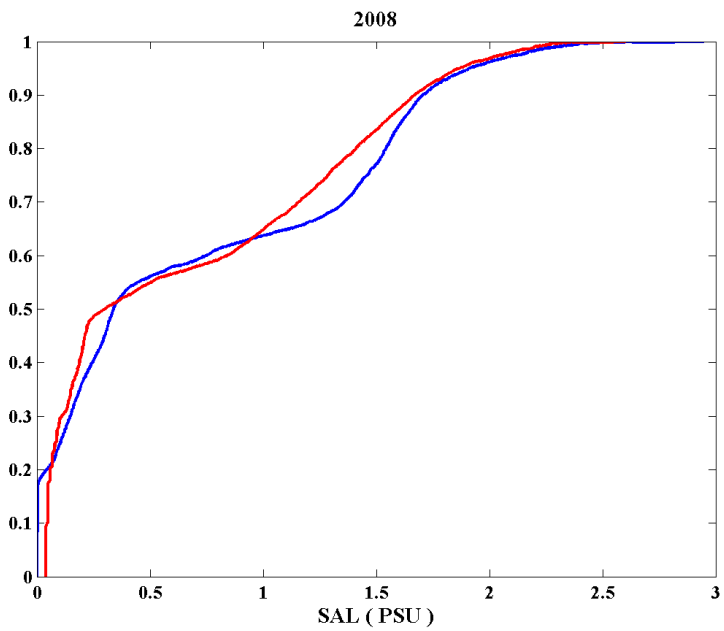


Figure 2-3-8. Comparison of accumulative distribution of model calibration results (Year 2008).

3.0 Model Scenario Description

The original plan was to simulate over multiple years for the impact of withdrawal and discharge to account for hydrological variation. Based on data analysis and from the model calibration, it can be seen that, during year 2007, salinity has the largest seasonal variation and ranges from 0.0 to 3.0 psu at Chickahominy Haven. The salinity is higher during the low flow period, but lower during high flow period. This year is ideal for model experiments for the different withdrawal and discharge scenarios. The model experiments were conducted for the year 2007. The simulation scenario is listed in Table 1. The location of withdrawal and discharge are shown in Figure 2-2-2. The salinity concentration distributions at withdrawal locations are shown in Figure 3-1-1, respectively, for Brickyard Landing and Chickahominy Riverfront Park. The salinity ranges from 0 to 6 psu and from 0 to 8 psu at Brickyard Landing and Chickahominy Riverfront Park, respectively. The salinity concentration of discharge is 4 times higher than the salinity during the withdrawal processes.

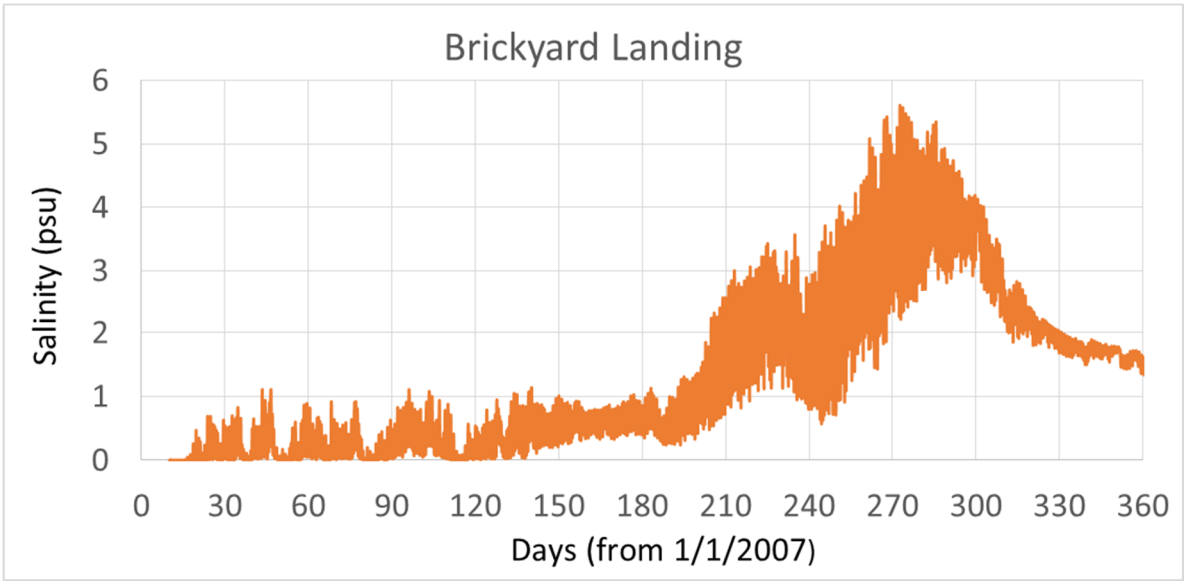
Table 1. Model Scenario Description

	Withdrawal (mgd)	Discharge (mgd)
Phase I	6	1.3
Phase II	12	2.7
Phase III	18	4

The initial test runs show that Phase I causes minor salinity changes because of low withdrawal and discharge. Therefore, the simulation results of Phase II and Phase III are presented here. For each experiment, the withdrawal and discharge were assumed to have occurred simultaneously, i.e., withdrawal occurred at the upstream, and four times the concentration at the withdrawal site is discharged to the downstream discharge location. For each phase, 3 model experiments will be conducted. One experiment is for the withdrawal-discharge at Brickyard Landing. Two experiments were conducted for Chickahominy Riverfront Park for two discharge locations, respectively. The model simulation results will be presented in Section 4.

A 12 mgd withdrawal is about 0.53 cms and 45,792 m^3d^{-1}. The model grid size at the withdrawal site is about 90×42 m^2 and 55×39 m^2, at Brickyard Landing and Chickahominy Riverfront Park, respectively. As water is continuously withdrawn, it will cause a change of the flow condition. The influence of withdrawal can influence both upstream and downstream salinity, depending on the tide. Salinity can be increased or decreased, depending on the replacement of water with higher or lower salinity. The results are not the same as the simulation conducted based on steady flow such as using CORMIX model.

To evaluate the change of salinity, we have plotted the comparison of salinity at selected locations surrounding the withdrawal and discharge locations. The locations for output of time series are shown in Figures 3-1-2 to 3-1-5. The stations for comparison are selected at the discharge/withdrawal location, its upstream and downstream grids, upstream and downstream grids close to discharge/withdrawal location, and location in the channel. These selected surrounding locations will show the local changes of salinity concentration in the discharge/withdrawal site.



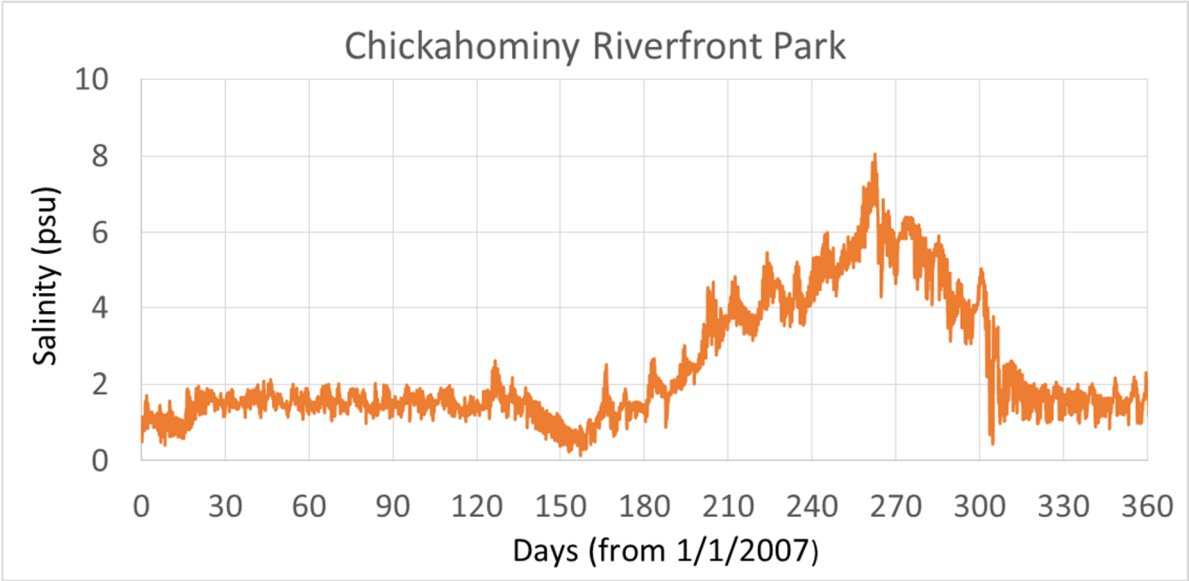


Figure 3-1-1. Salinity concentration at withdrawal location

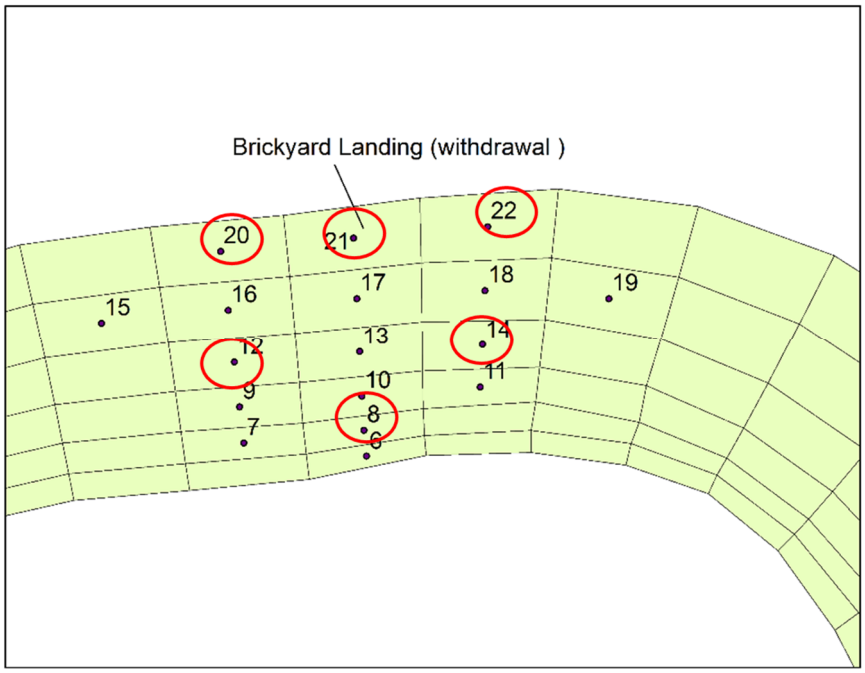


Figure 3-1-2. Locations of output of salinity time series for comparison (circles are locations for time series and numbers are stations ID for time series plots).

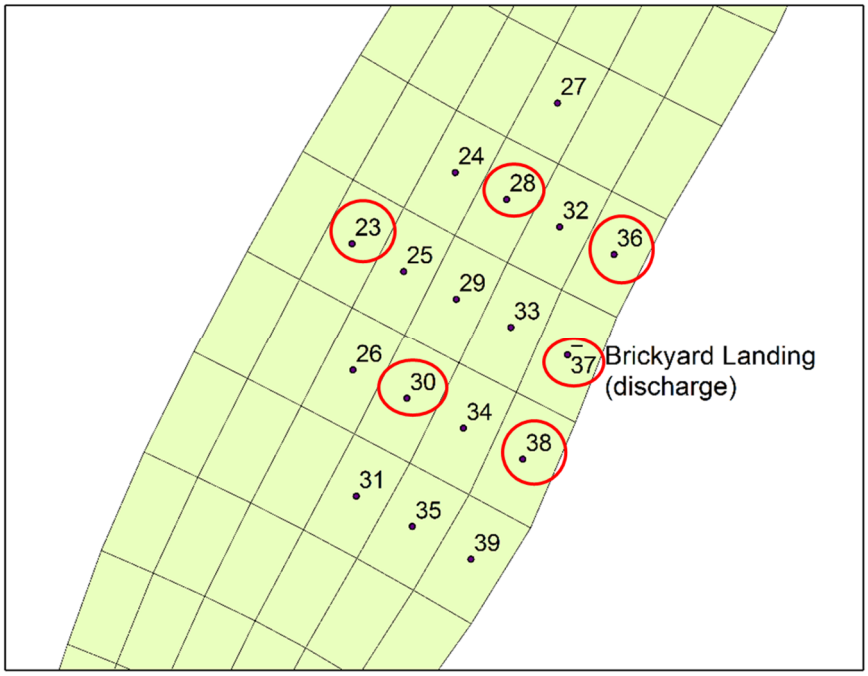


Figure 3-1-3. Locations of output of salinity time series for comparison (red circles are locations for time series and numbers are station ID for time series plots).

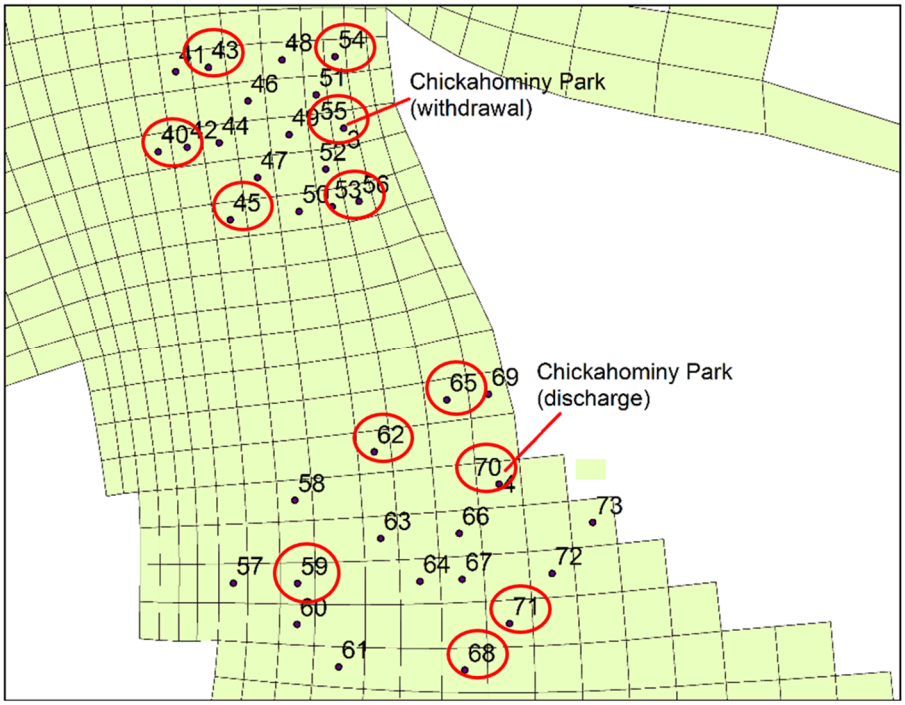


Figure 3-1-4. Locations of output of salinity time series for comparison (red circles are locations for time series and numbers are station ID for time series plots).

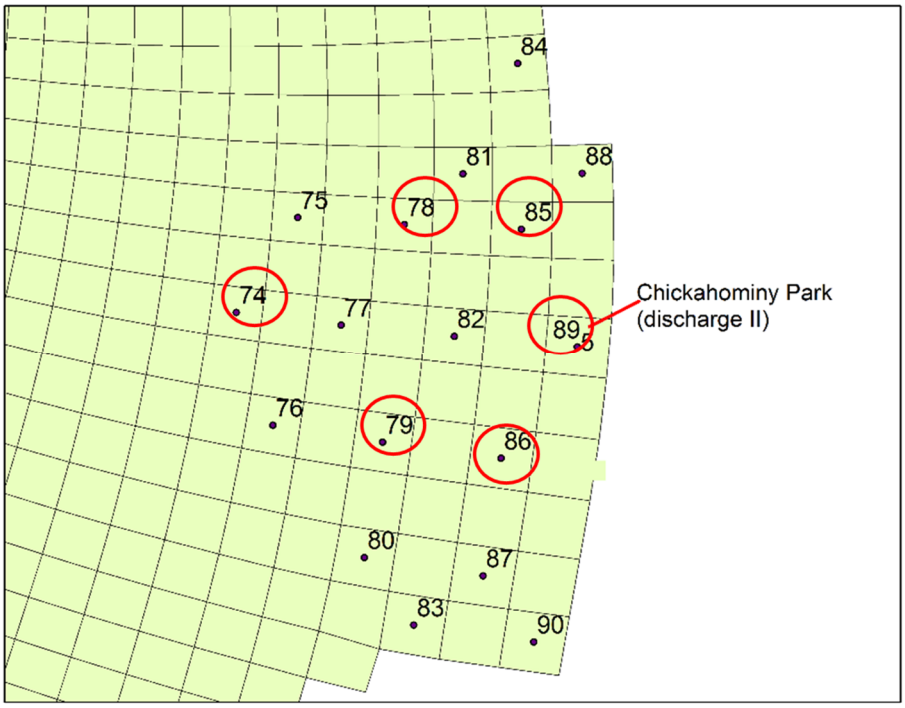


Figure 3-1-5. Locations of output of salinity time series for comparison (red circles are locations for time series and numbers are station ID for time series plots).

4.0 Model Results

4.1 Brickyard Landing--Phase II

The time series plot of the model simulation results at withdrawal location of Brickyard Landing are shown in Figure 4-1-1. The blue lines are baseline condition and red lines are scenario results at selected locations near the withdrawal location (see Figs 3-1-2 to 3-15). The difference between scenario and baseline salinity together with salinity comparison at the surface and bottom are shown in the figure. It can be seen that changes of salinity near the withdrawal location are minor. The largest difference is less than 0.31 psu. Compared to the variation of salinity, which varies from 0.0 to 6.0 psu, changes are minor. As water is pumped out, water will be quickly replaced by upstream or downstream waters. The salinity can be increased during flood tide and decreased during ebb tide. A slight increase of salinity occurred for most of the simulation period.

Figure 4-1-2 show the change of salinity at the discharge location. The discharge outlet is near the bottom. The difference between scenarios and baseline condition near the bottom is plotted for comparison together with surface and bottom salinity. It can be seen that salinity increased about 1.18 psu, which is about 19% of its maximum salinity. Because the discharge flow is 22% of withdrawal, the increase of salinity is not very significant due to the strong tidal effect at this location. Dilution caused by tide reduces the impact of discharge of salt water. The negative values of the difference between scenario and baseline condition are caused by the tide and depend on tidal phase. The variation further increases at the location away from the discharge location.

Figures 4-1-3 and 4-1-4 show the comparison of surface and bottom salinity at Day 150, which experiences a high flow and low salinity intrusion. The hourly salinity plots for a tidal cycle are presented. It can be seen that salinity will increase slightly during flood tide, but will decrease during ebb tide. The salinity contour shows a slight migration upstream at different phases of the tide. Figures 4-1-5 and 4-1-6 show the comparison of surface and bottom salinity at Day 300, which represents the condition of low flow with high salinity. The change of salinity is different from the high-flow period. It can be seen that the salinity intrusion upstream of withdrawal decreases, but increases lightly at the discharge site at the bottom. As brine water is removed from the channel during the low-flow period, the density changes and a rebalance of the pressure gradient results in a decrease of salt water intrusion in the upstream. However, the change of the salinity contour distribution is within a narrow range.

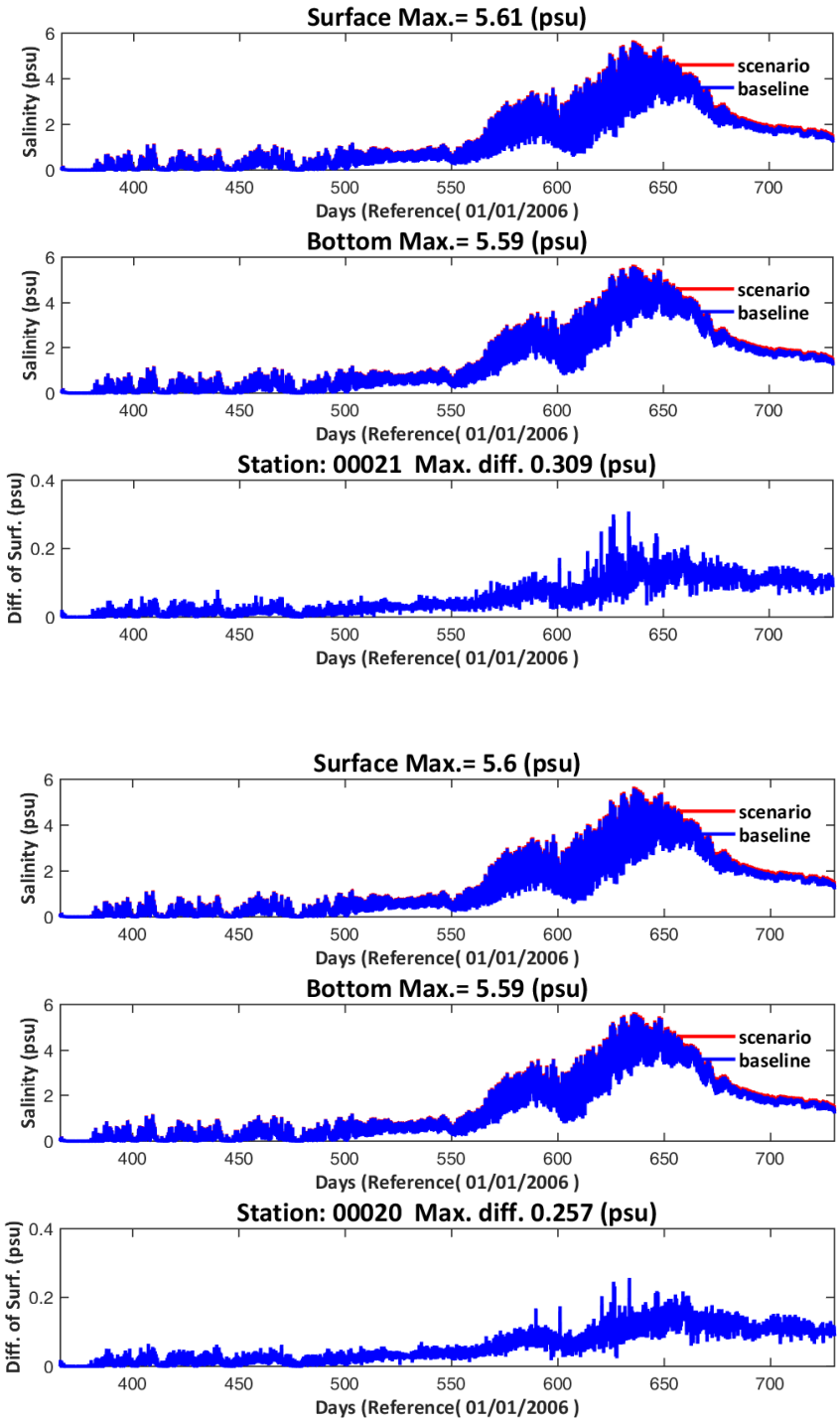


Figure 4-1-1. Comparison of time series of salinity, and difference between scenario and baseline near the surface at selected station at Brickyard Landing withdrawal site (number shown in 3rd panel is station ID).

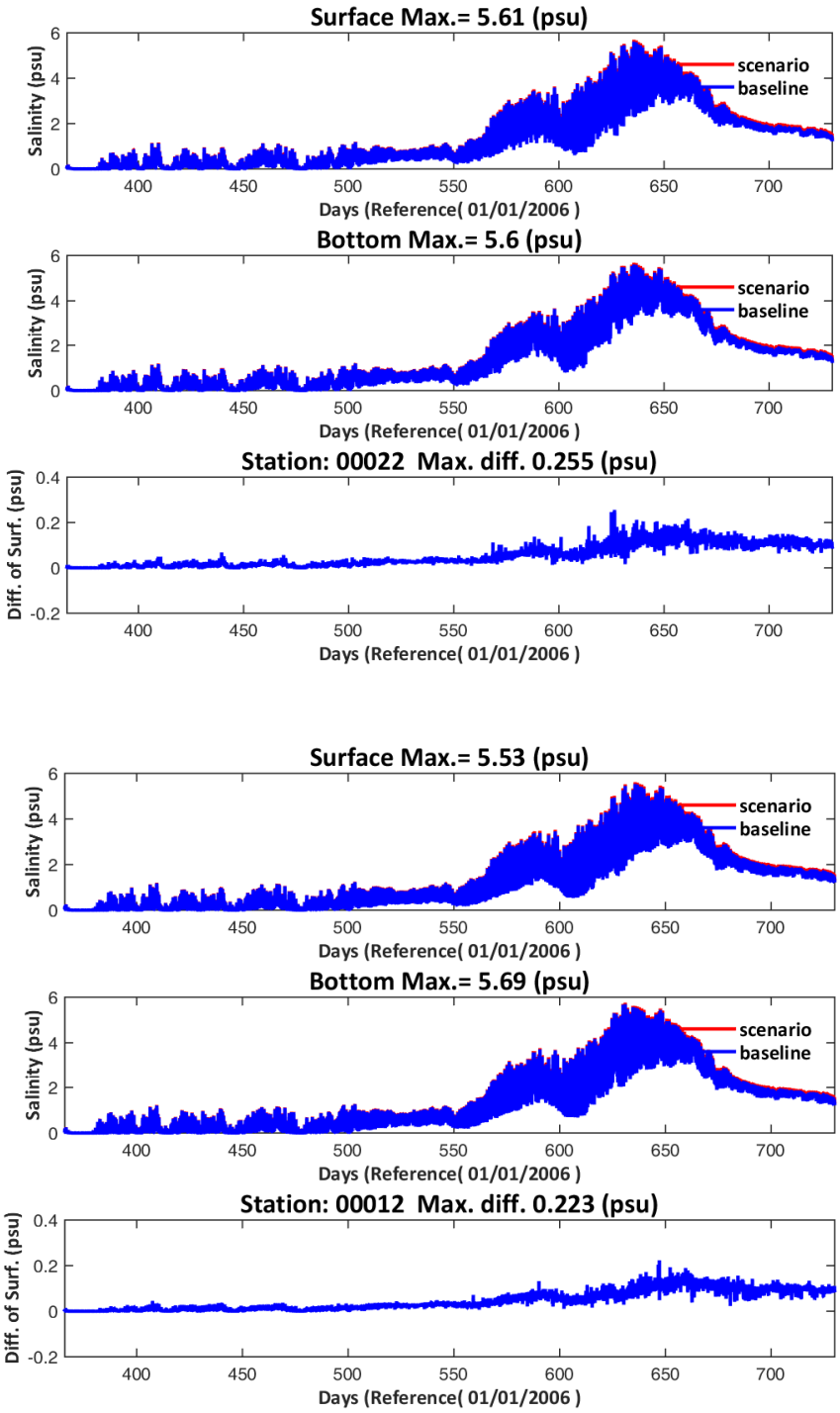


Figure 4-1-1. Continue.

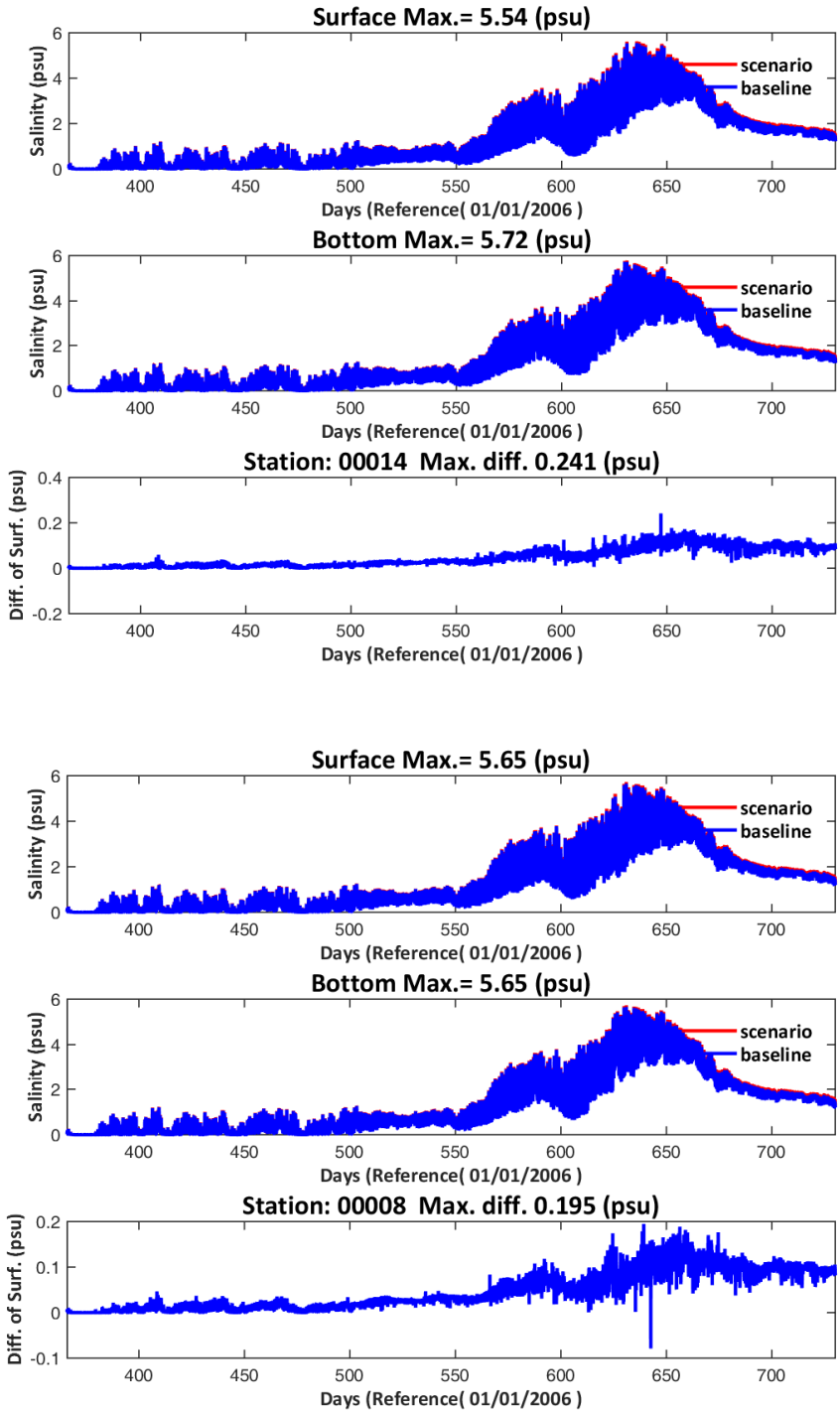


Figure 4-1-1. Continue.

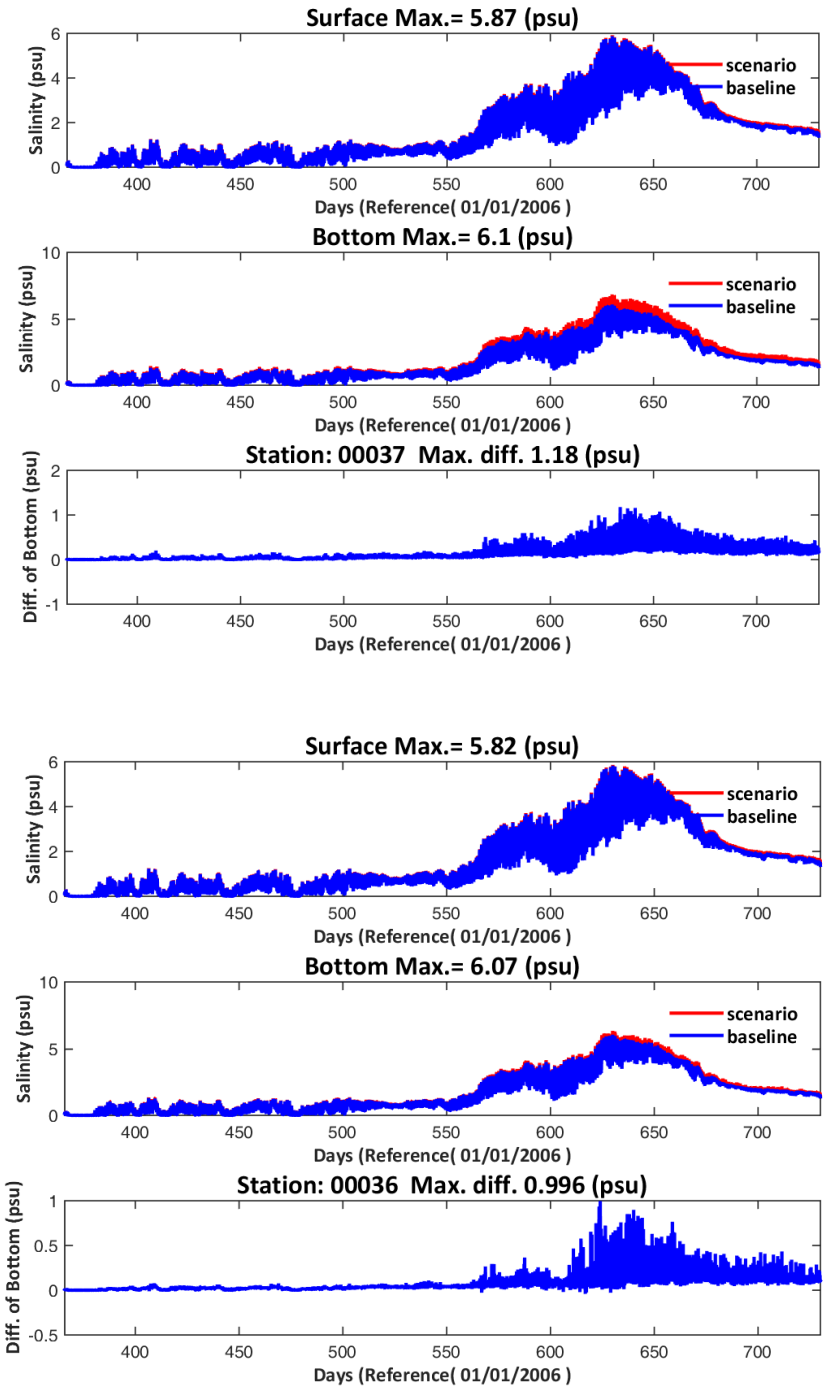


Figure 4-1-2. Comparison of time series of salinity, and difference between scenario and baseline near the bottom at selected station at Brickyard Landing discharge site (number shown in 3rd panel is station ID)

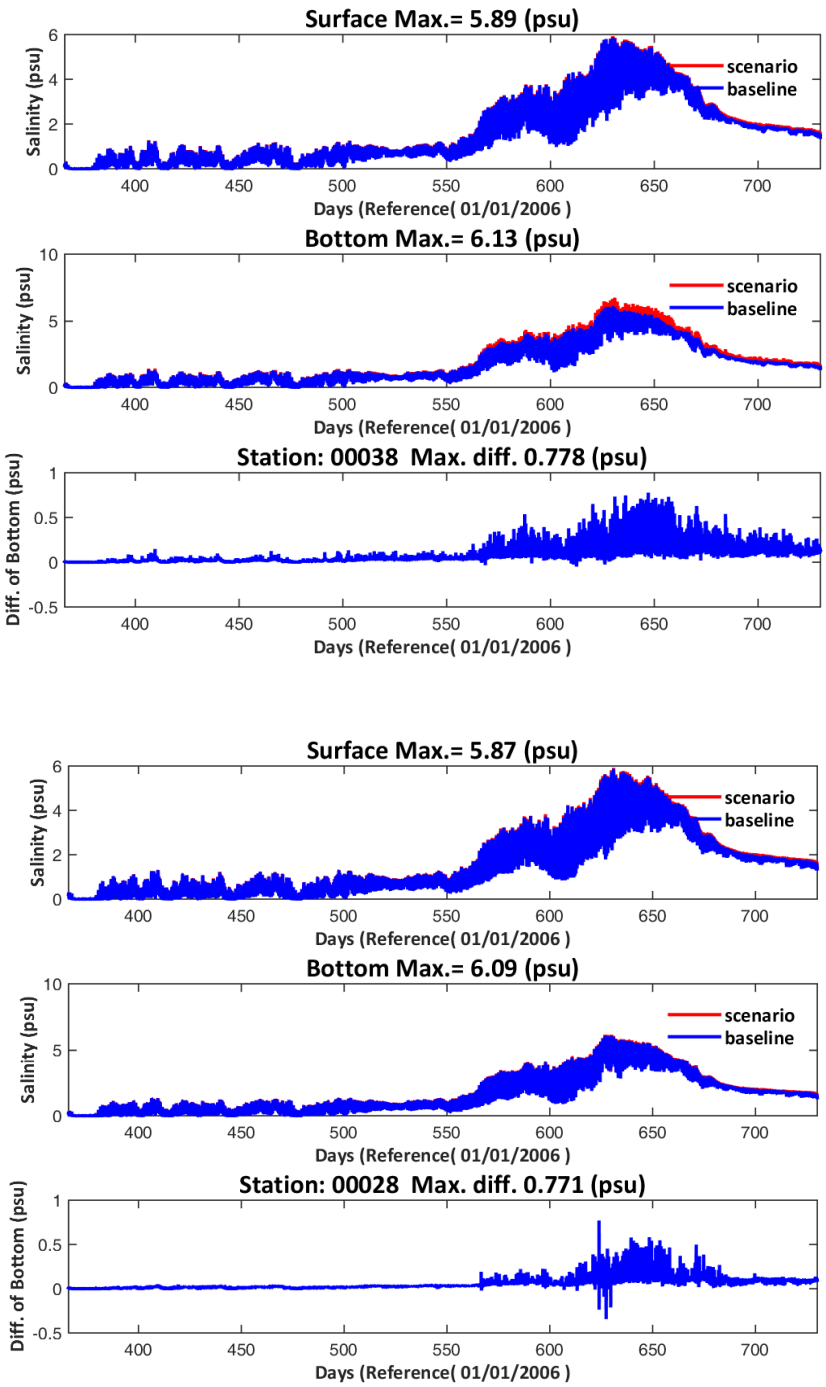


Figure 4-1-2. Continue.

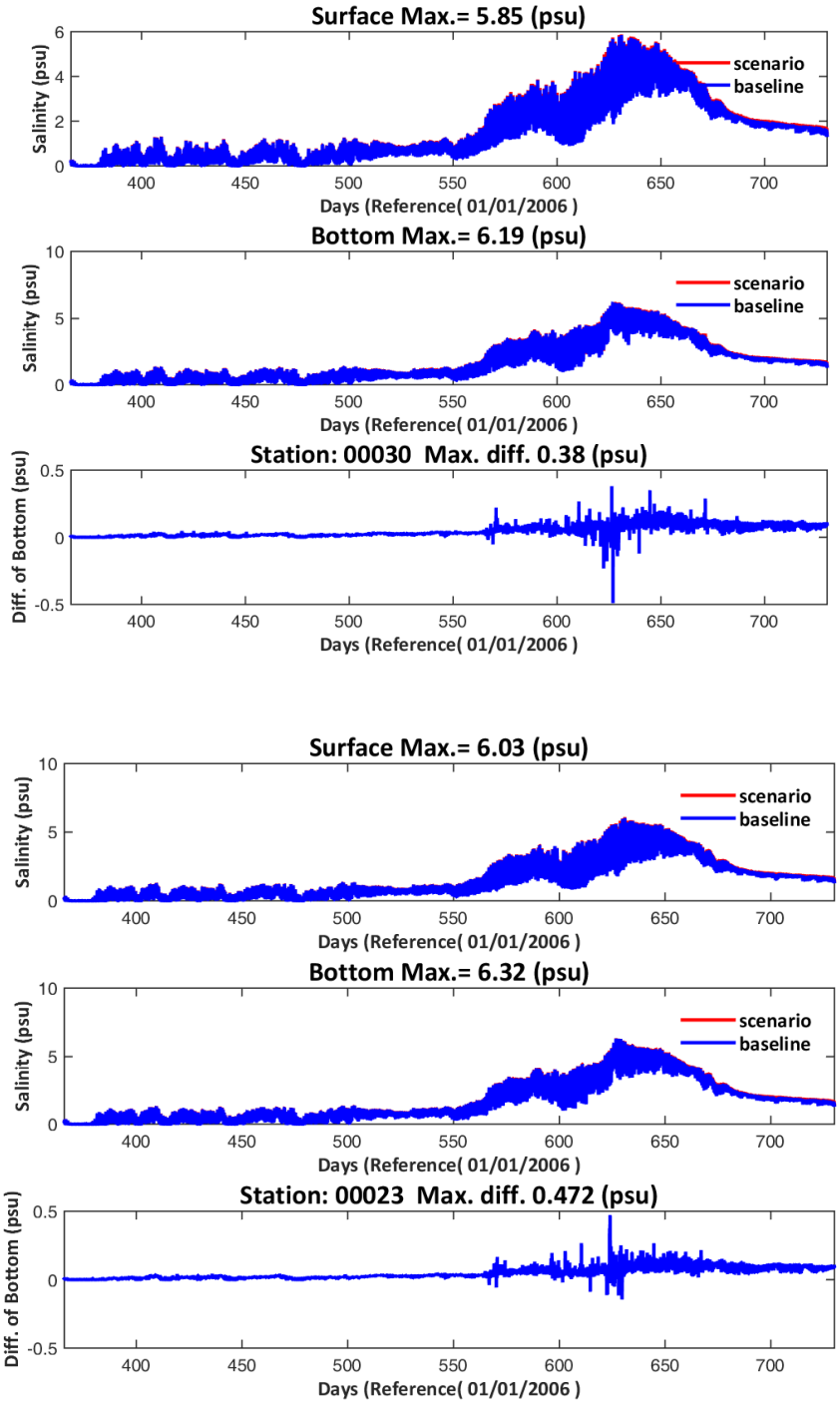
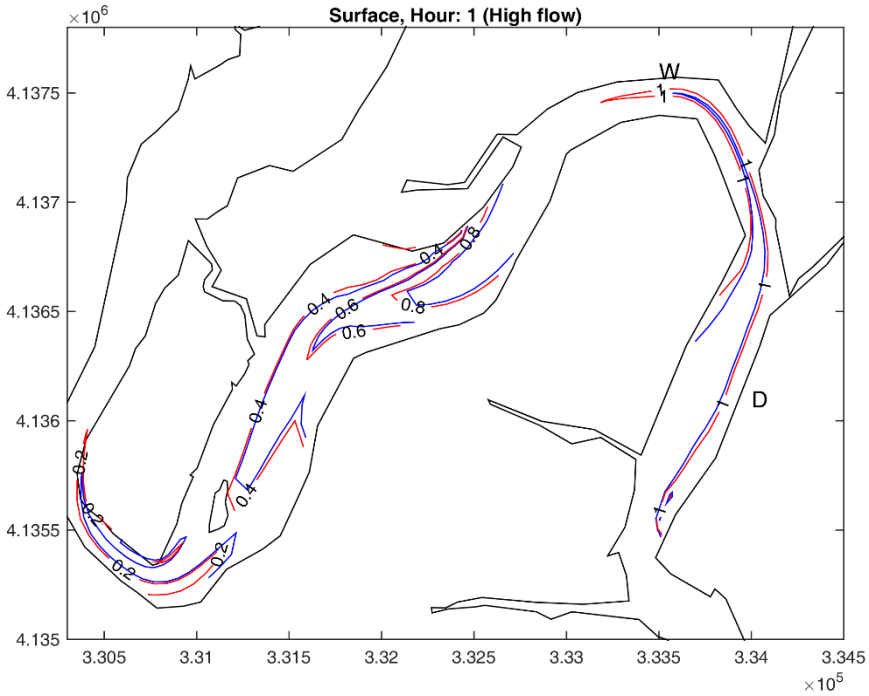
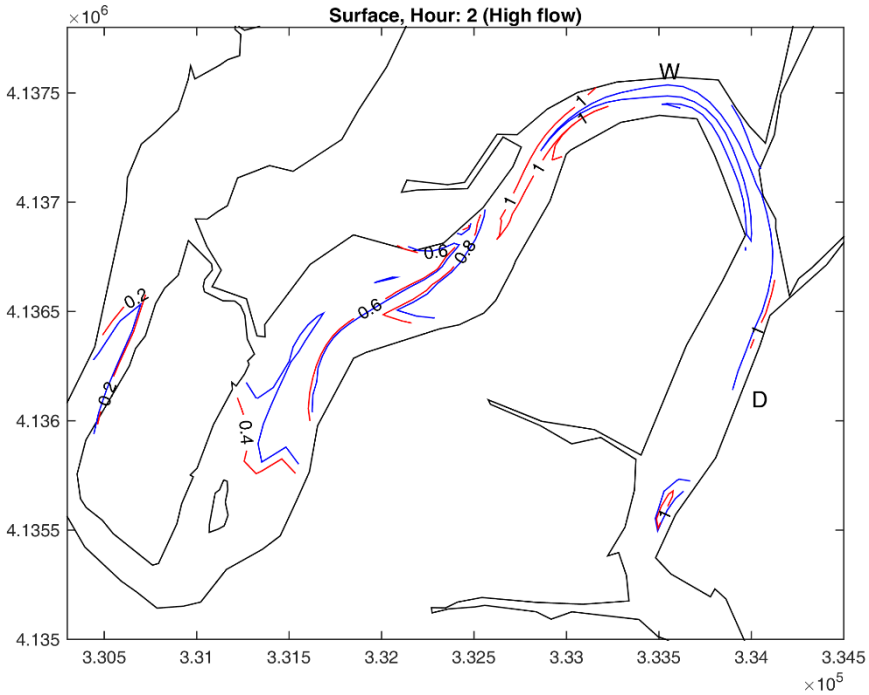
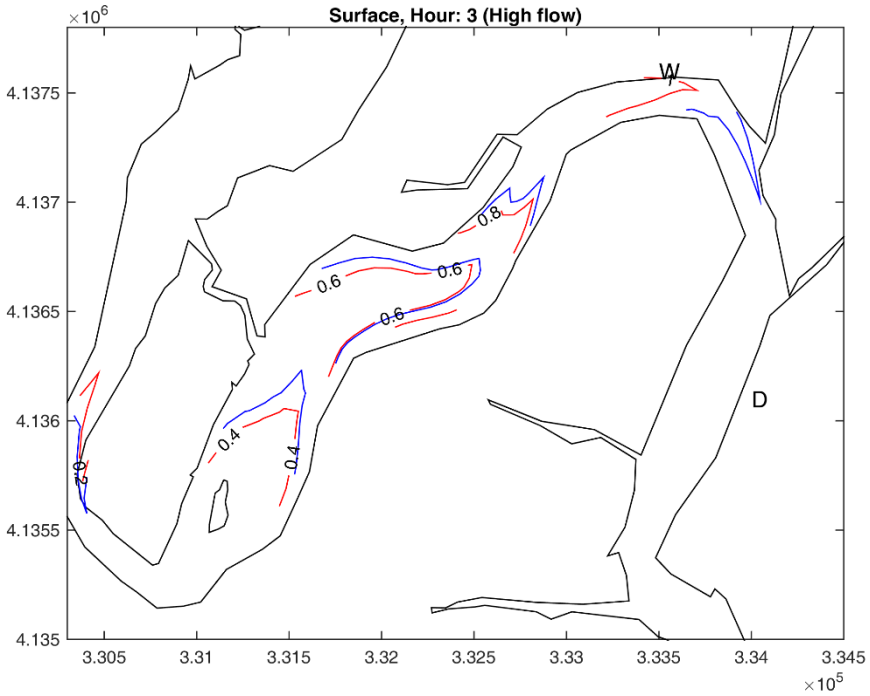
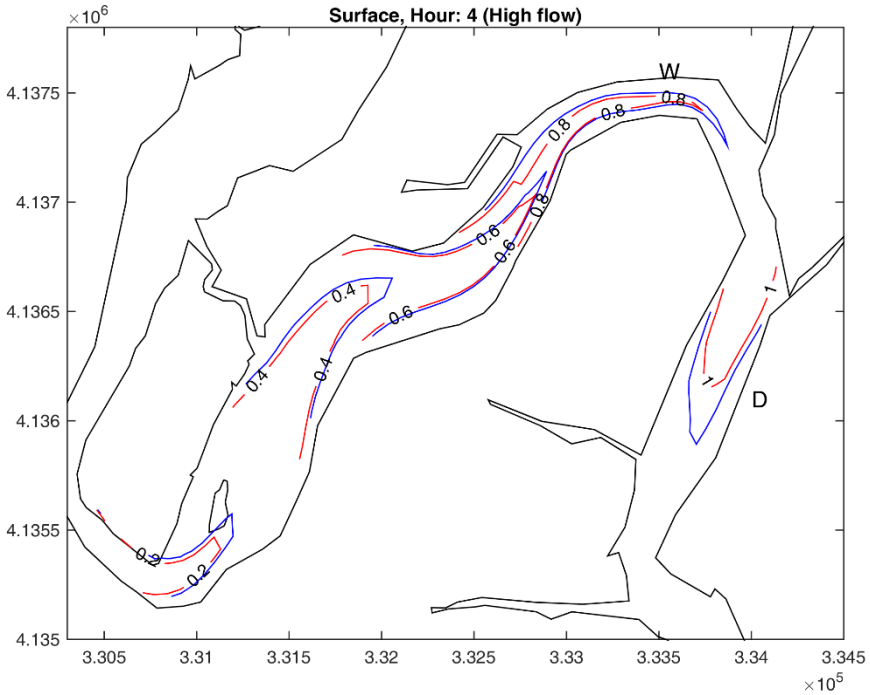


Figure 4-1-2. Continue.


Surface, Hour: 1 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.2
0.4
0.6
0.8
1


Surface, Hour: 2 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.2
0.4
0.6
0.8
1


Surface, Hour: 3 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.8
0.6
0.6
0.6
0.4
0.4
0.2


Surface, Hour: 4 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.8
0.8
0.8
0.8
0.6
0.6
0.6
0.4
0.4
0.4
1
1
1
0.2
0.2

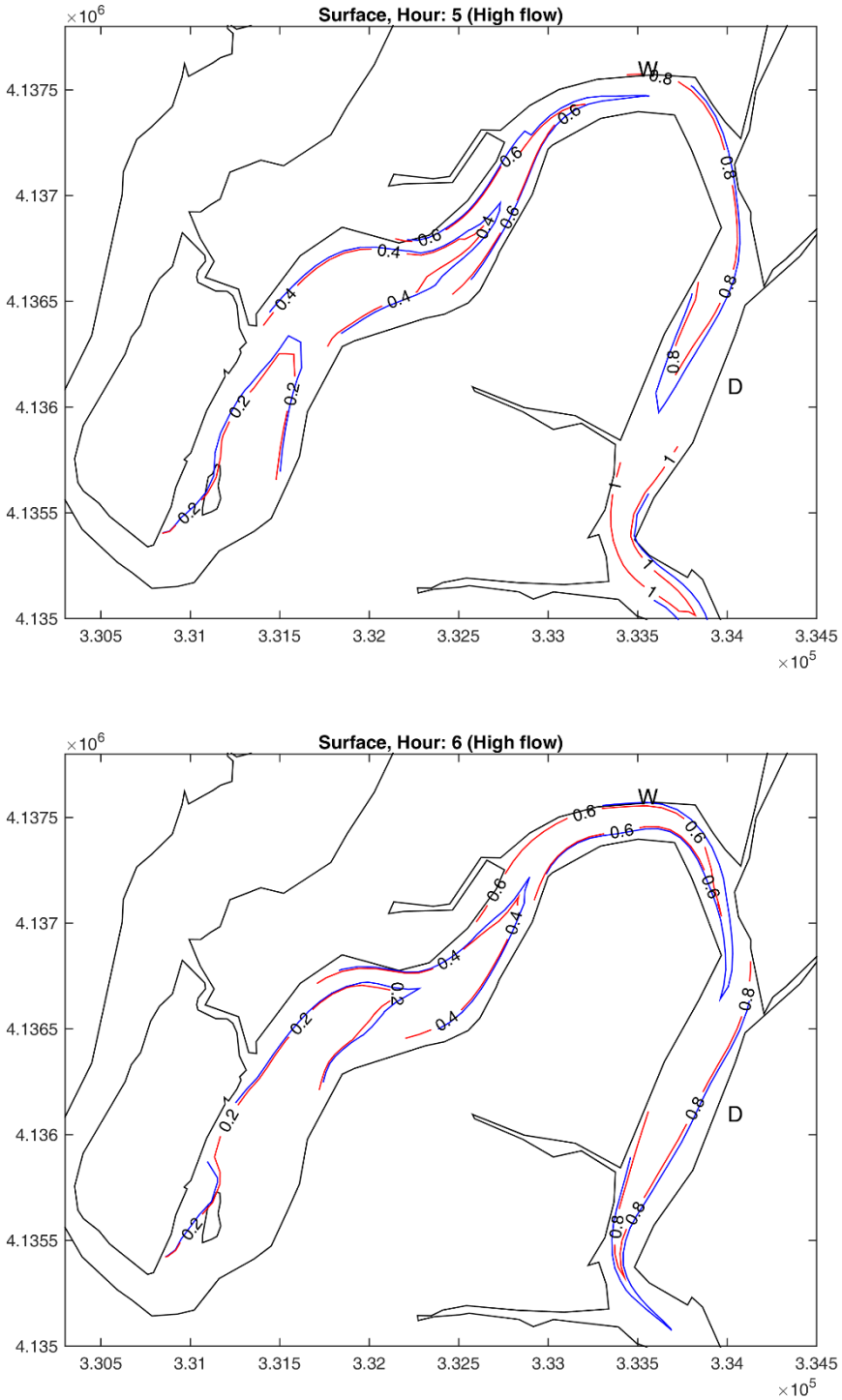
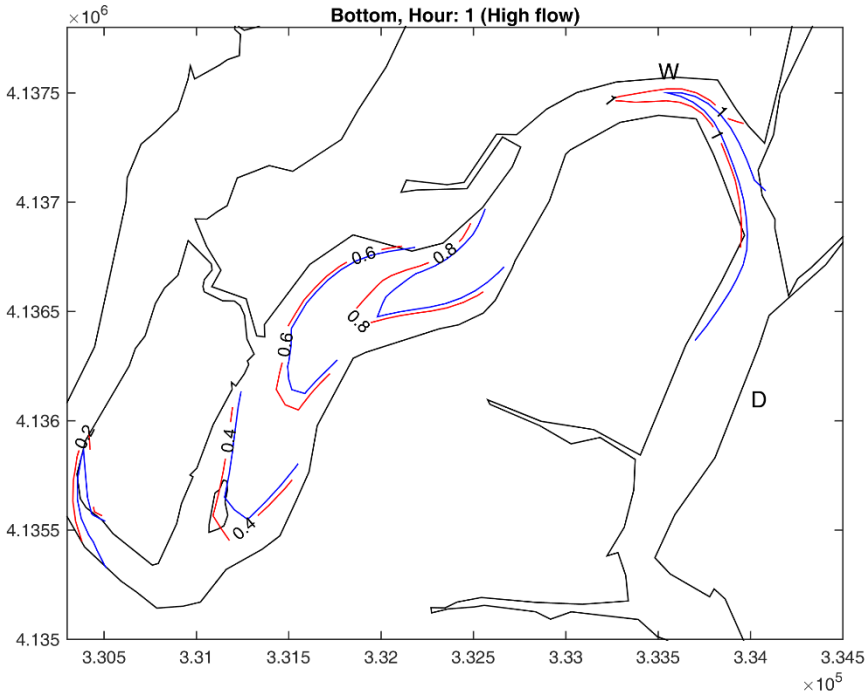
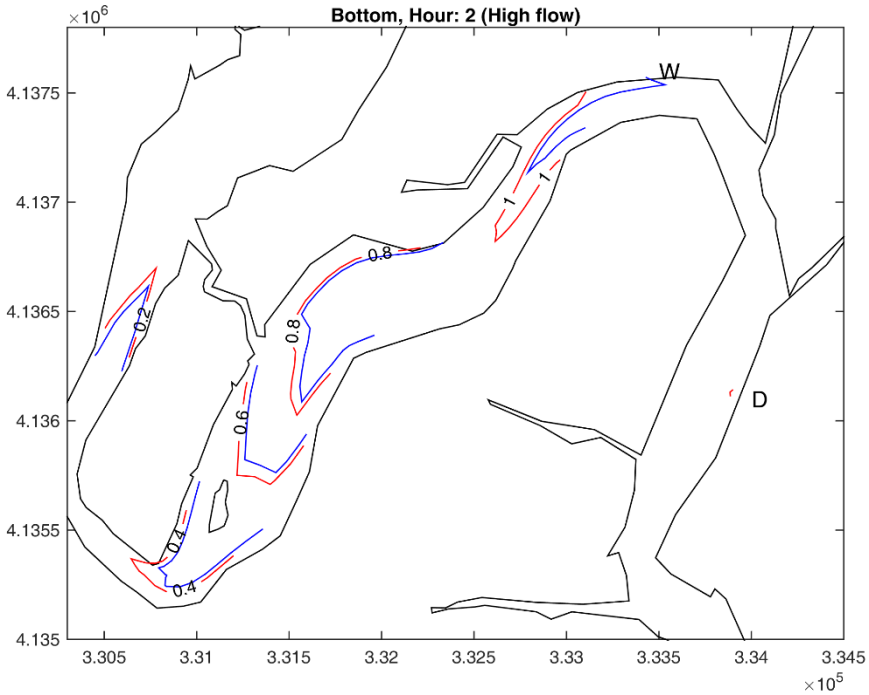
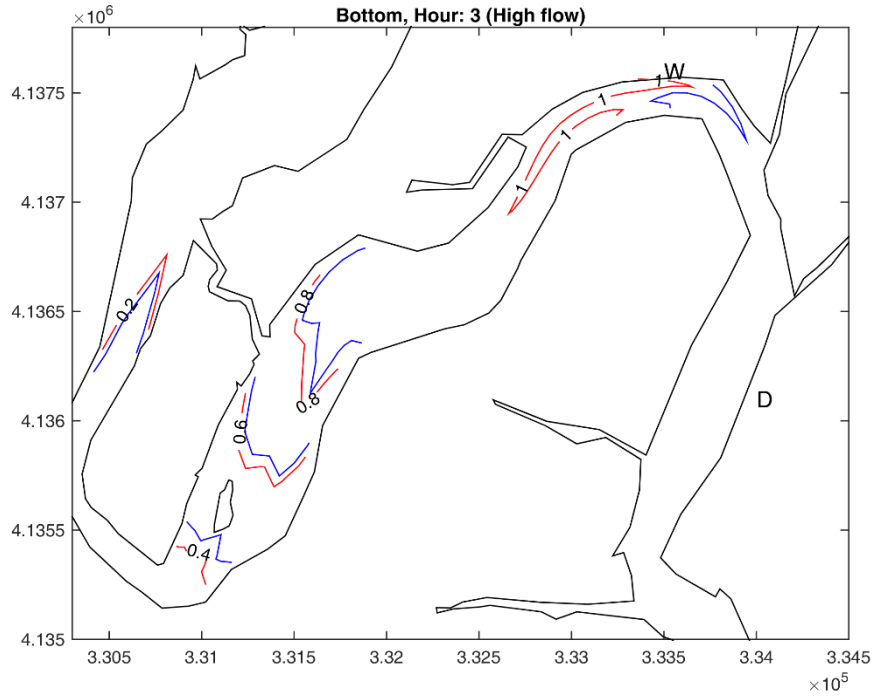
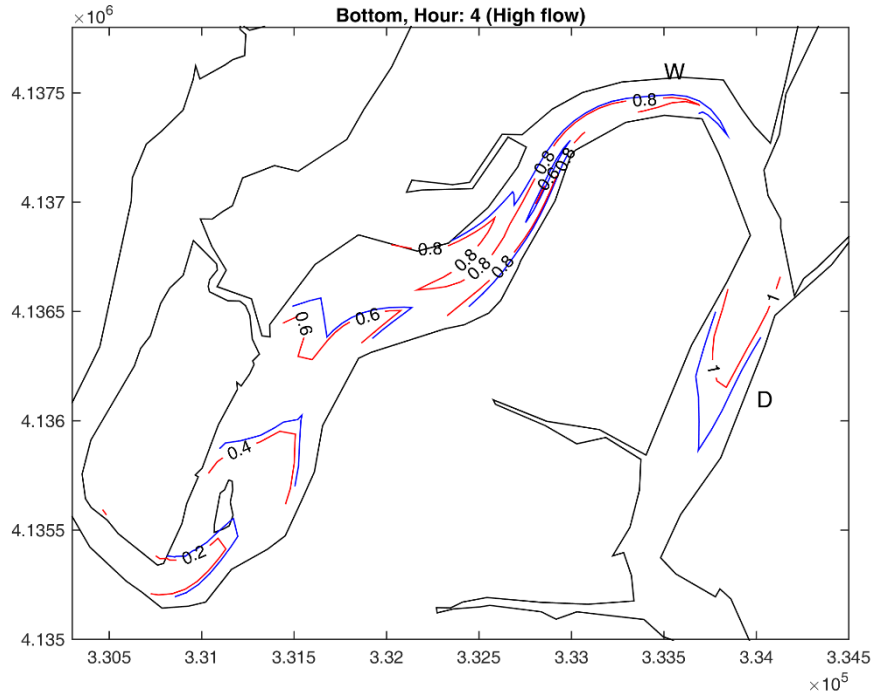


Figure 4-1-3. Comparison of surface salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during high flow period (W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
1
0.6
0.8
0.8
0.6
0.2
0.4
0.4


Bottom, Hour: 2 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
1
0.8
0.8
0.2
0.6
0.4
0.4


Bottom, Hour: 3 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.2
0.8
0.6
0.4


Bottom, Hour: 4 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.8
0.6
0.4
0.2
1

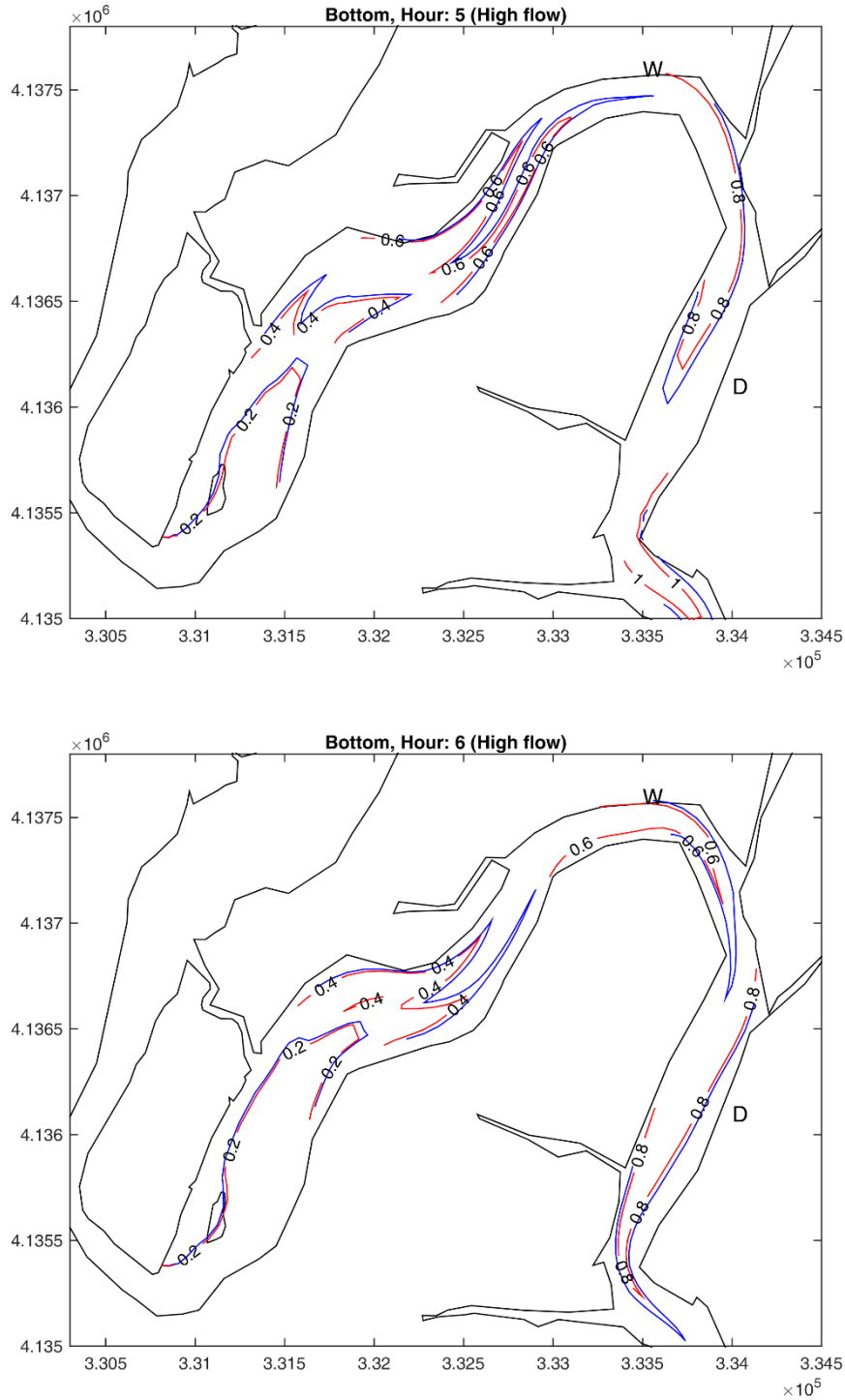
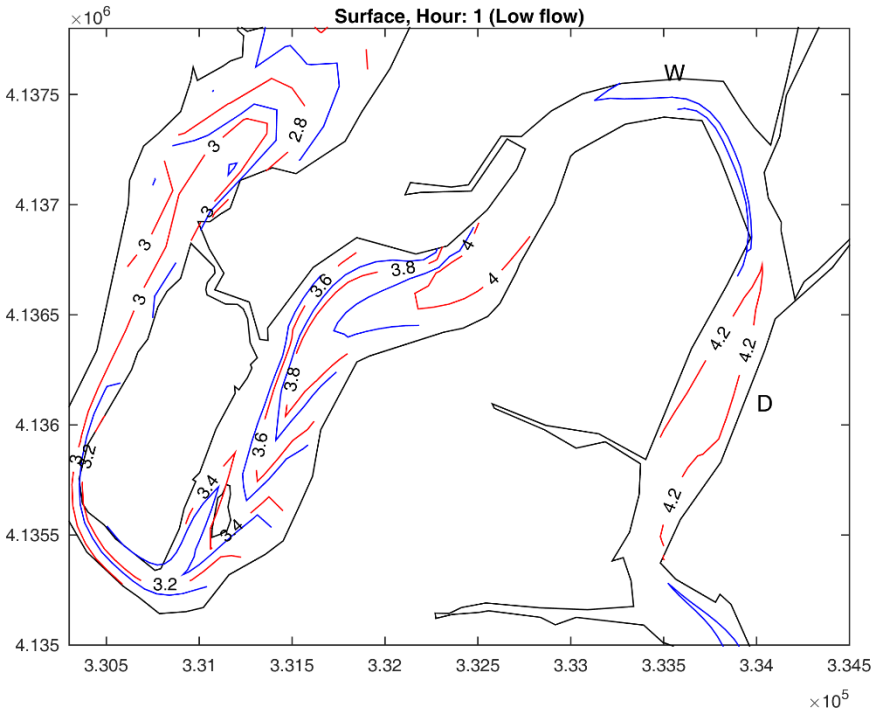
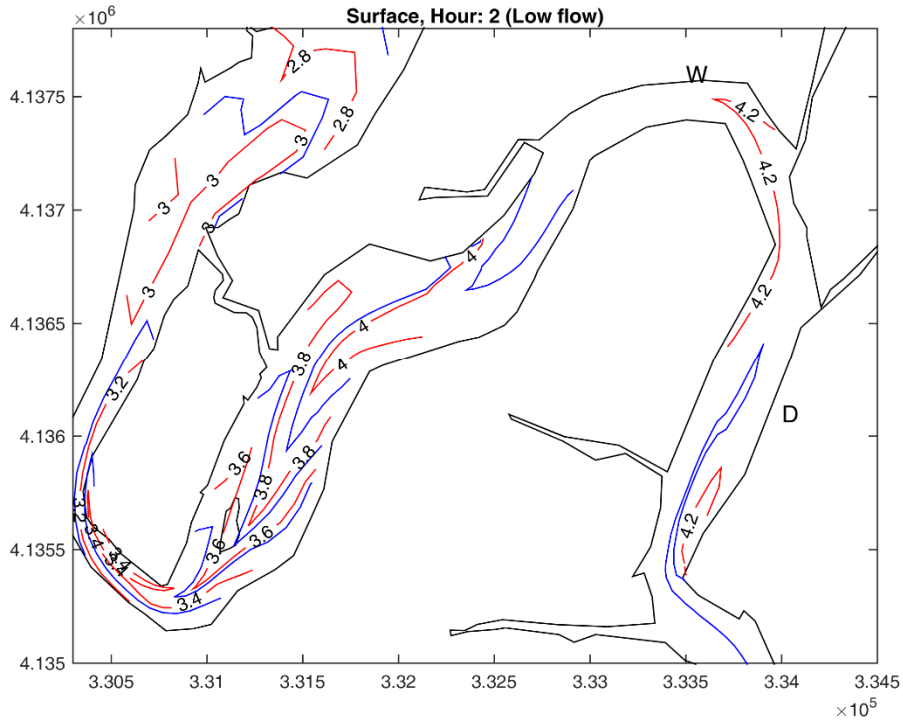
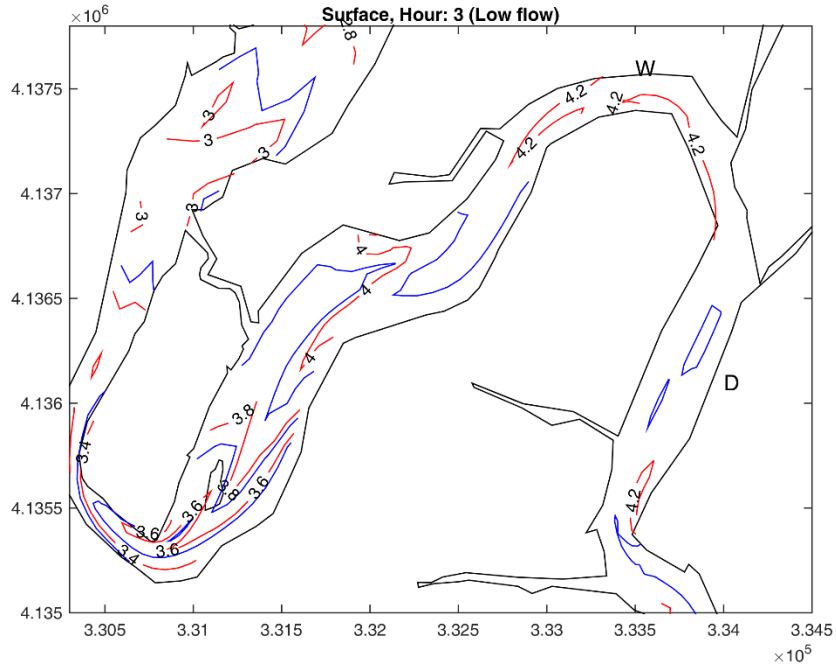
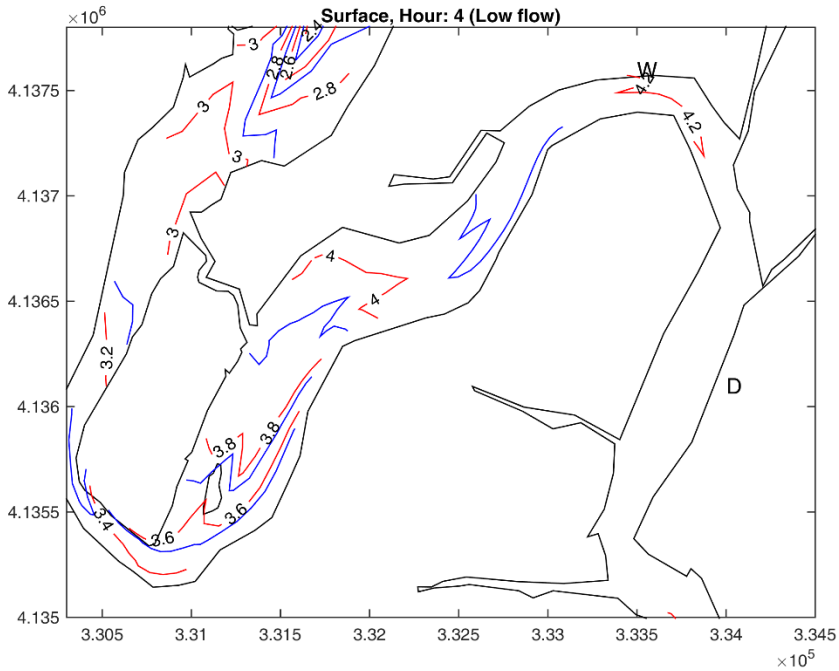


Figure 4-1-4. Comparison of bottom salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
2.8
3
3.2
3.4
3.6
3.8
4
4.2


Surface, Hour: 2 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
2.8
3
3.2
3.4
3.6
3.8
4
4.2


Surface, Hour: 3 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D


Surface, Hour: 4 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D

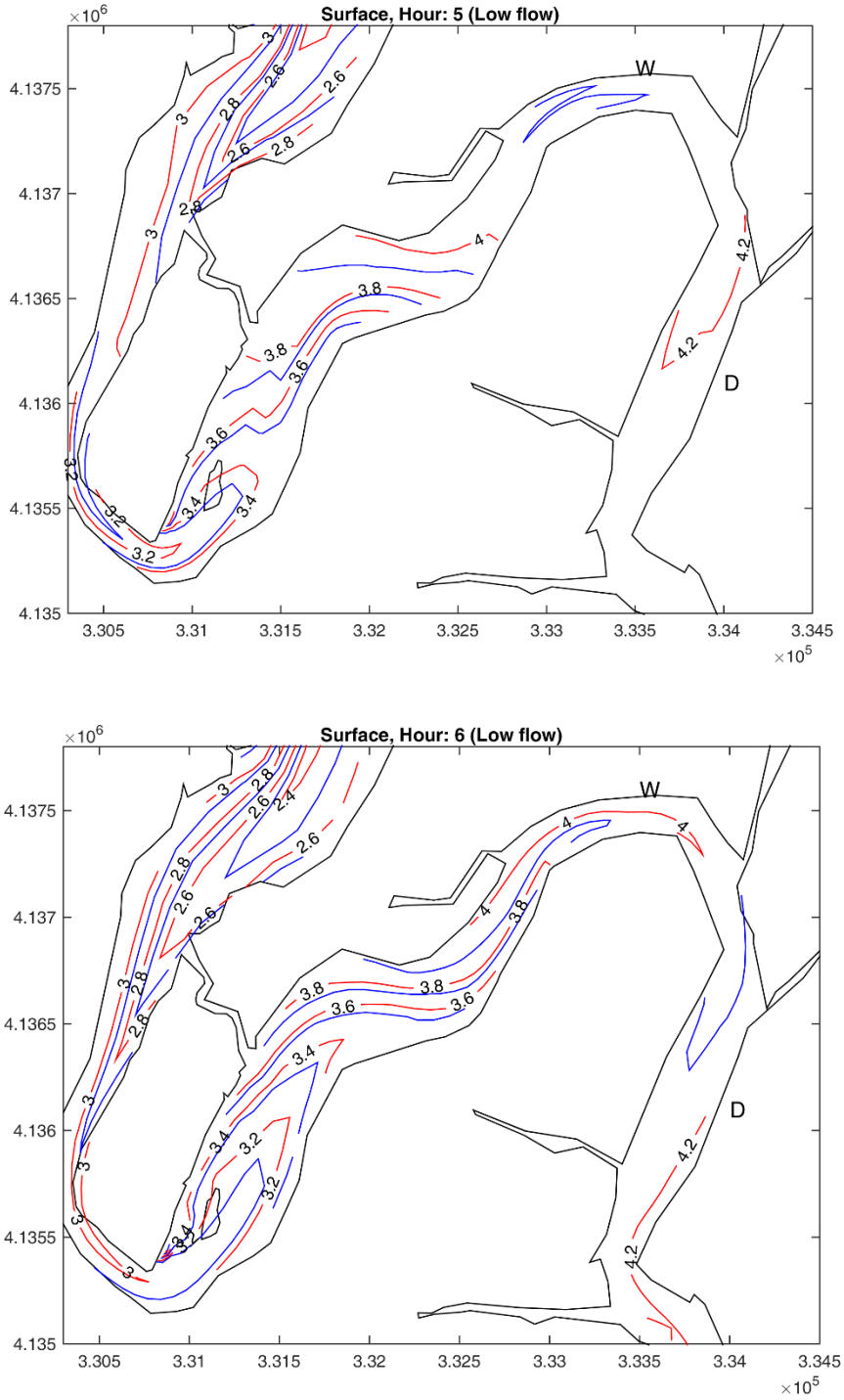
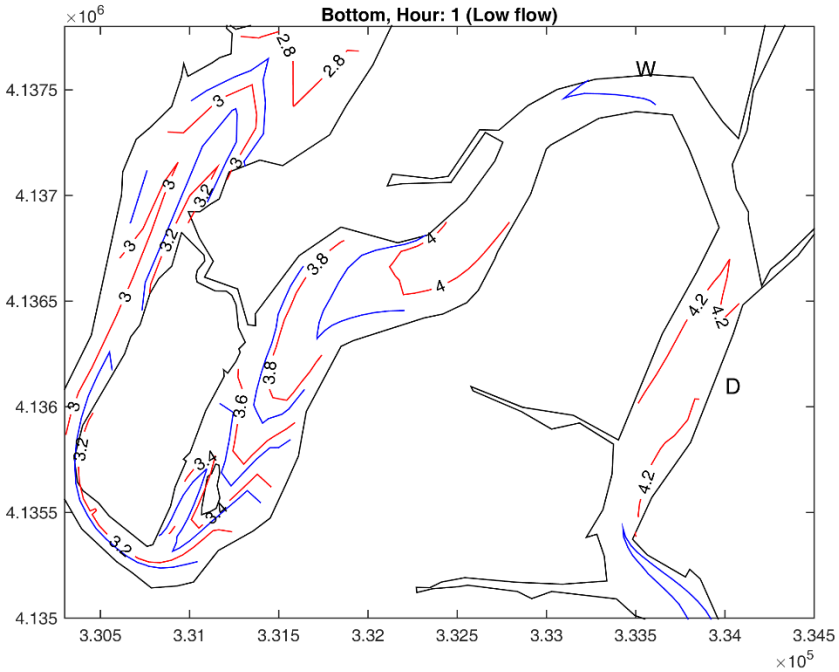
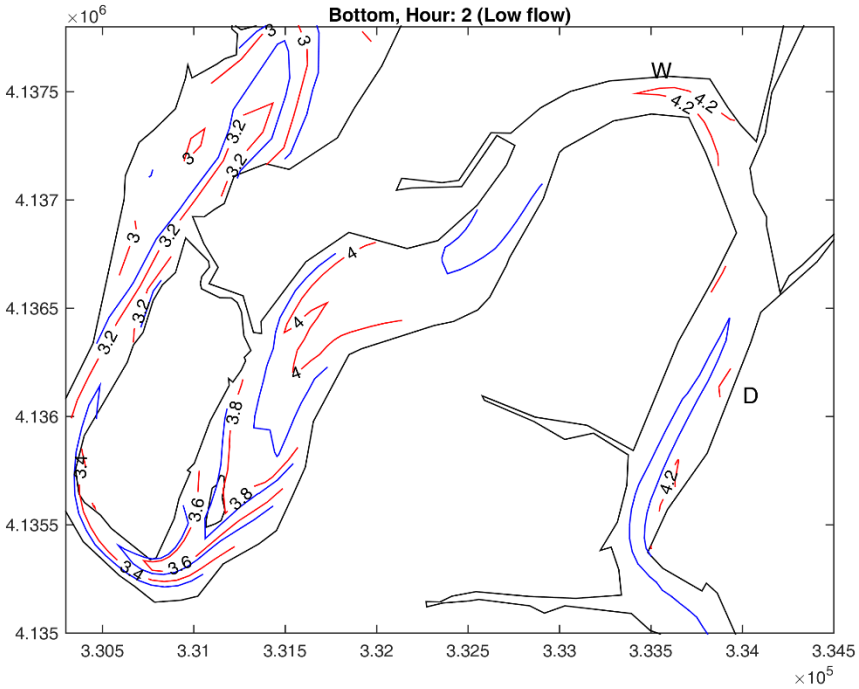
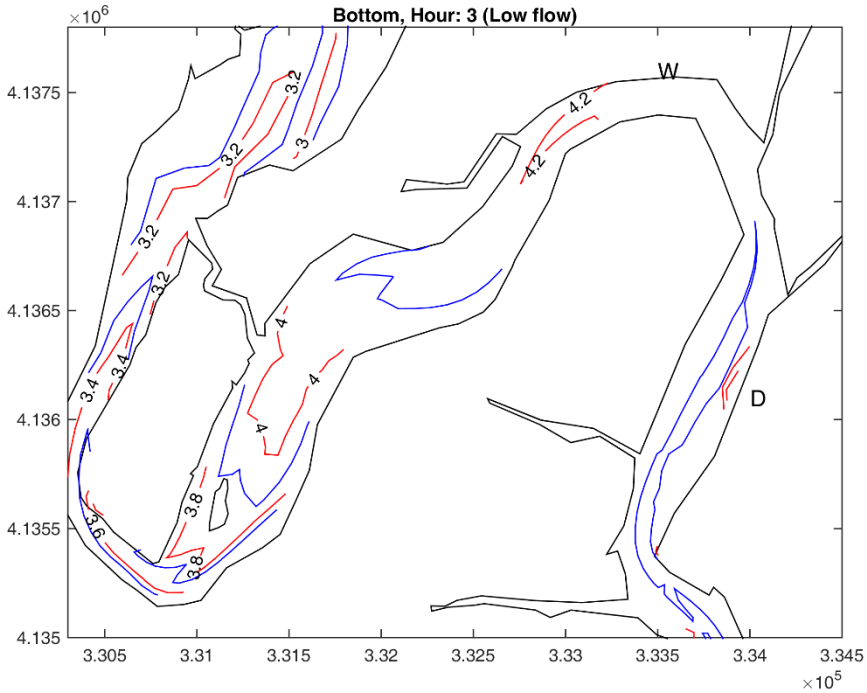
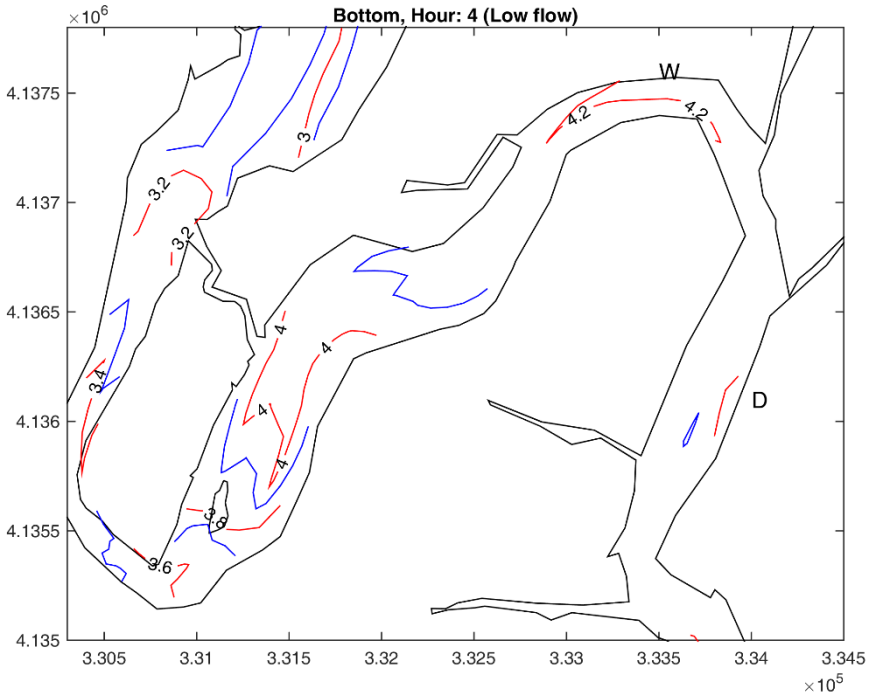


Figure 4-1-5. Comparison of Surface salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D


Bottom, Hour: 2 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D


Bottom, Hour: 3 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3.2
3
4.2
4
3.4
3.8
3.6


Bottom, Hour: 4 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3
3.2
4.2
4
3.4
3.6

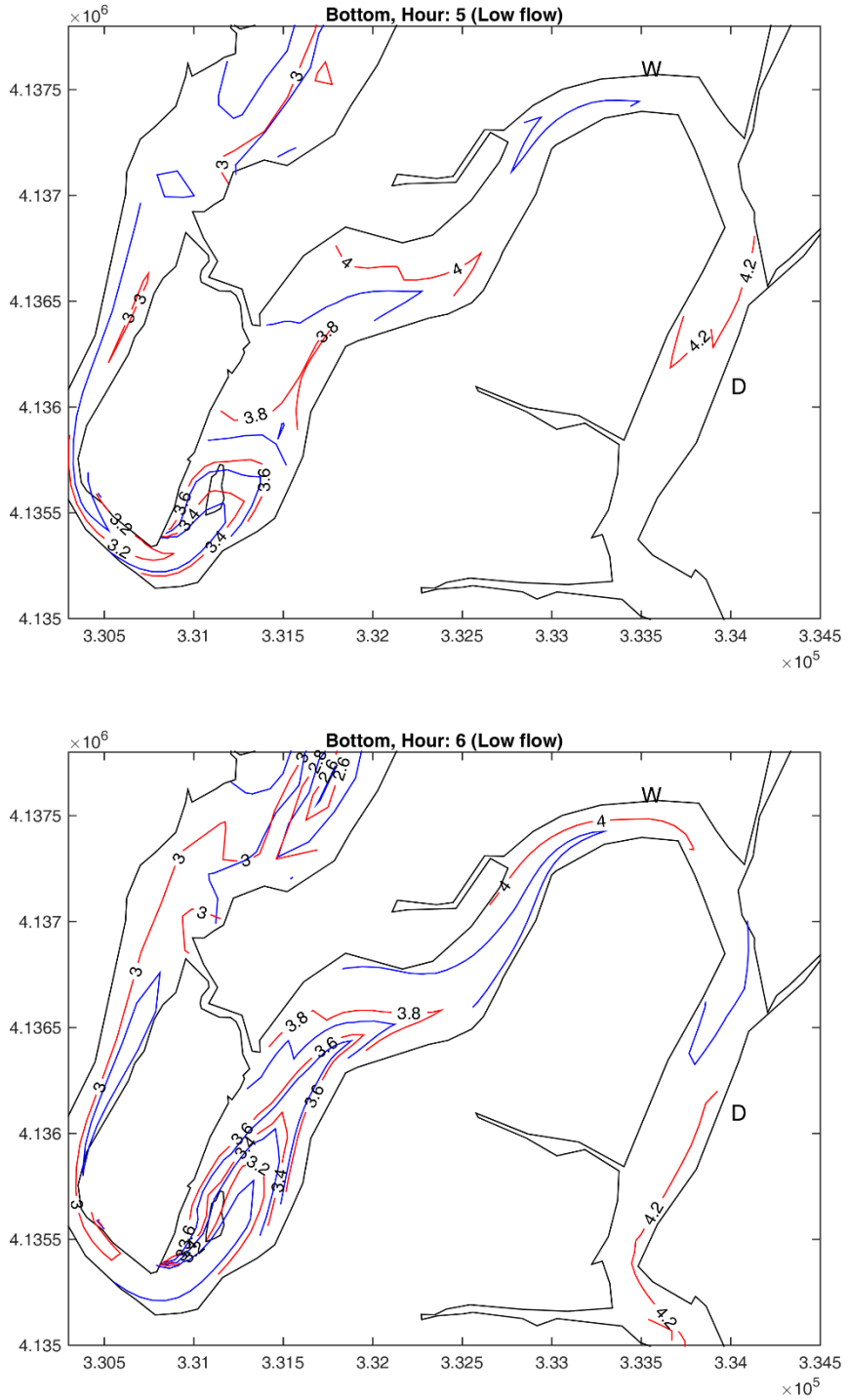
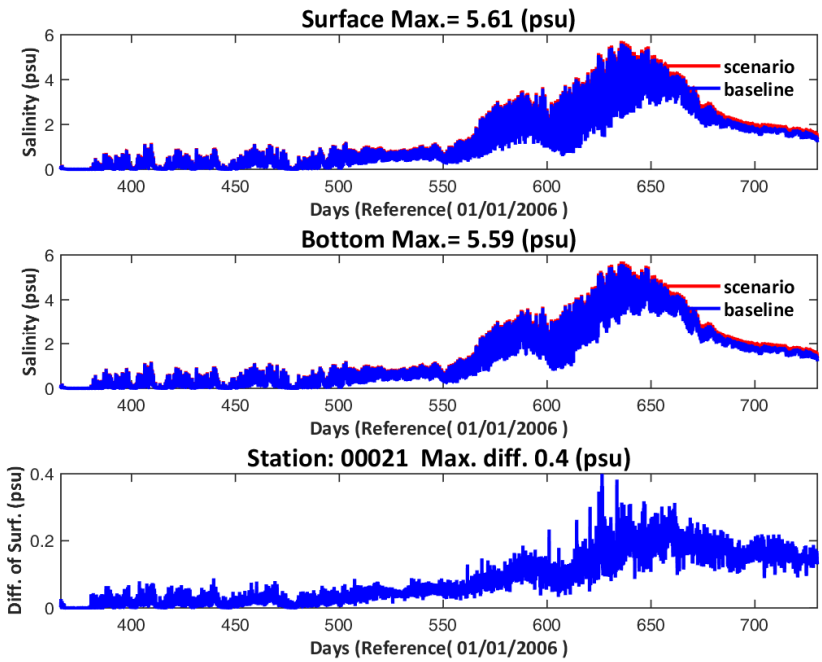


Figure 4-1-6. Comparison of bottom salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

4.2 Brickyard Landing--Phase III

Similar to Phase II, the time series and salinity distributions are compared in Figures 4-2-1 to 4-2-6. The results are similar to those of Phase II with slight increases of salinity at withdrawal location. Salinity increases at withdrawal location is about 0.4 psu. The maximum salinity at discharge site is about 1.7 psu, which is about 28% of maximum salinity during low flow period. Horizontal distributions of salinity at surface and bottom are shown in Figures 4-2-3 to 4-2-6. Salinity changes with tide phase. The salinity intrusion increased slightly compared to the salinity distribution of Phase II.



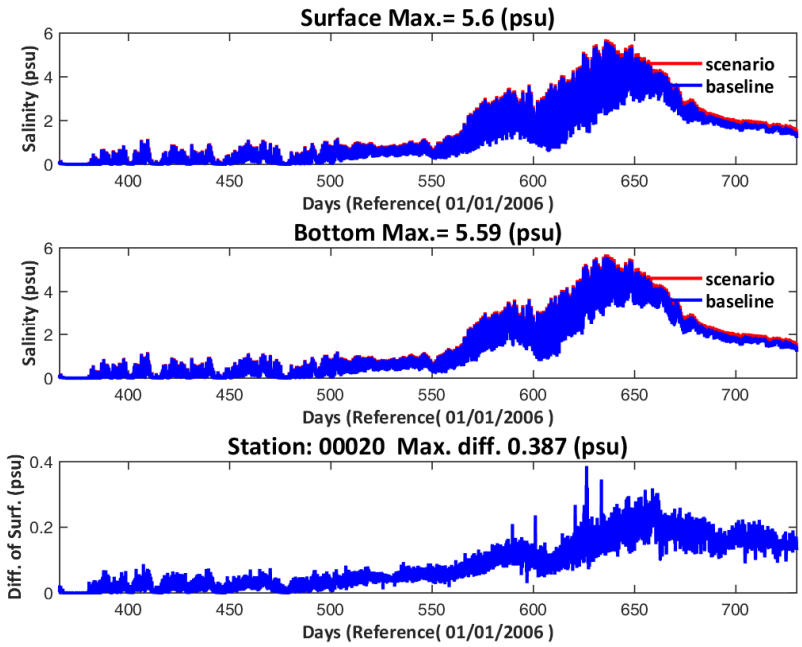
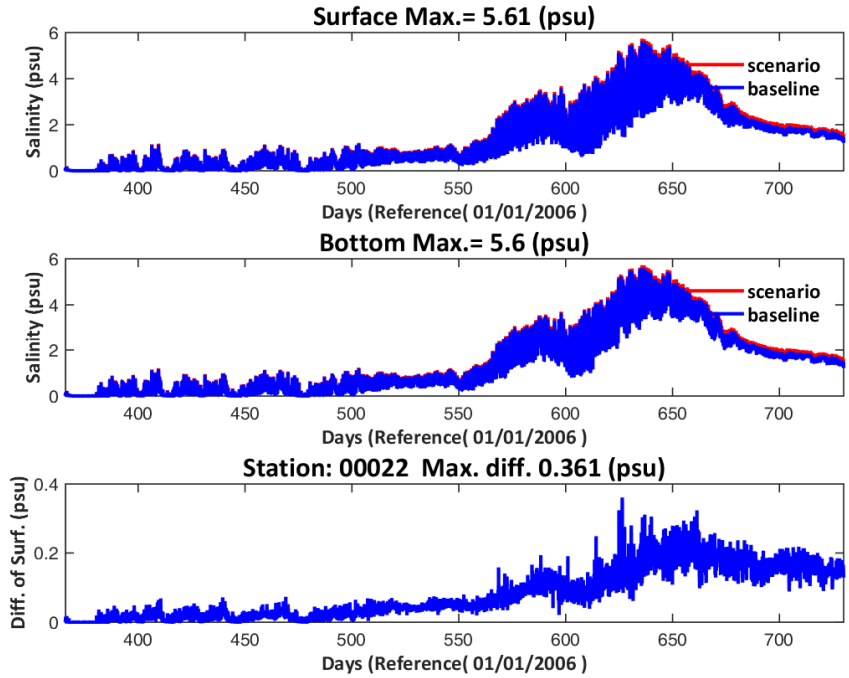


Figure 4-2-1. Comparison of time series of salinity and difference between scenario and baseline near the surface at selected stations at Brickyard Landing withdrawal site (number shown in third panel is station ID).


Surface Max.= 5.61 (psu)
Salinity (psu)
scenario
baseline
Days (Reference(01/01/2006)
Bottom Max.= 5.6 (psu)
Salinity (psu)
scenario
baseline
Days (Reference(01/01/2006)
Station: 00022 Max. diff. 0.361 (psu)
Diff. of Surf. (psu)
Days (Reference(01/01/2006)

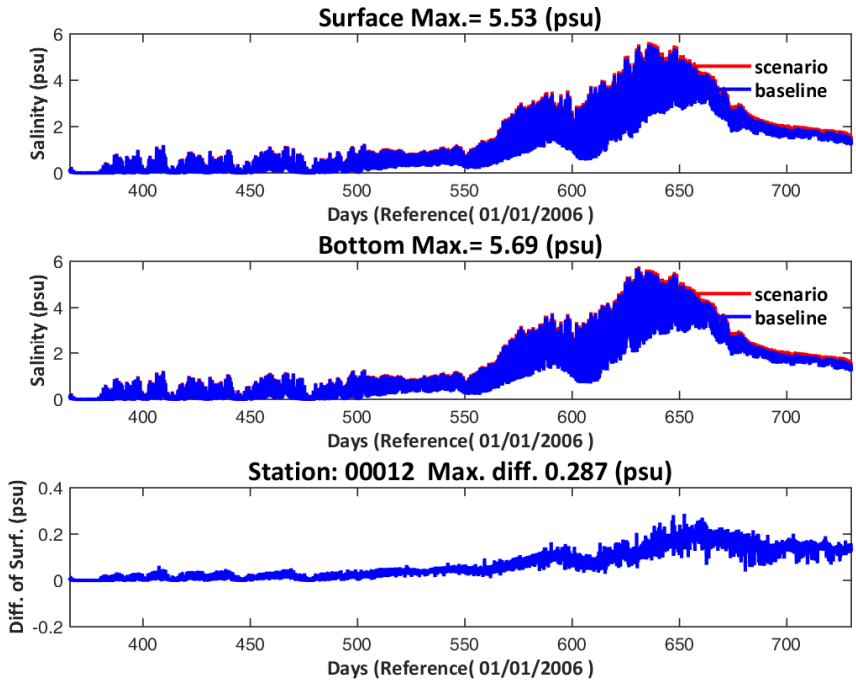
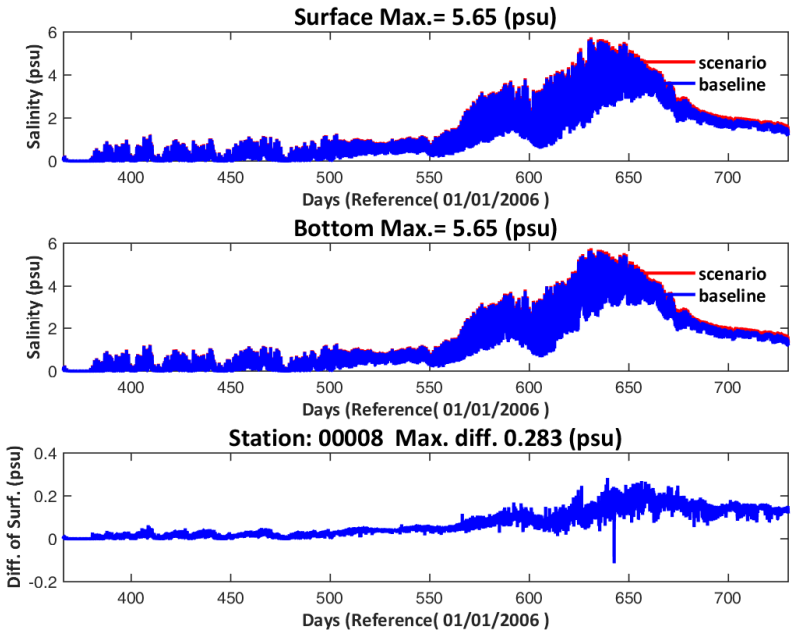

Surface Max.= 5.53 (psu)
Salinity (psu)
scenario
baseline
Days (Reference(01/01/2006)
Bottom Max.= 5.69 (psu)
Salinity (psu)
scenario
baseline
Days (Reference(01/01/2006)
Station: 00012 Max. diff. 0.287 (psu)
Diff. of Surf. (psu)
Days (Reference(01/01/2006)

Figure 4-2-1. Continue.



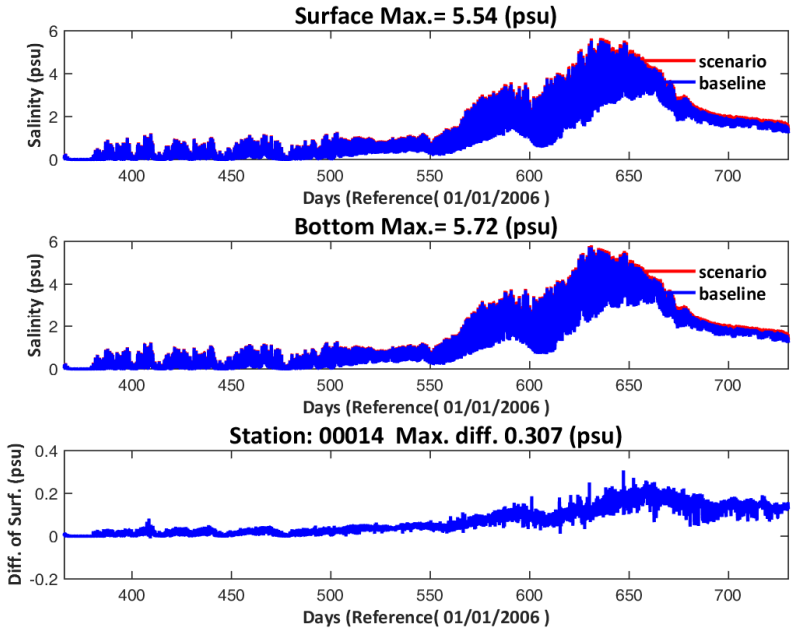


Figure 4-2-1. Continue.

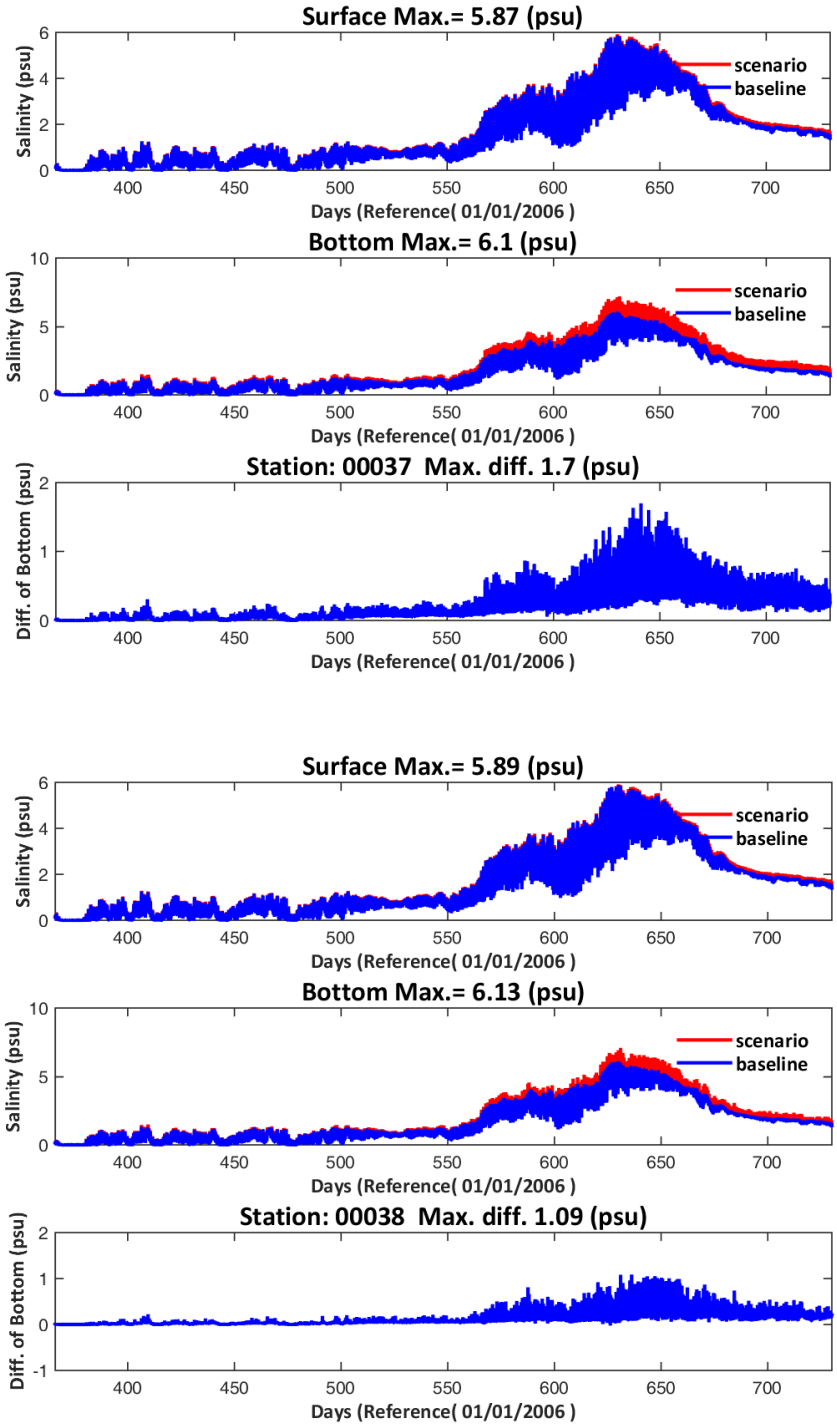


Figure 4-2-2. Comparison of time series of salinity, and difference between scenario and baseline near the bottom at selected stations at Brickyard Landing discharge site (number shown in third panel is station ID).

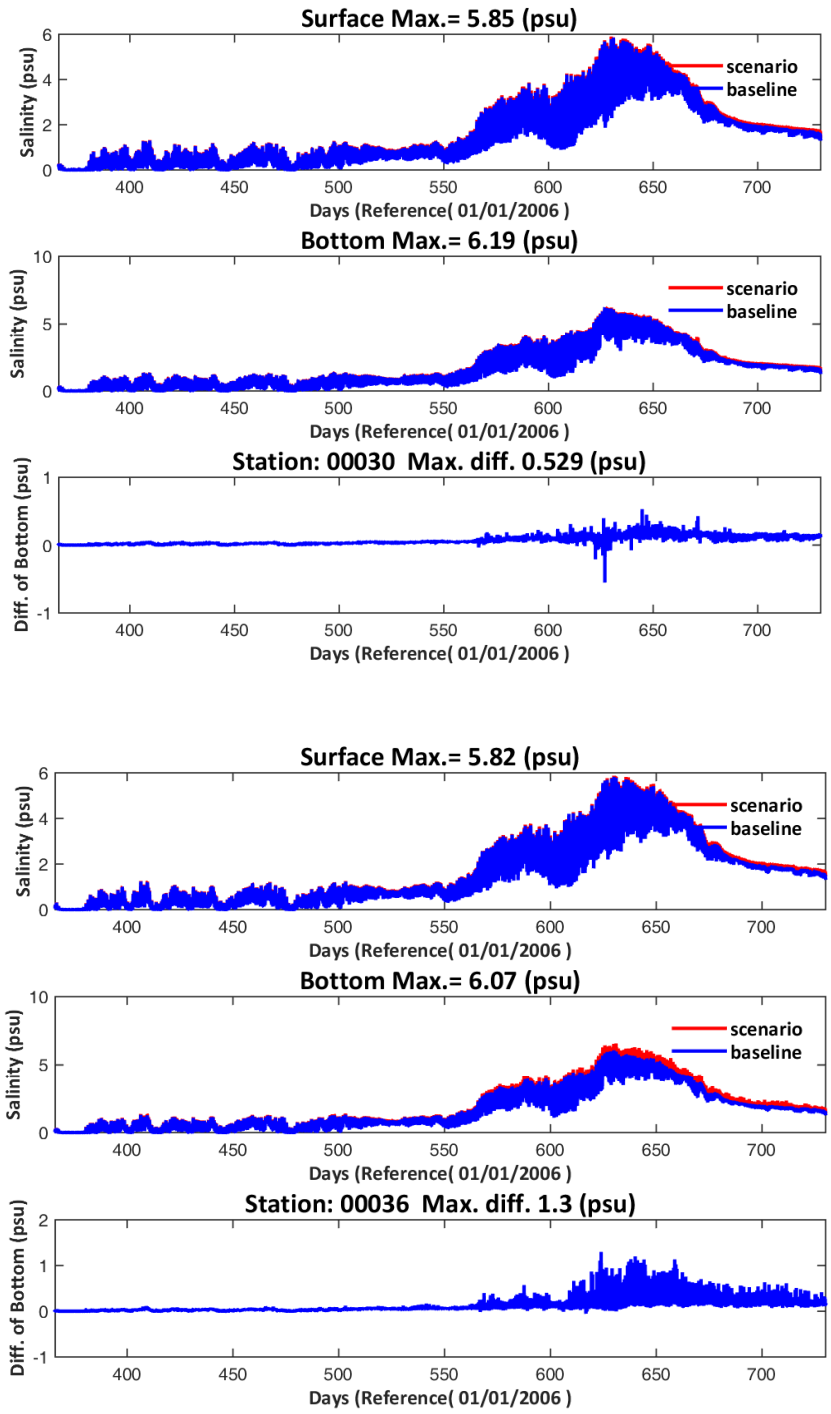


Figure 4-2-2. Continue.

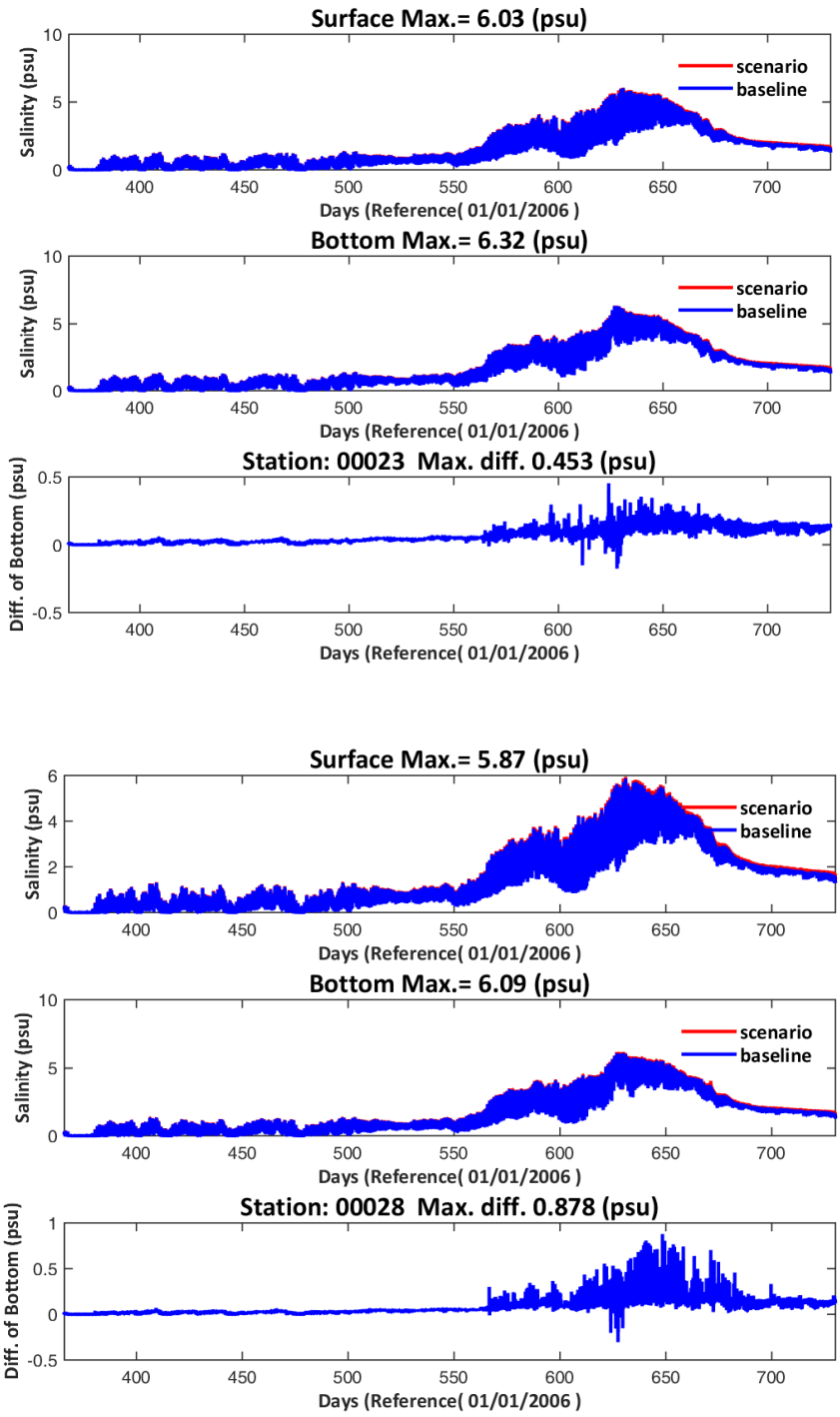
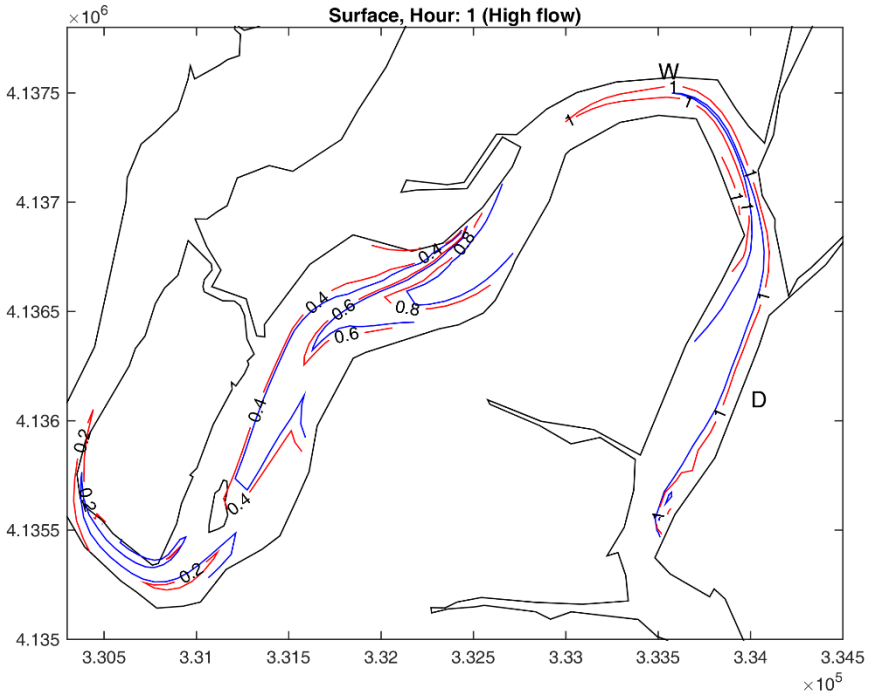
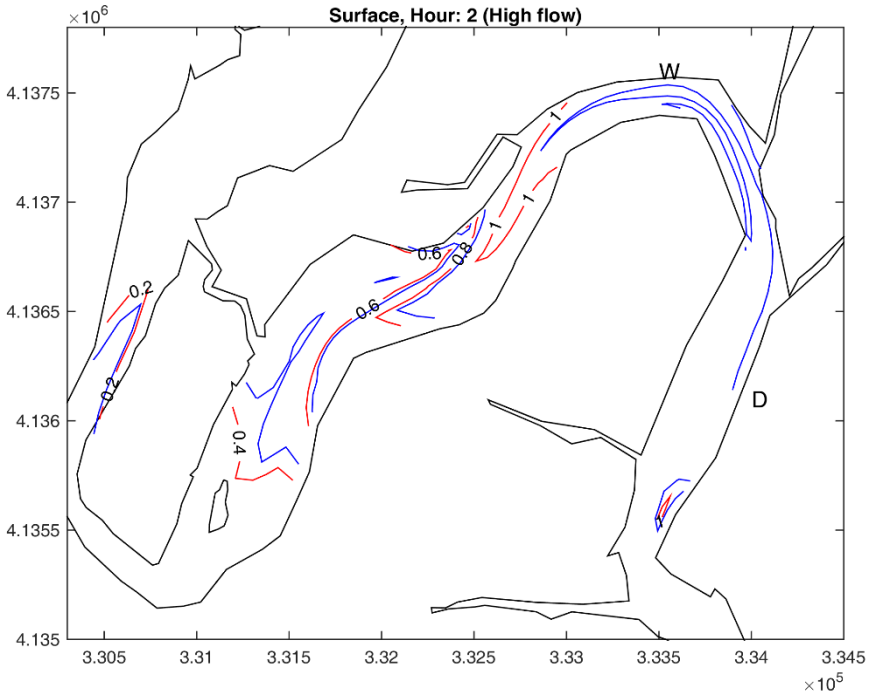
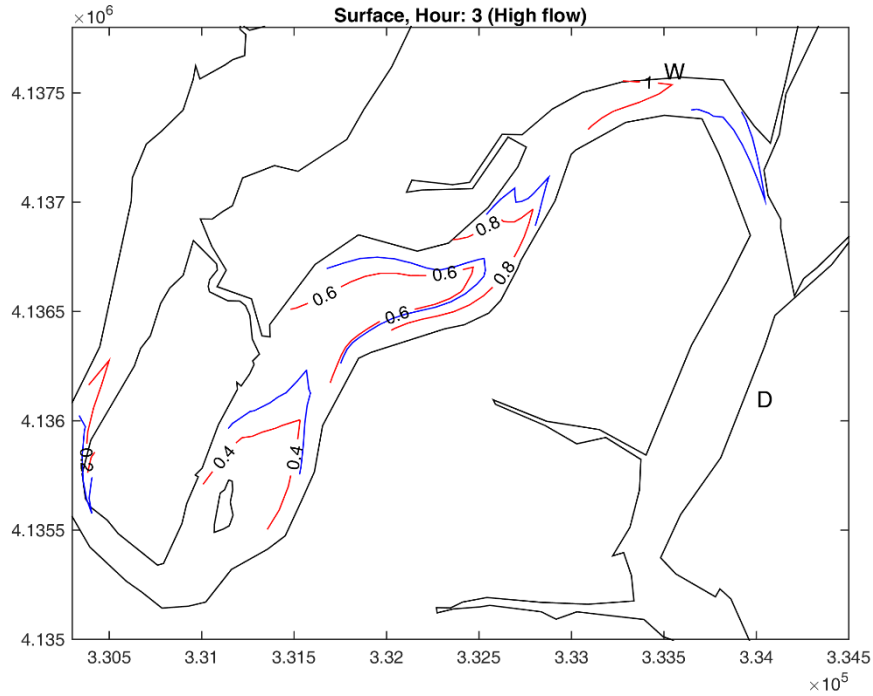
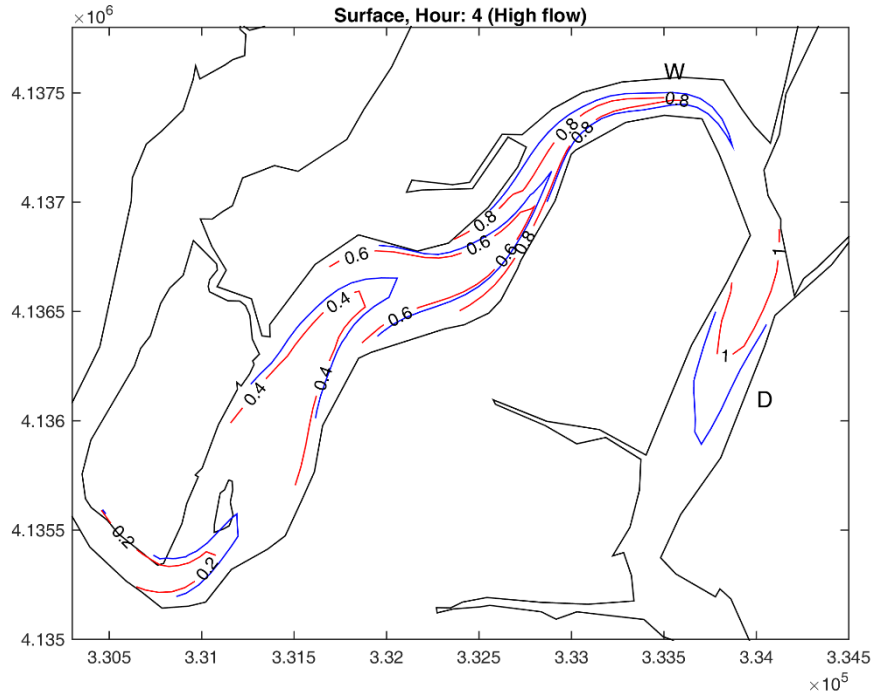


Figure 4-2-2. Continue.


Surface, Hour: 1 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.2
0.4
0.6
0.8
1


Surface, Hour: 2 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.2
0.4
0.6
0.8
1


Surface, Hour: 3 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.8
0.6
0.4
0.2


Surface, Hour: 4 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.8
0.6
0.4
0.2

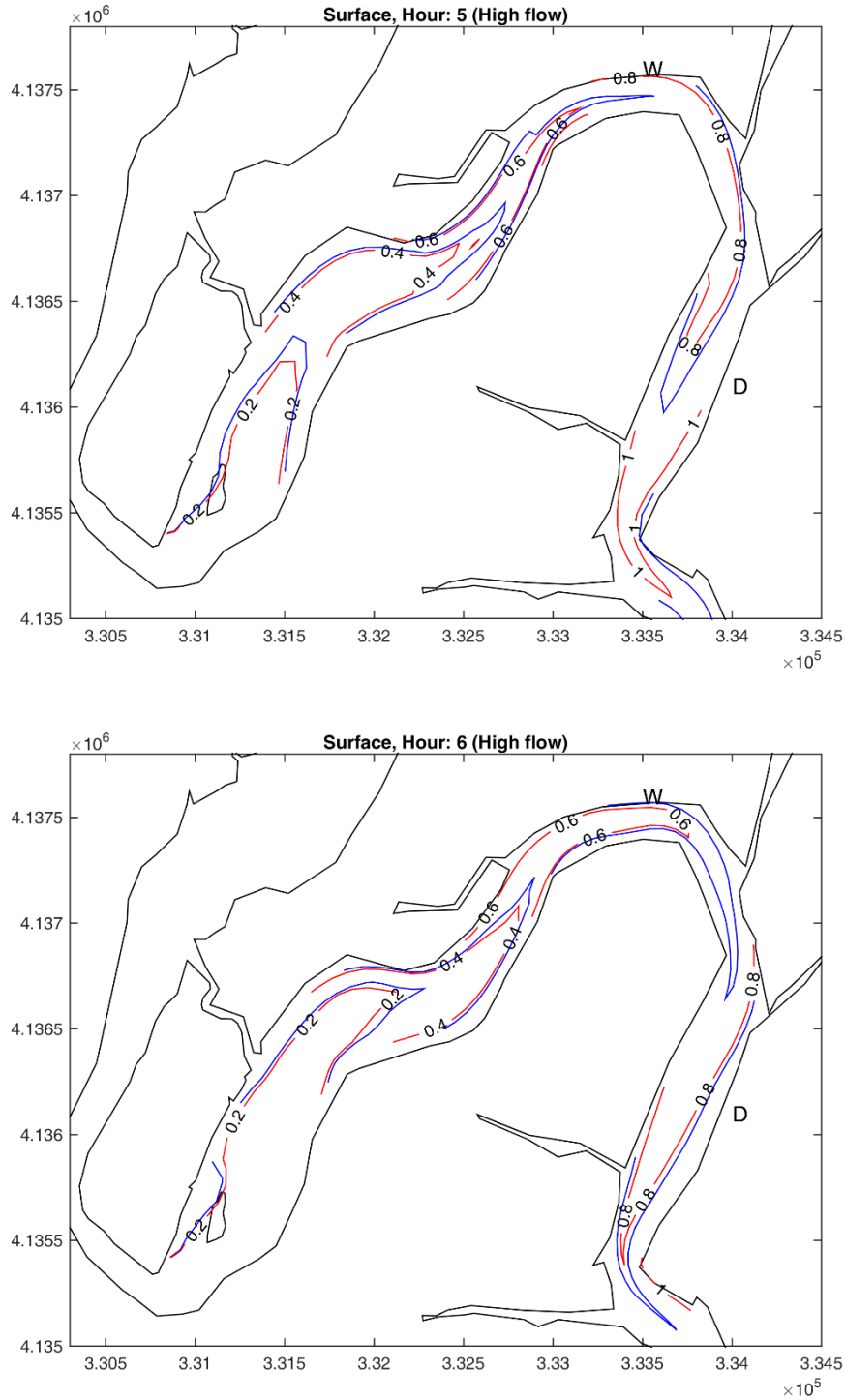
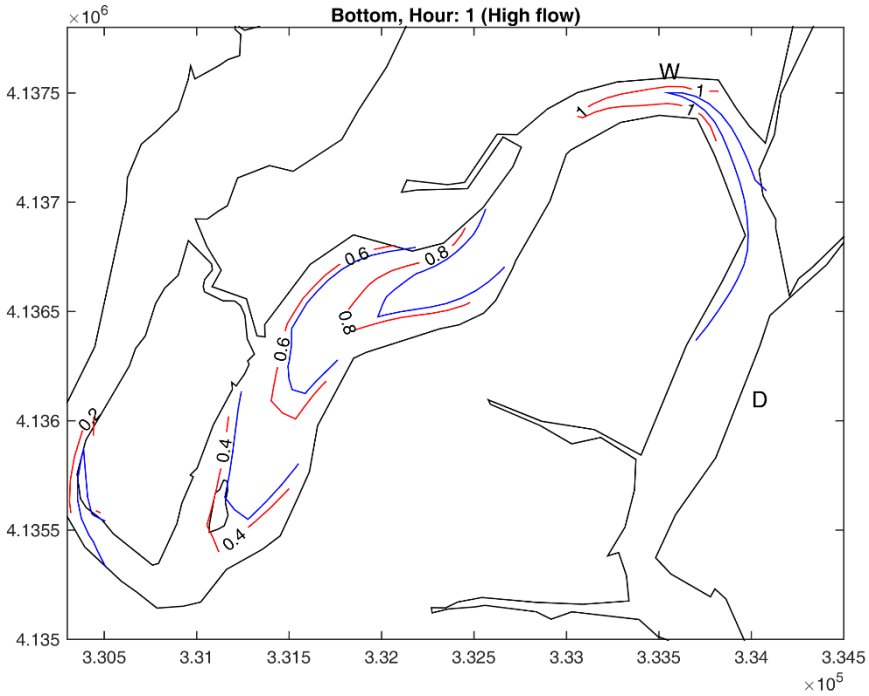
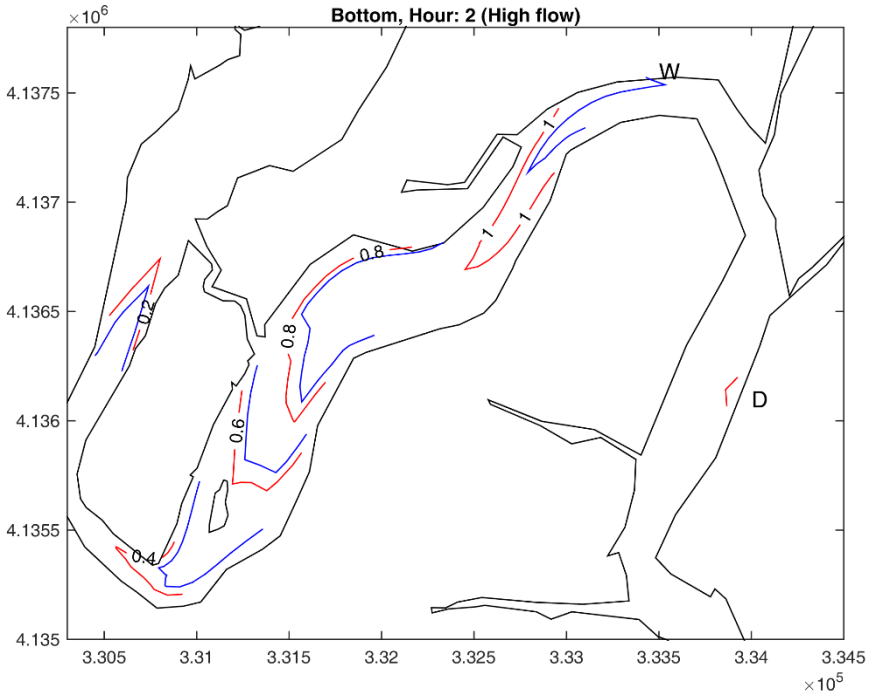
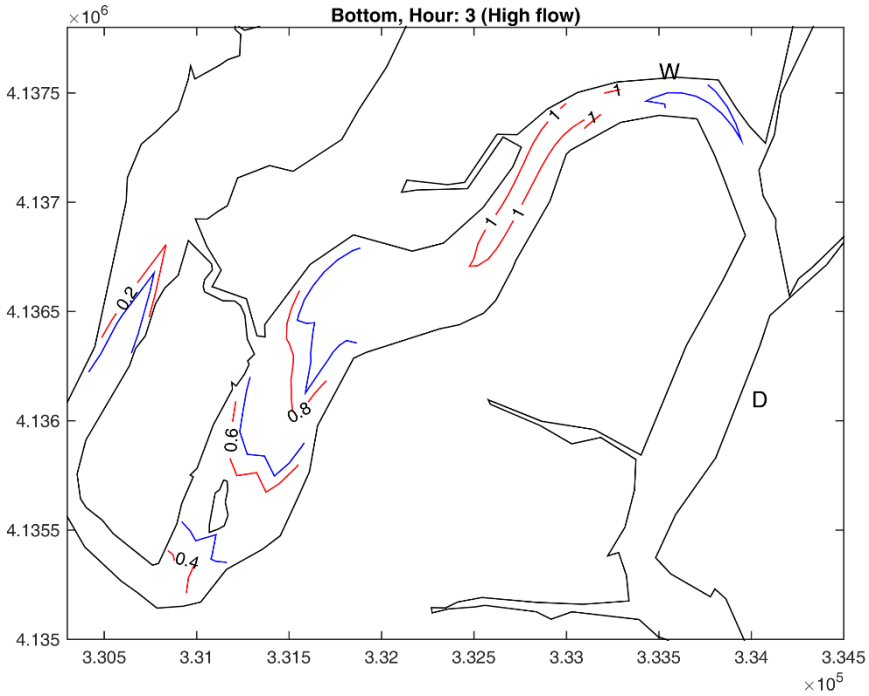
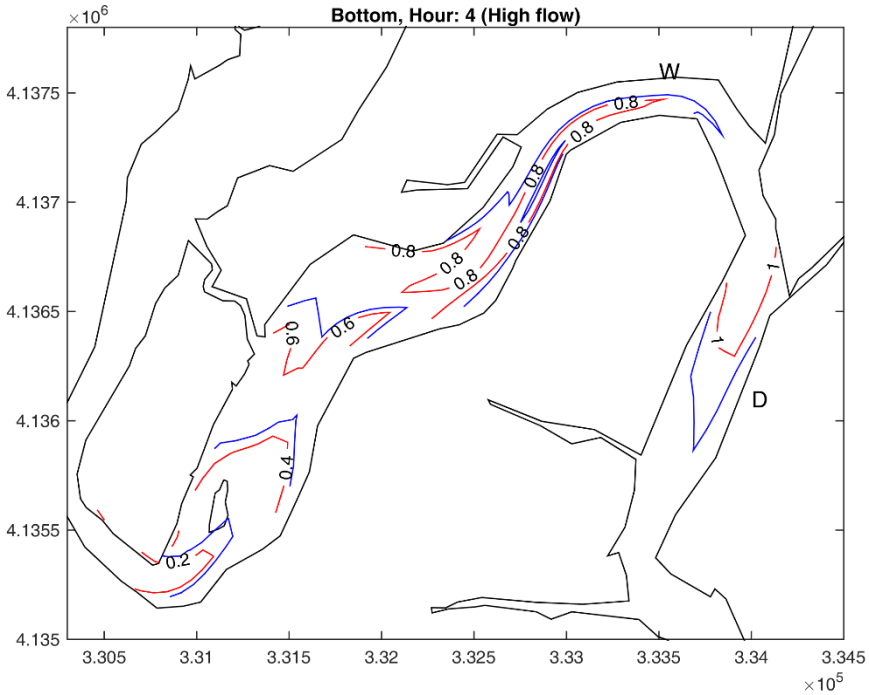


Figure 4-2-3. Comparison of surface salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.6
0.8
0.2
0.4


Bottom, Hour: 2 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.8
0.2
0.6
0.4


Bottom, Hour: 3 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
1
0.2
0.6
0.8
0.4


Bottom, Hour: 4 (High flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
0.8
1
0.6
0.5
0.4
0.2

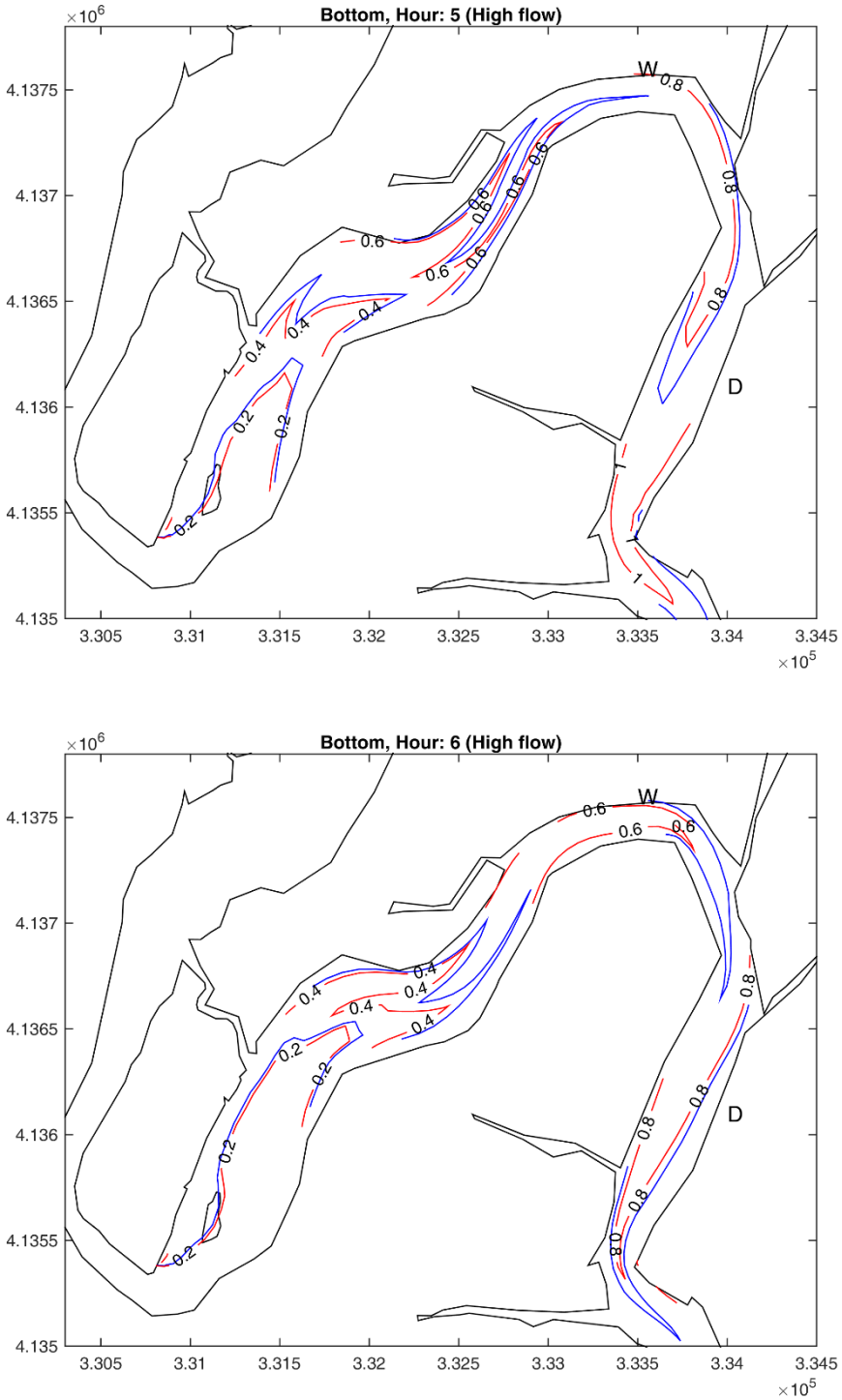
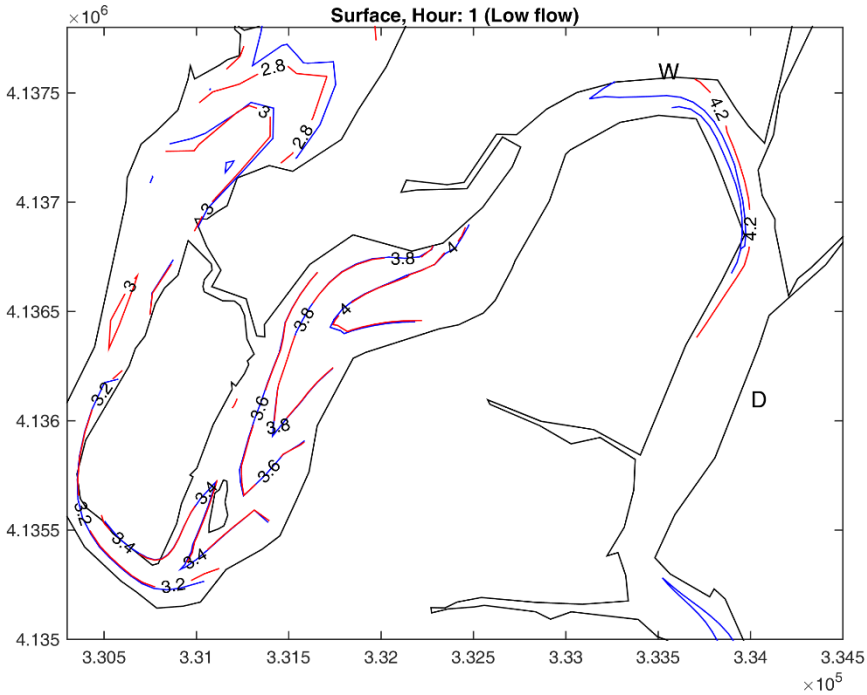
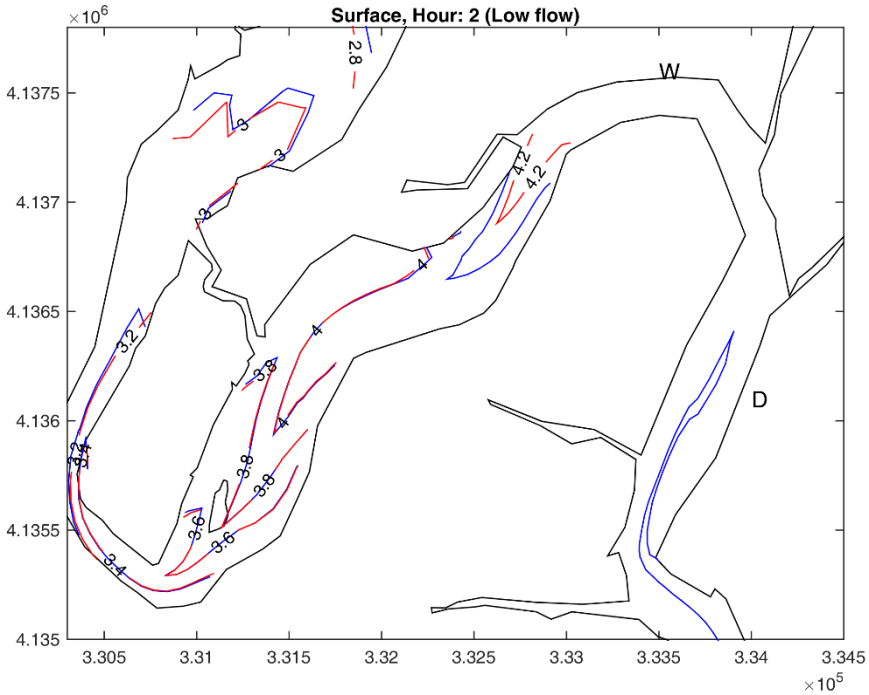
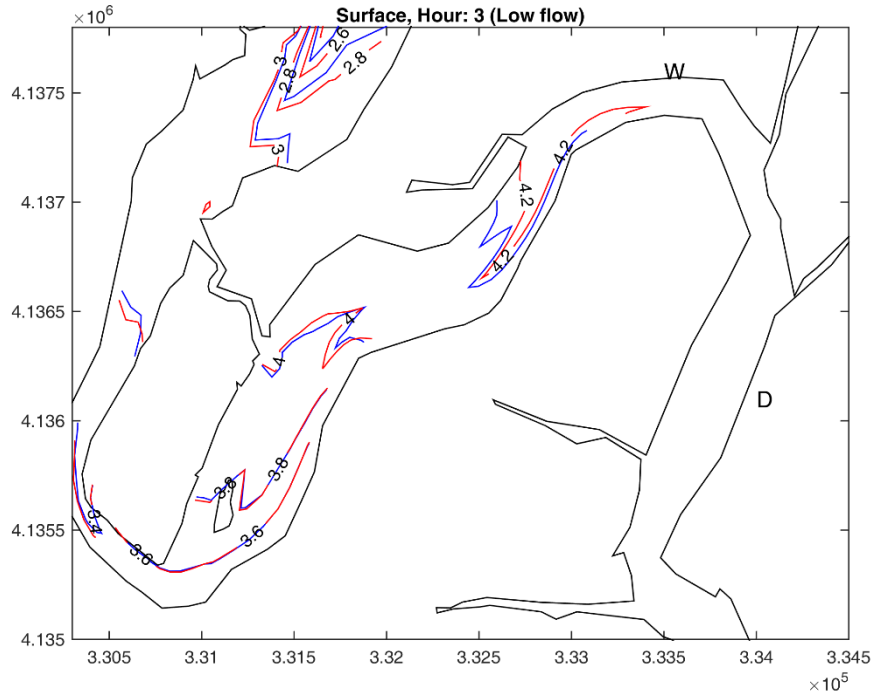
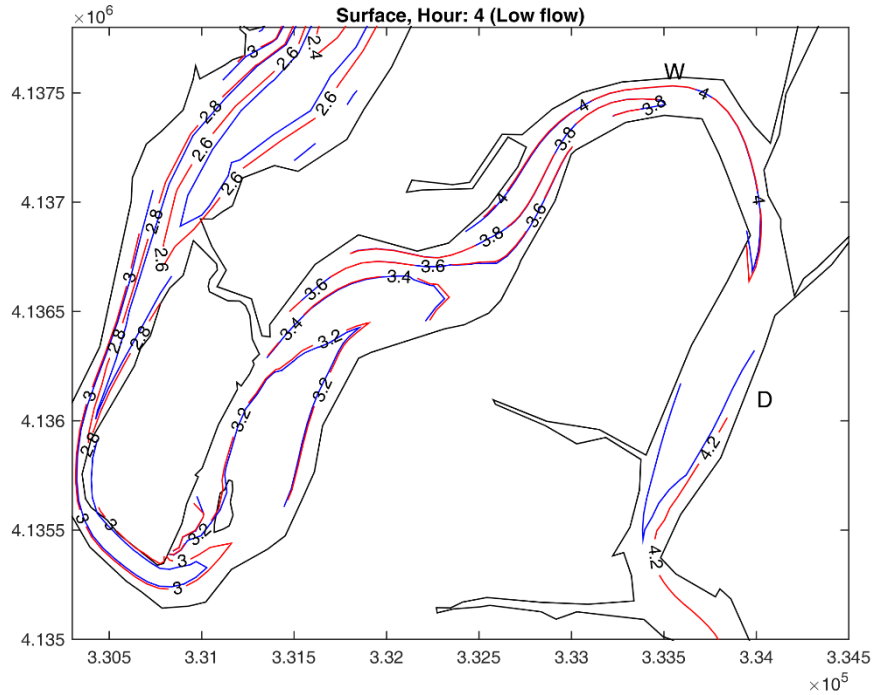


Figure 4-2-4. Comparison of bottom salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
2.8
3
3.2
3.4
3.6
3.8
4
4.2


Surface, Hour: 2 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
2.8
3
3.2
3.4
3.6
3.8
4
4.2


Surface, Hour: 3 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D


Surface, Hour: 4 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D

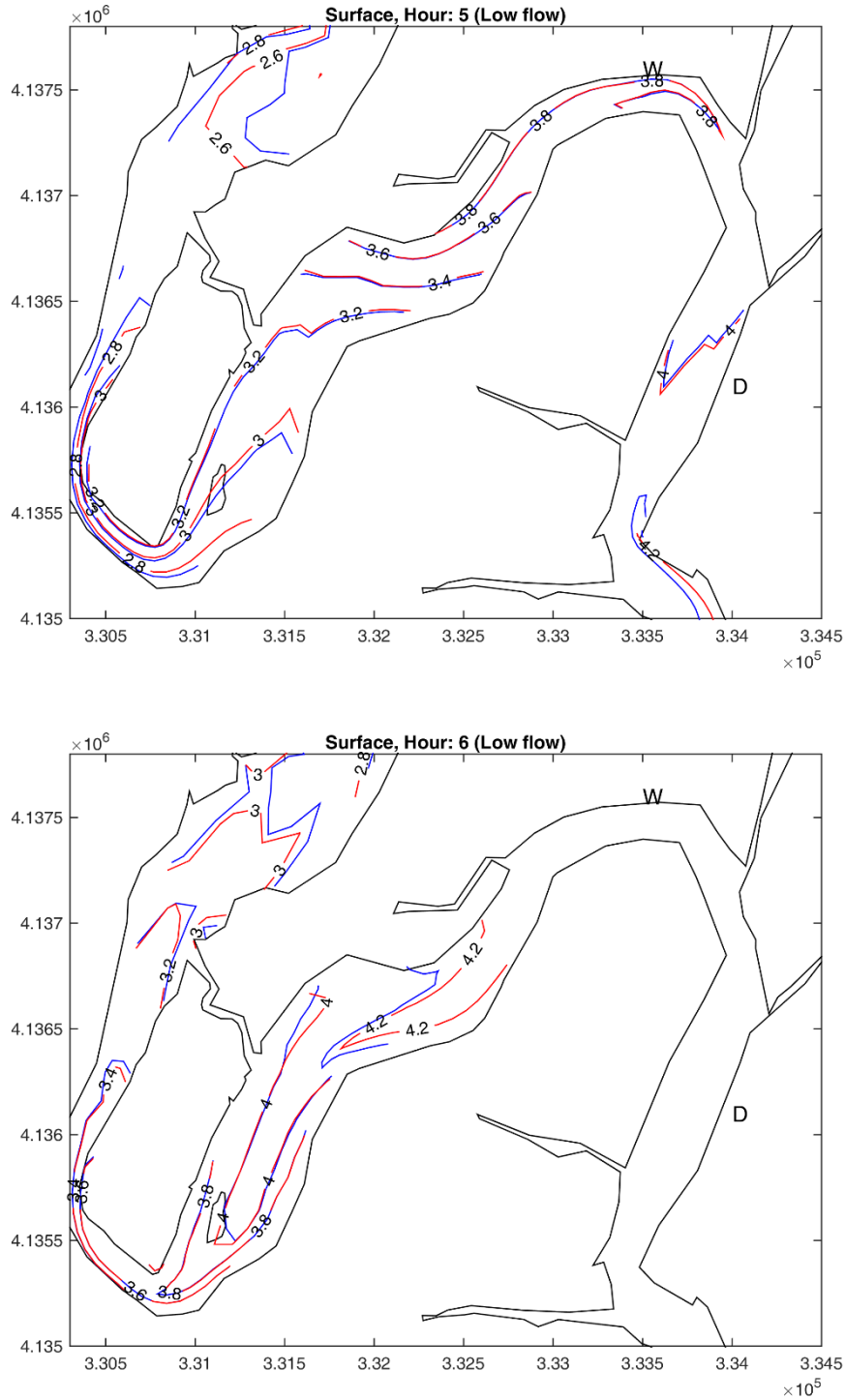
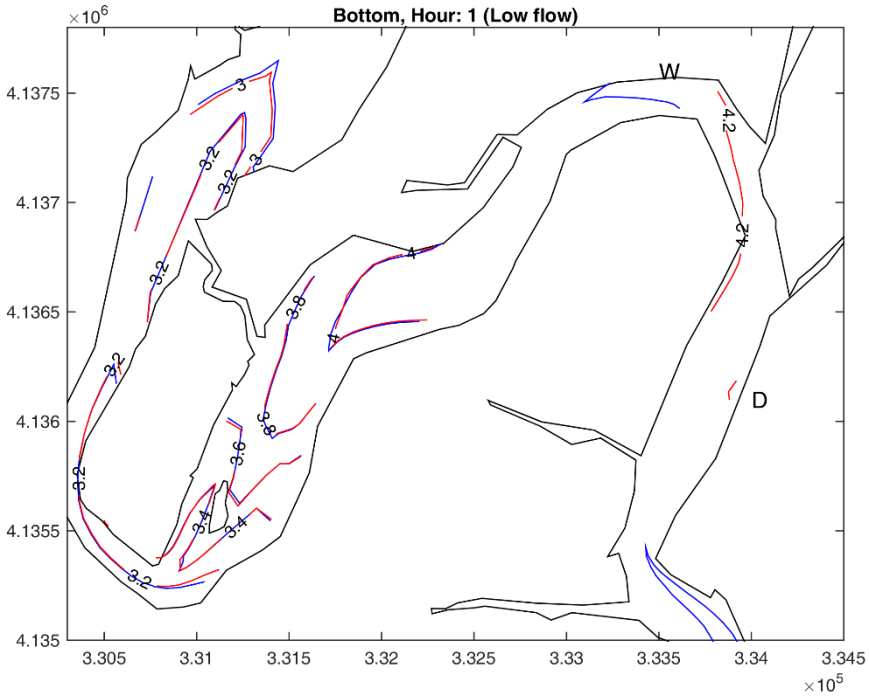
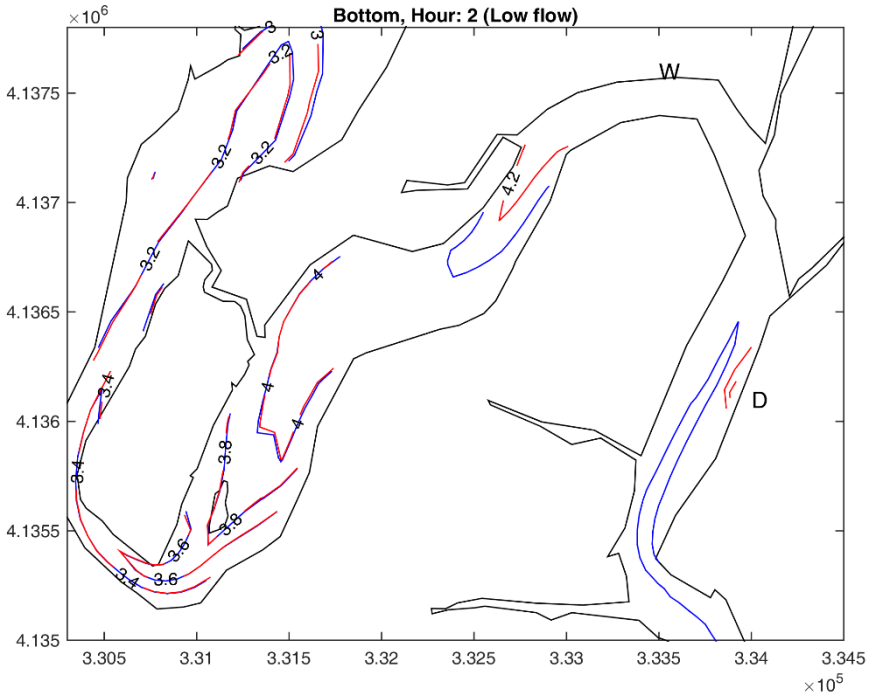
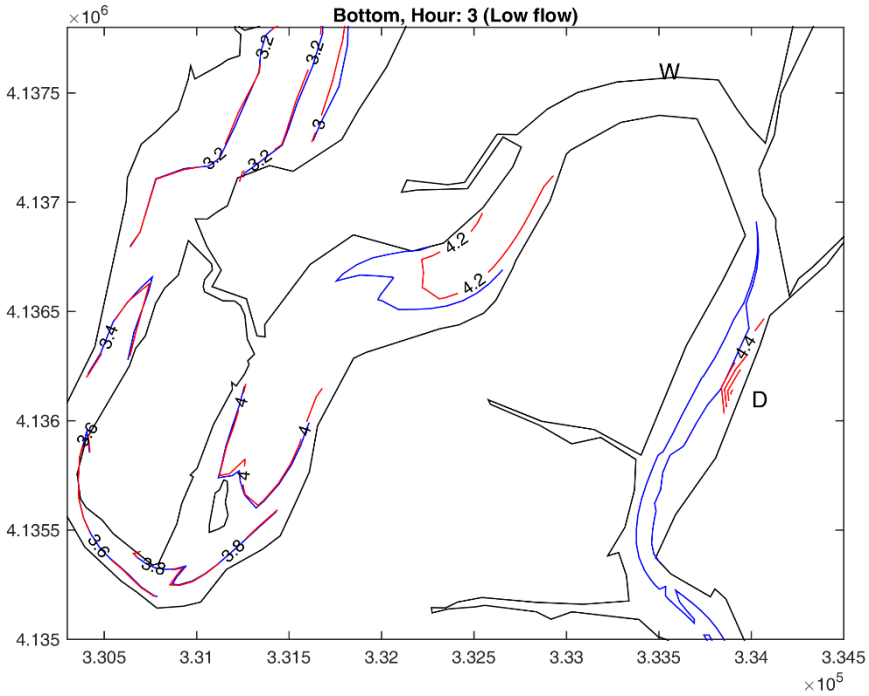
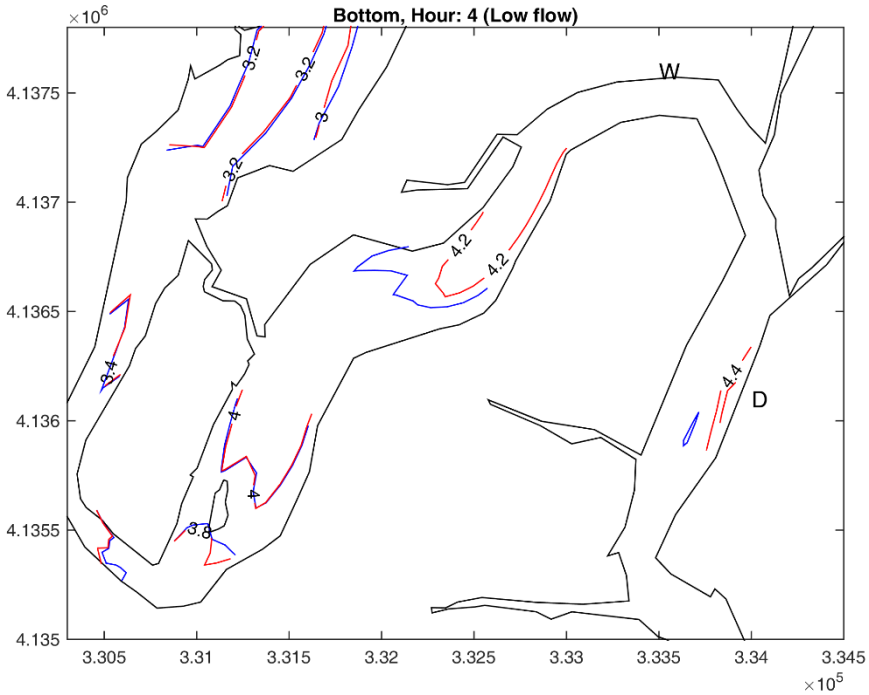


Figure 4-2-5. Comparison of surface salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs W is withdrawal site and D is discharge site)


Bottom, Hour: 1 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3
3.2
3.4
3.6
3.8
4
4.2


Bottom, Hour: 2 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3
3.2
3.4
3.6
3.8
4
4.2


Bottom, Hour: 3 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3.2
3
3.4
3.6
3.8
4
4.2
4.4


Bottom, Hour: 4 (Low flow)
×10^6
4.1375
4.137
4.1365
4.136
4.1355
4.135
3.305
3.31
3.315
3.32
3.325
3.33
3.335
3.34
3.345
×10^5
W
D
3.2
3
3.4
3.8
4
4.2
4.4

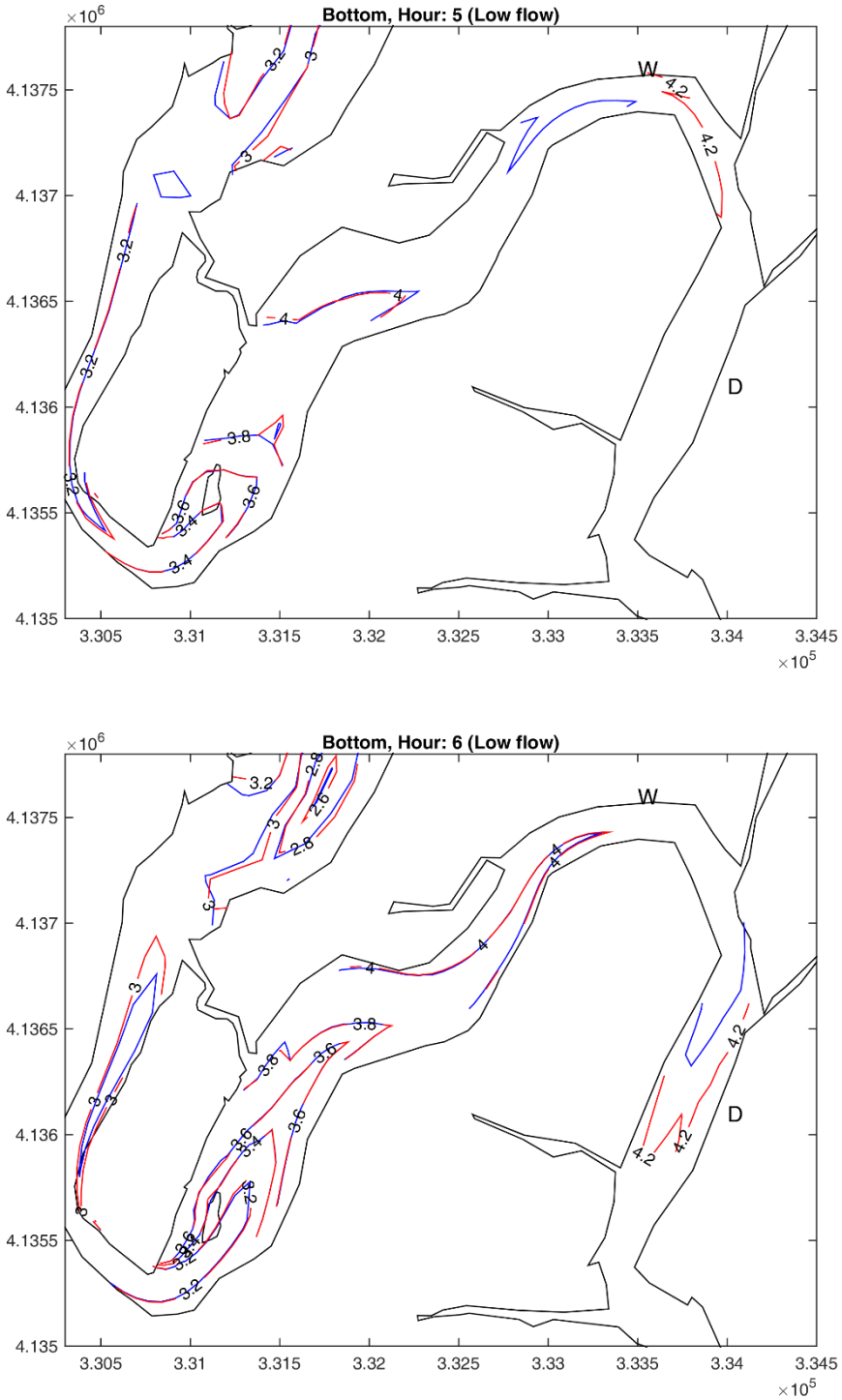


Figure 4-2-6. Comparison of bottom salinity distribution near the Brickyard Landing withdrawal and discharge sites for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

4.3 Chickahominy Riverfront Park Discharge Site I --Phase II

Similar to what was done for Brickyard Landing, the time series and salinity distributions are compared in Figures 4-3-1 to 4-3-2. The salinity only changed slightly at the withdrawal site. The maximum change is about 0.32 psu. The salinity increases about 1.59 psu at the discharge site at the bottom during low flow period, which is about 18% of maximum salinity of 8.89 psu. Horizontal plots of salinity distributions at Days 150 (high flow) and 300 (low flow) show changes of salinity distribution. Salinity change is larger during low flow period than that during high flow period. The salinity change depends on tide. Both increase and decrease occur during different phase of tide. Because of large water volume in this lower estuary and large tide mixing. The change of salinity is not significant.

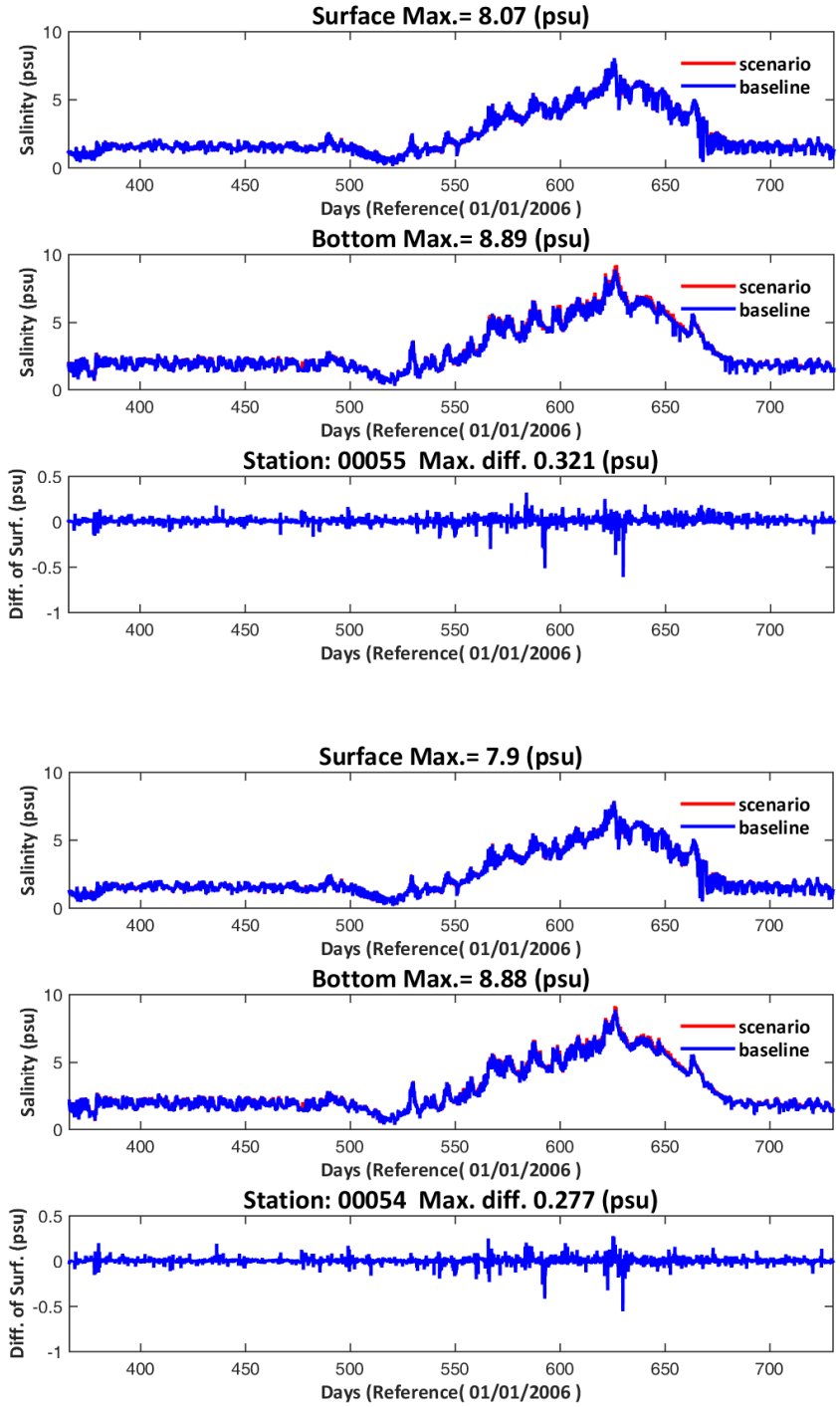


Figure 4-3-1. Comparison of salinity time series at selected locations, and difference between scenario and baseline near the surface at Chickahominy Riverfront Park withdrawal site (number shown in 3rd panel is station ID).

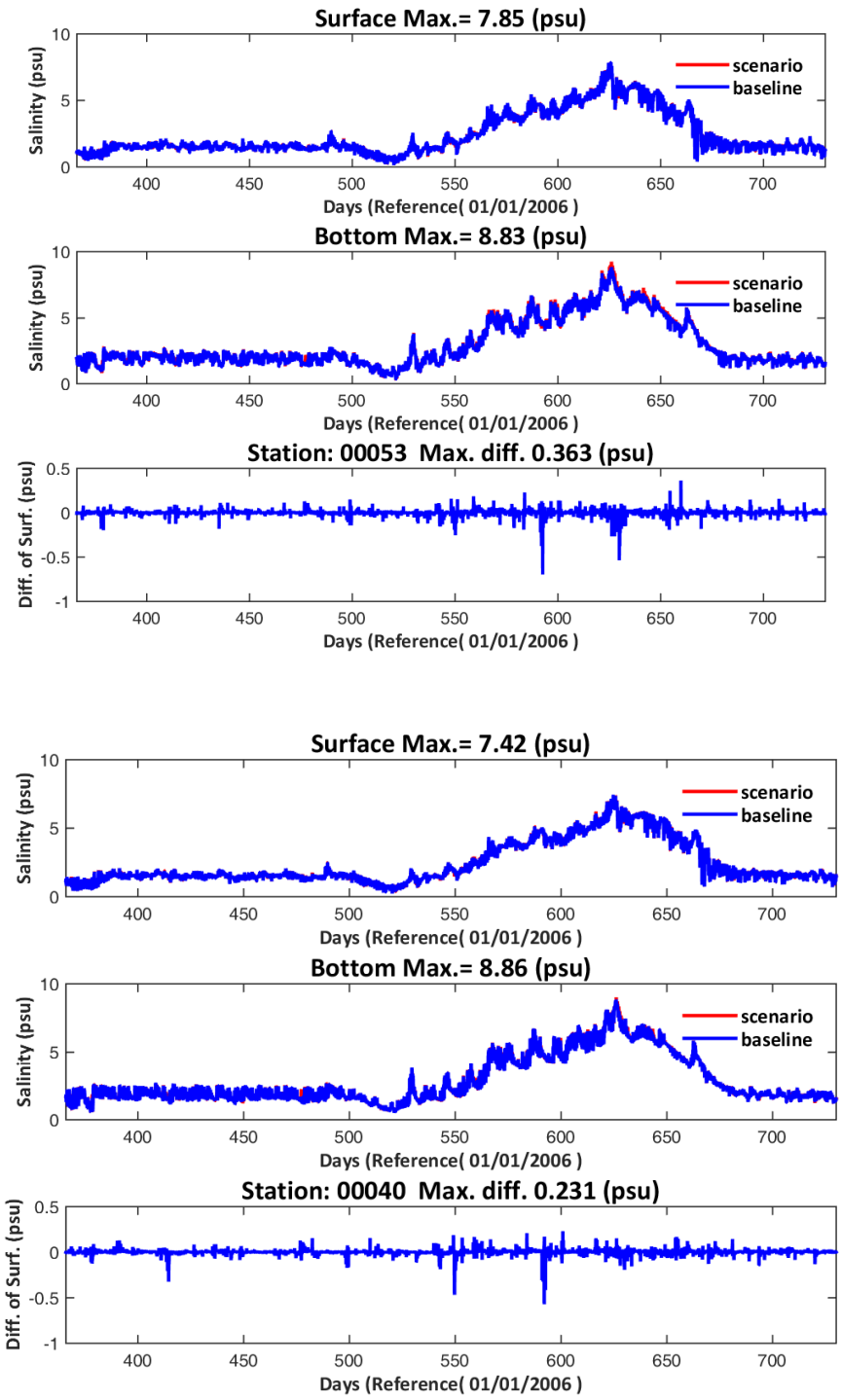


Figure 4-3-1. Continue.

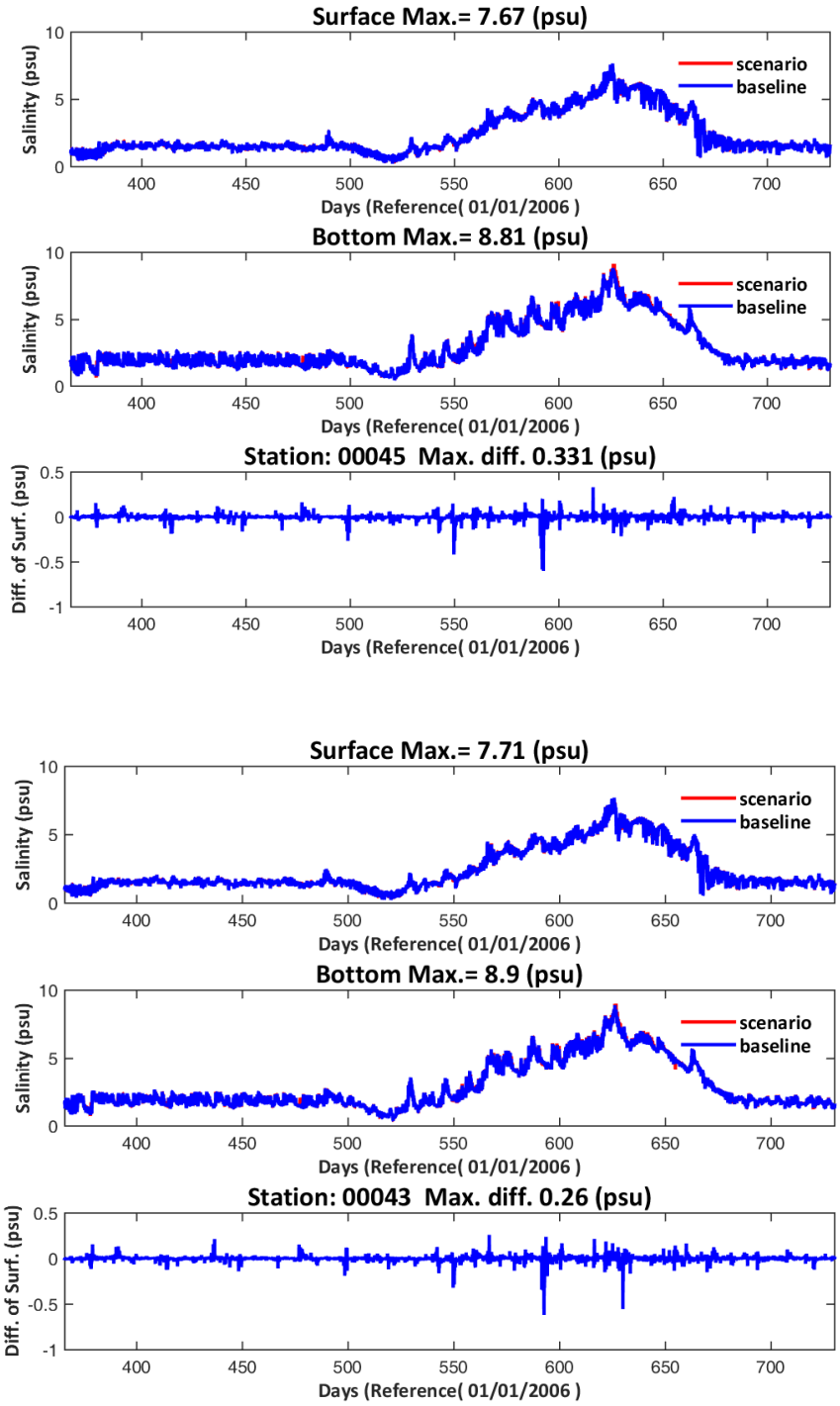


Figure 4-3-1. Continue.

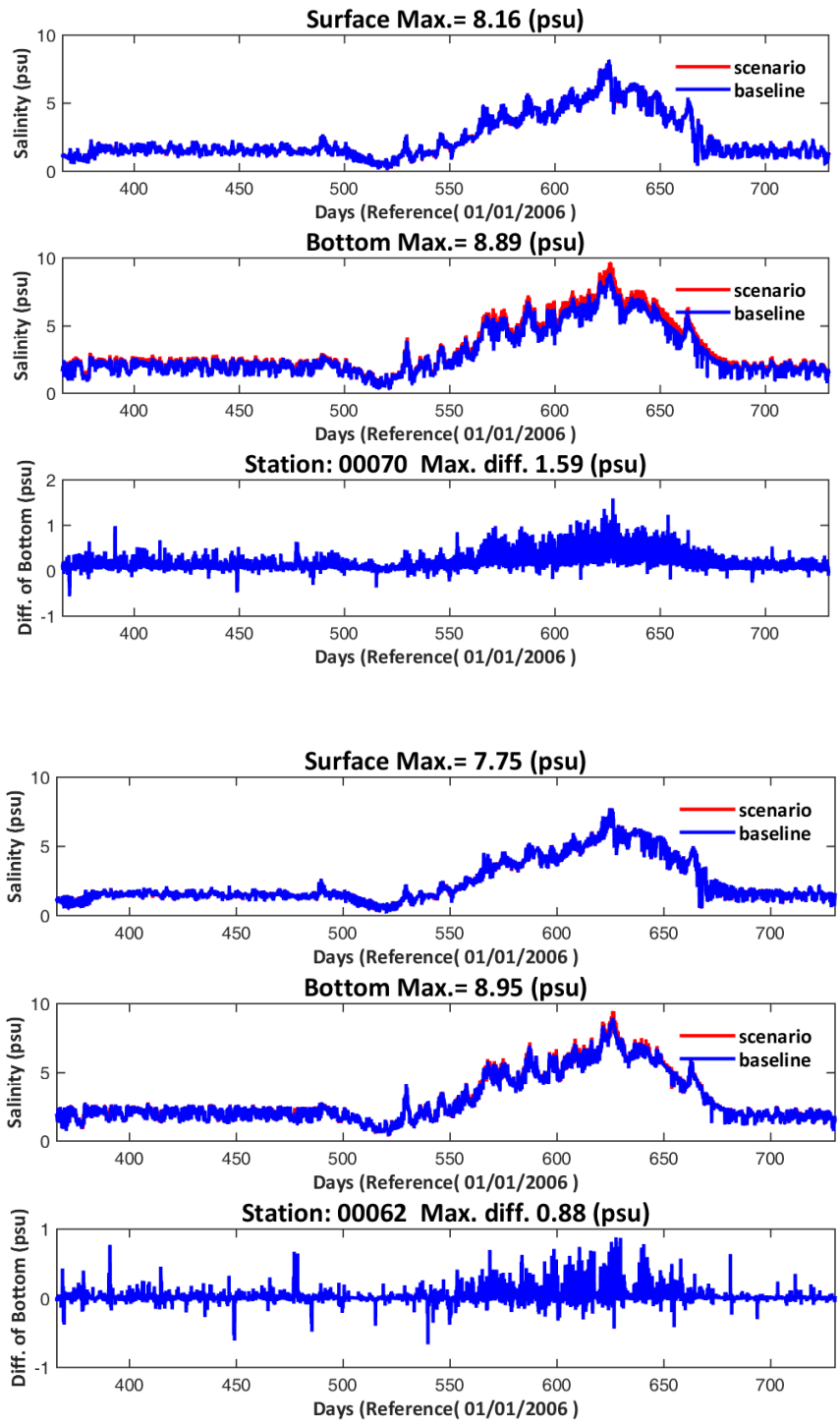


Figure 4-3-2. Comparison of salinity time series at selected locations, and difference between scenario and baseline near the bottom at Chickahominy Riverfront Park discharge site I (number shown in 3rd panel is station ID).

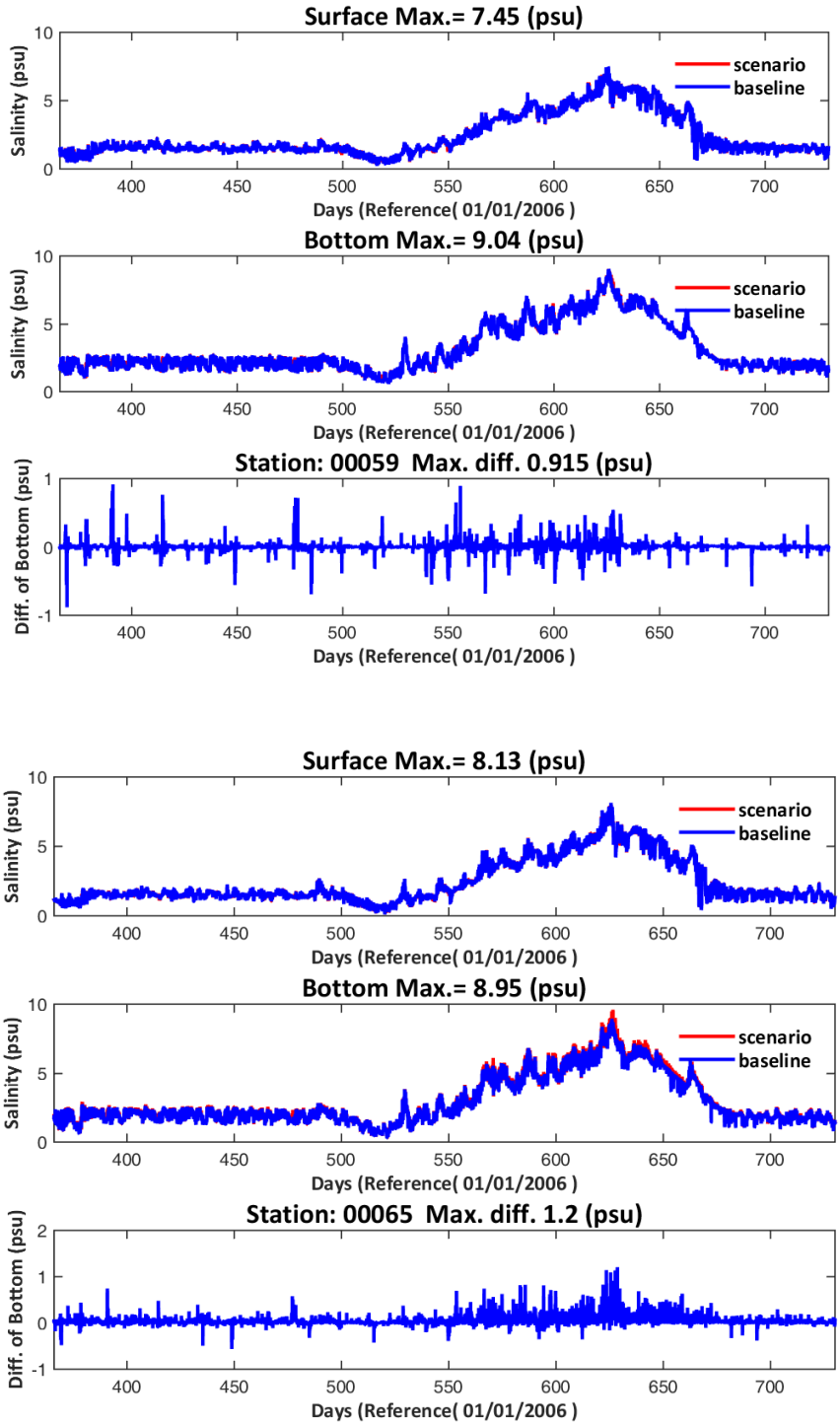


Figure 4-3-2. Continue.

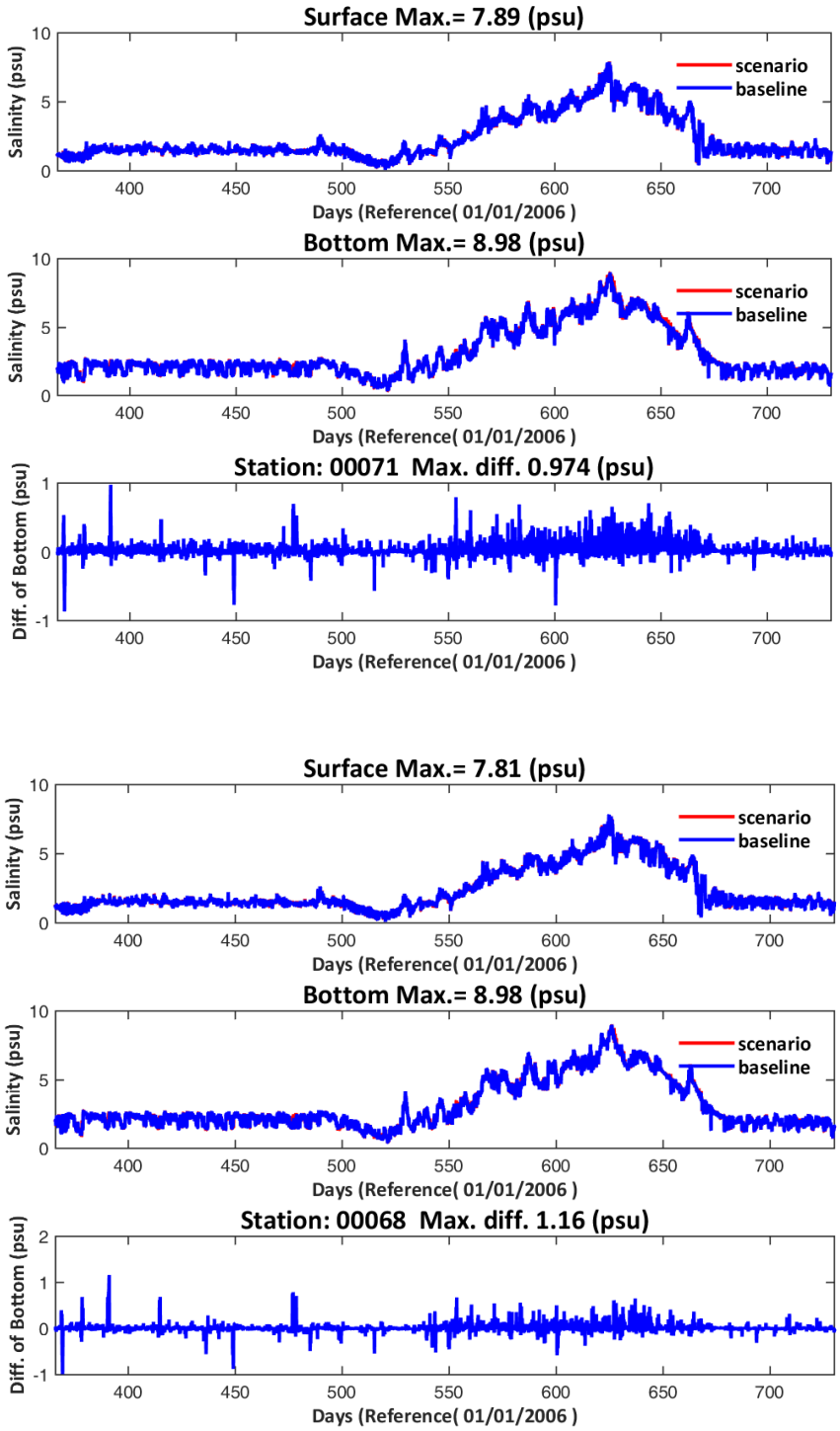
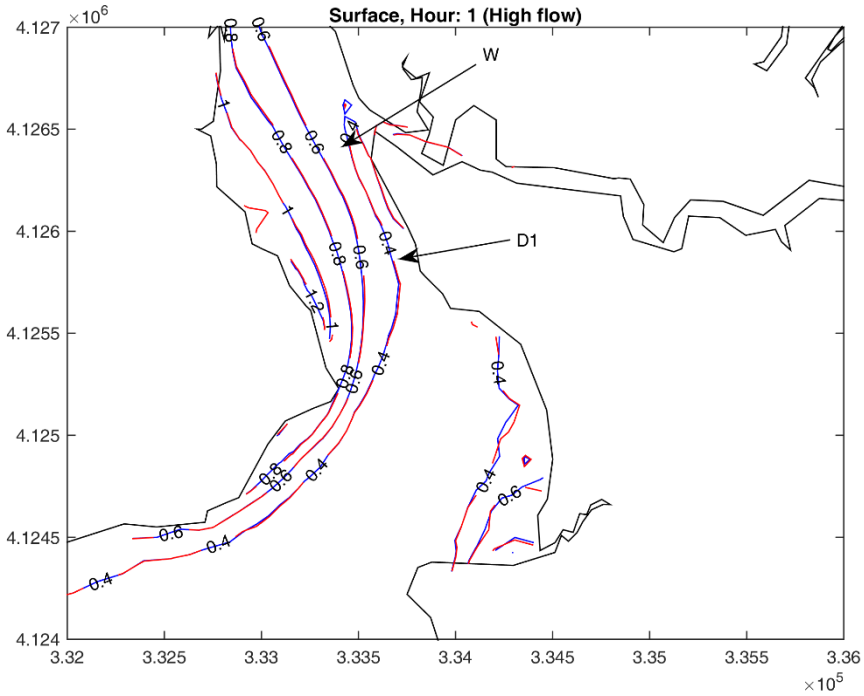
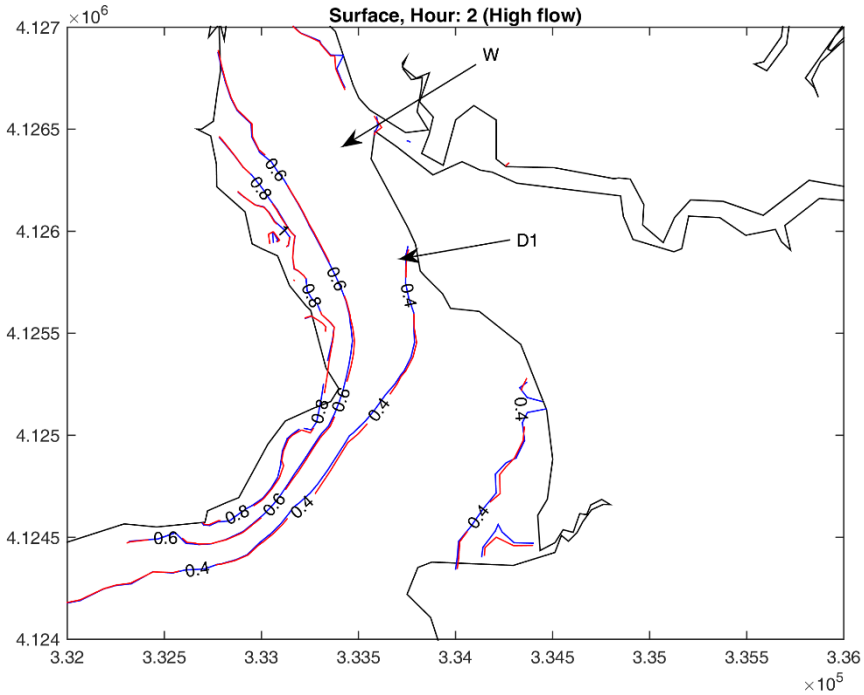
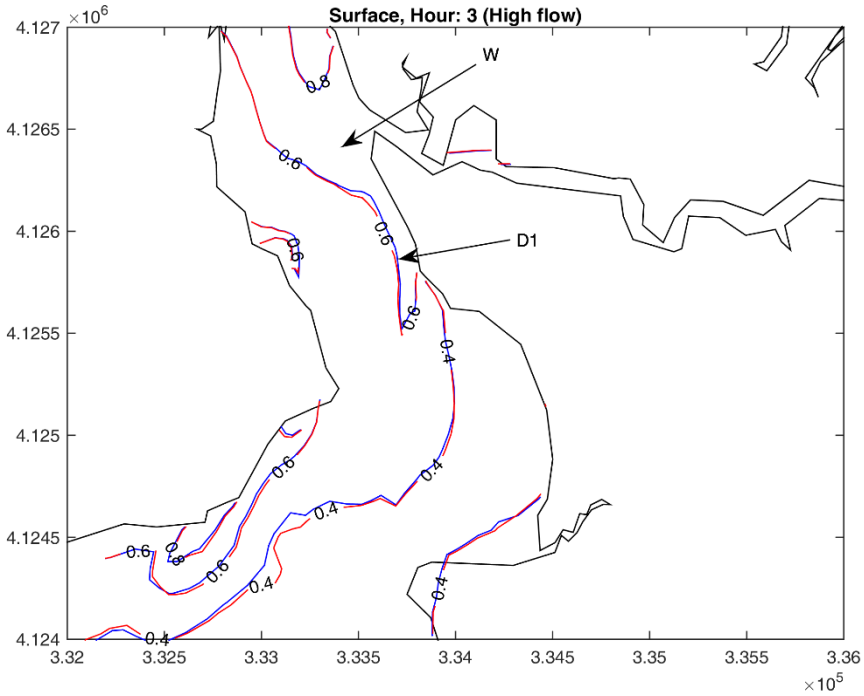
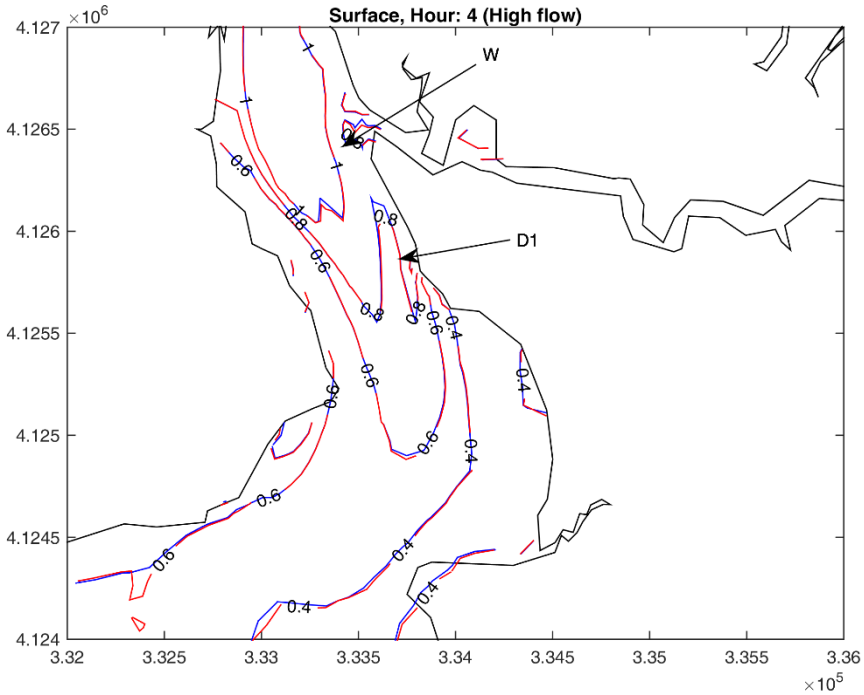


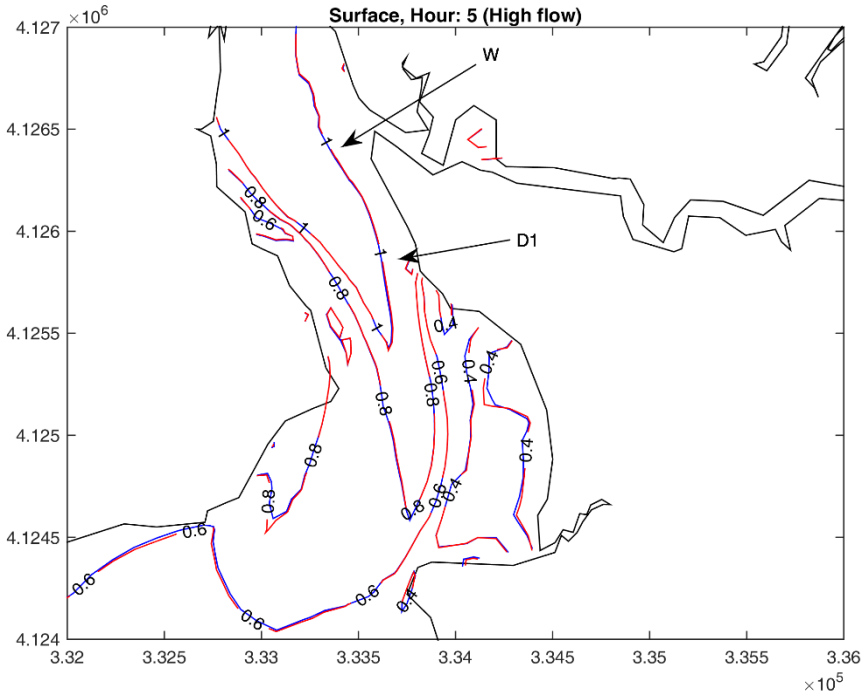
Figure 4-3-2. Continue.


Surface, Hour: 1 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5



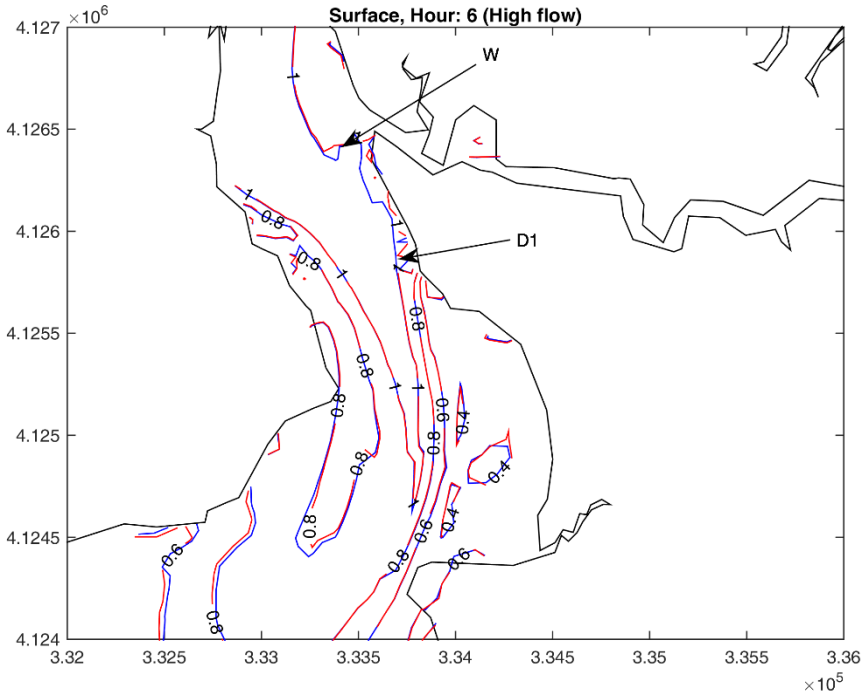


Figure 4-3-3. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

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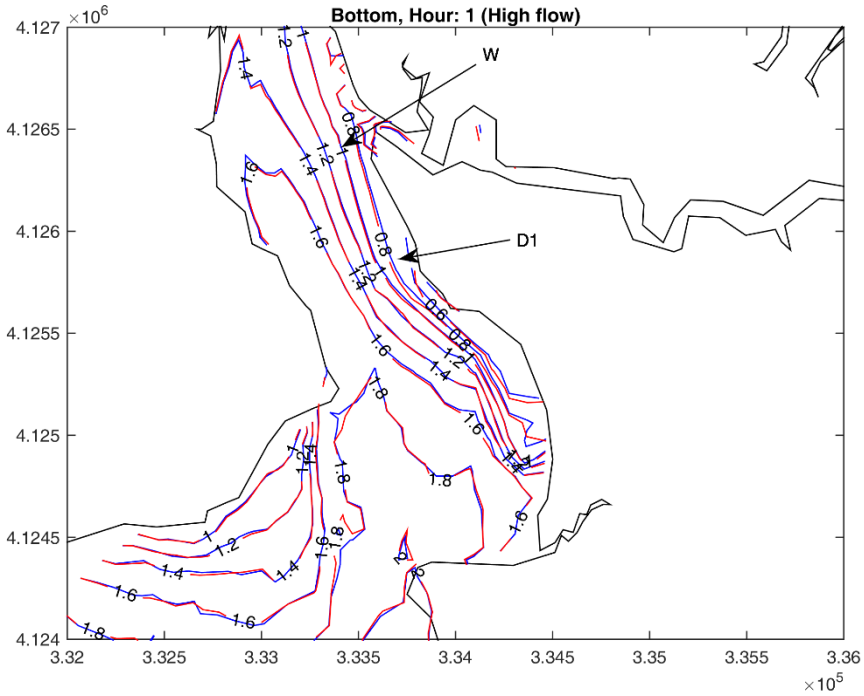
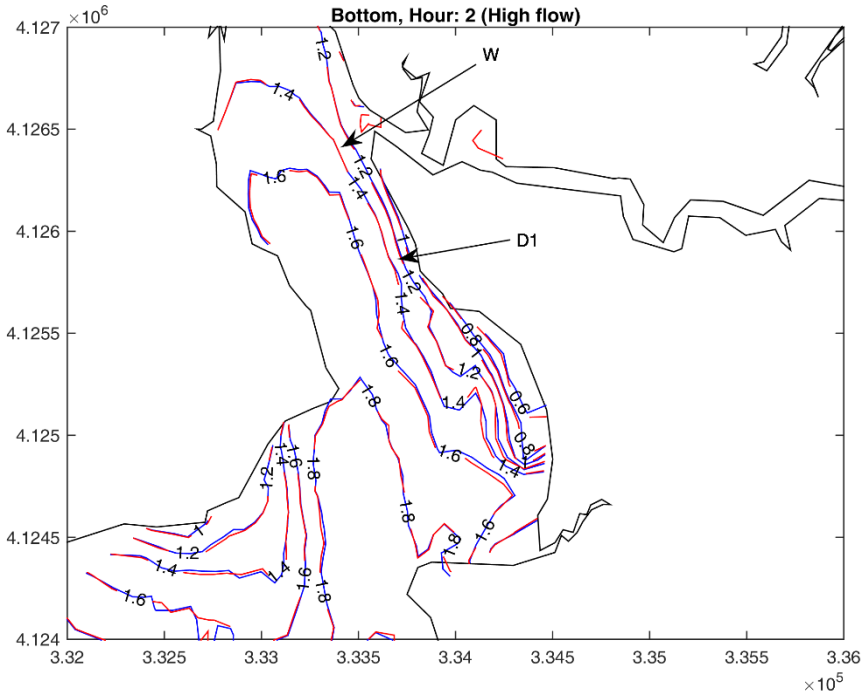
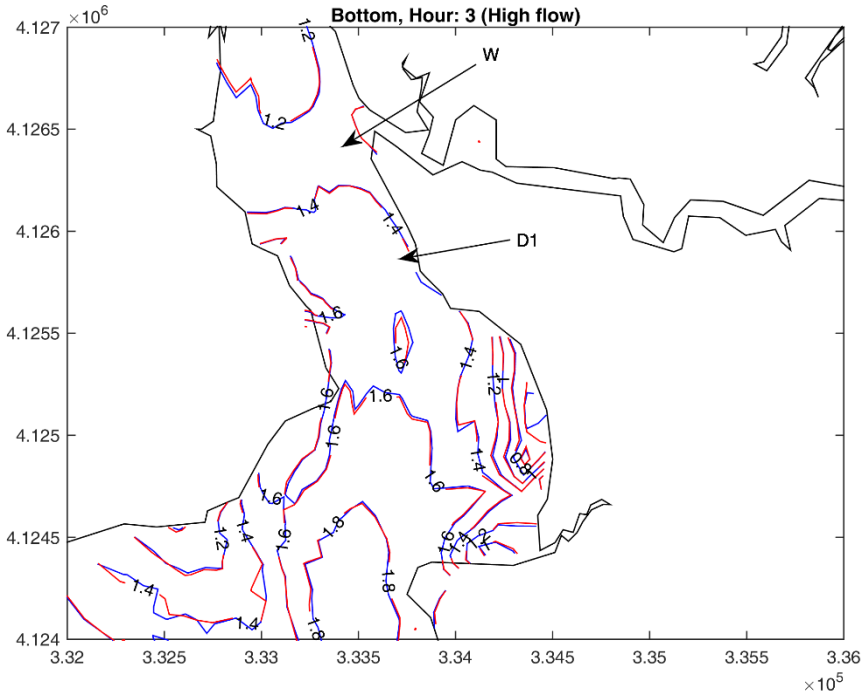
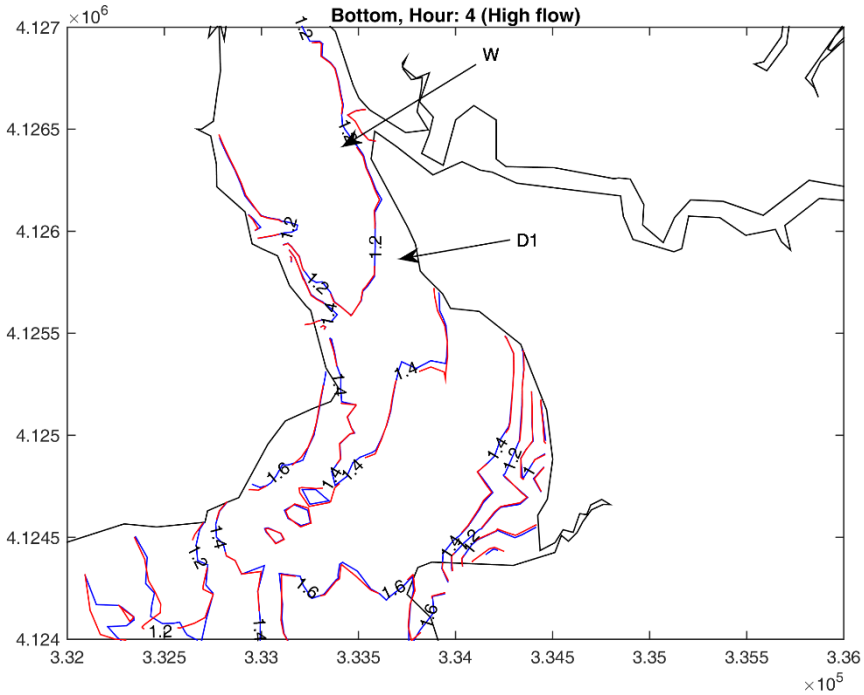

Bottom, Hour: 1 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

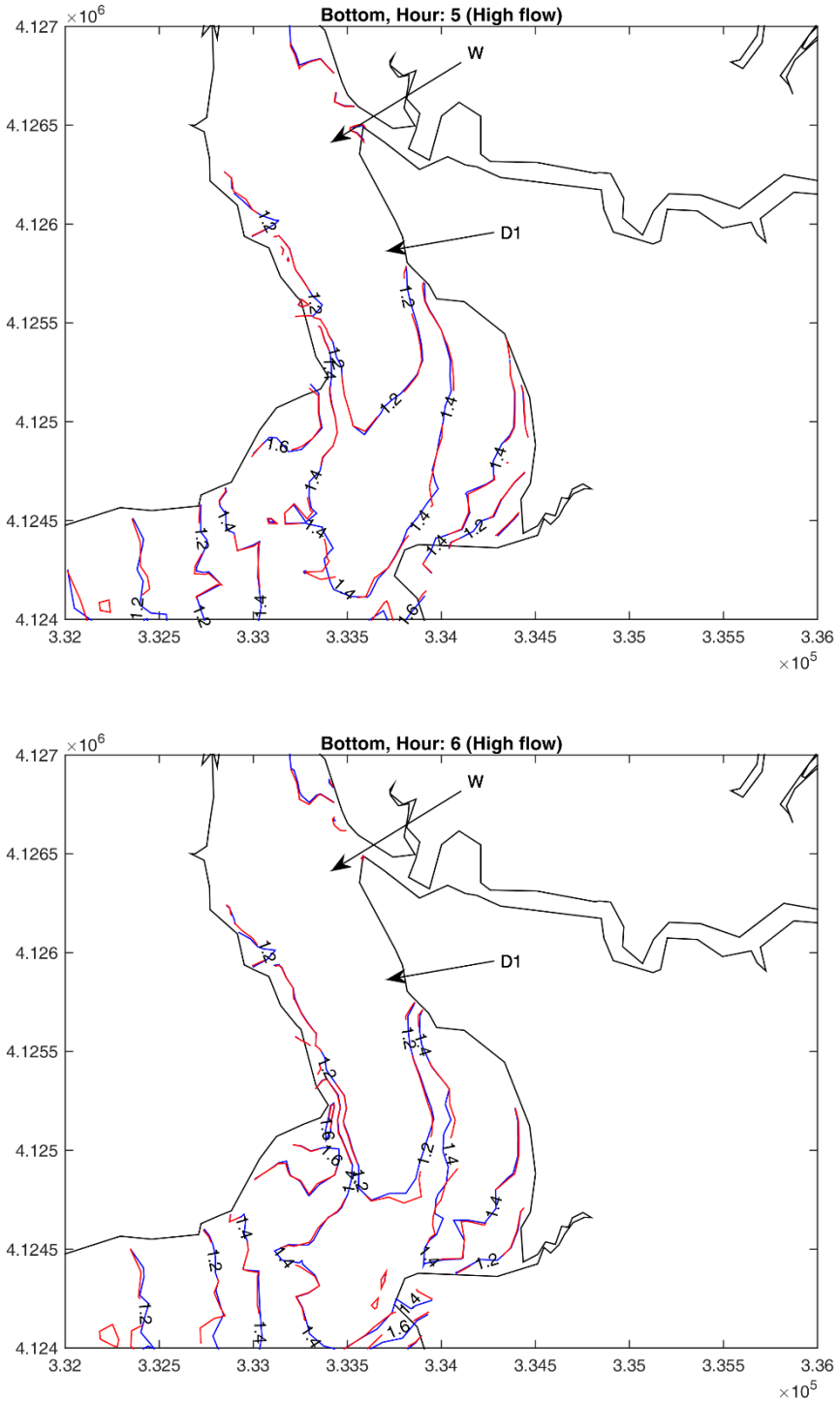
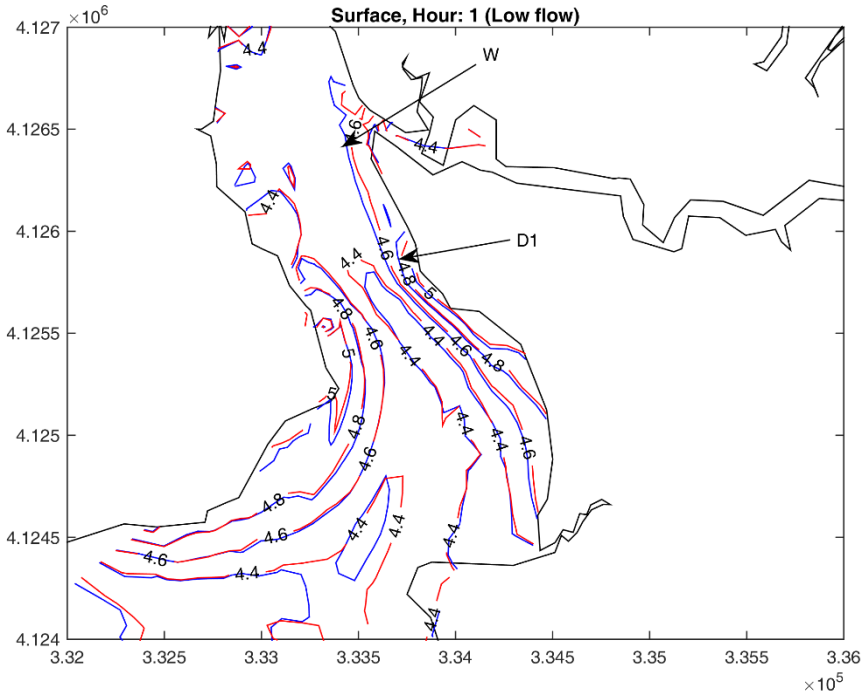
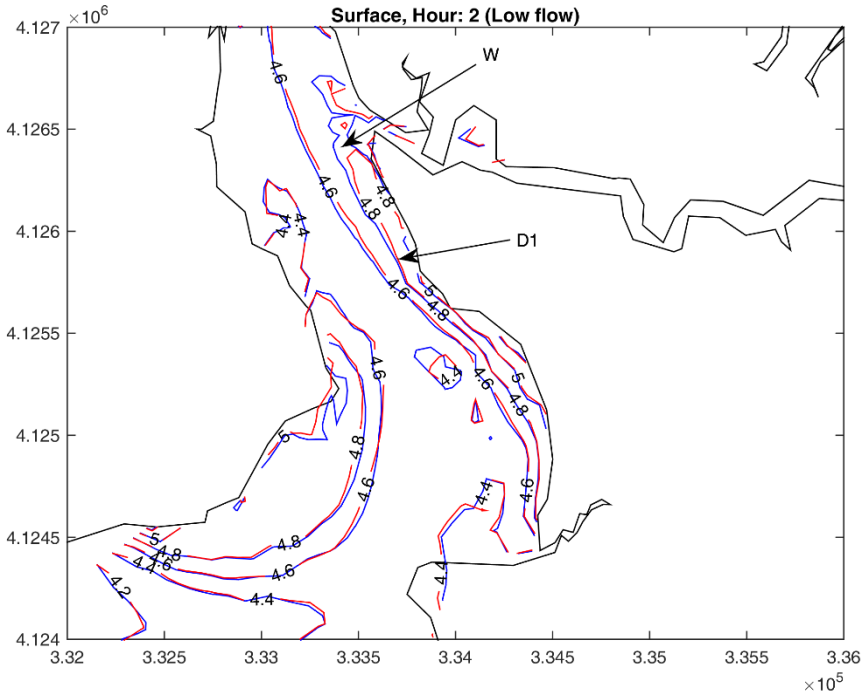
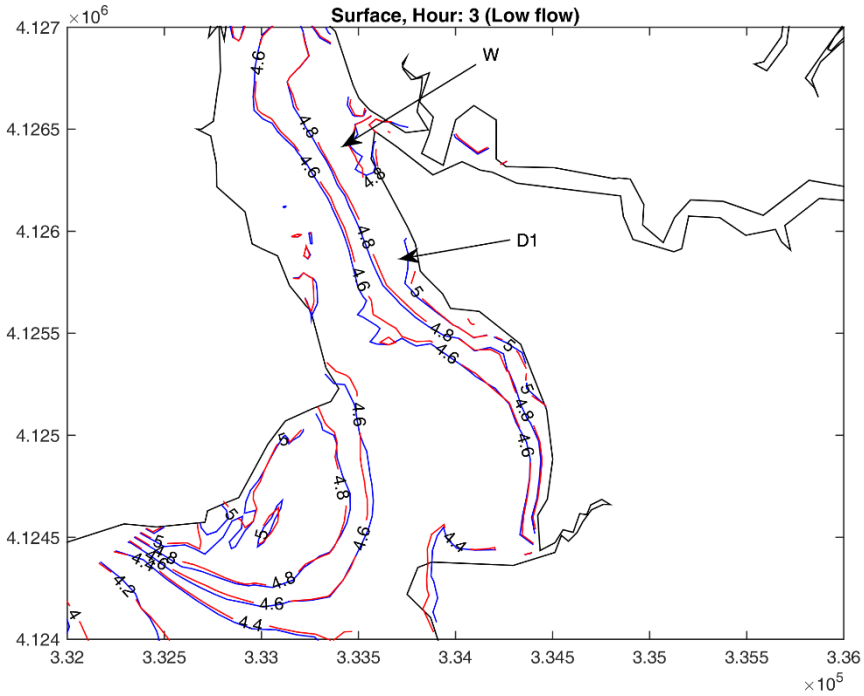
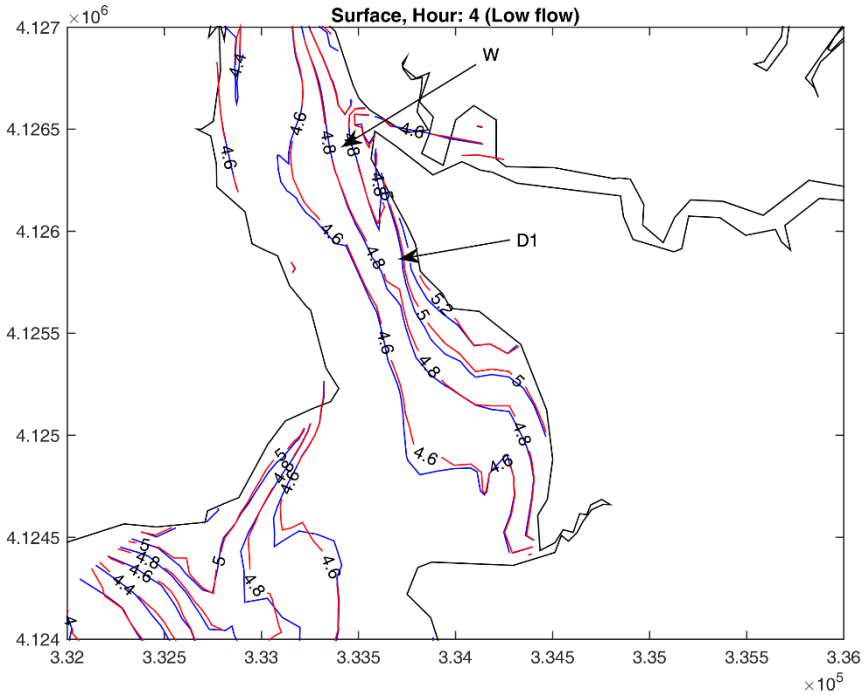


Figure 4-3-4. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5


Surface, Hour: 2 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5


Surface, Hour: 3 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

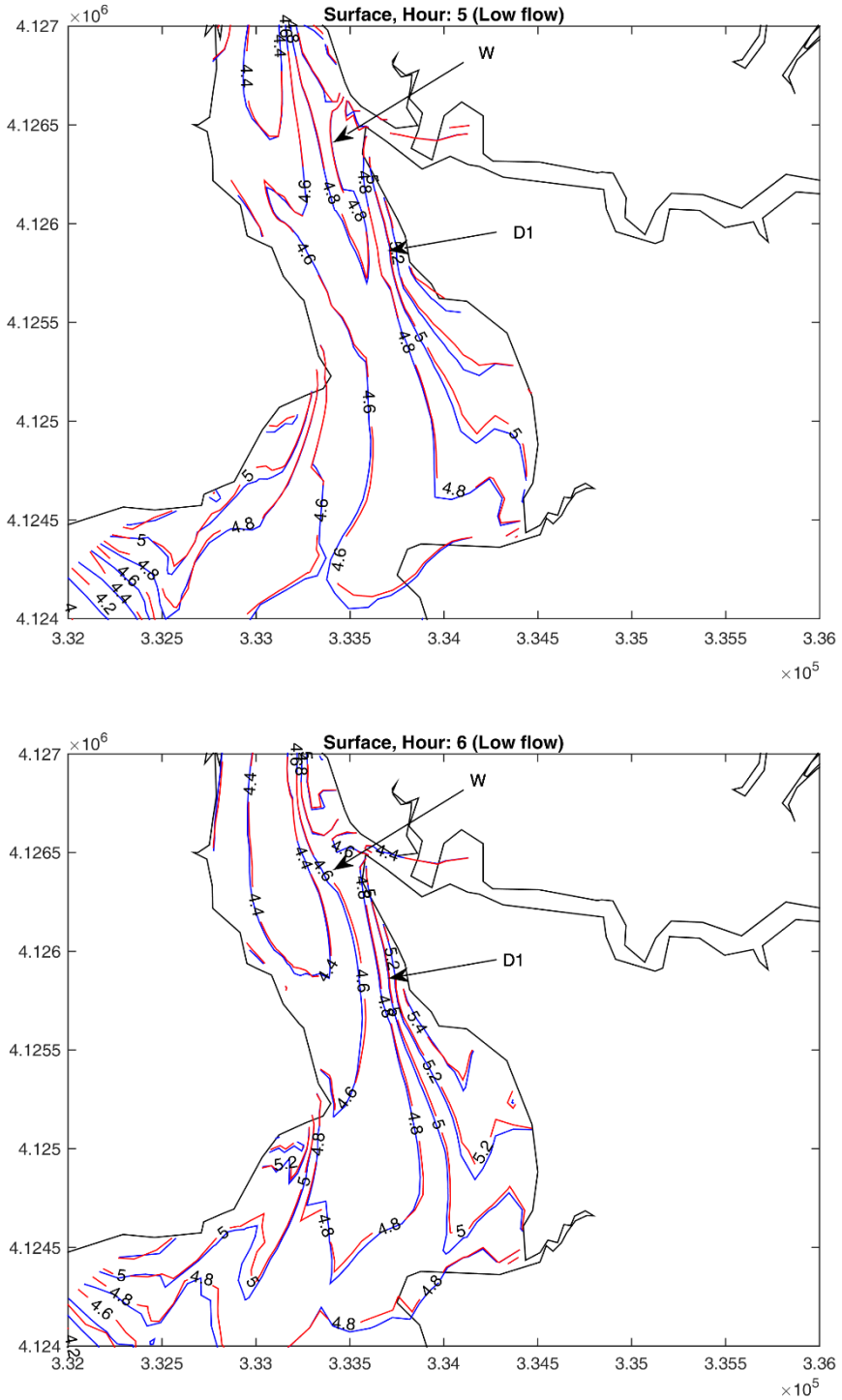
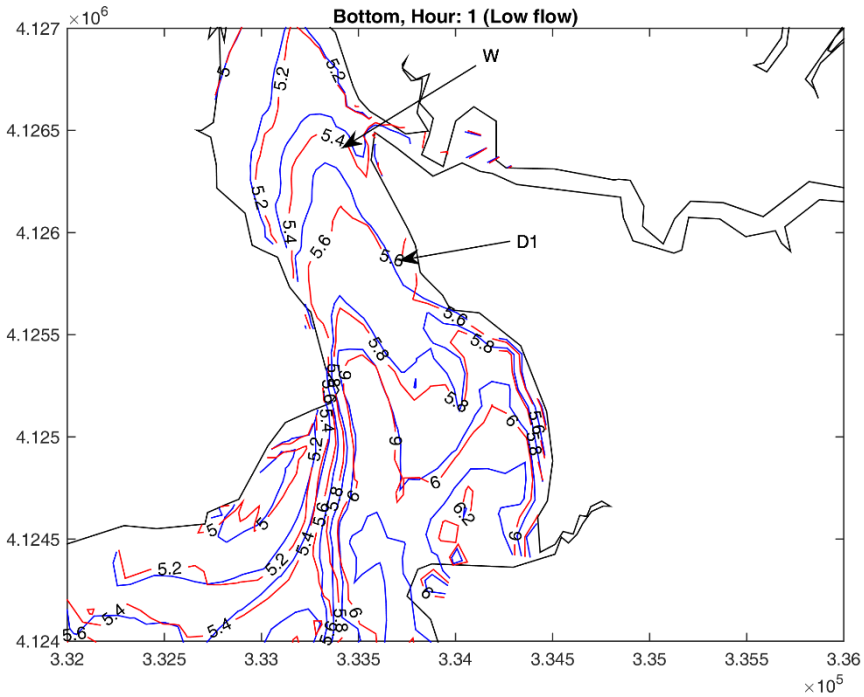
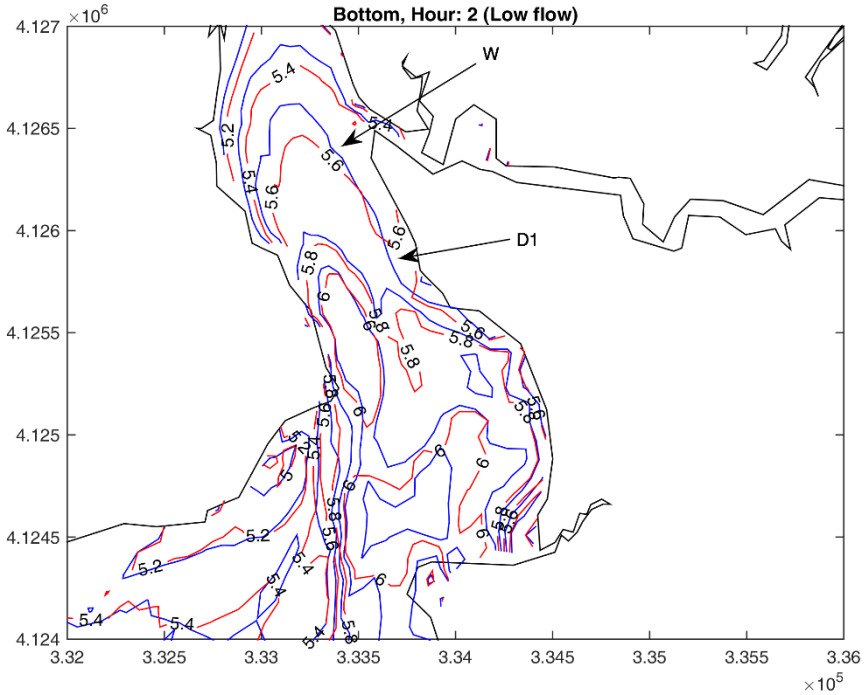
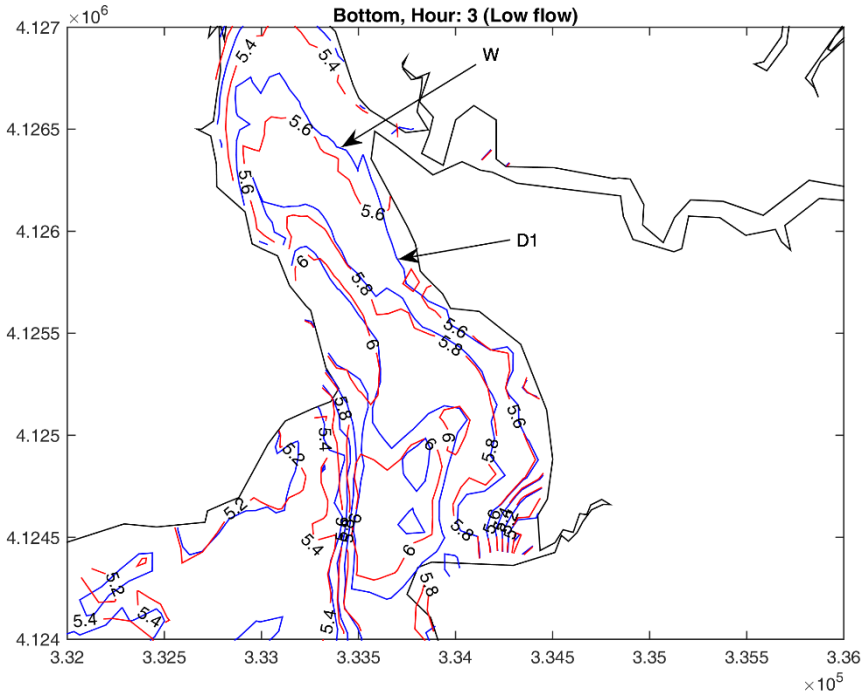
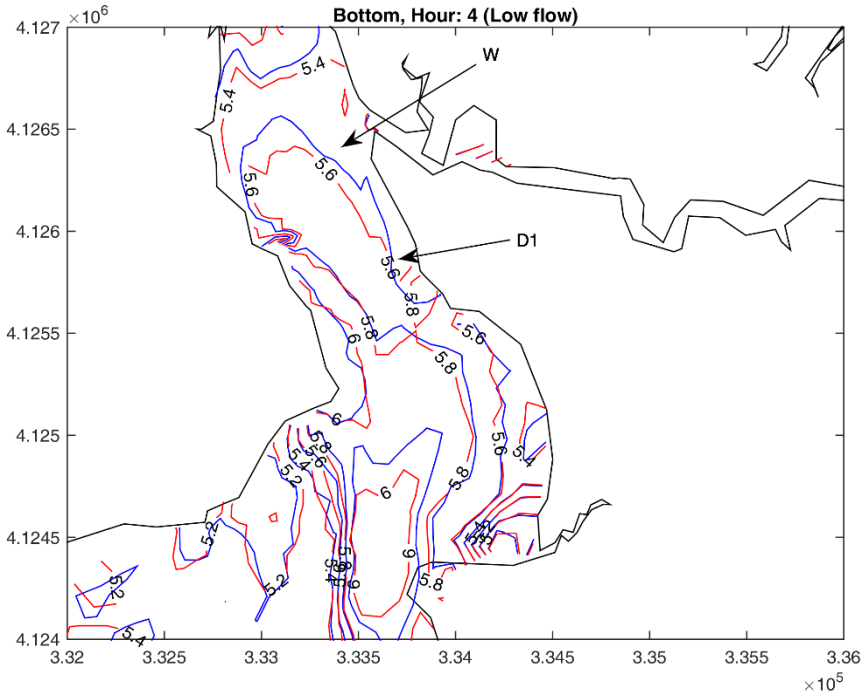


Figure 4-3-5. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site)


Bottom, Hour: 1 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
×10^6
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
×10^6
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

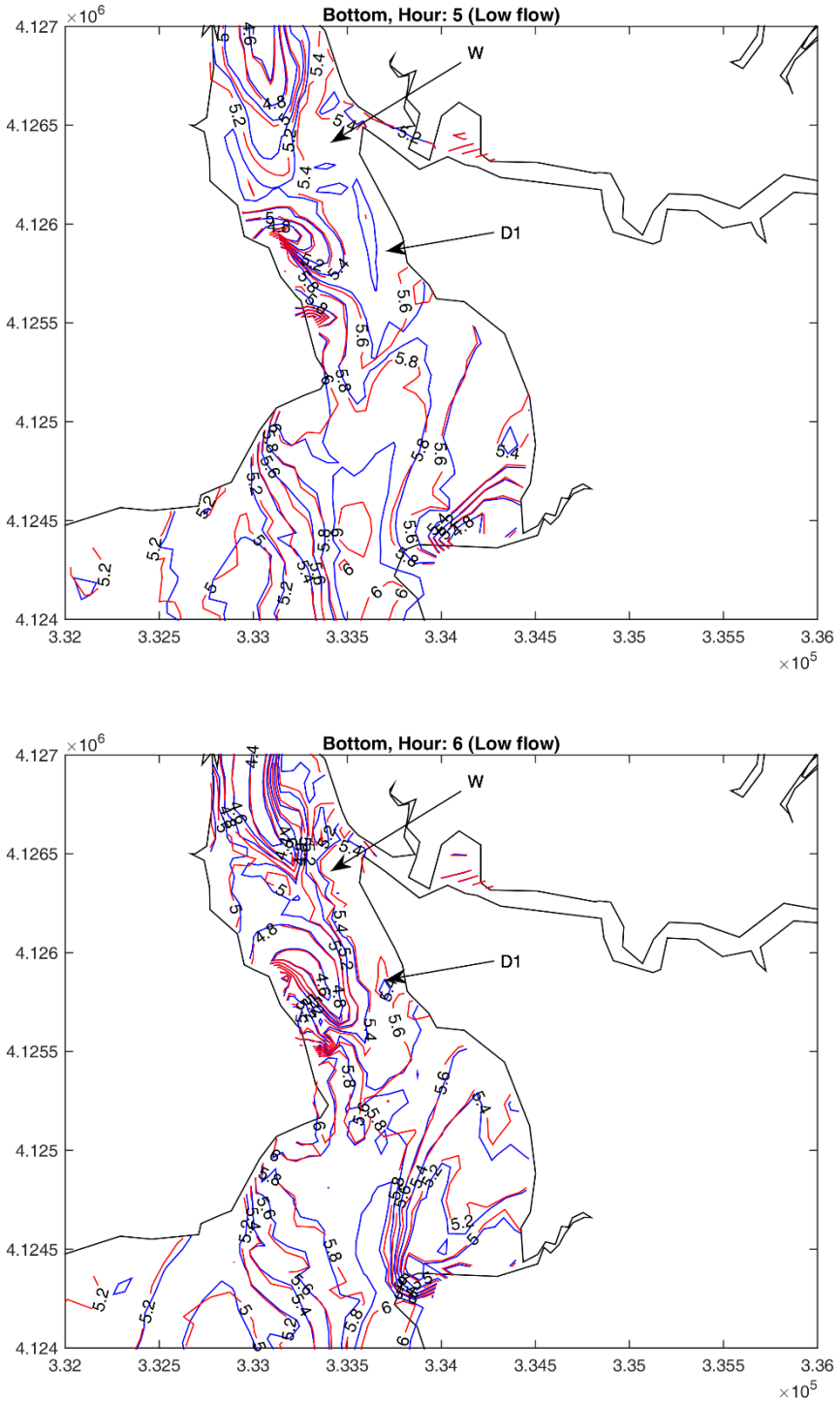


Figure 4-3-6. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

4.4 Chickahominy Riverfront Park Discharge Site I --Phase III

Similar to what was done for the Chickahominy Riverfront Park Phase II case, the time series and salinity distributions are compared in Figures 4-4-1 to 4-4-2. The salinity only changed slightly at the withdrawal site. The change is about 0.3 psu. But slightly higher than Phase II. The salinity increases and decreases occurred at the discharge location. The decrease of salinity is related to the withdrawal and discharge of flow, which can change dynamic conditions near withdrawal and discharge locations and depend on tide. The maximum salinity change at the discharge location is about 2.03 psu. Compared to maximum salinity of 8.9 psu at that site, the change is about 23%. Horizontal plots of salinity distributions at Days 150 (high flow) and 300 (low flow) show some changes of salinity distribution in general. The slightly larger change occurs at the bottom at Day 300 (low flow) near the eastern shore. The salinity change depends on tide. Both an increase and a decrease occur during different phases of the tide. Because of a large water volume in this lower estuary and a large tide mixing, the change of salinity is less than 20% near discharge site at the bottom.

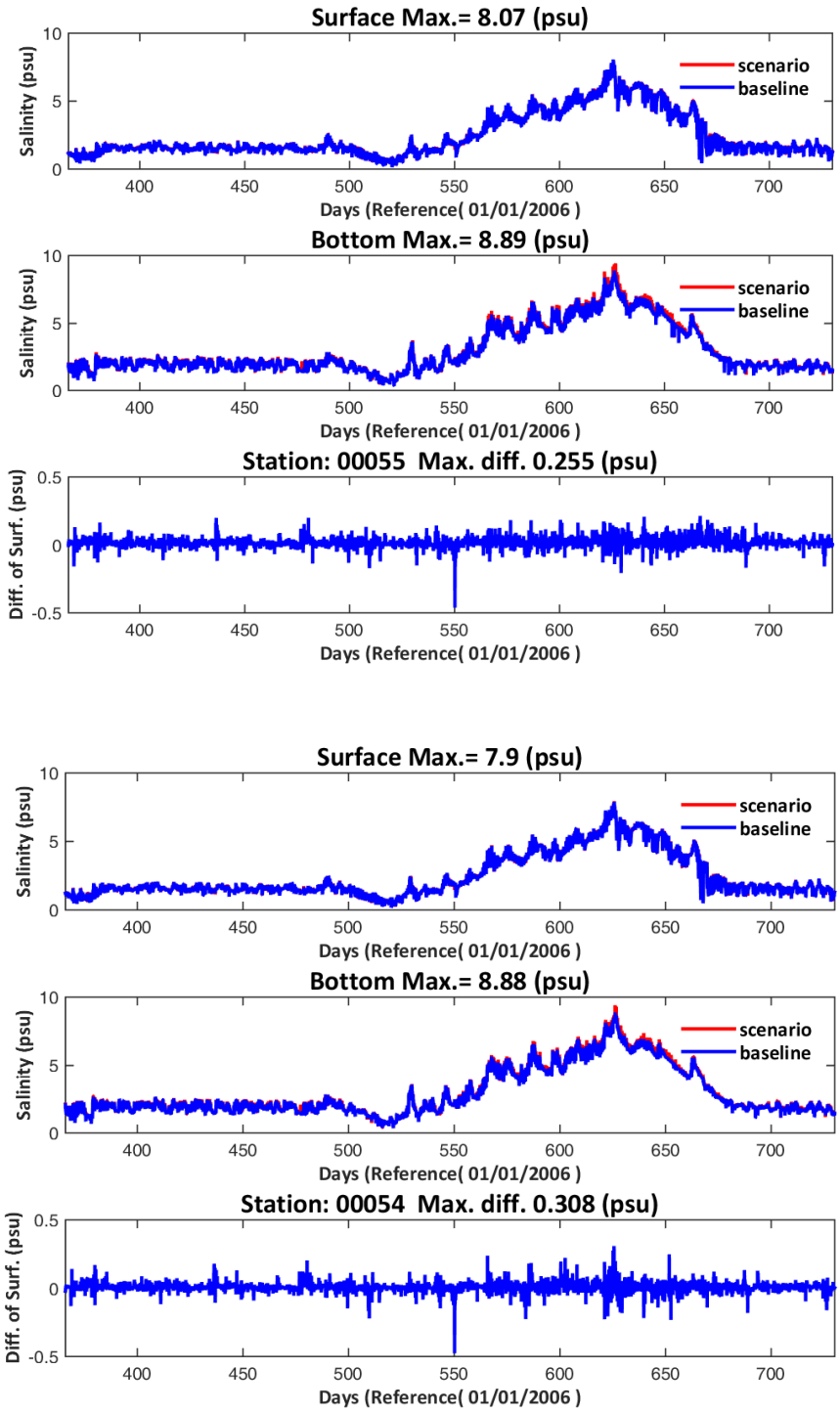


Figure 4-4-1. Comparison of salinity time series at selected locations, and difference between scenario and baseline near the surface at Chickahominy Riverfront Park withdrawal site (number shown in 3rd panel is station ID).

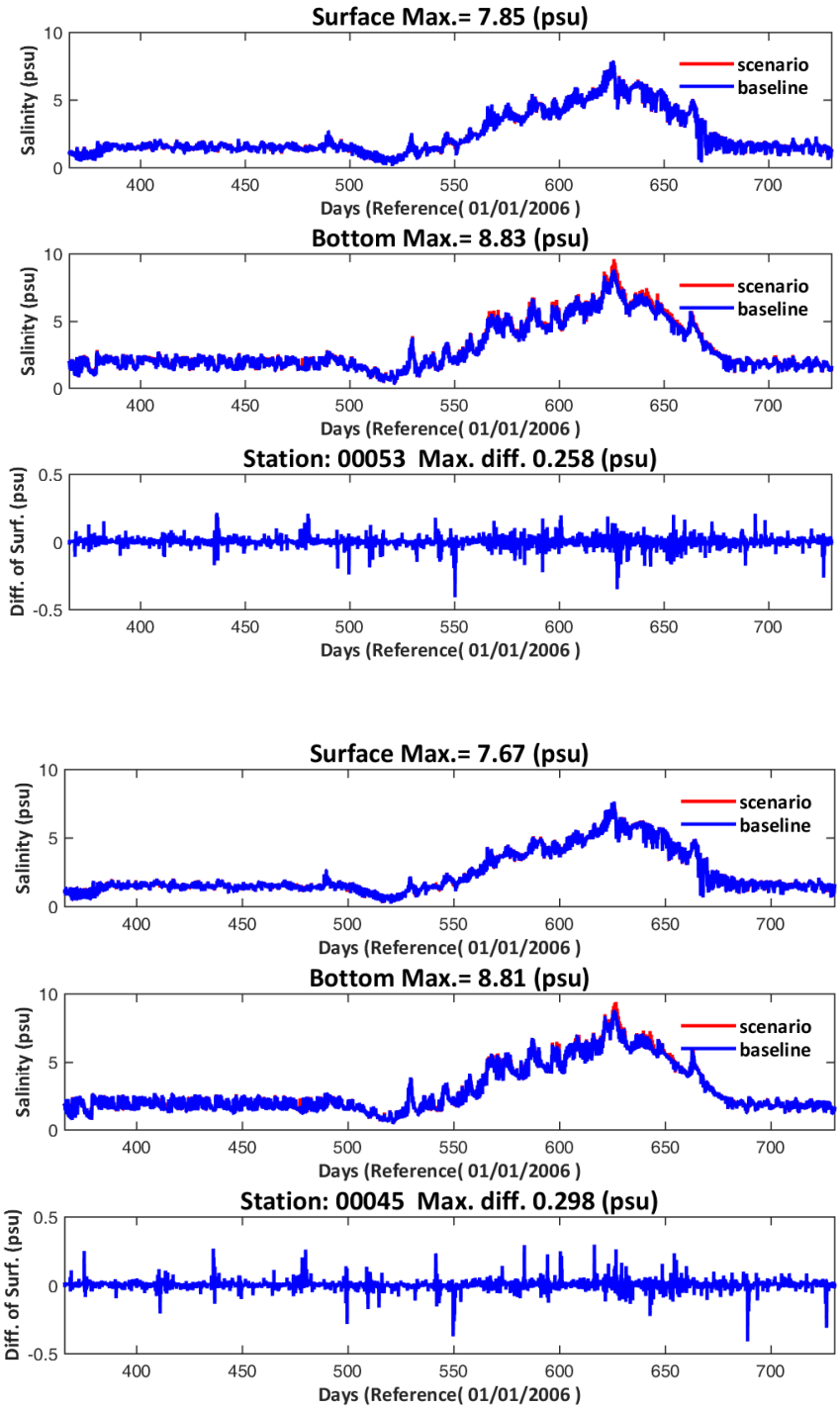


Figure 4-4-1. Continue.

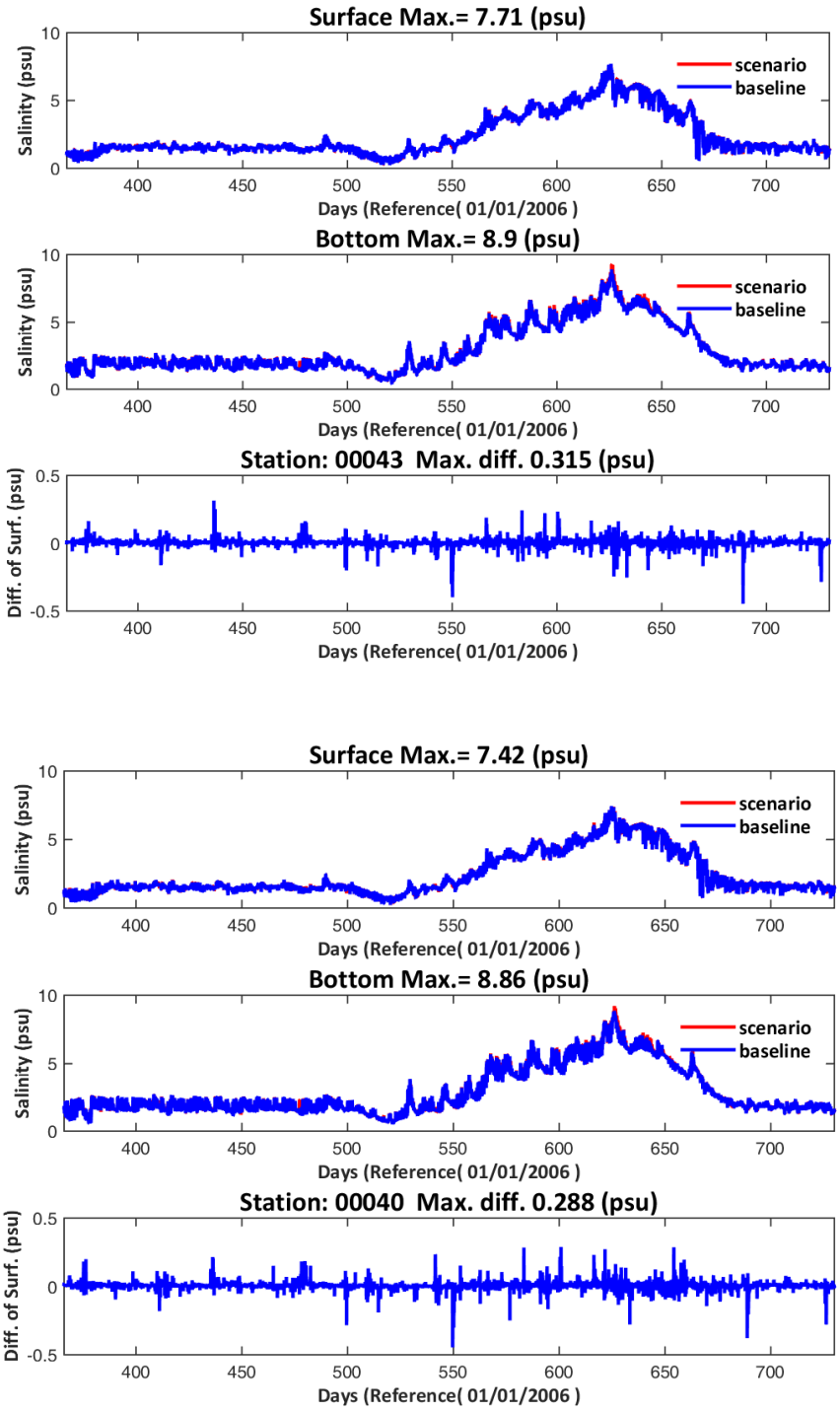


Figure 4-4-1. Continue.

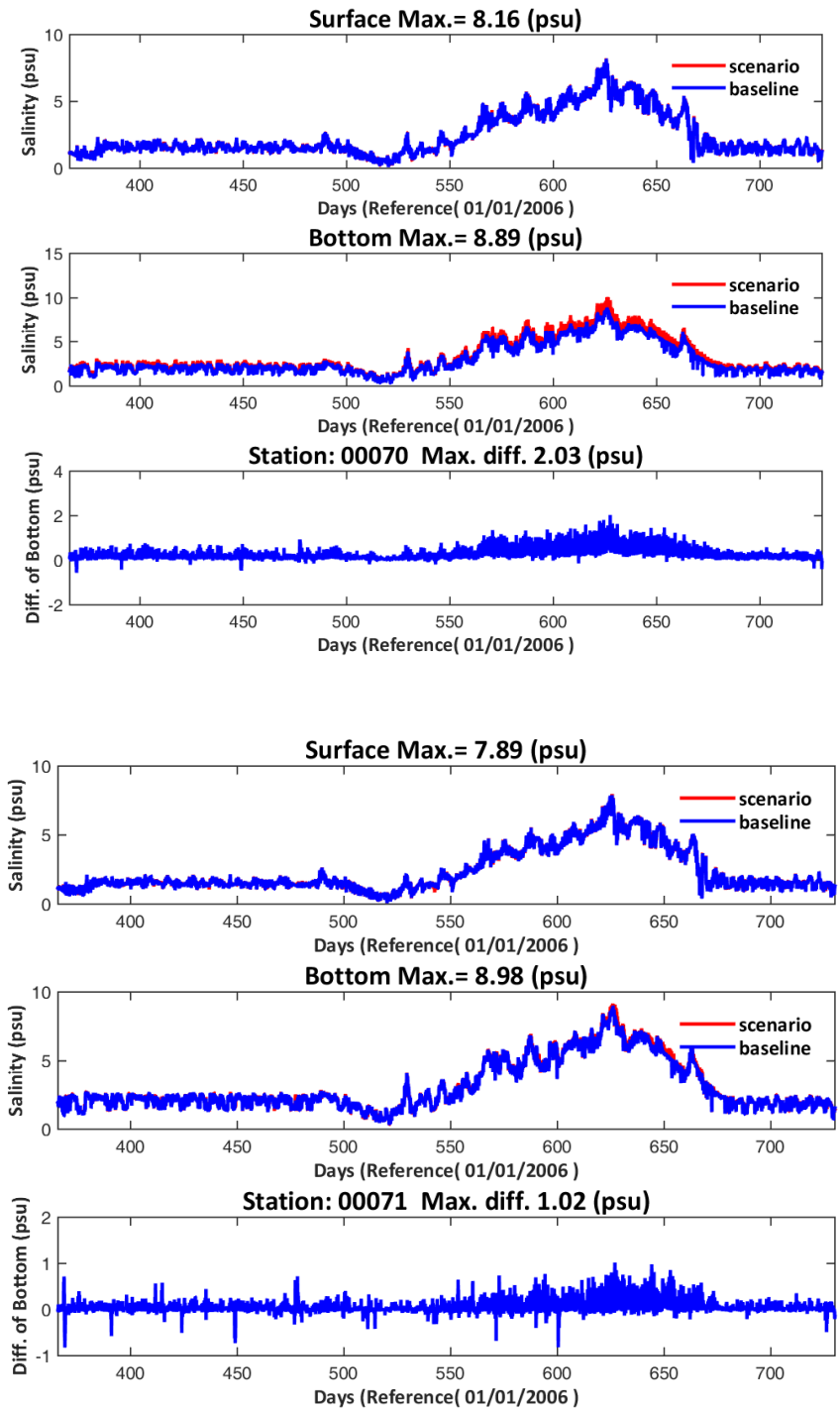


Figure 4-4-2. Comparison of salinity time series at selected locations, and difference between scenario and baseline near the bottom at Chickahominy Riverfront Park discharge site I (number shown in 3rd panel is station ID).

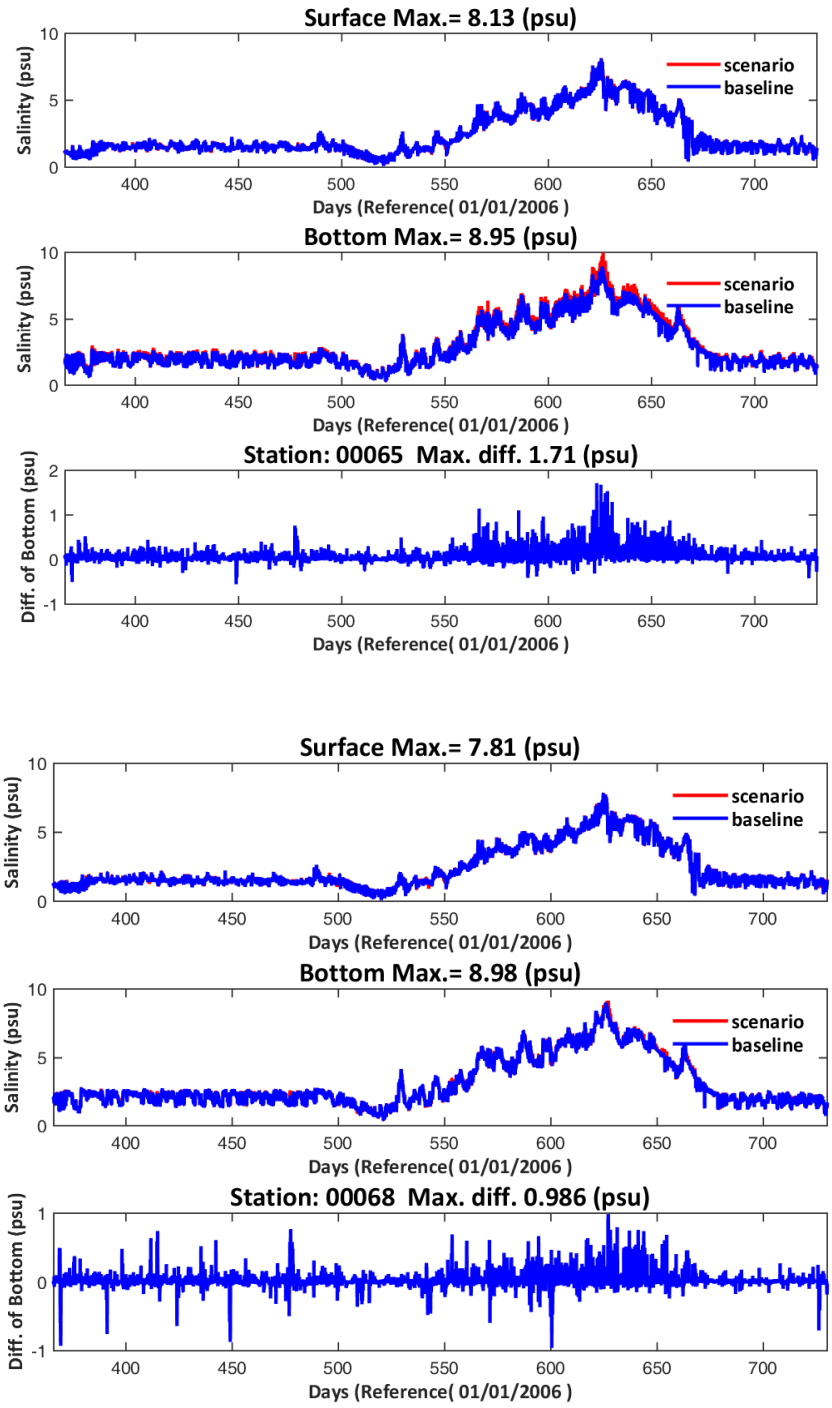
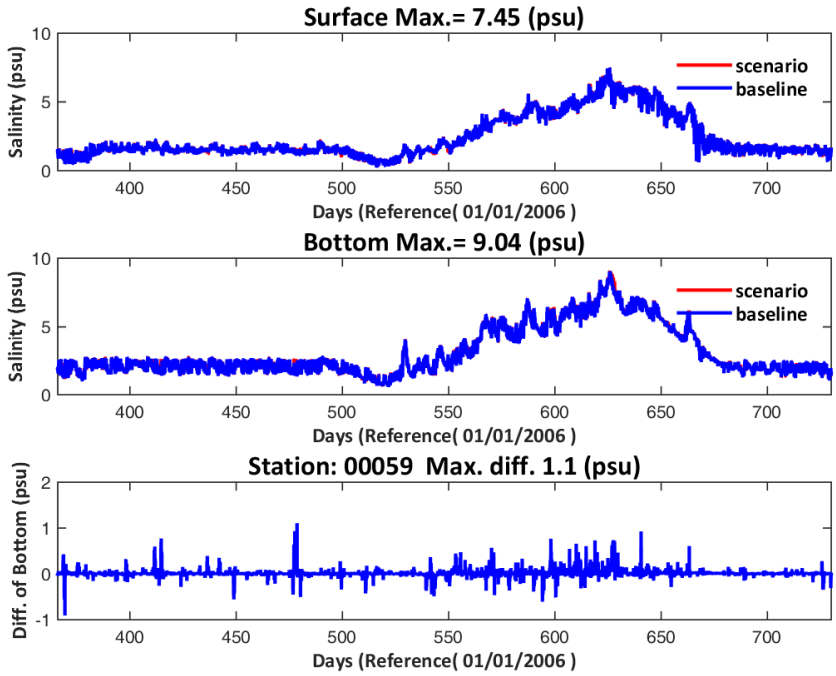


Figure 4-4-2. Continue.



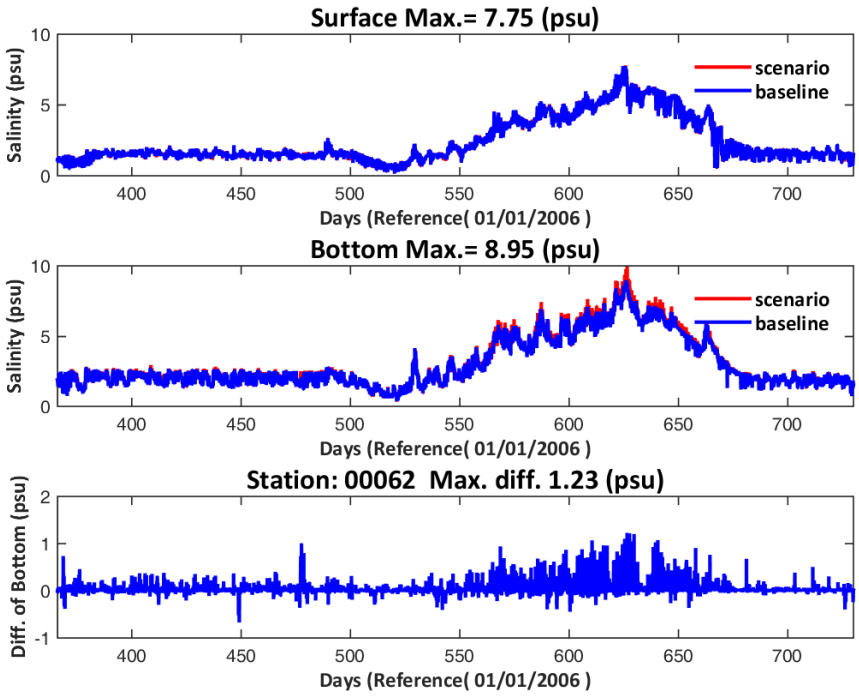
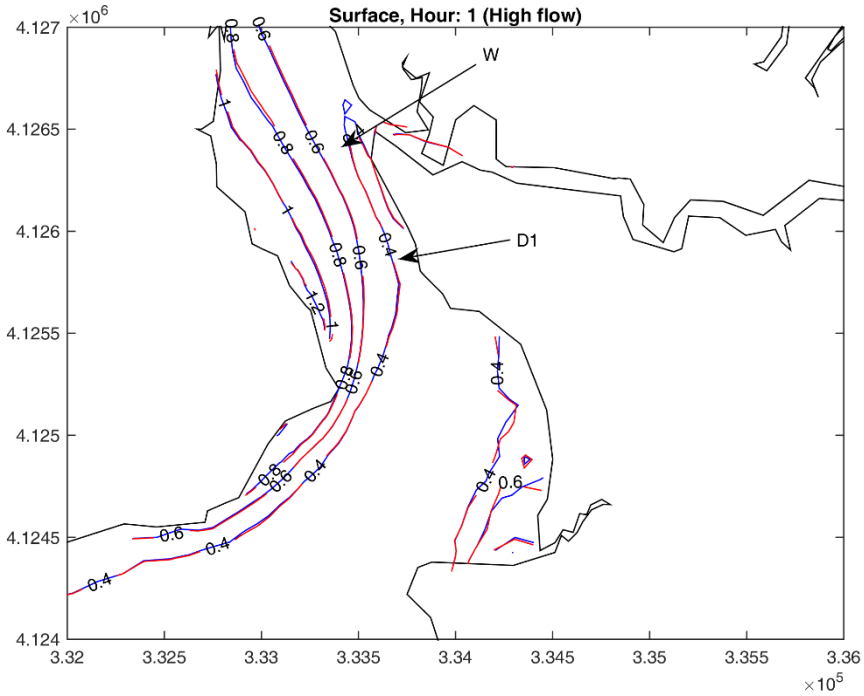
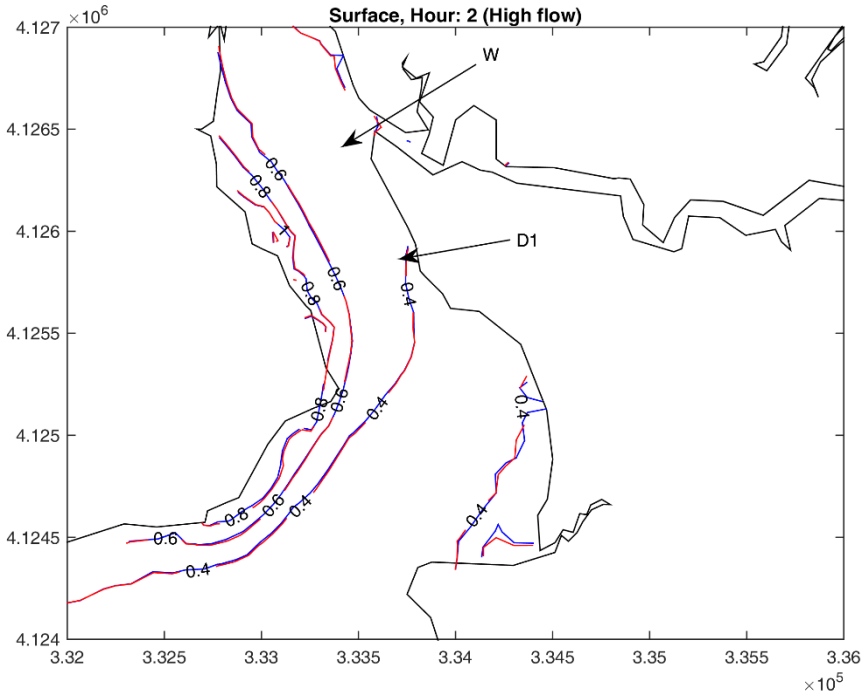
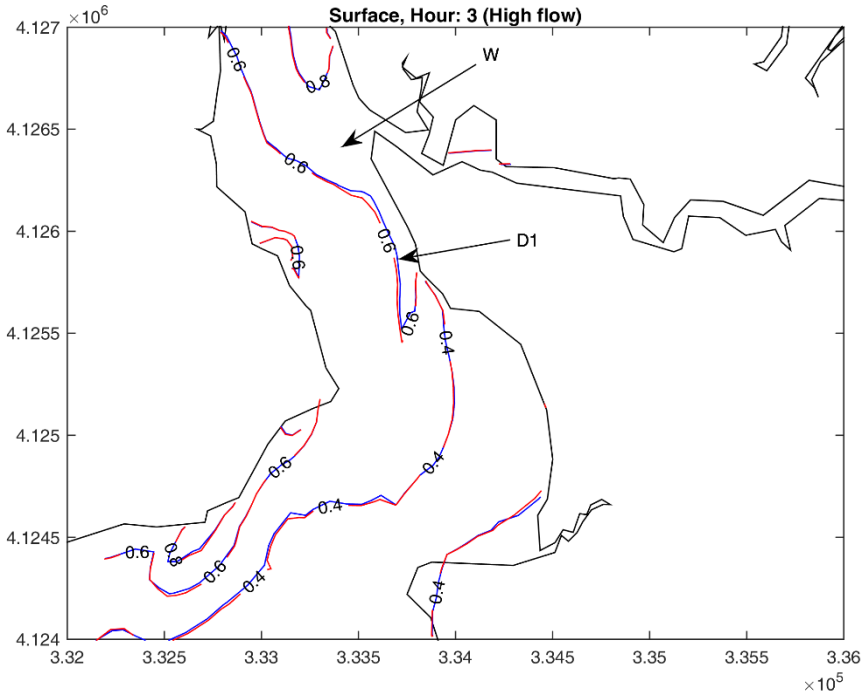
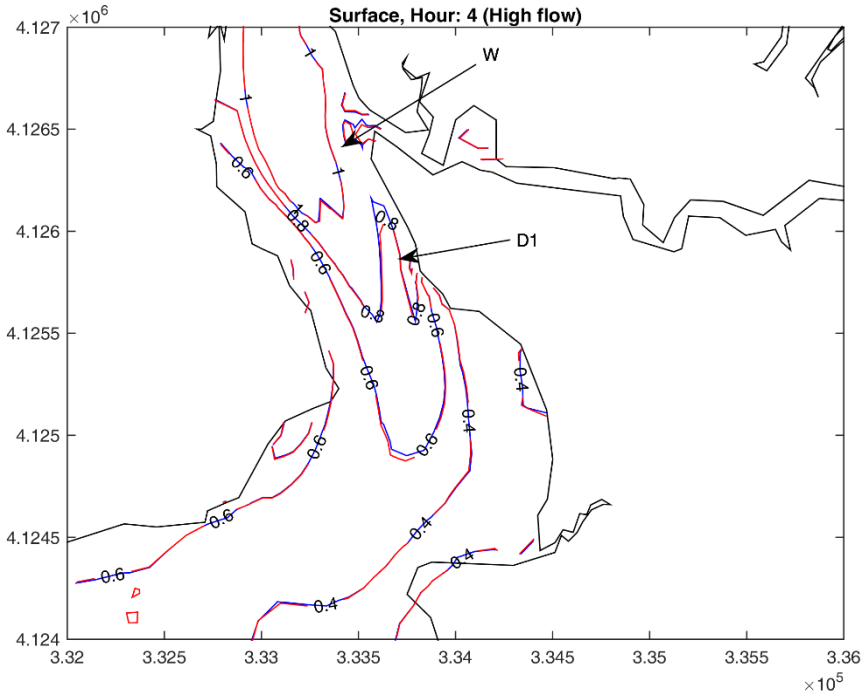


Figure 4-4-2. Continue.


Surface, Hour: 1 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

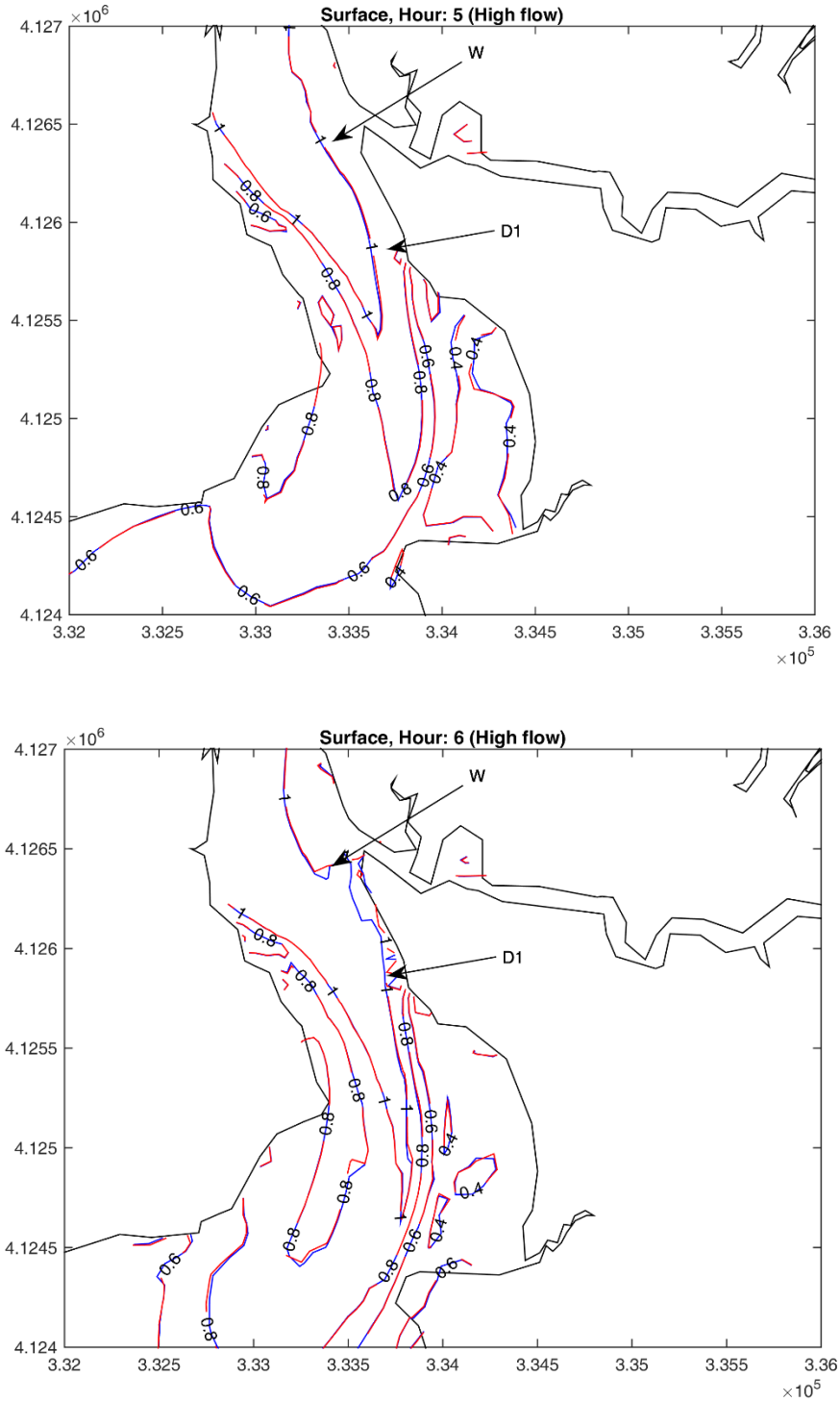
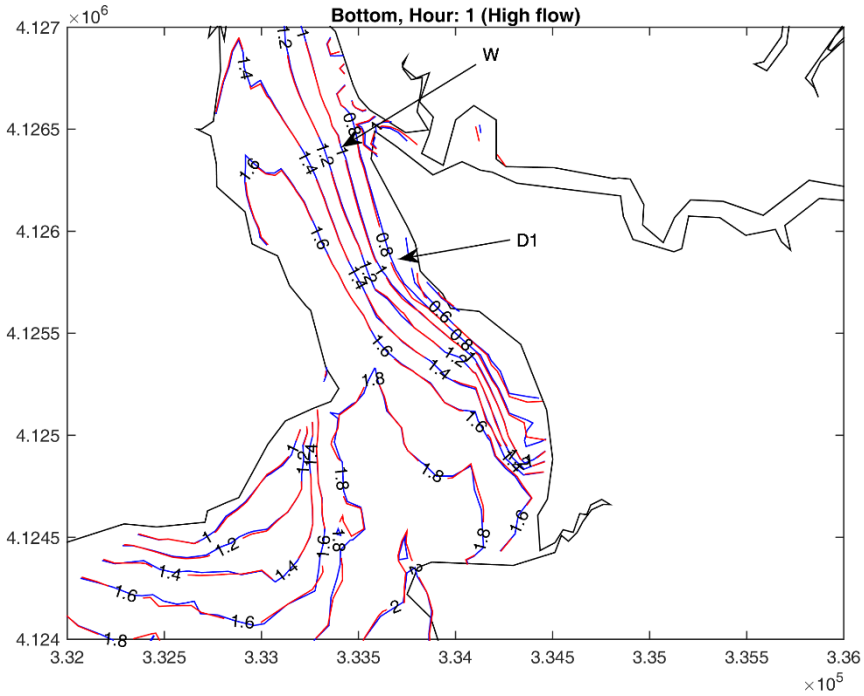
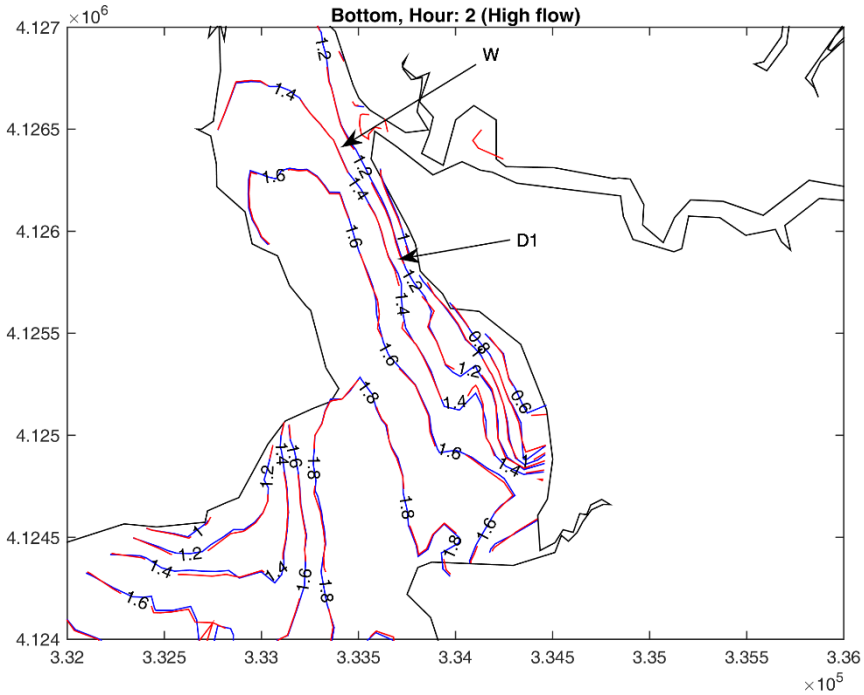
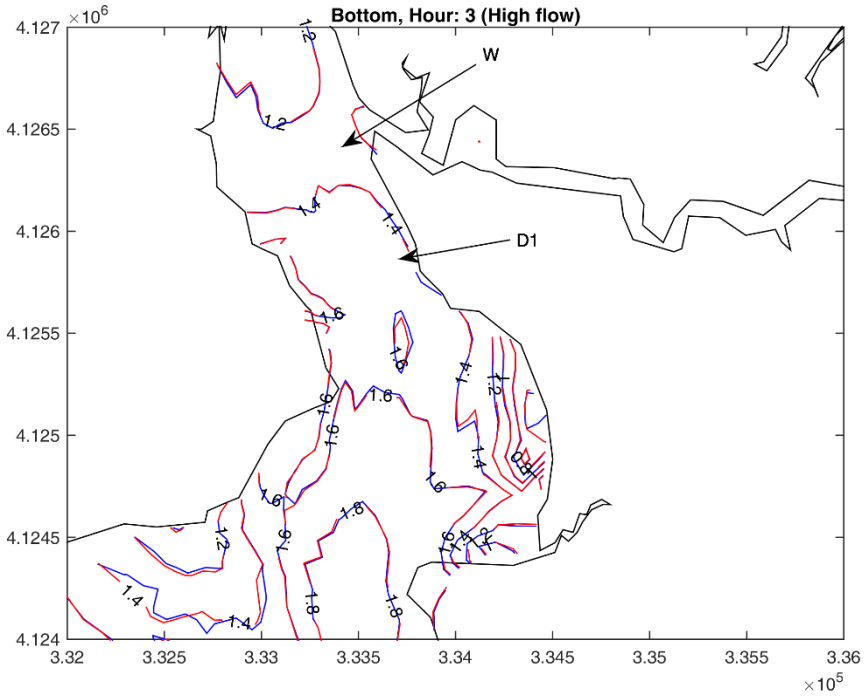
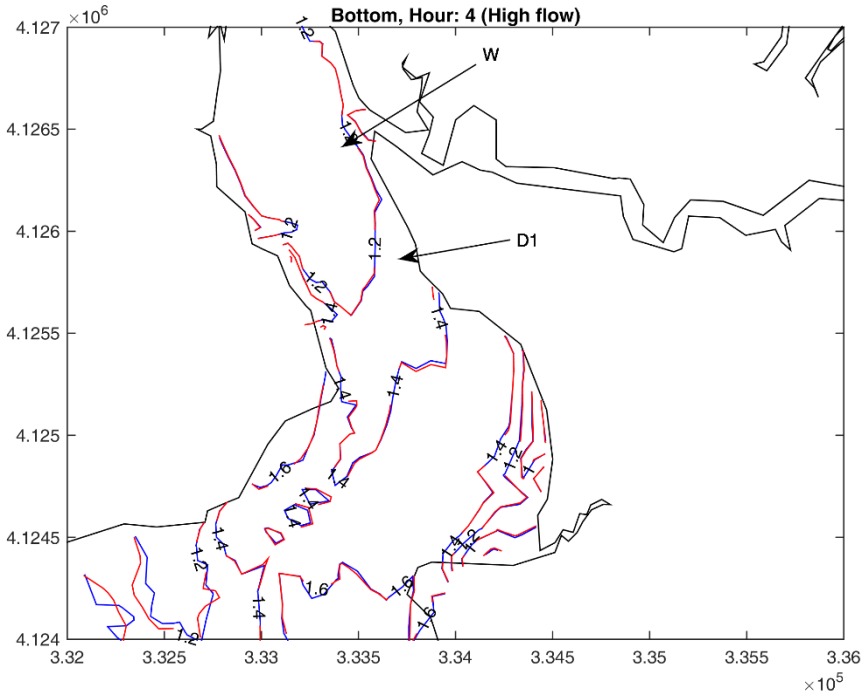


Figure 4-4-3. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (High flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

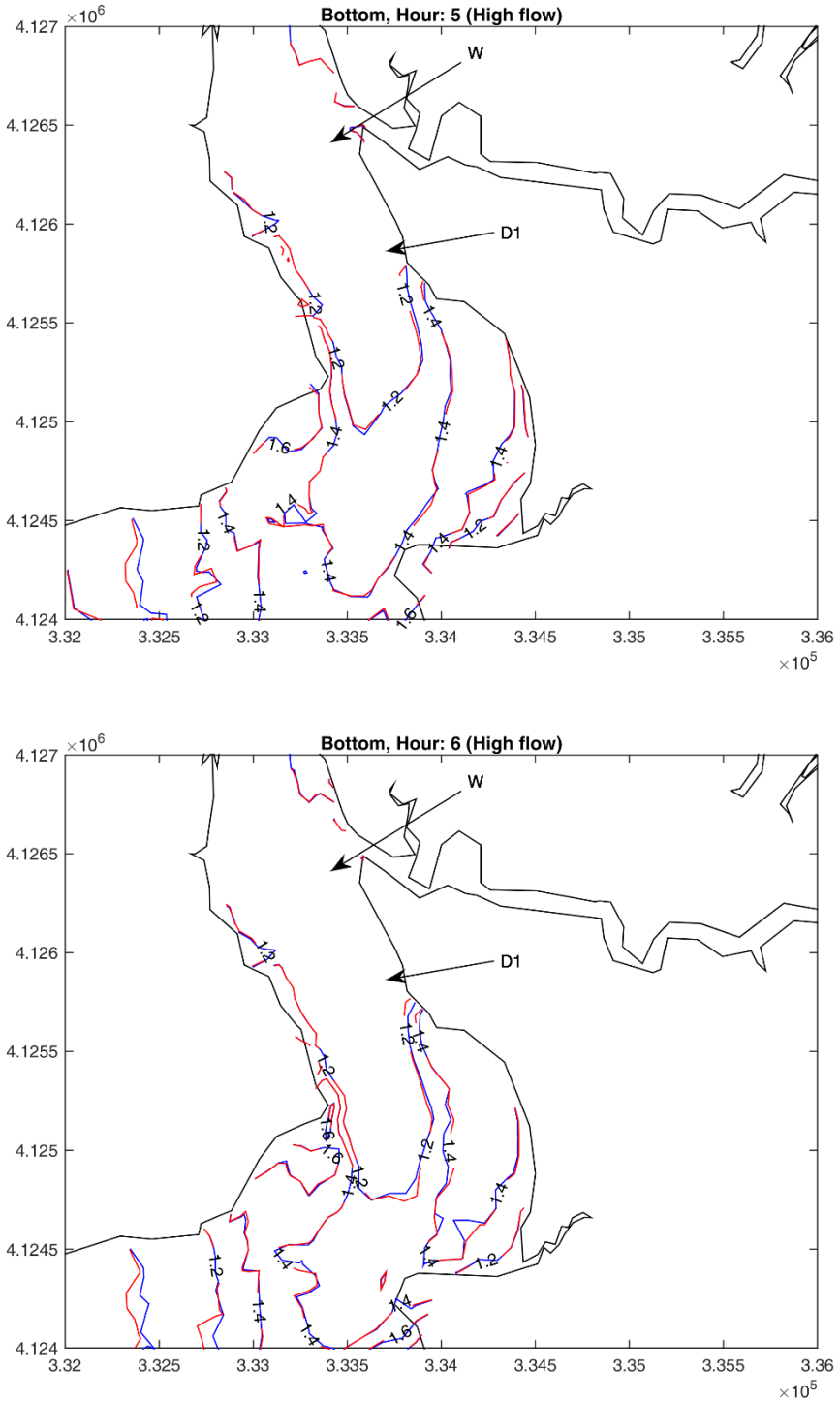
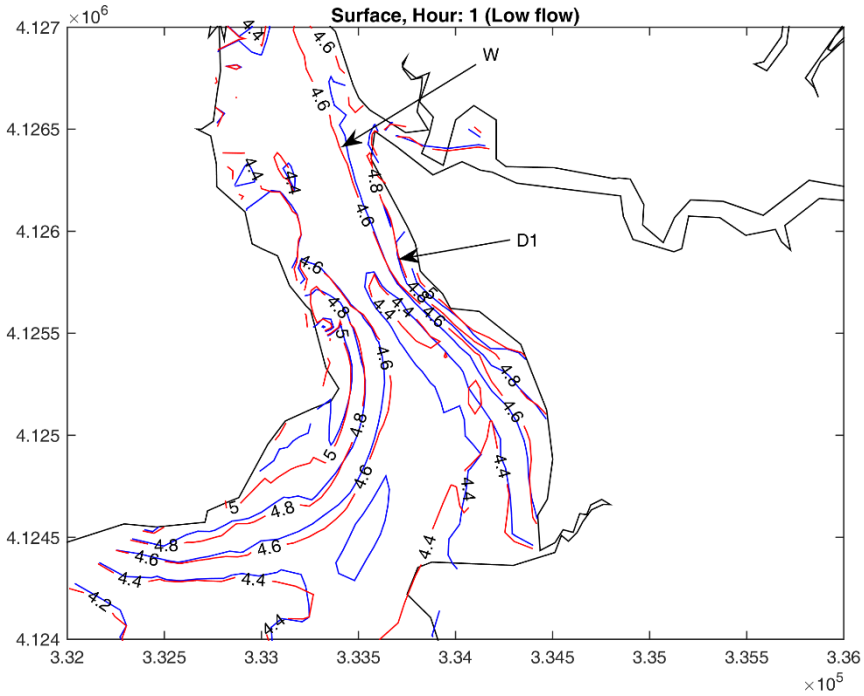
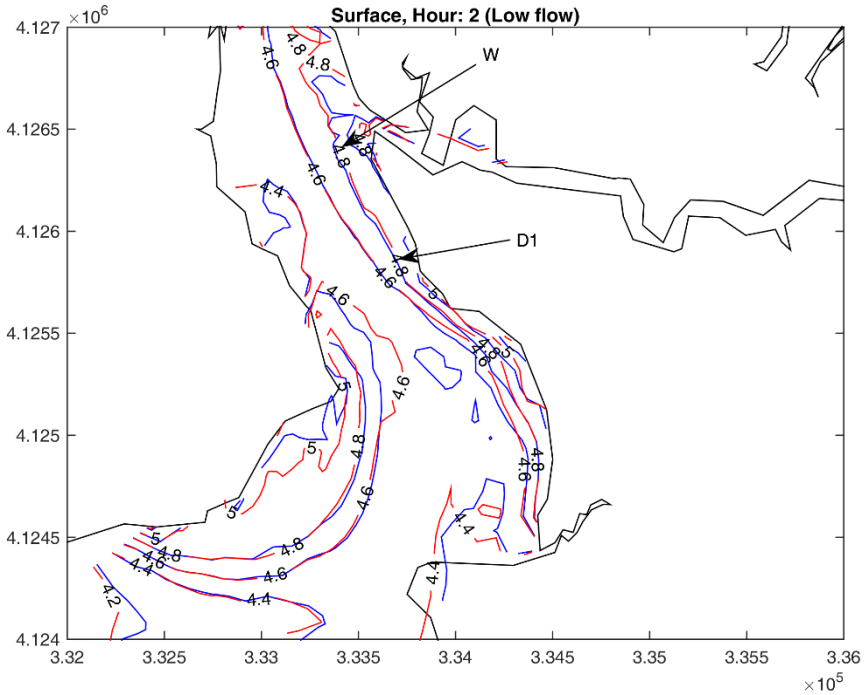
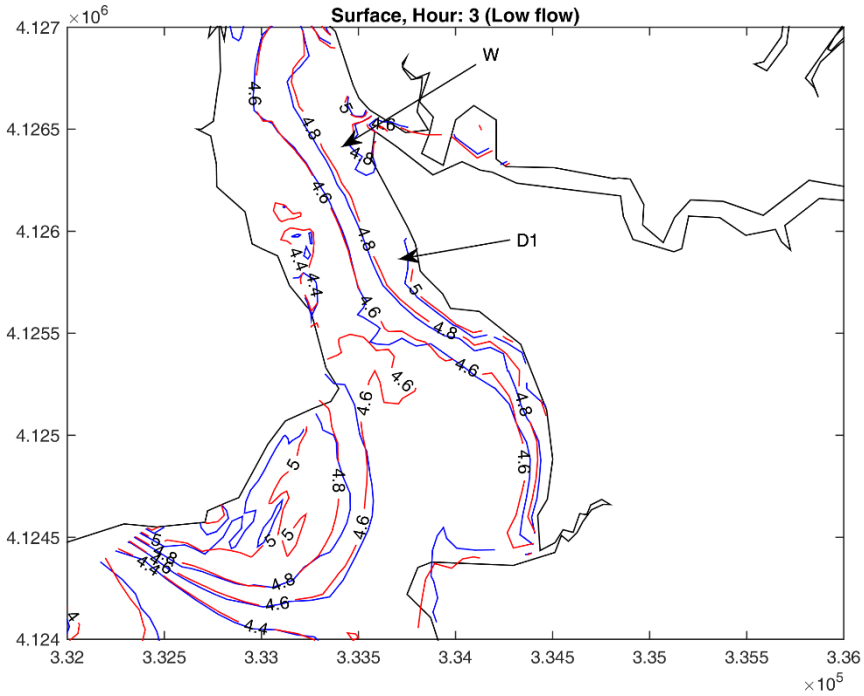
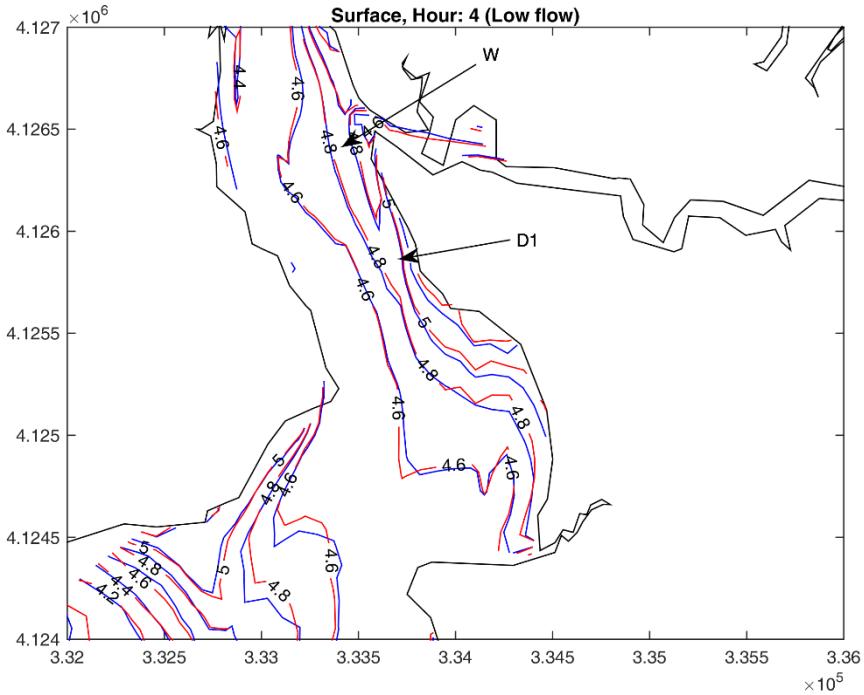


Figure 4-4-4. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (Low flow)
W
D1
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

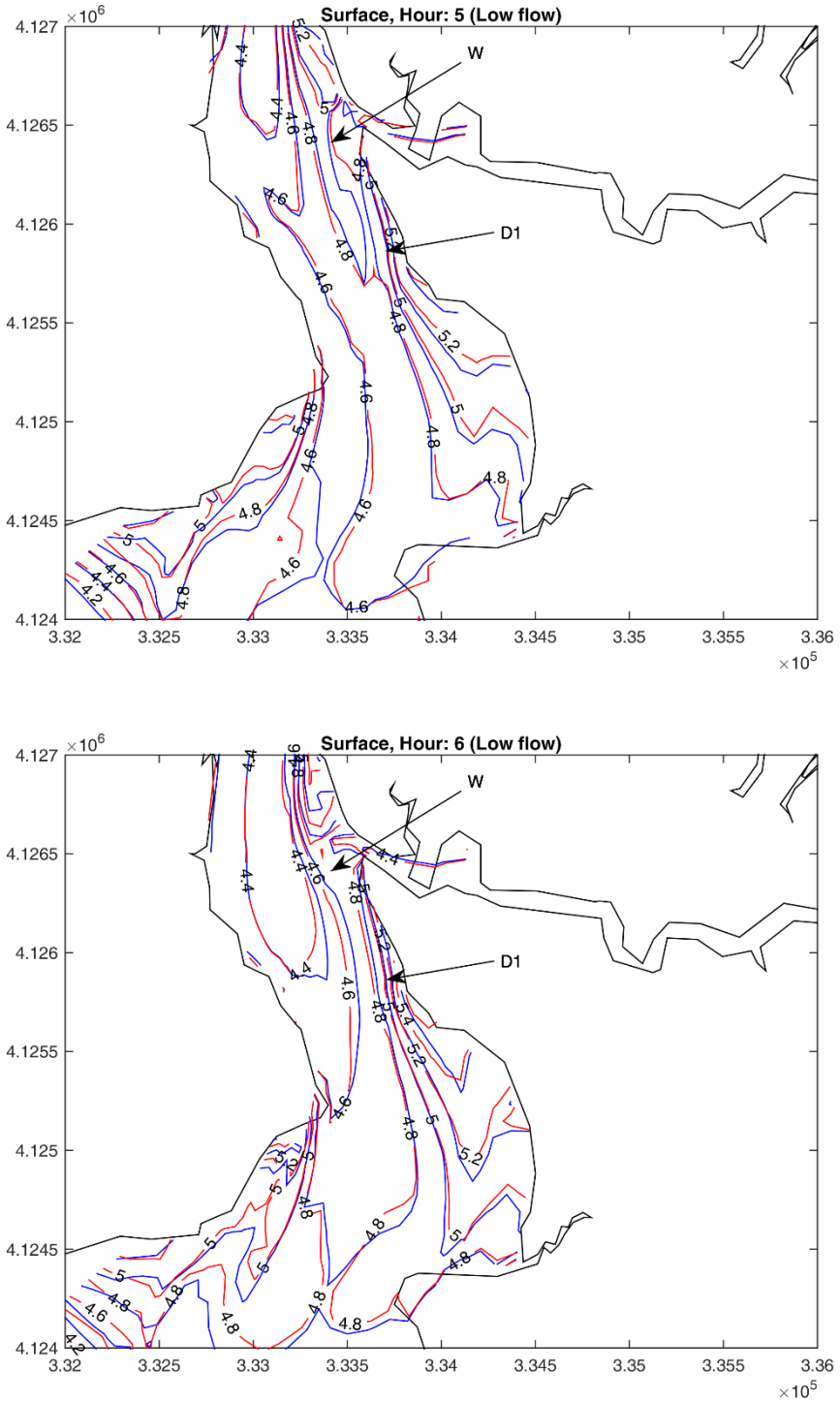
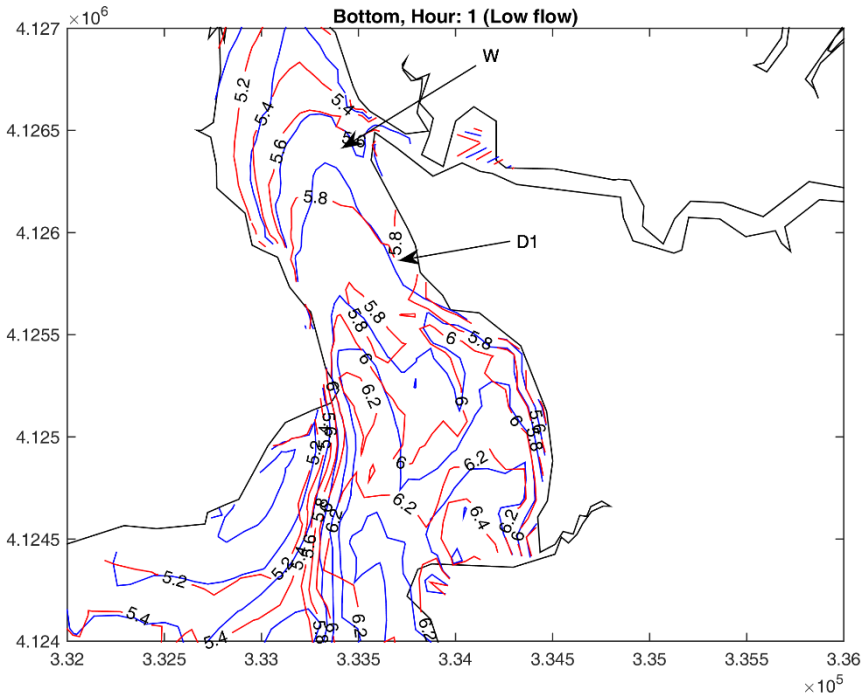
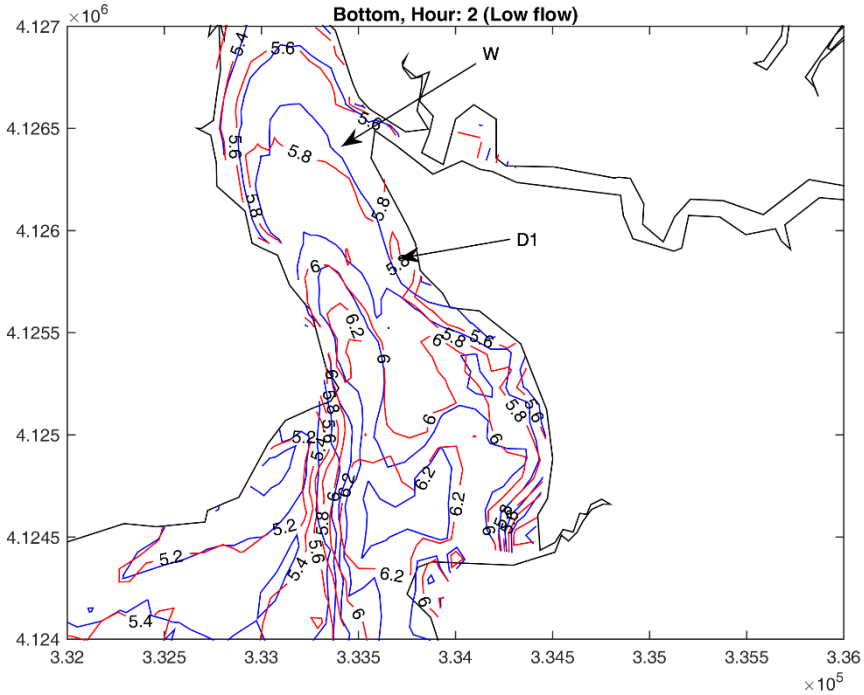
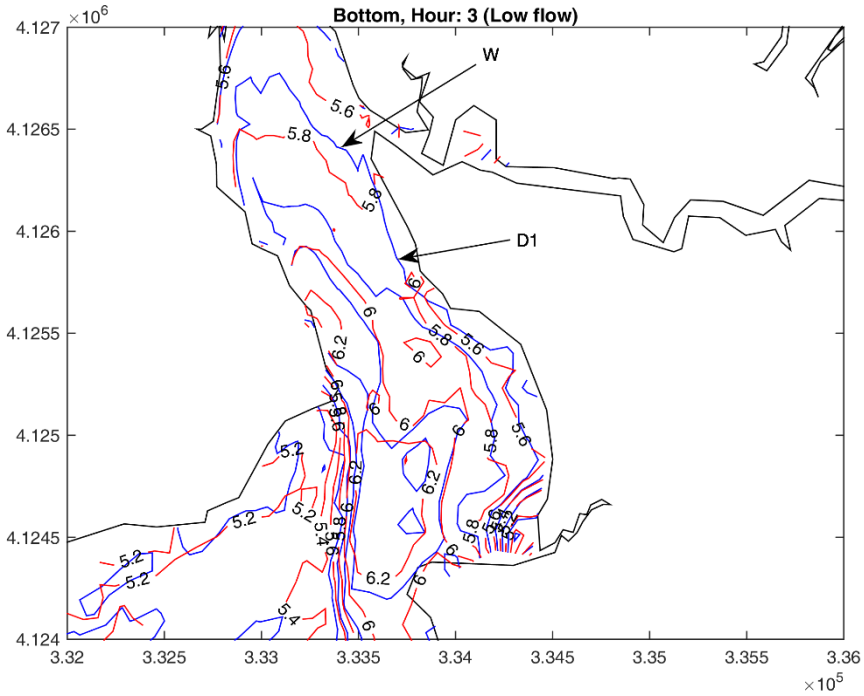
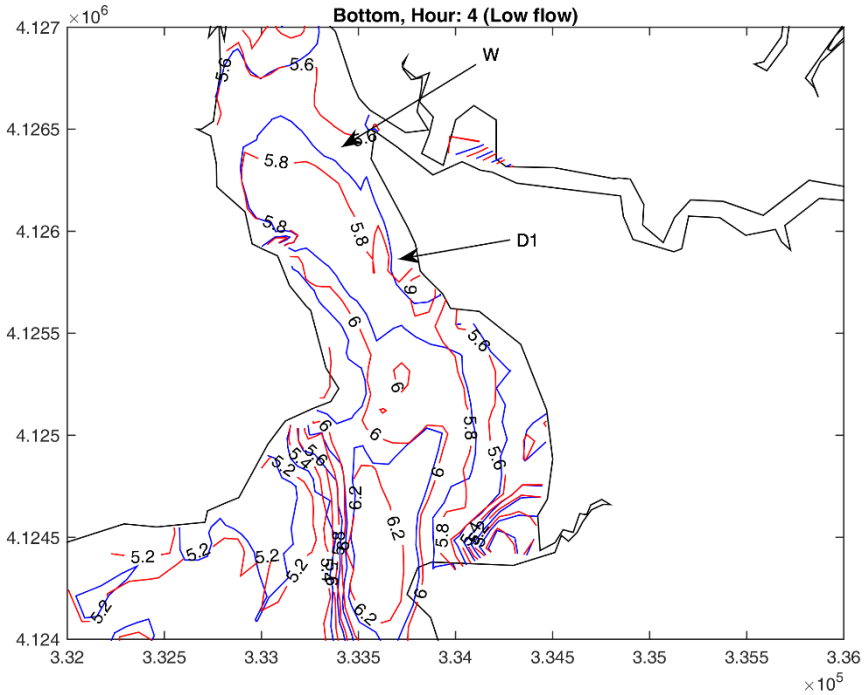


Figure 4-4-5. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
×10^6
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
×10^6
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5


Bottom, Hour: 4 (Low flow)
W
D1
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5

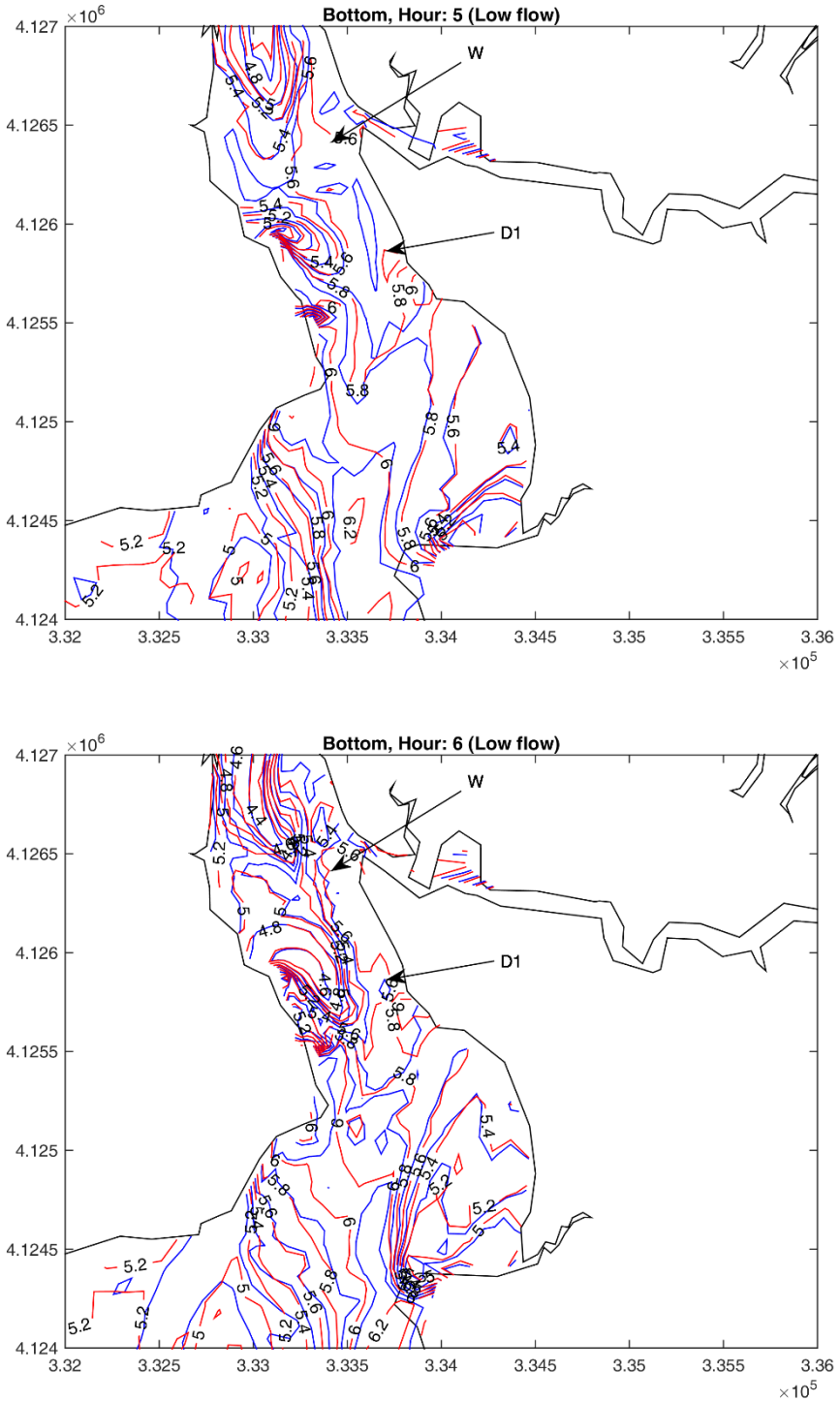


Figure 4-4-6. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site I for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

4.5 Chickahominy Riverfront Park Discharge Site 2 --Phase II

The comparisons of the simulation of Phase II for discharge at site 2 to the baseline condition are shown in Figures 4-5-1 to 4-5-2. Salinity does not change much at the withdrawal site. The salinity change is about 0.46 psu. The change is less than discharge at Site 1. The maximum change of salinity at the discharge site is about 1.89 psu, which is about 21% of maximum salinity at that site. The salinity increase more at discharge location 2. The salinity increase is more than 1.5 psu. The increase is higher than salinity at discharge Site 1. Horizontal plots of salinity distributions at Days 150 (high flow) and 300 (low flow) show little changes of the salinity distribution in general, except near the discharge location. As flow is lower and tidal mixing decreases in this shallow region. The slightly high salinity can be expected. The increase of salinity can be up to 21%. Both increases and decreases of salinity occur depending on tide. A slightly larger change occurs at the bottom at Day 300 near the discharge location.

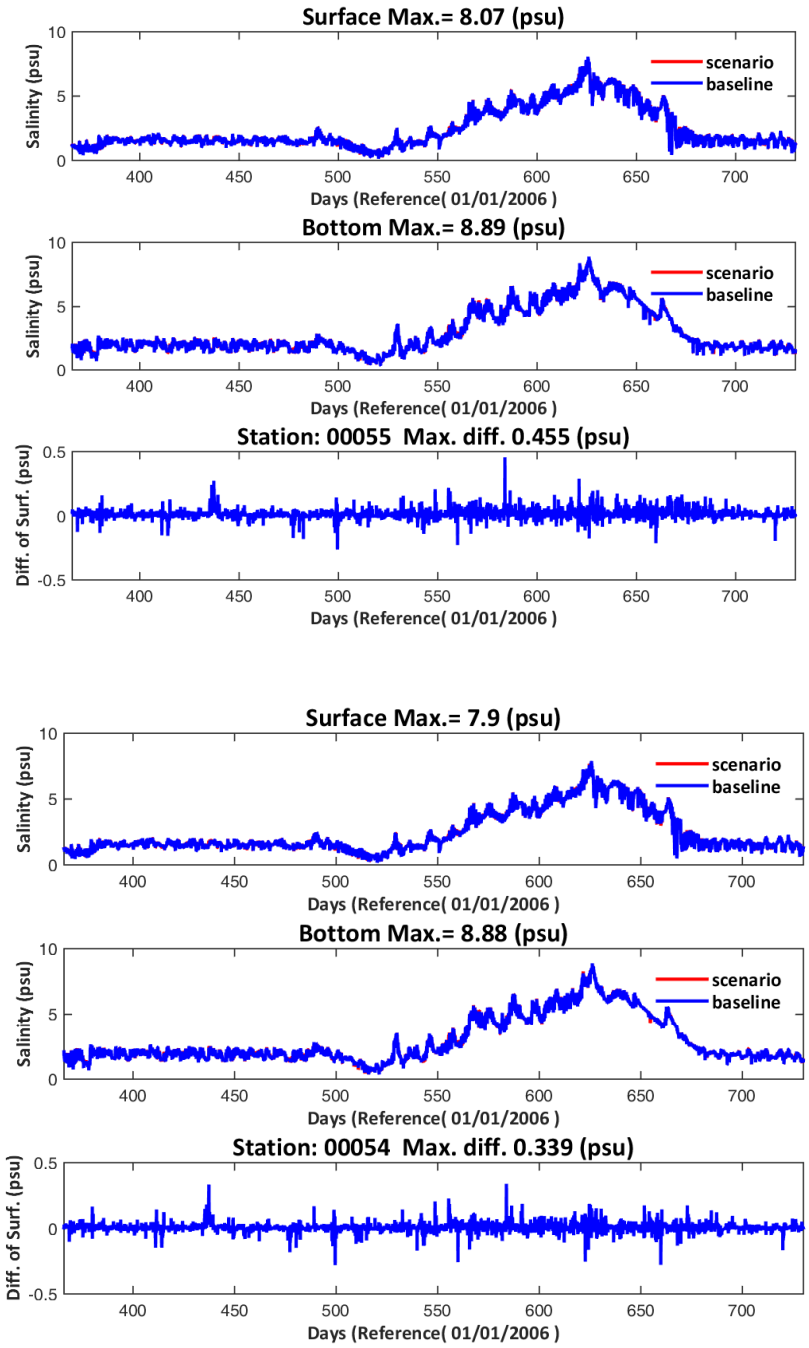


Figure 4-5-1. Comparison of time series of salinity at selected stations at Chickahominy Riverfront Park withdrawal site (difference between scenario and baseline near the surface, number shown in 3nd panel is location ID).

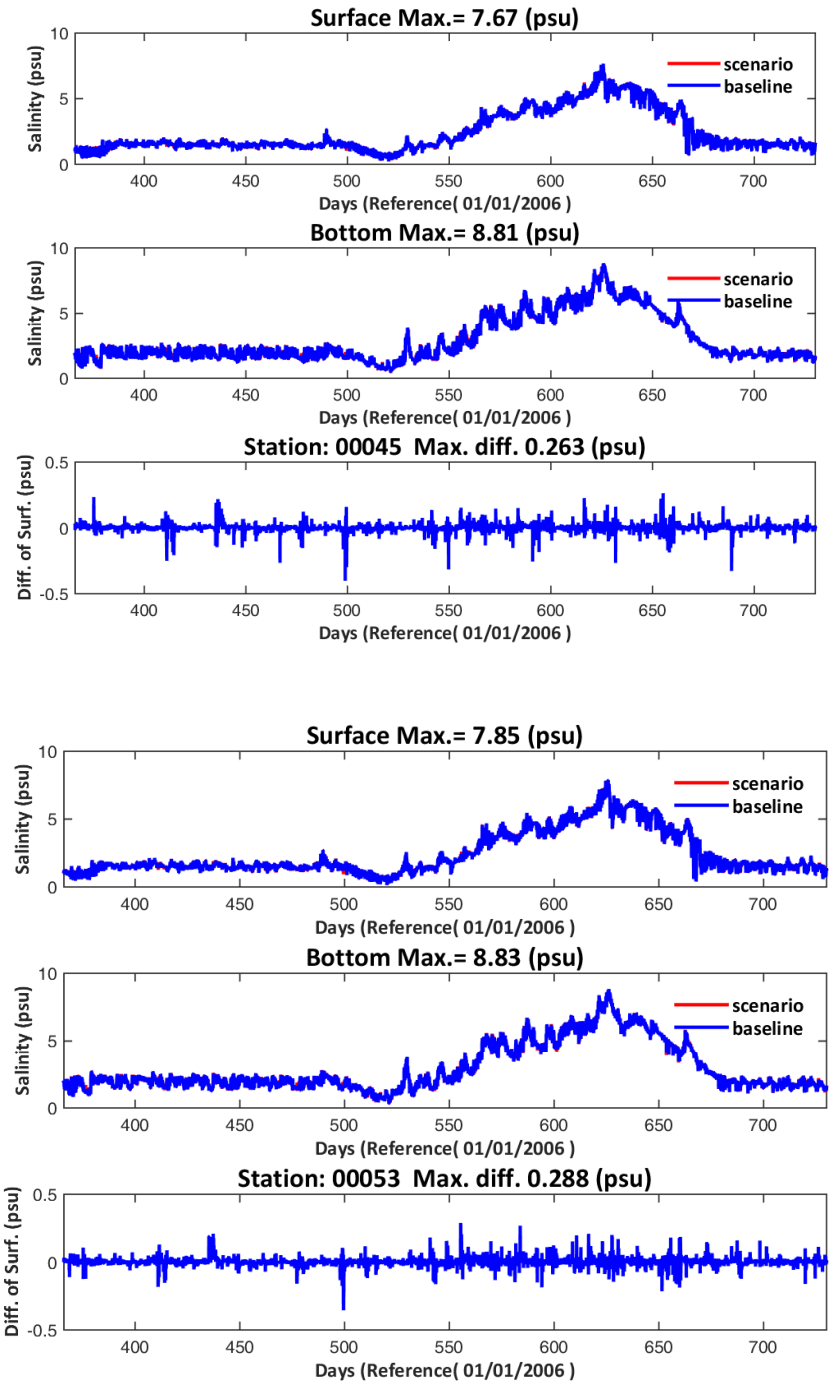


Figure 4-5-1. Continue.

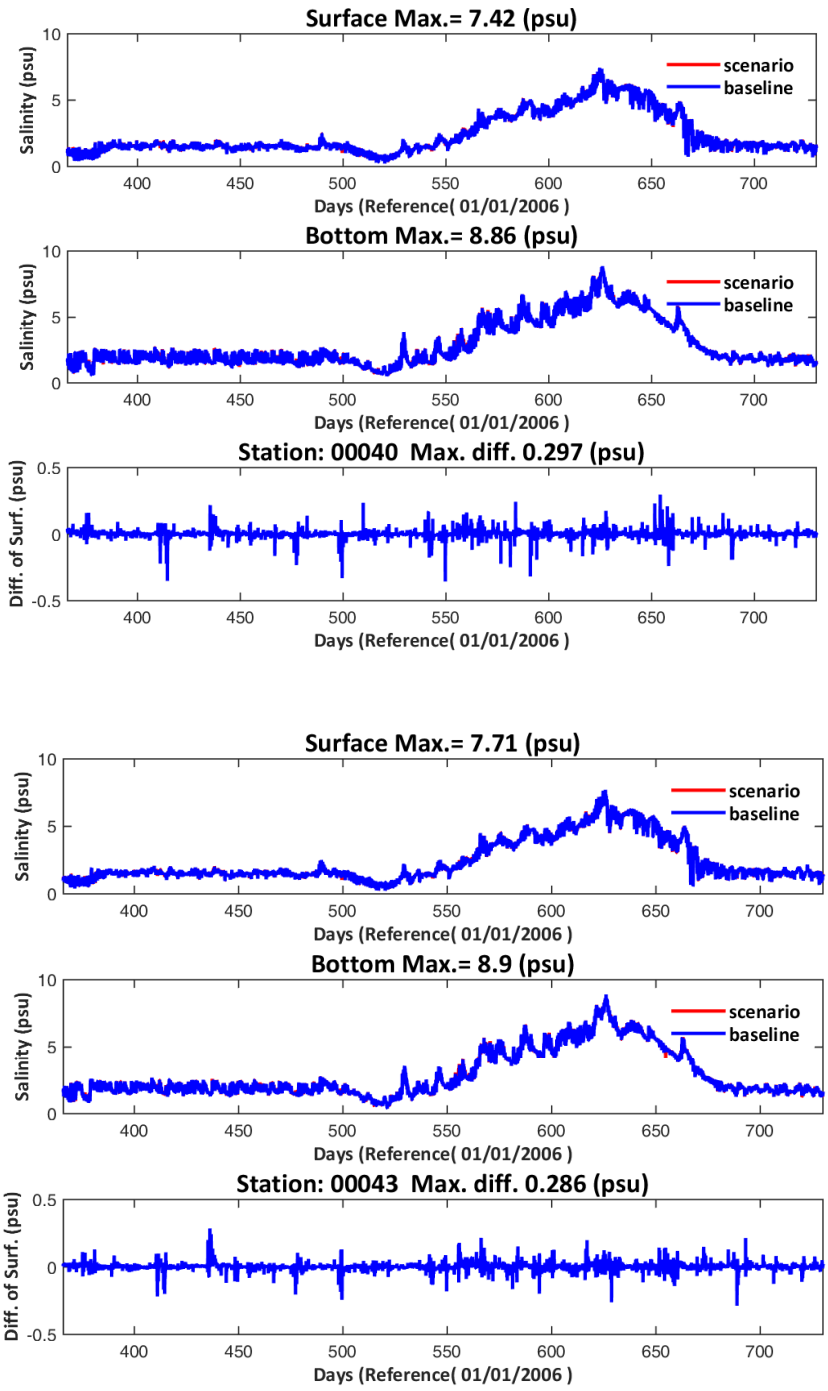


Figure 4-5-1. Continue.

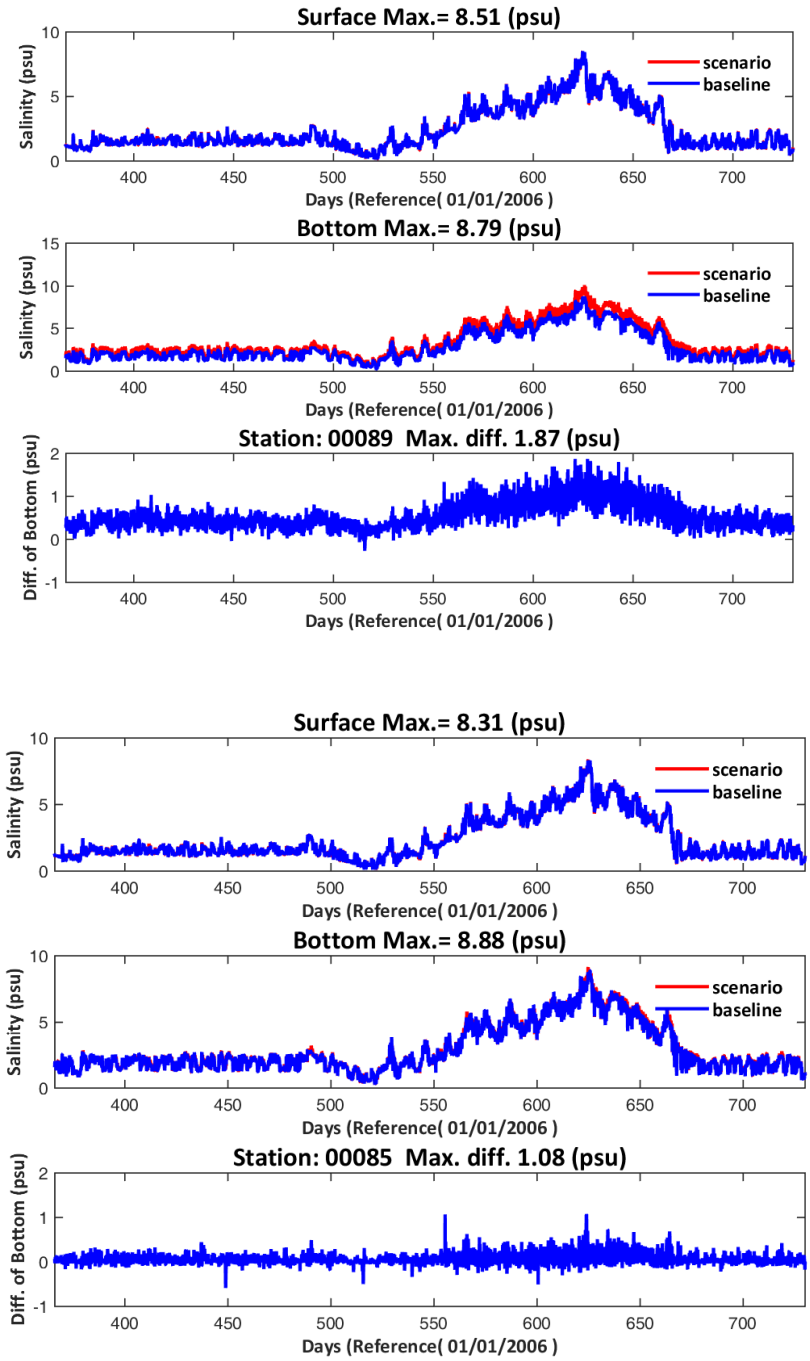
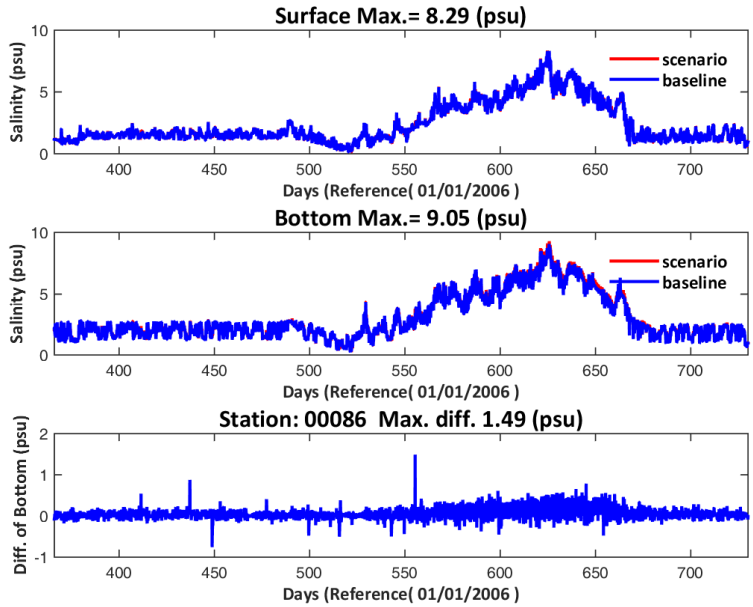


Figure 4-5-2. Comparison of time series of salinity at selected stations at Chickahominy Riverfront Park discharge site II (difference between scenario and baseline near the bottom, number shown in 3rd panel is location ID).



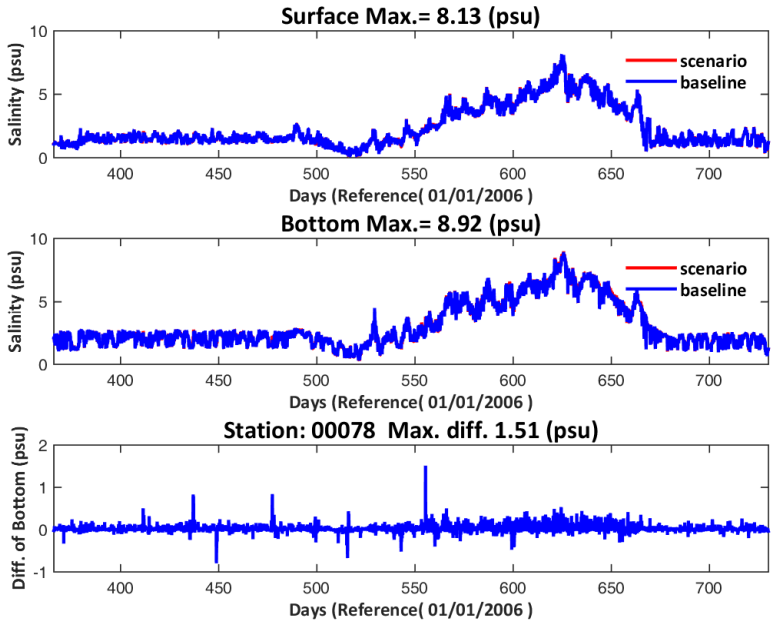


Figure 4-5-2. Continue.

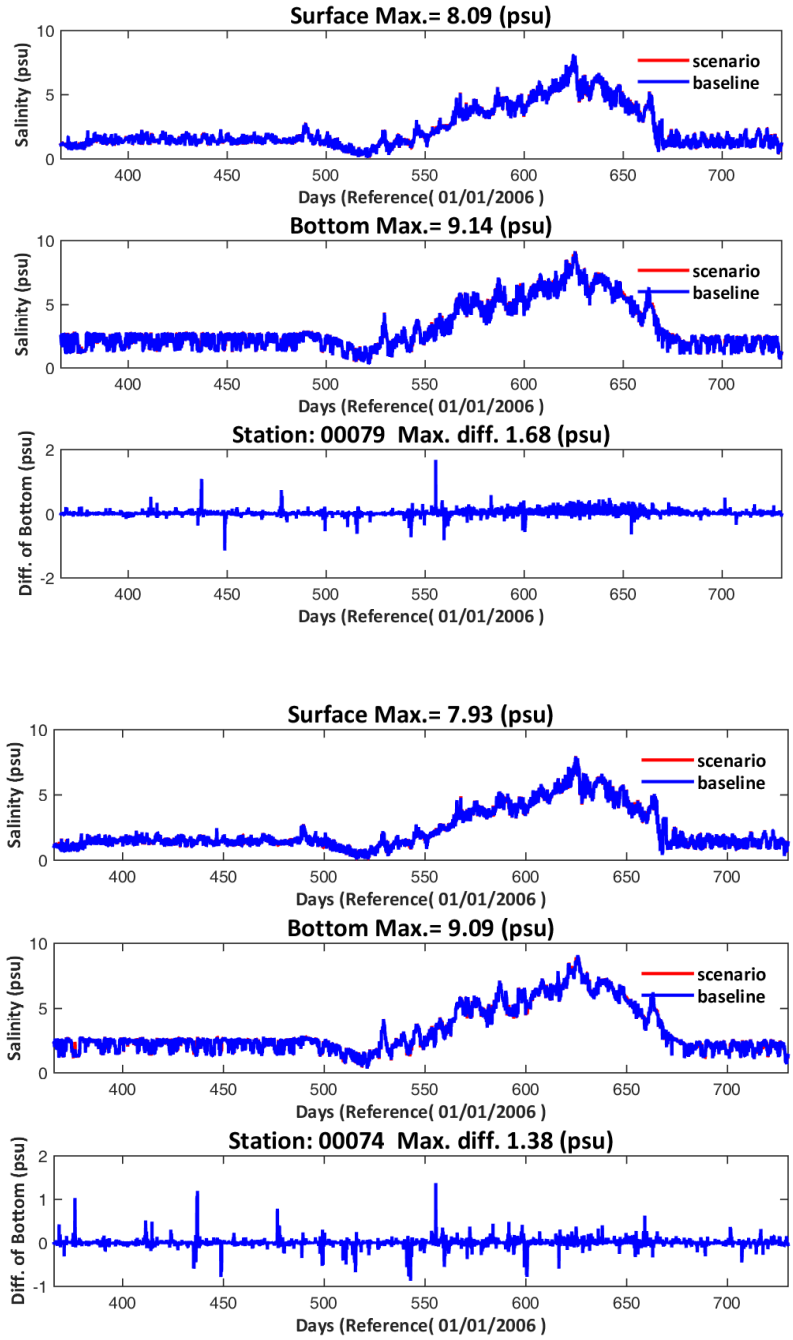
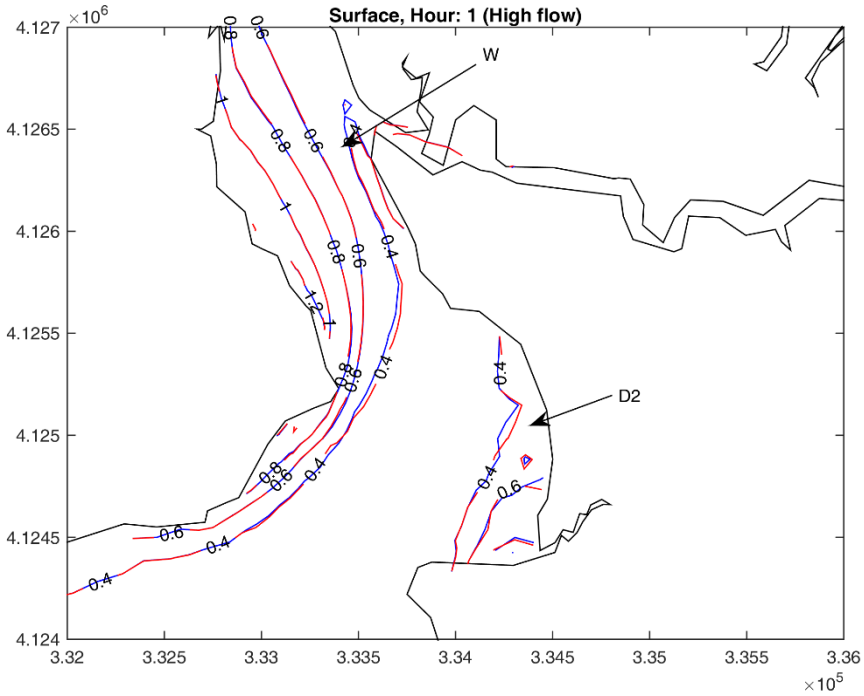
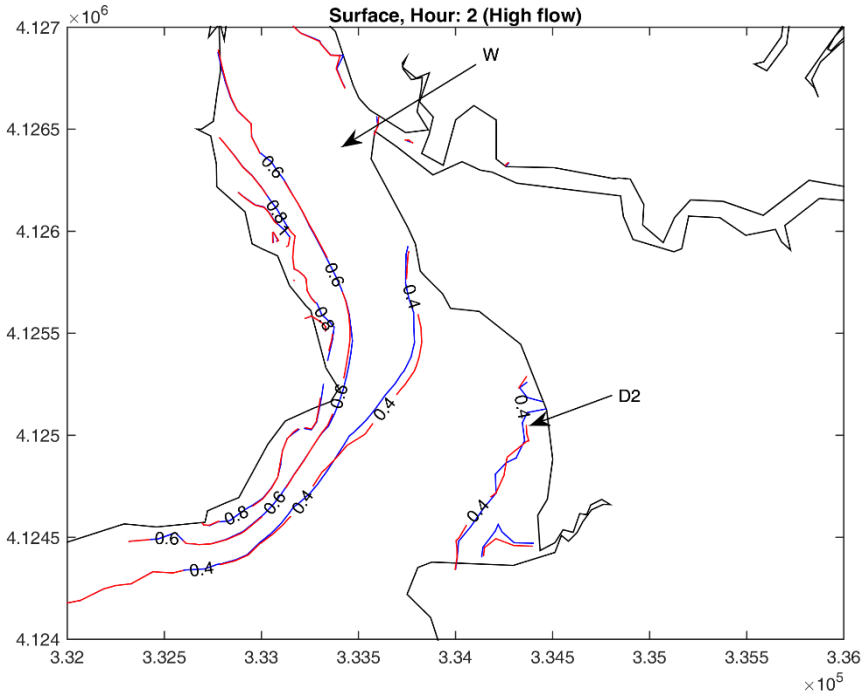
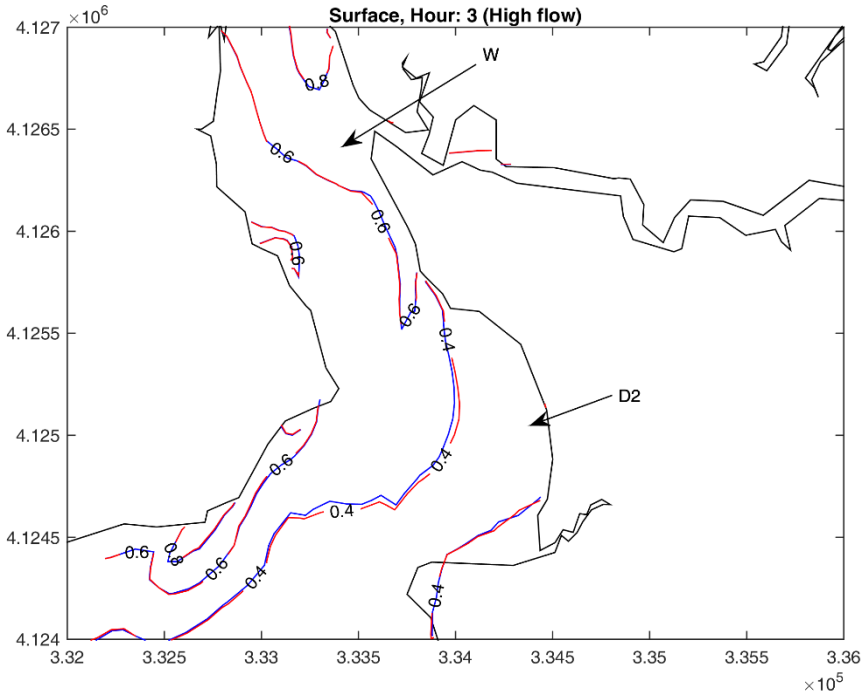
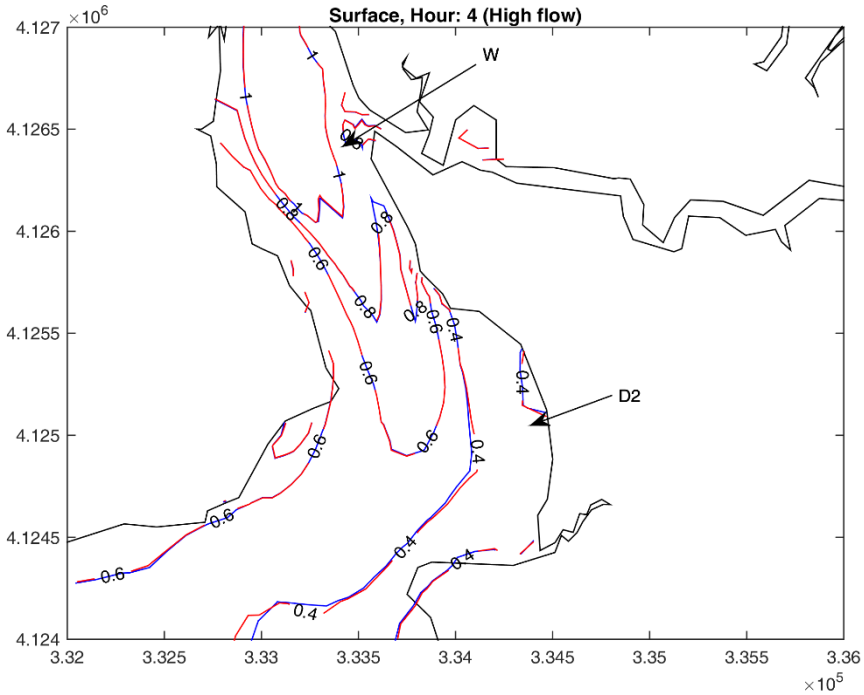


Figure 4-5-2. Continue.


Surface, Hour: 1 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

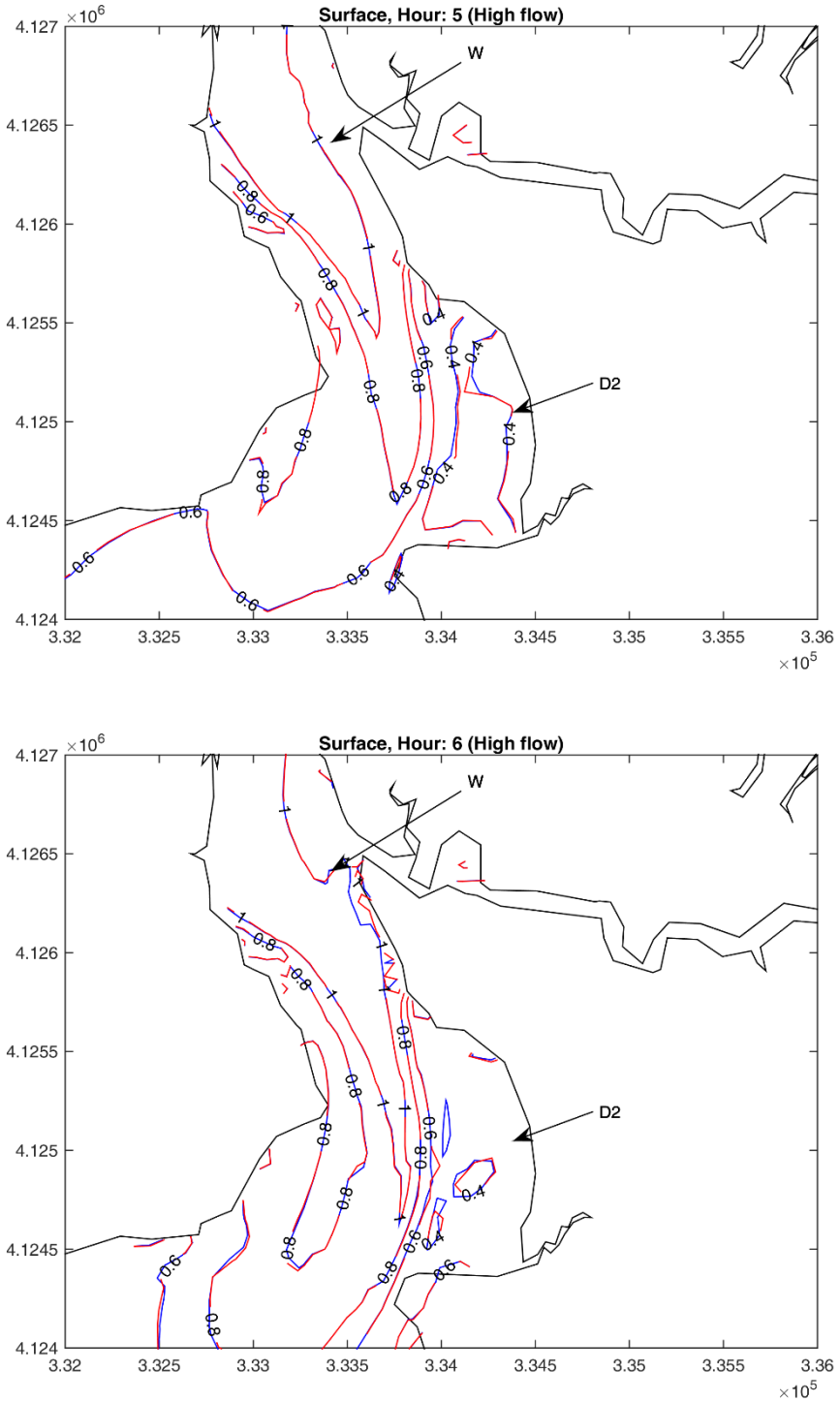
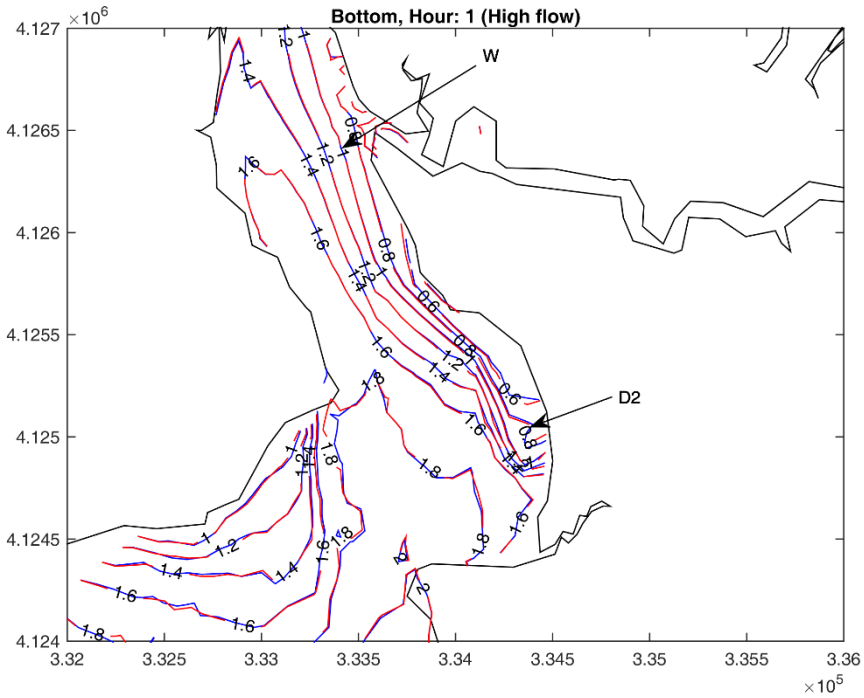
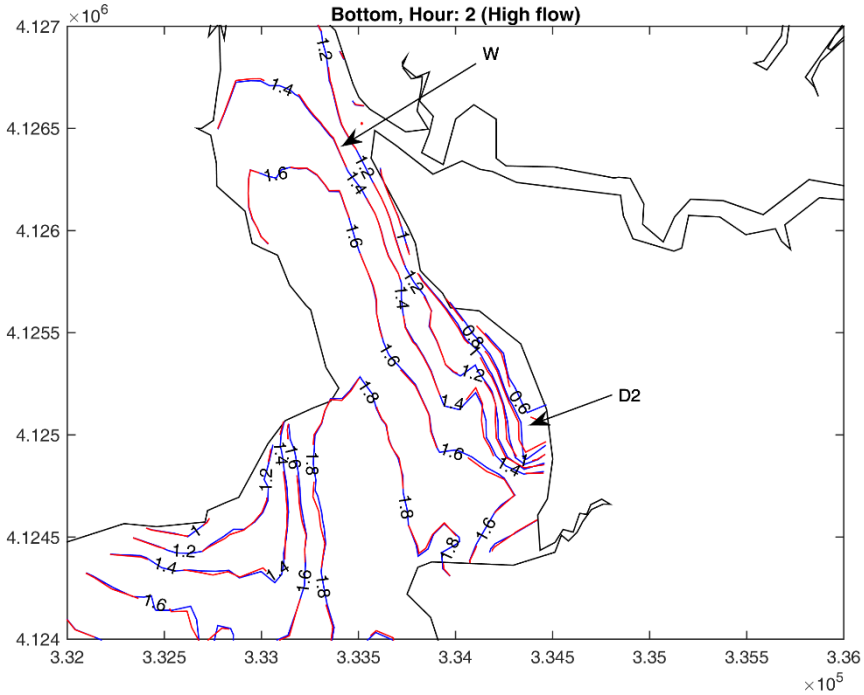
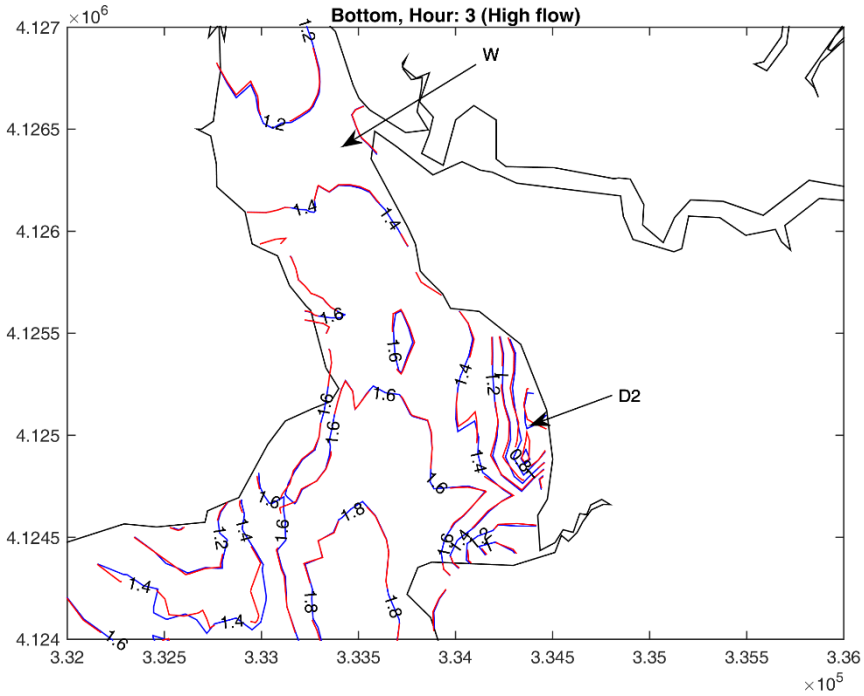
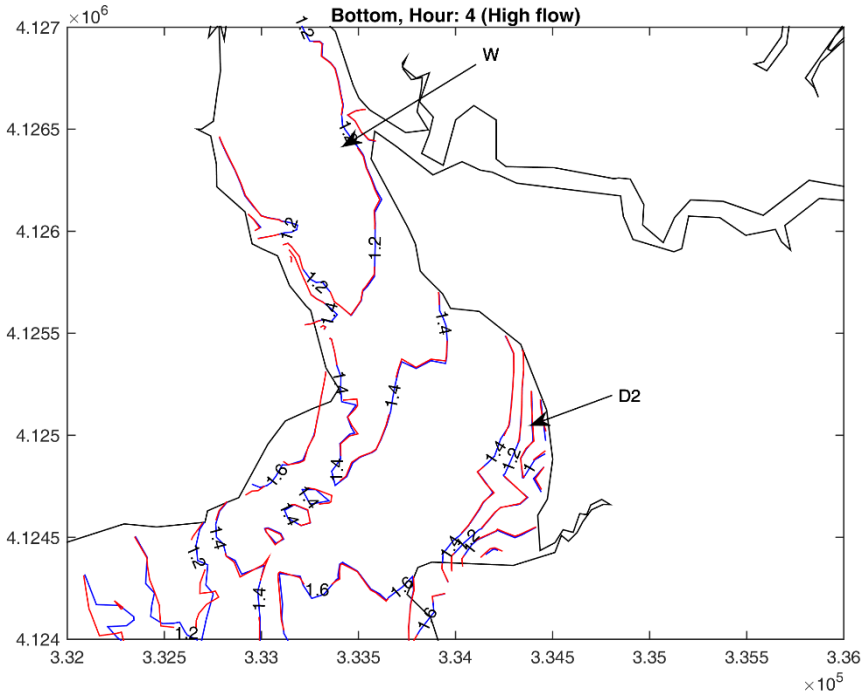


Figure 4-5-3. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

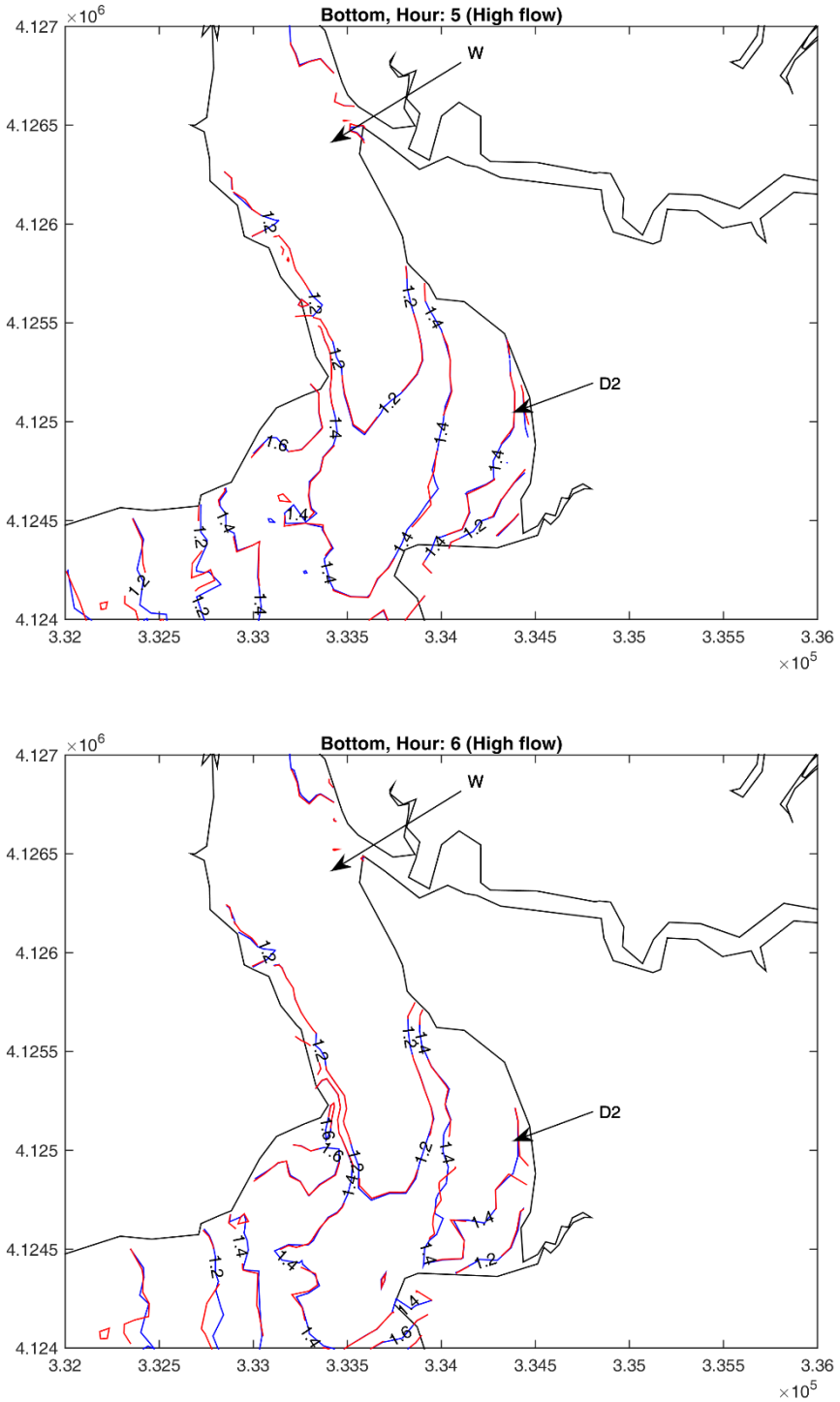
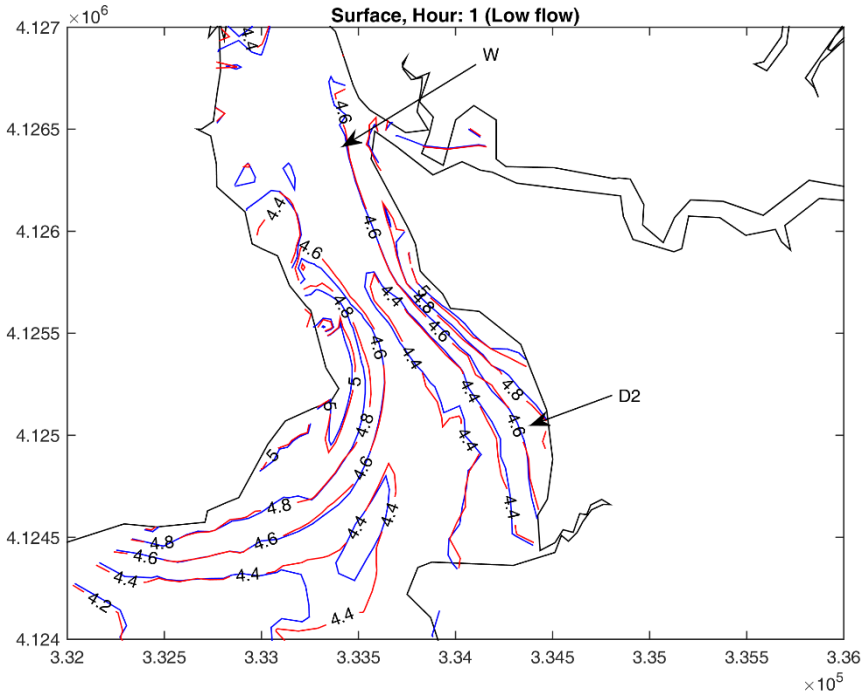
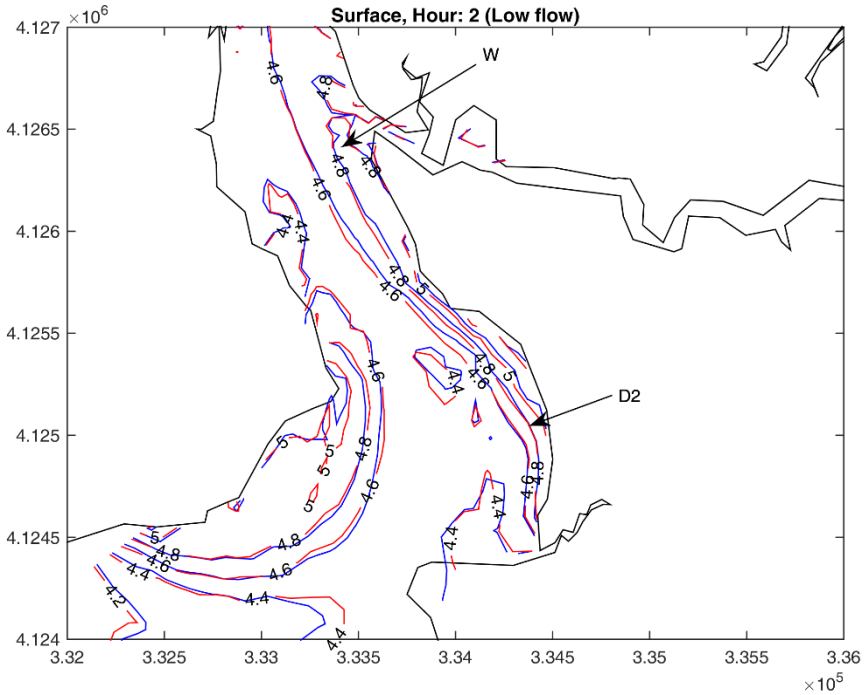
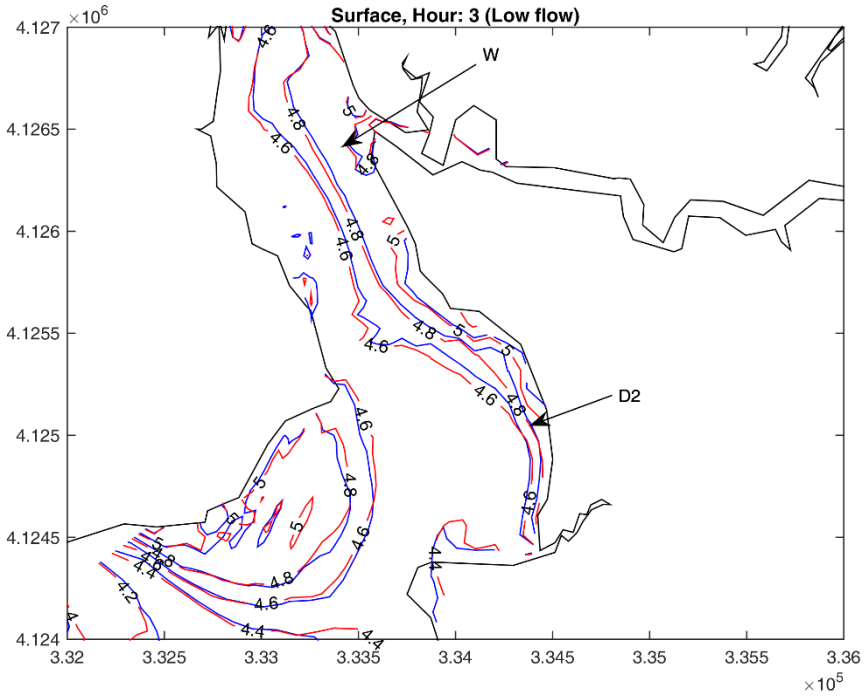
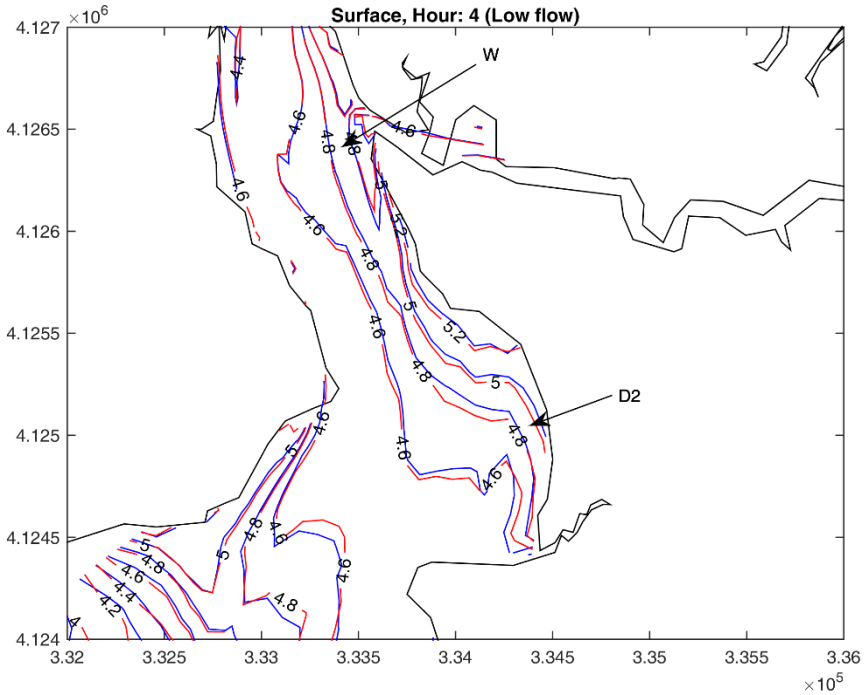


Figure 4-5-4. Comparison of Bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

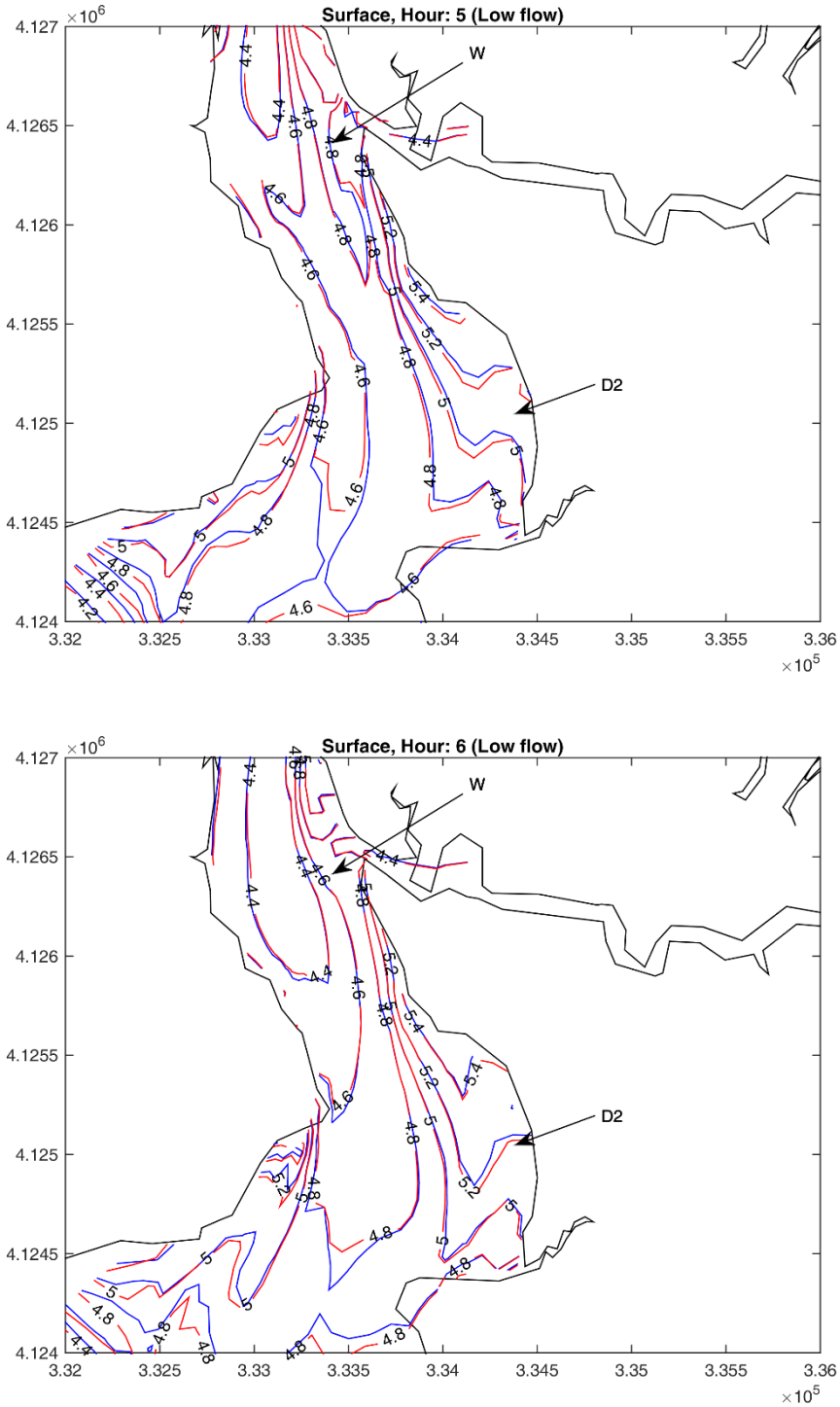
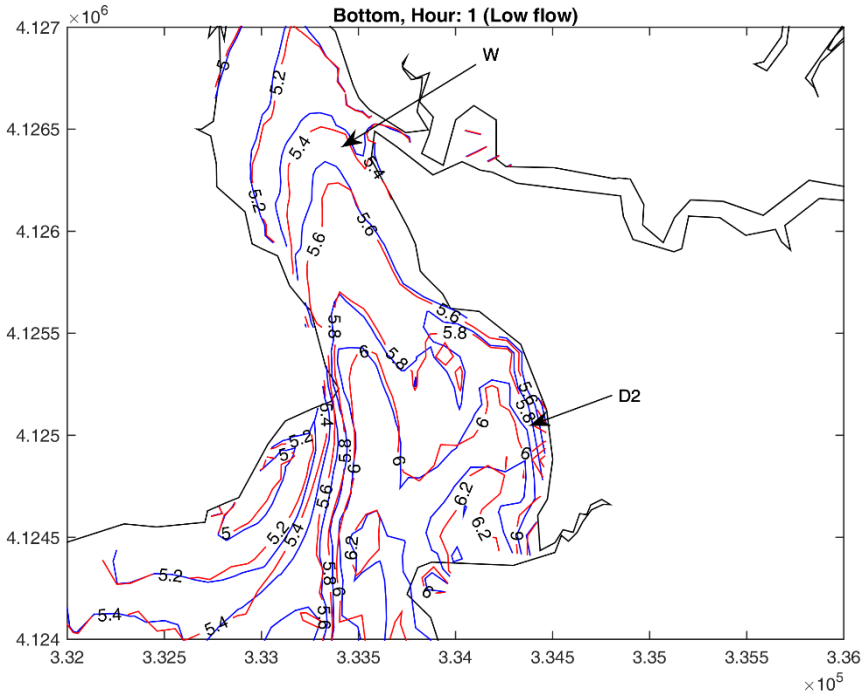
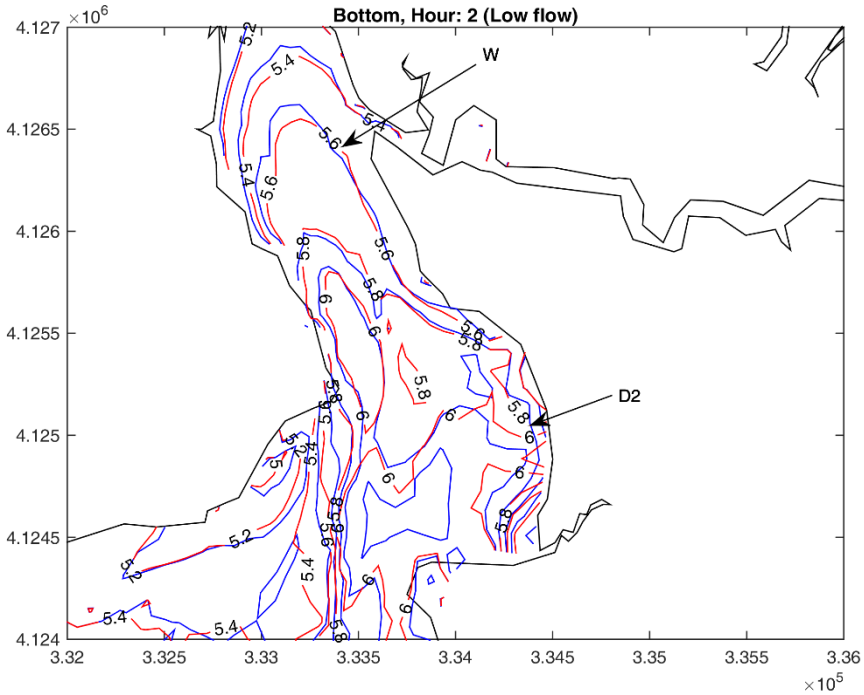
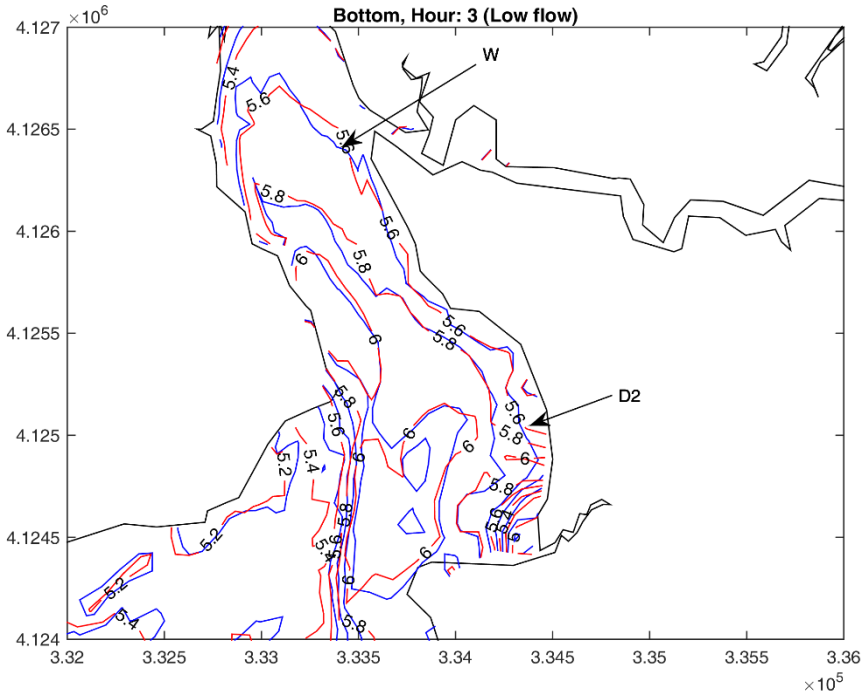
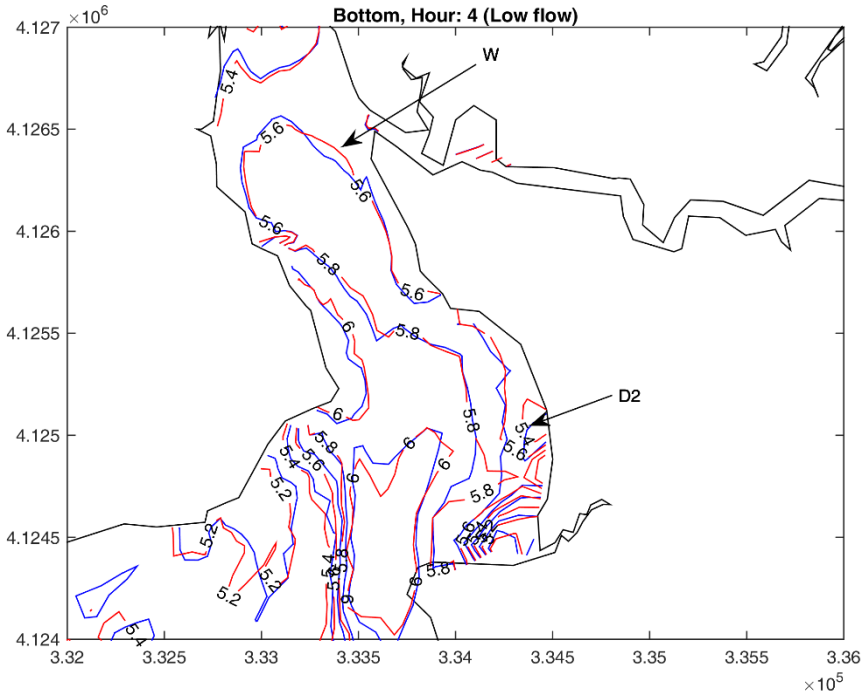


Figure 4-5-5. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

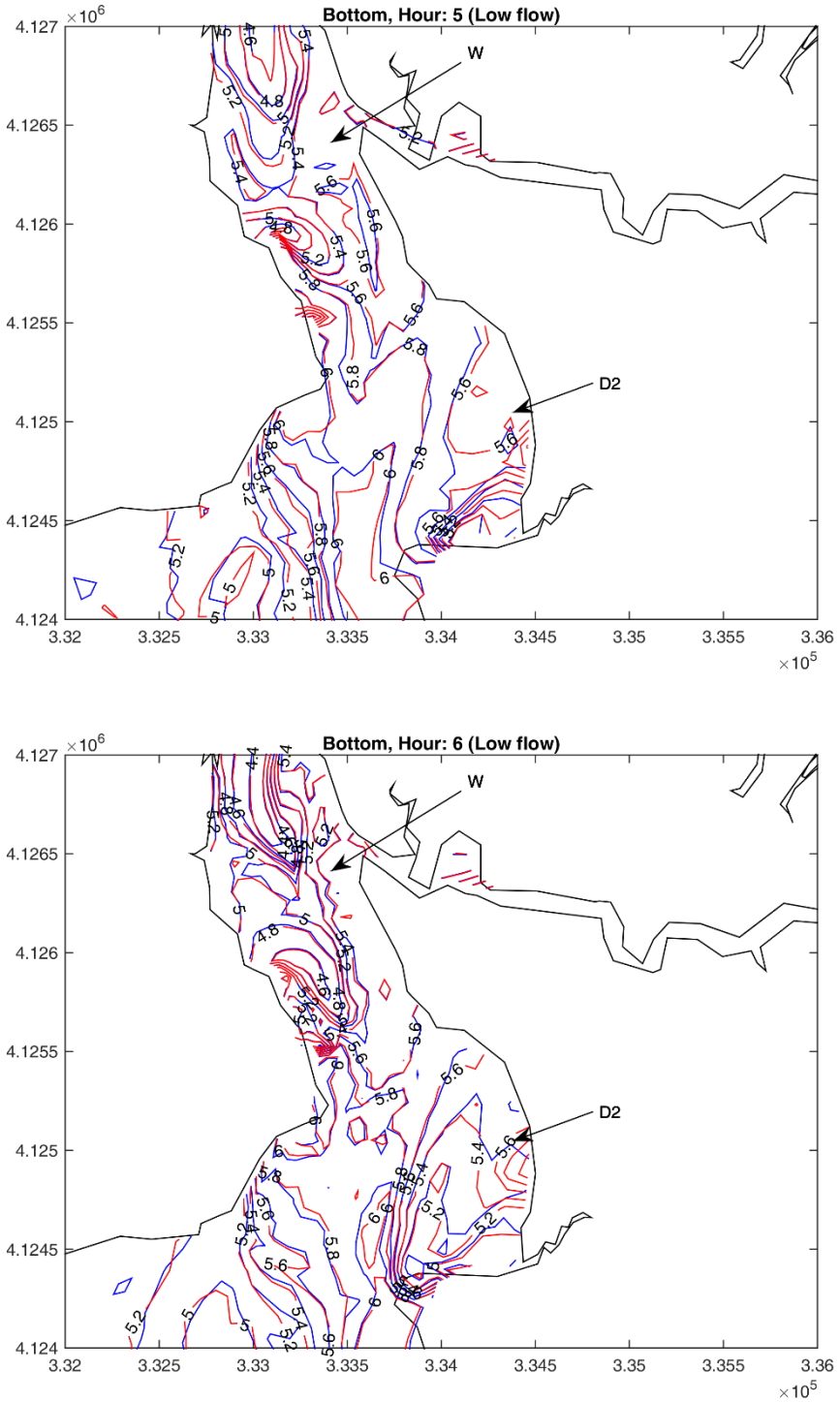


Figure 4-5-6. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

4.6 Chickahominy Riverfront Park Discharge Site 2 --Phase III

The comparisons of the simulation of Phase II for discharge at Site 2 to the baseline condition are shown in Figures 4-6-1 to 4-6-2. Salinity does not change much at the withdrawal site. The change is less than discharge at site 1. The salinity increase more at discharge location 2. The salinity increase is up to 2.03 psu, which is about 26% of maximum salinity at that location. The increase is higher than salinity at discharge site 1. Horizontal plots of salinity distributions at Days 150 (high flow) and 300 (low flow) show little changes of salinity distribution in general, except near the discharge location. As flow is lower and tidal mixing decrease in this shallow region, the slightly higher salinity can be expected. The increase of salinity can be up to 2.0 psu. Both increases and decreases of salinity occur depending on the tide. A slightly larger change occurs at the bottom at Day 300 near the discharge location.

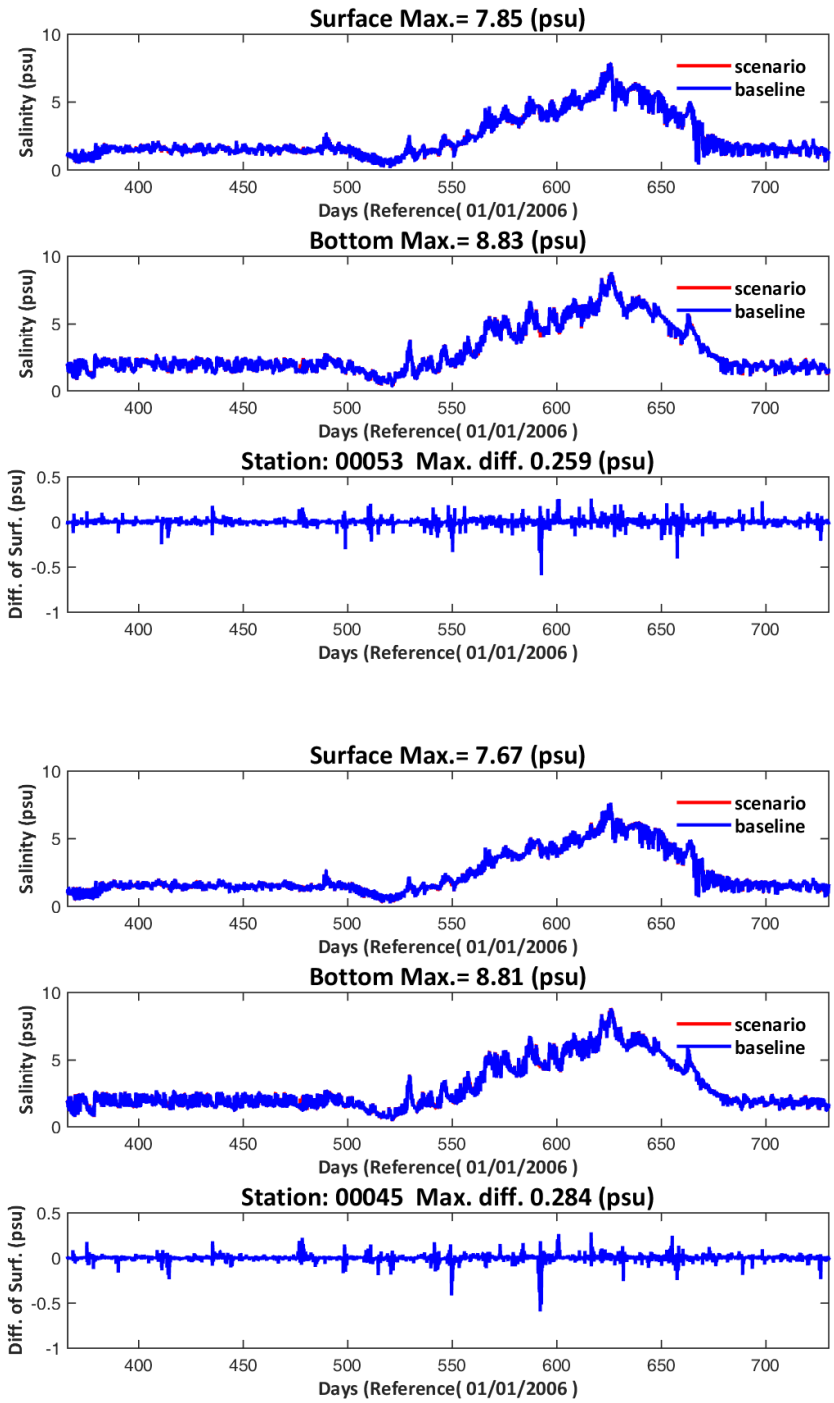


Figure 4-6-1. Comparison of time series of salinity, and difference between scenario and baseline near the surface at selected stations at Chickahominy Riverfront Park withdrawal site (number shown in 3rd panel is location ID).

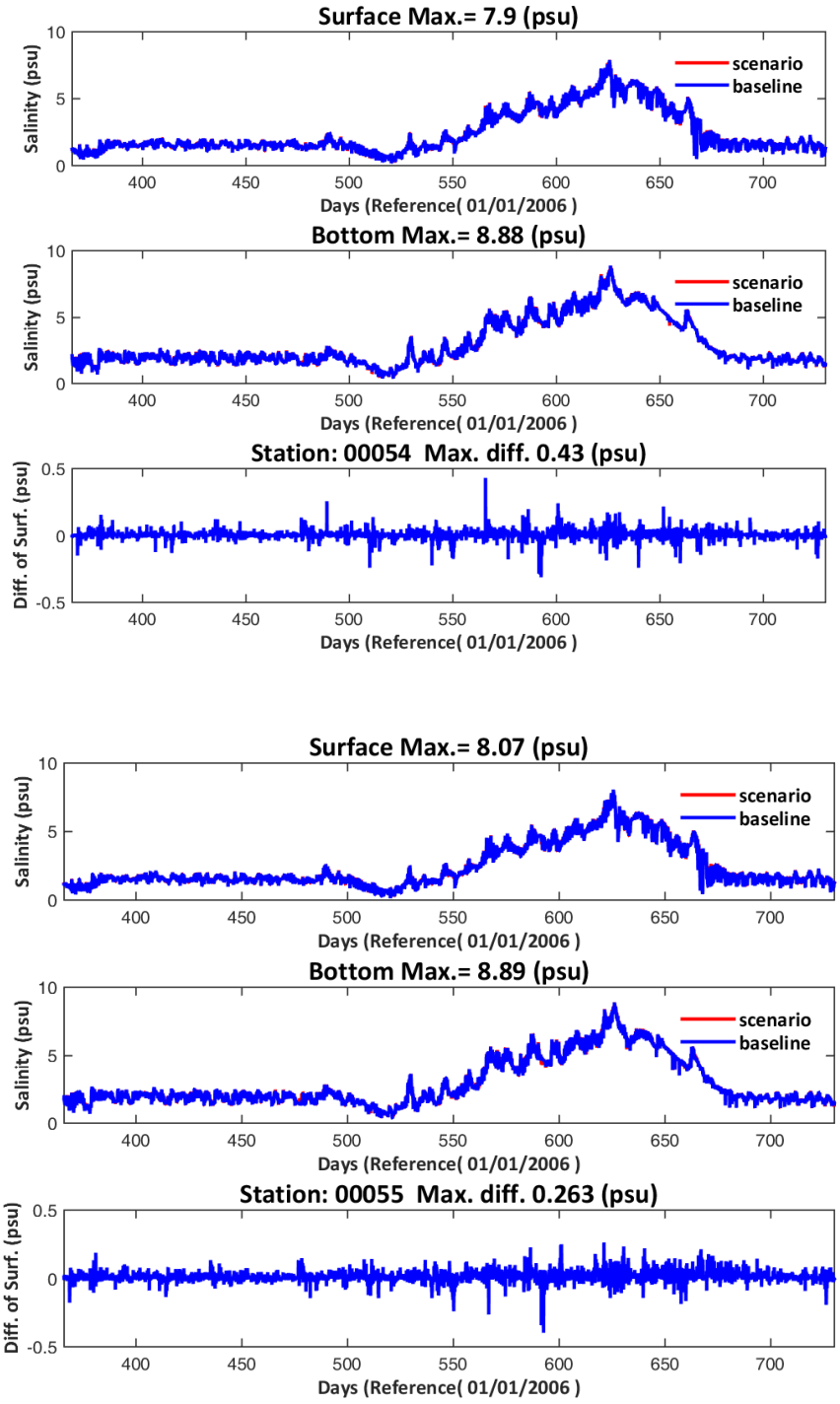
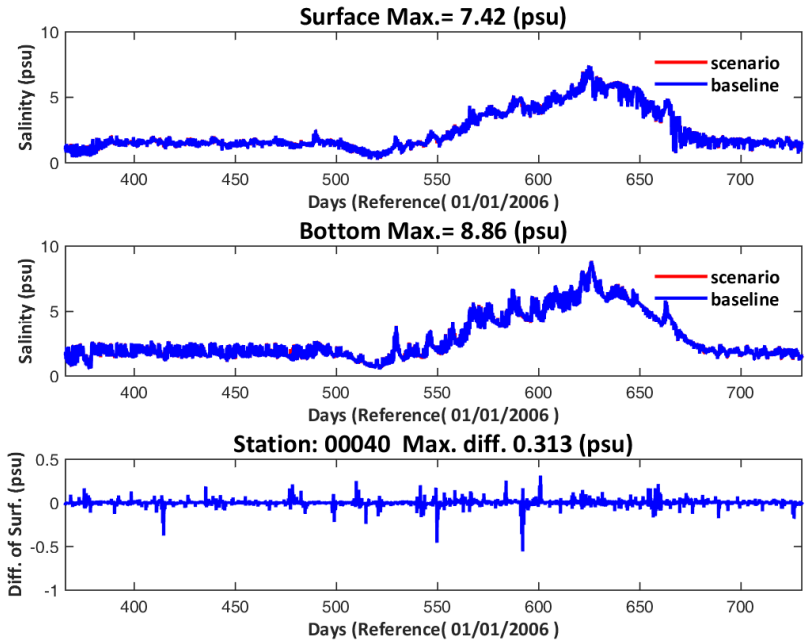


Figure 4-6-1. Continue.



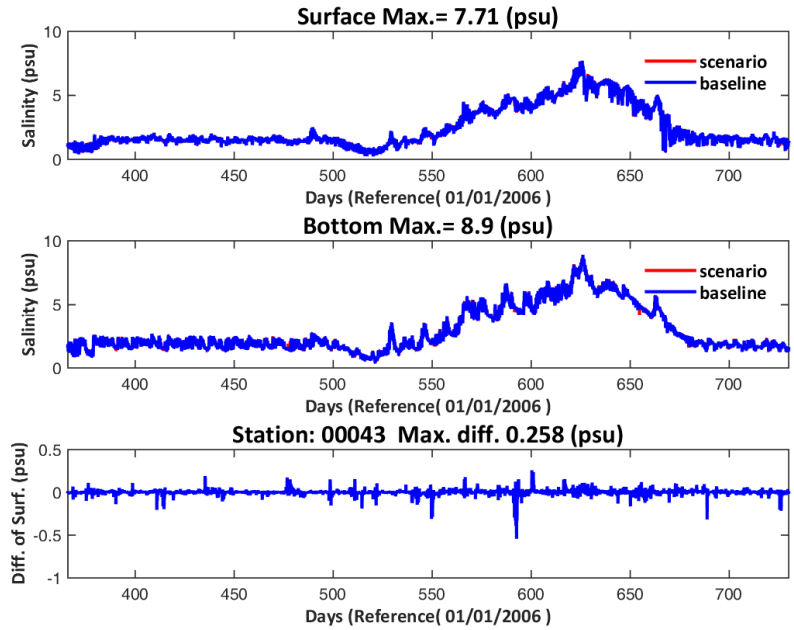


Figure 4-6-1. Continue.

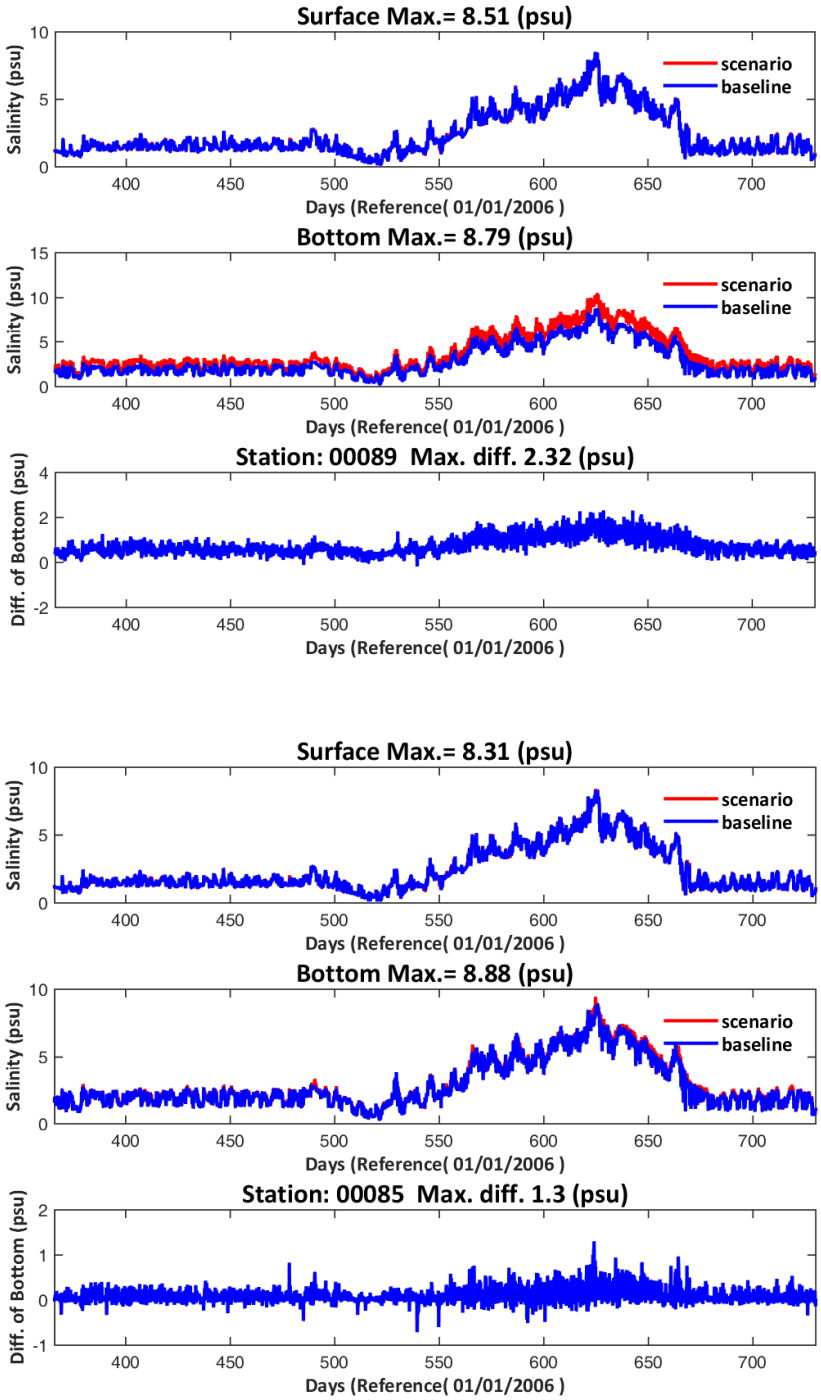


Figure 4-6-2. Comparison of time series of salinity, and difference between scenario and baseline near the bottom at selected stations at Chickahominy Riverfront Park discharge site II (number shown in 3rd panel is location ID).

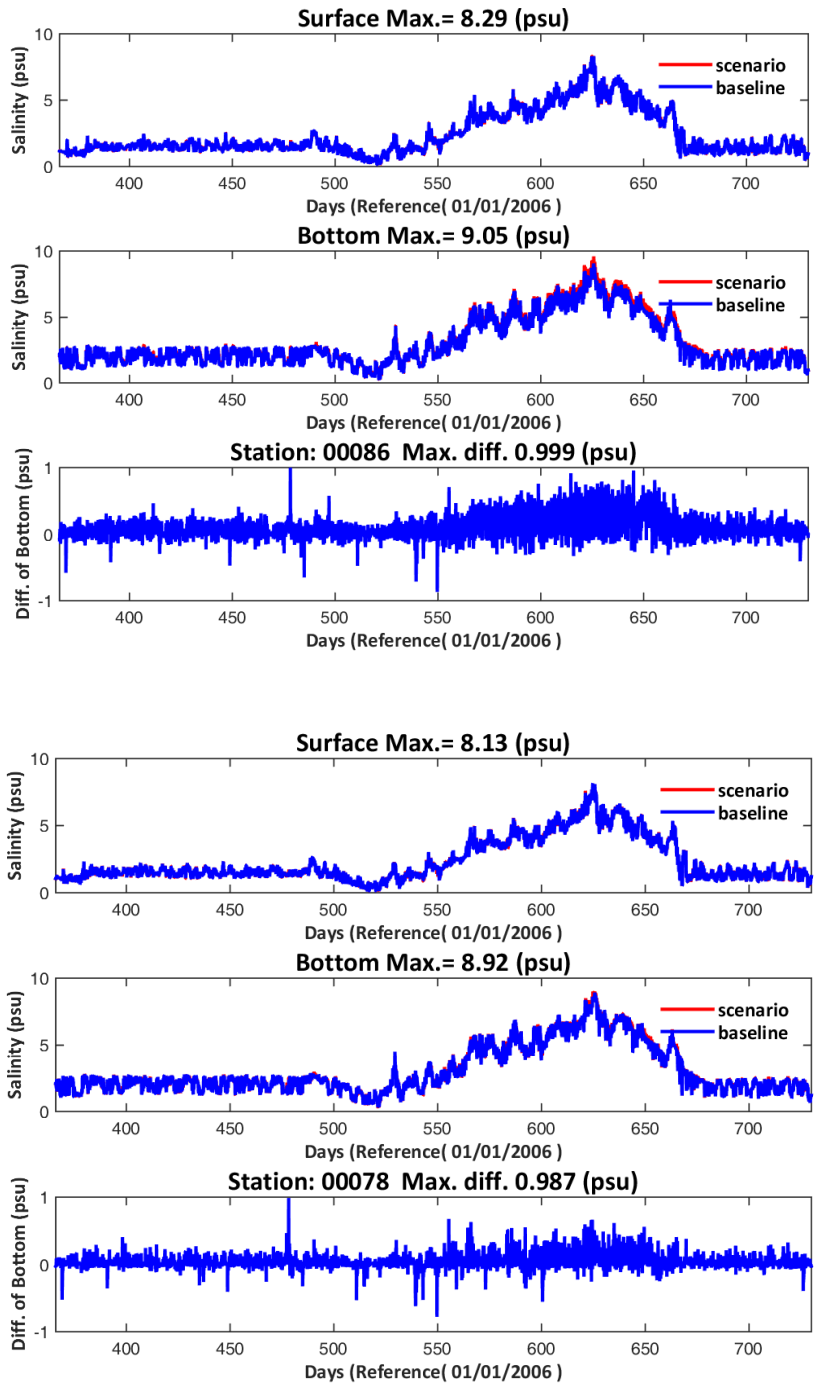
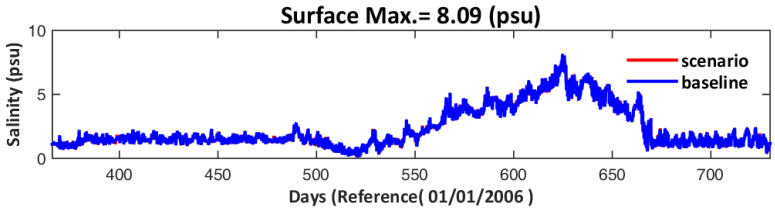
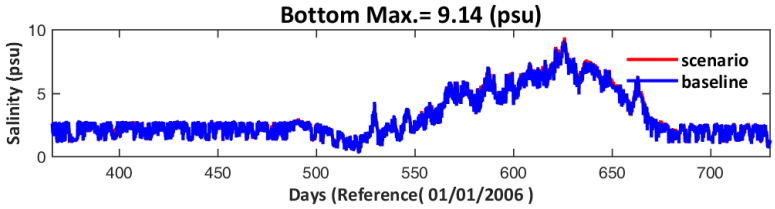
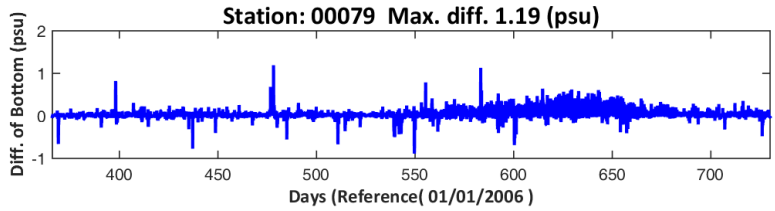
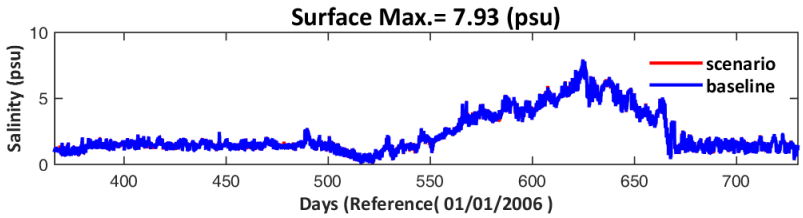


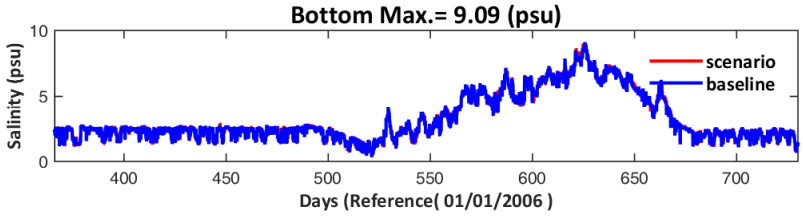
Figure 4-6-2. Continue.











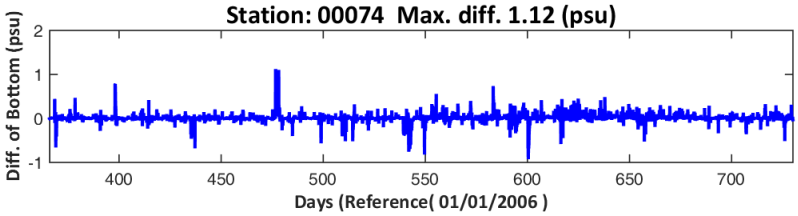
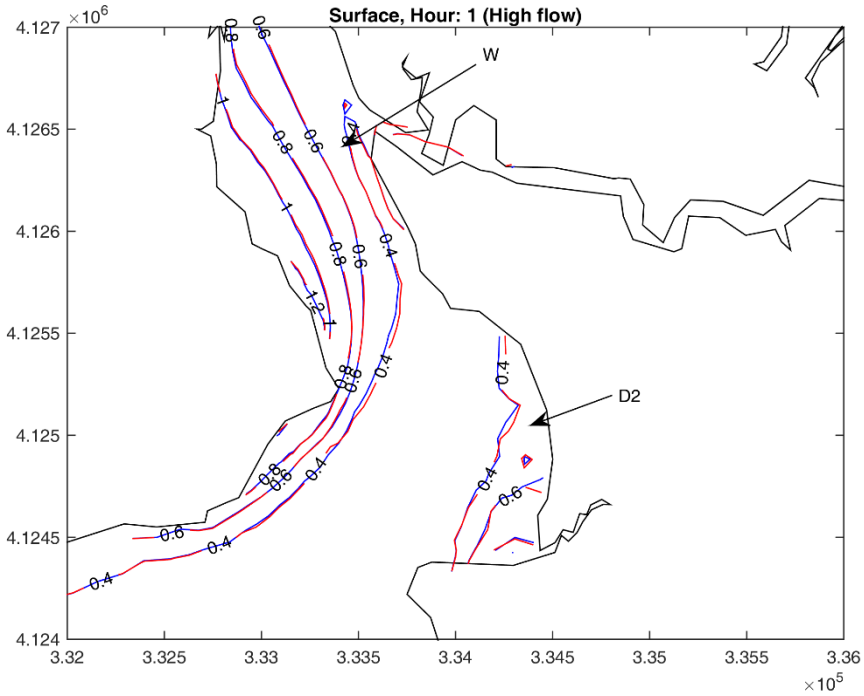
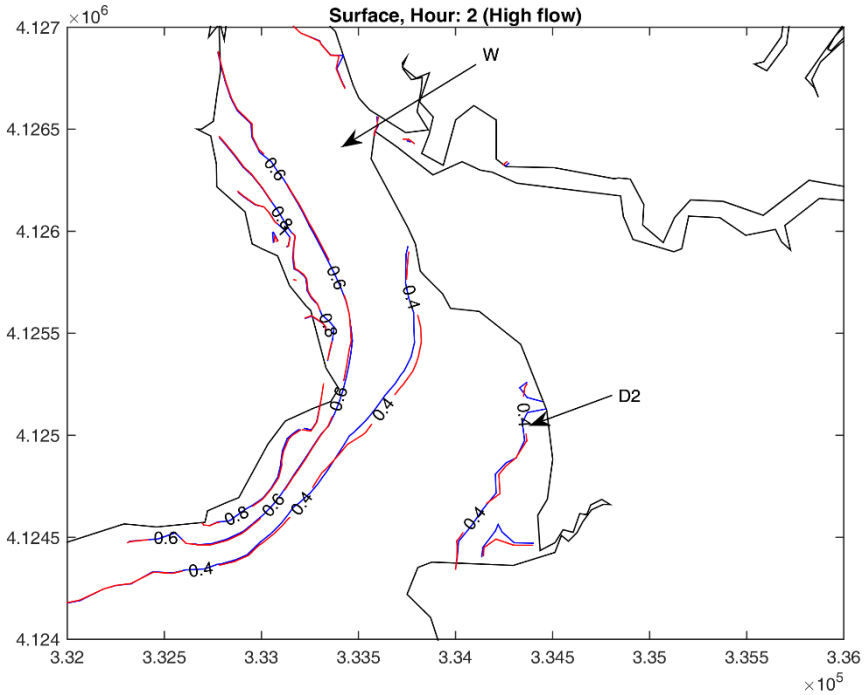
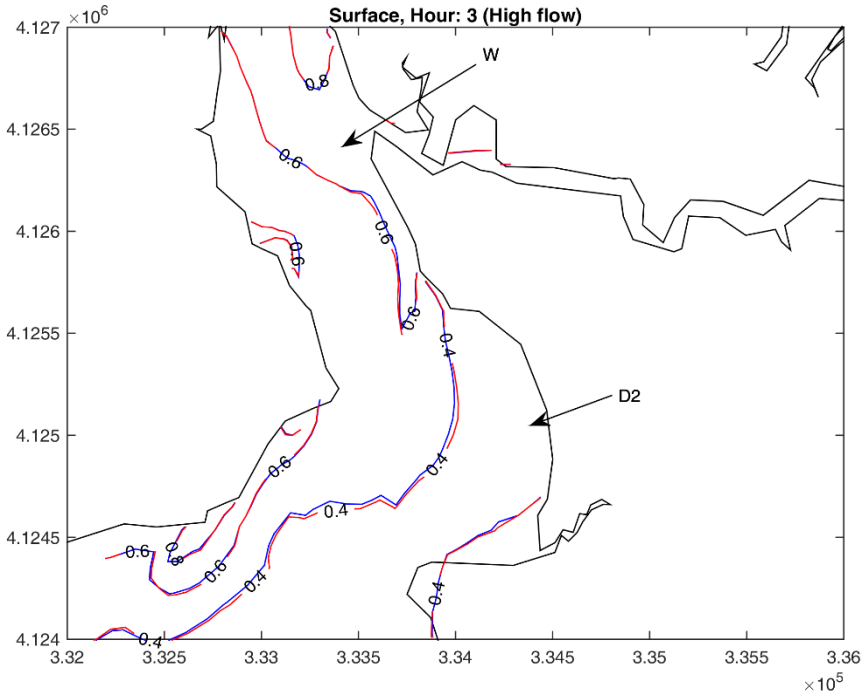
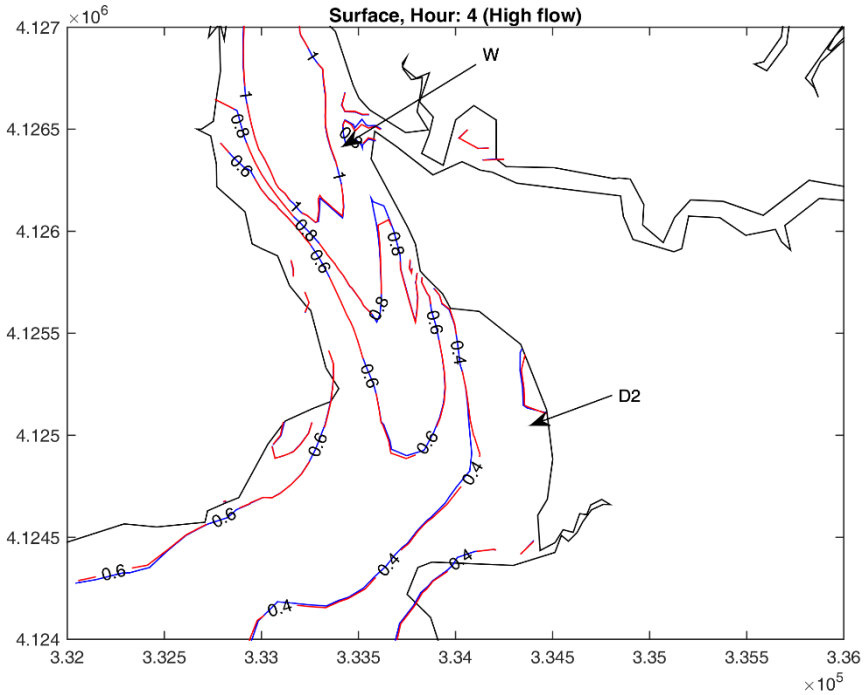


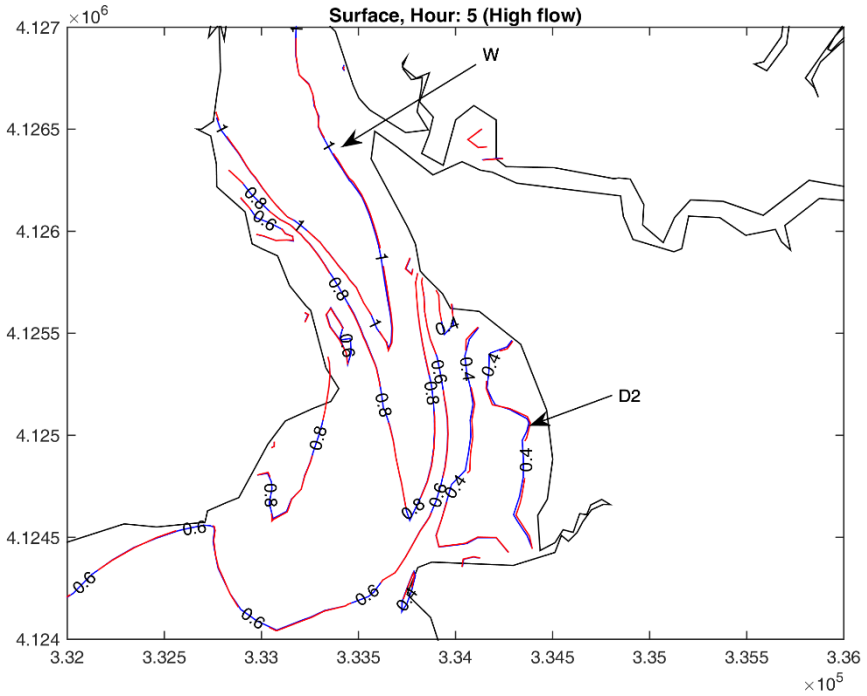
Figure 4-6-2. Continue.


Surface, Hour: 1 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5



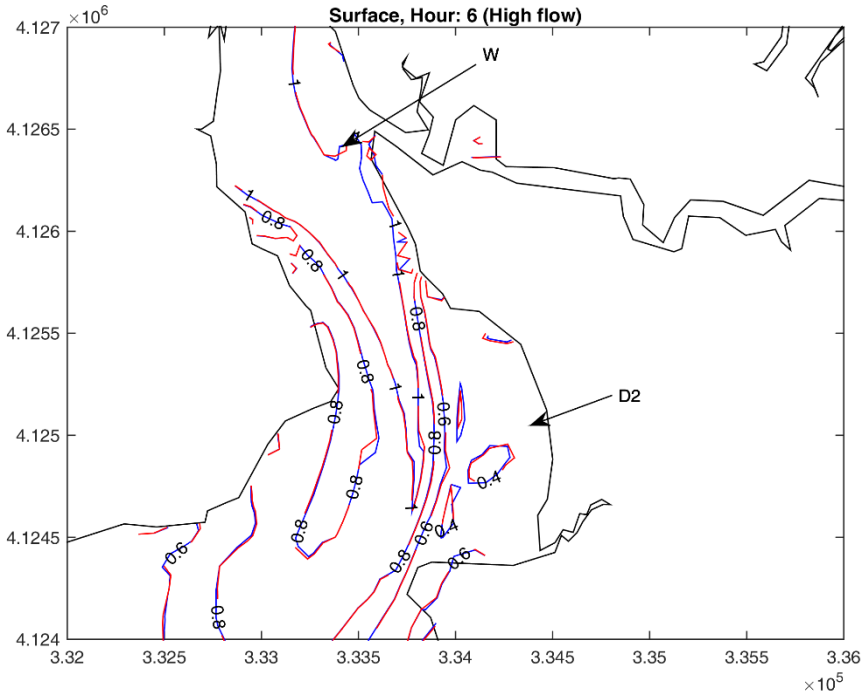
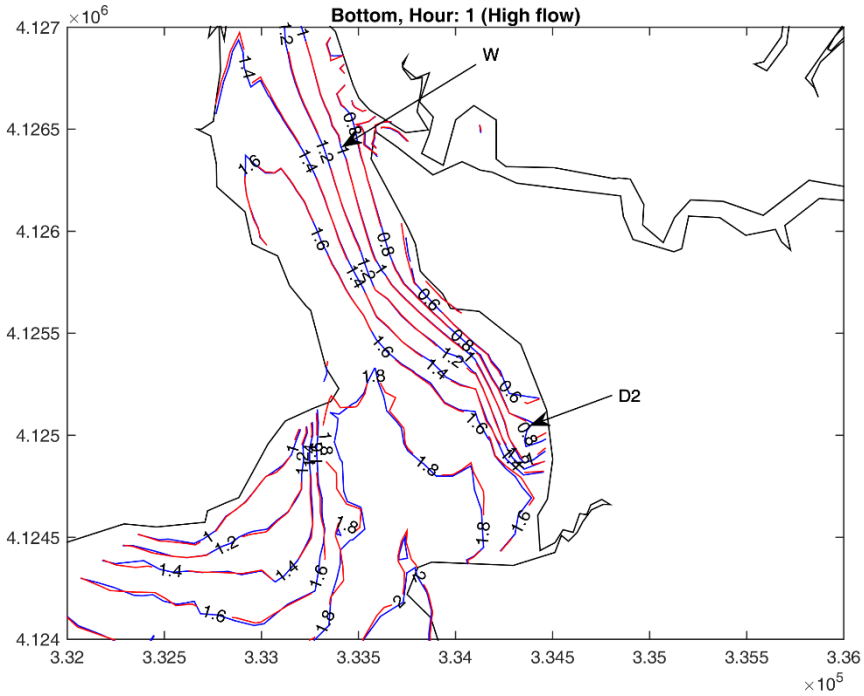
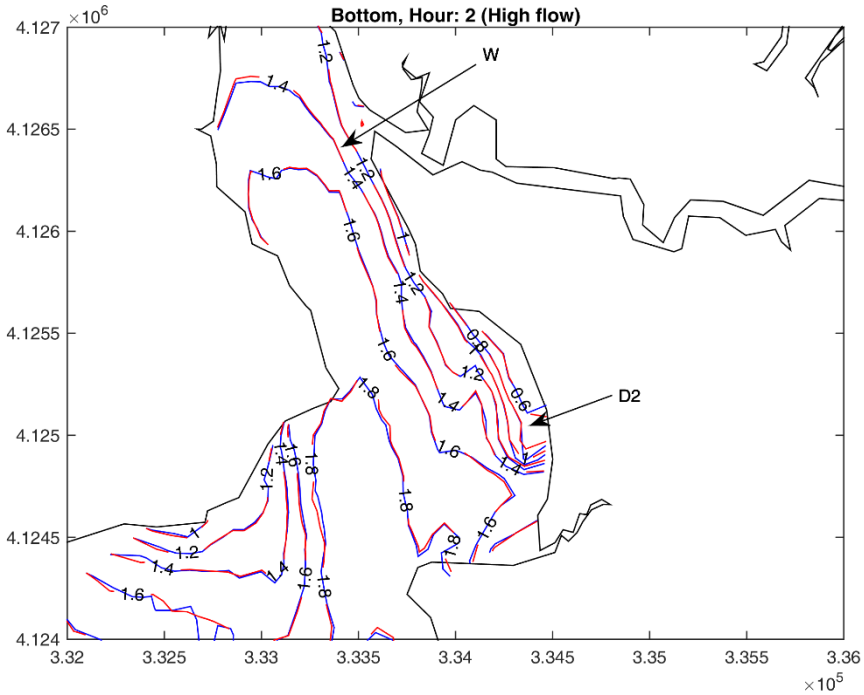
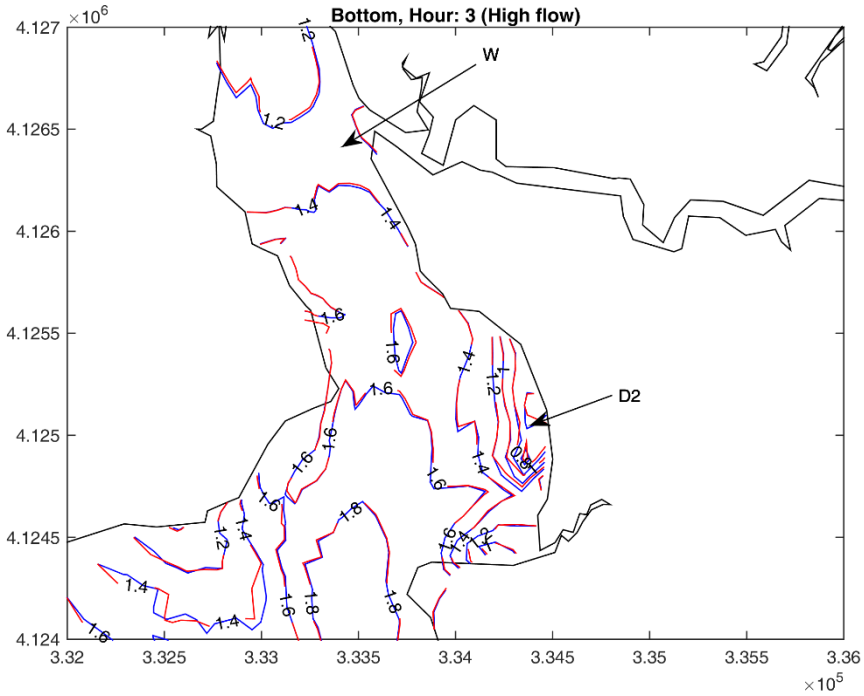
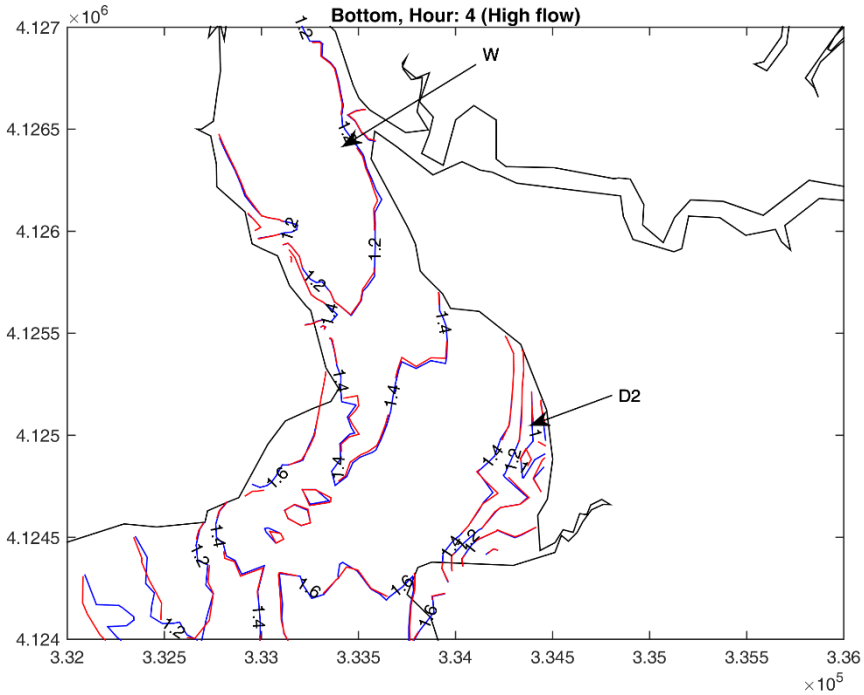


Figure 4-6-3. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 4 (High flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

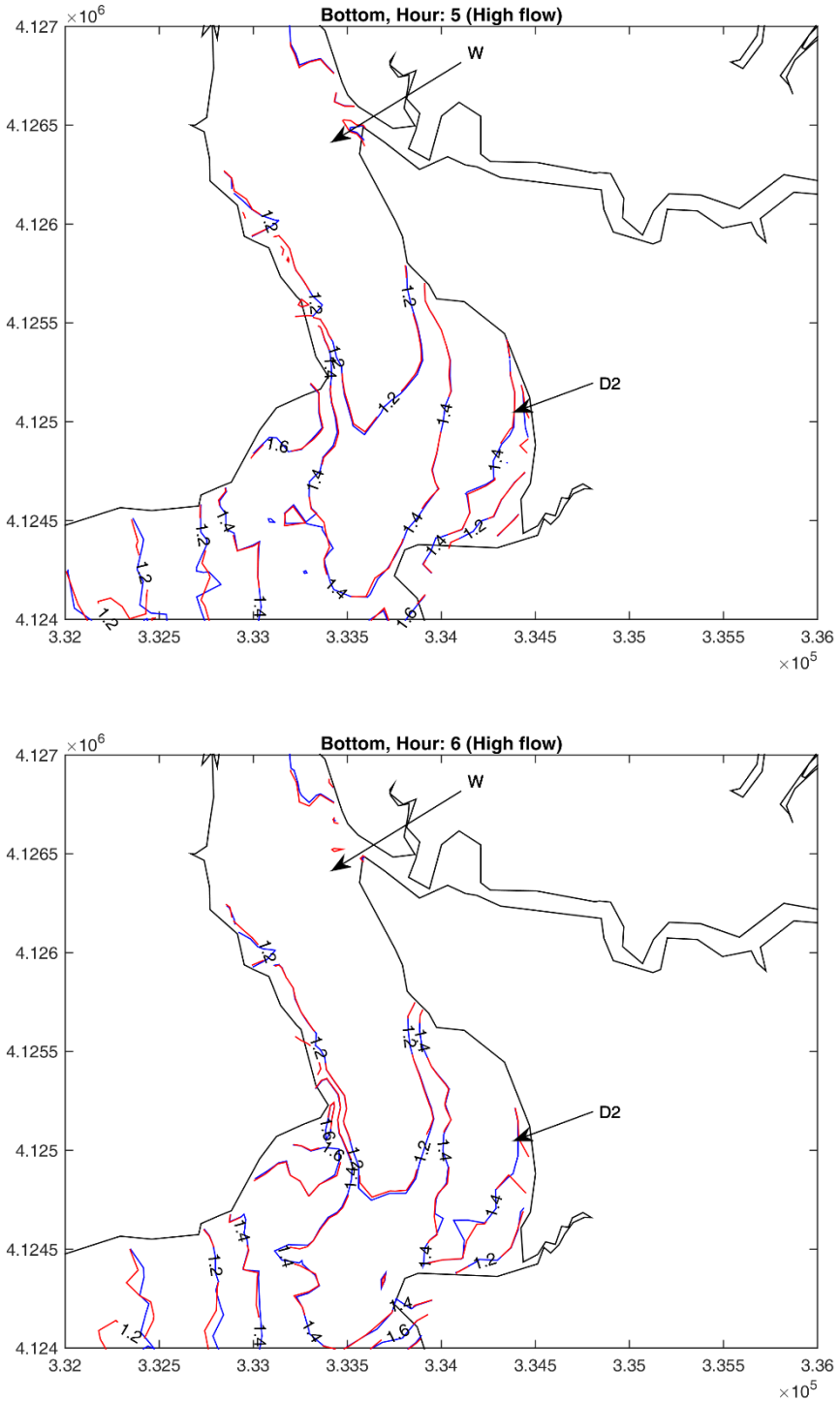
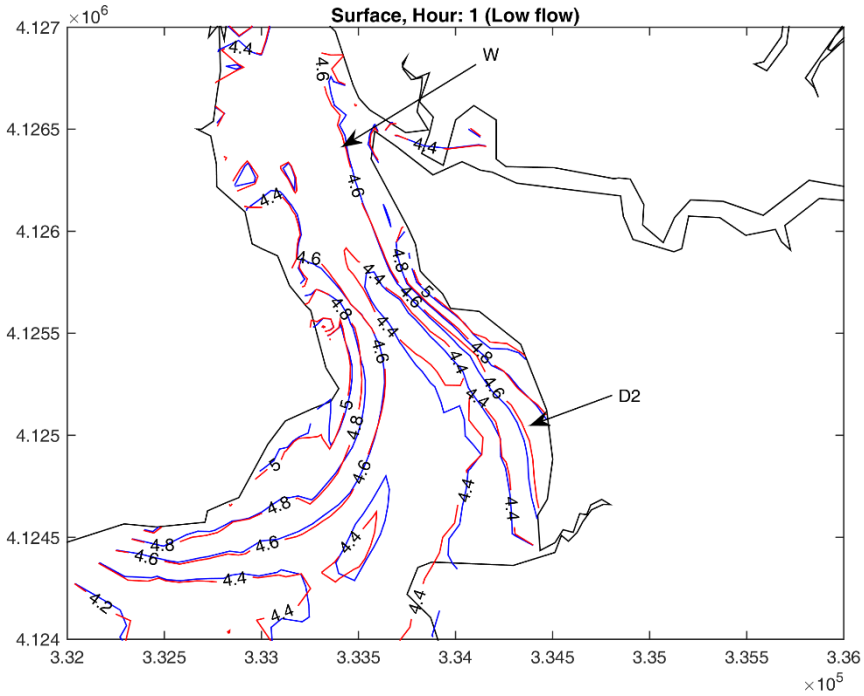
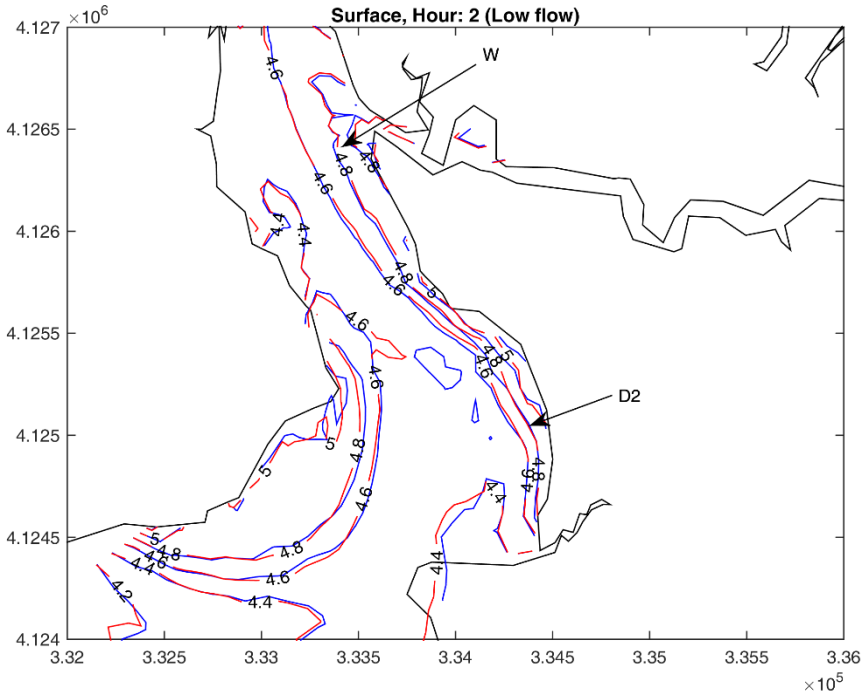
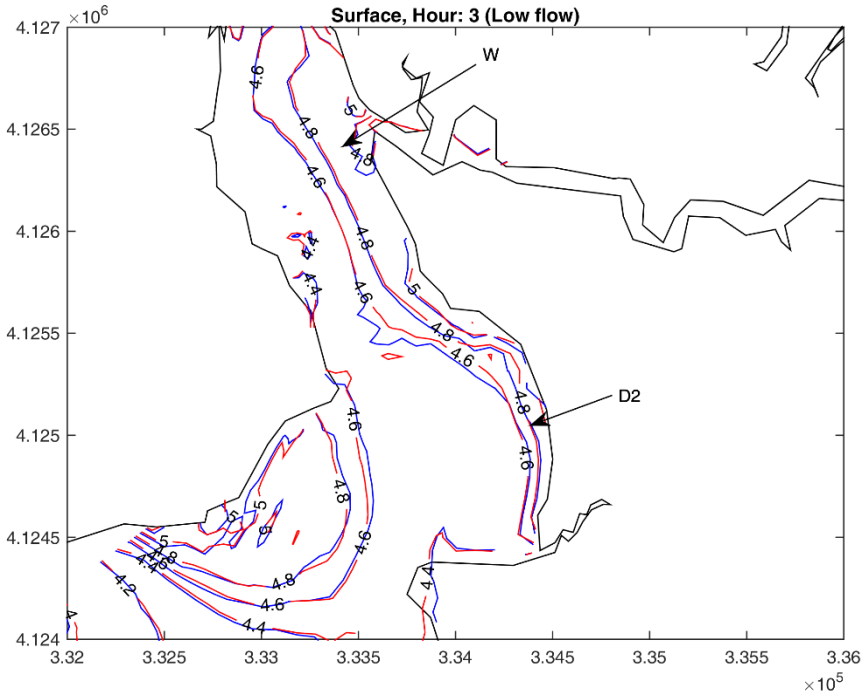
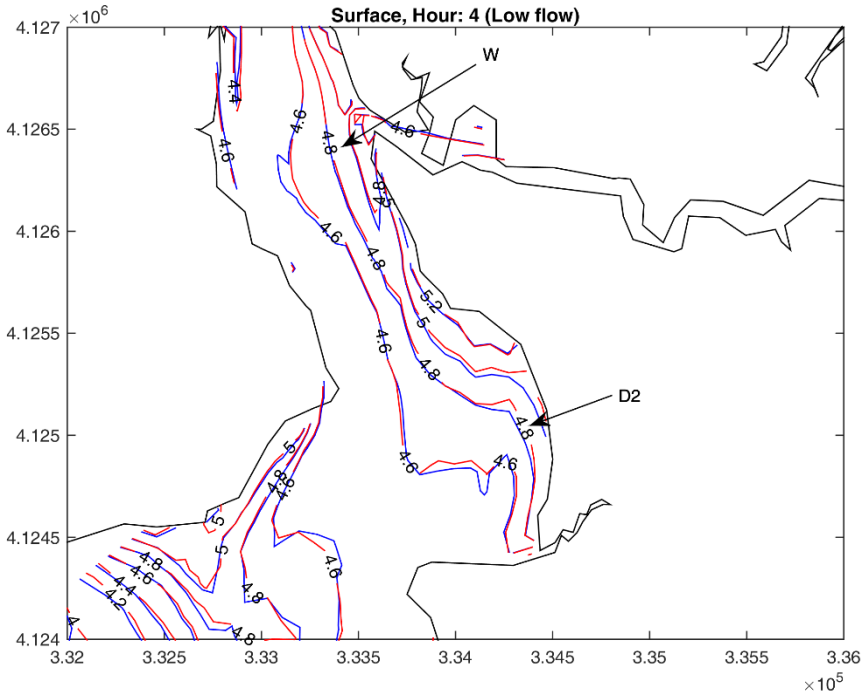


Figure 4-6-4. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during high flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Surface, Hour: 1 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 2 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 3 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Surface, Hour: 4 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5

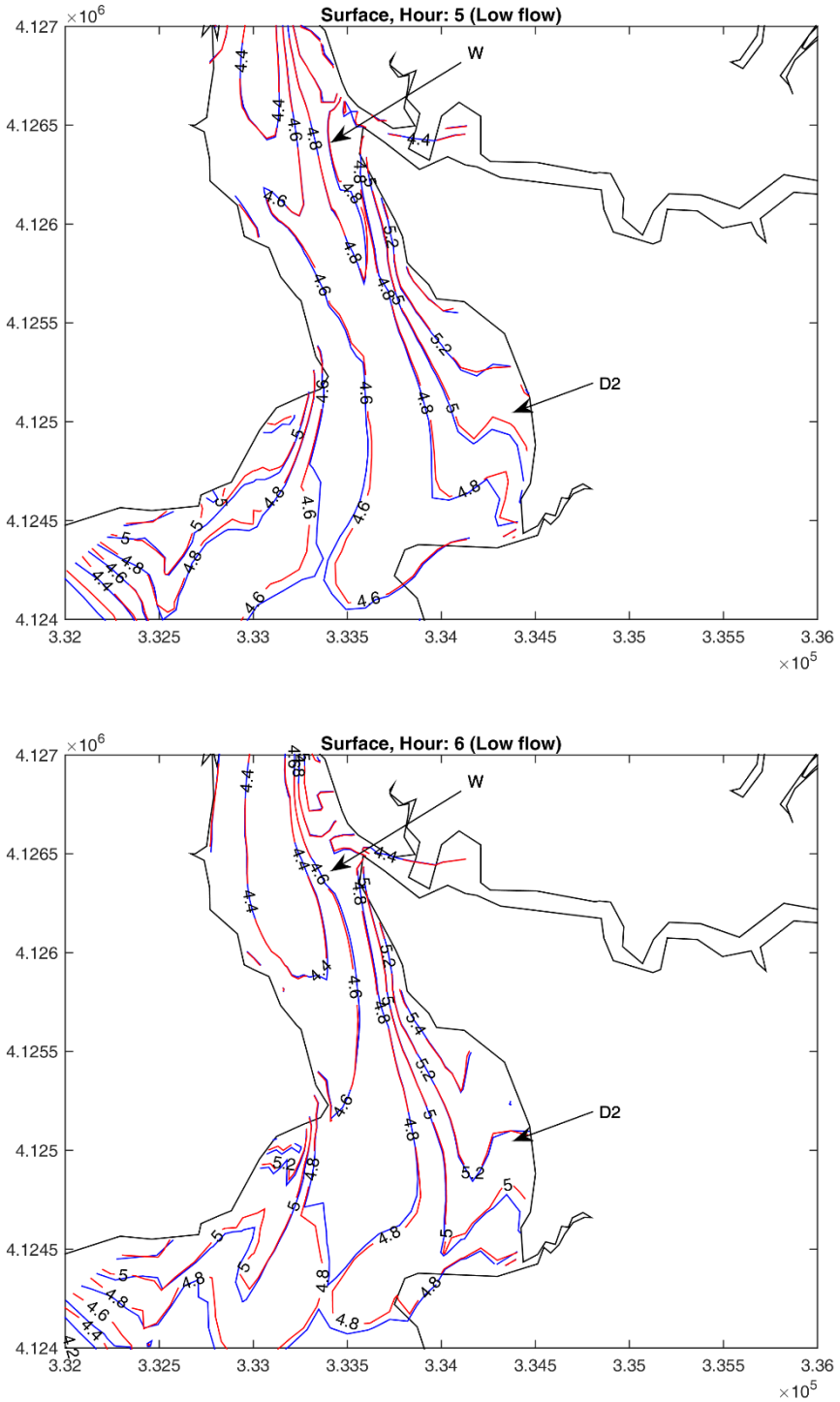
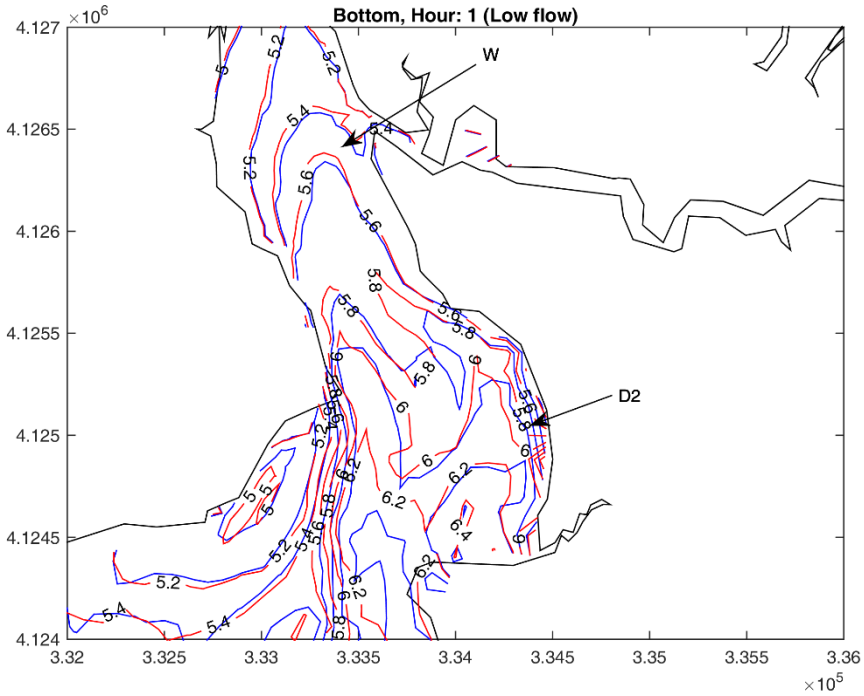
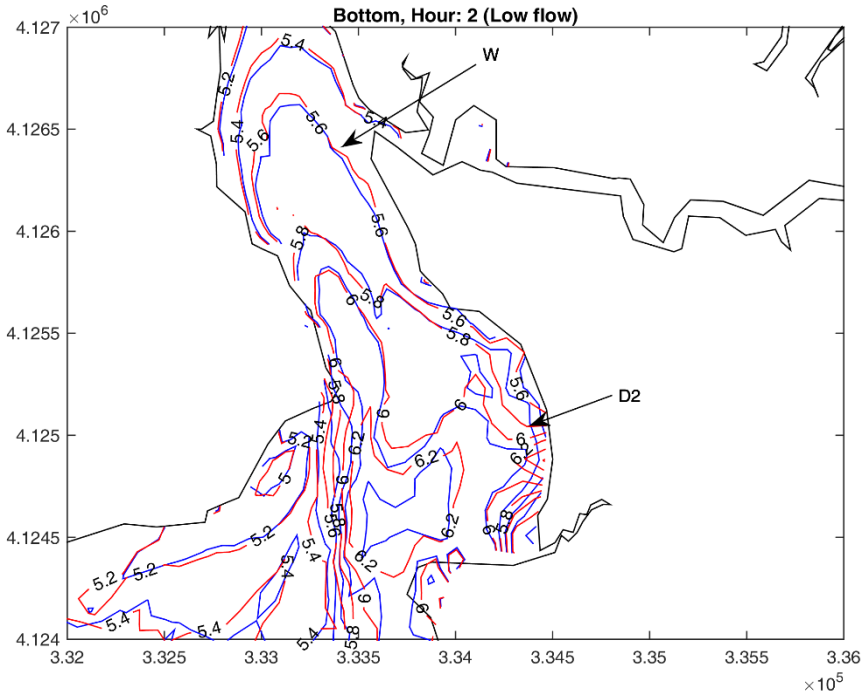
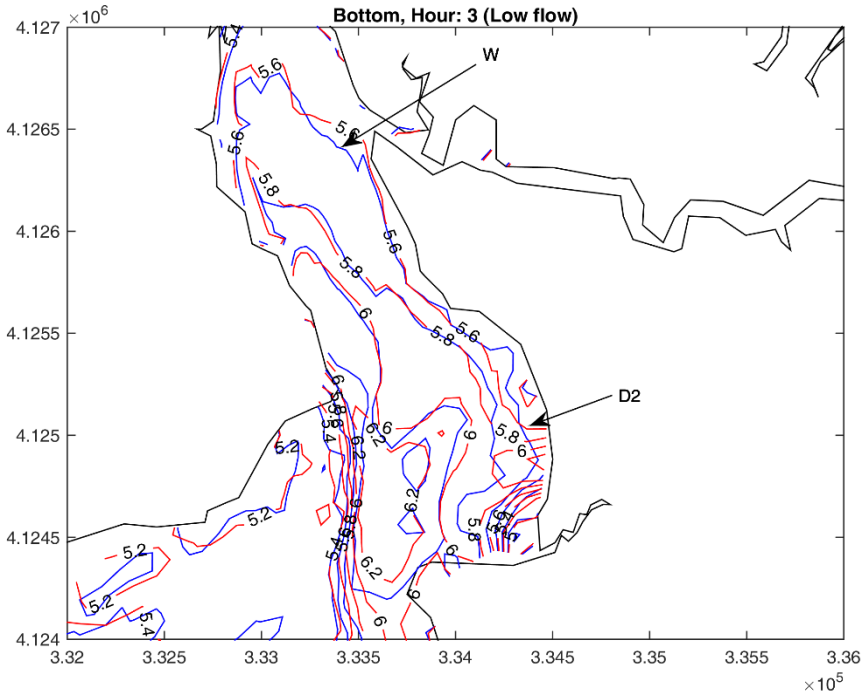
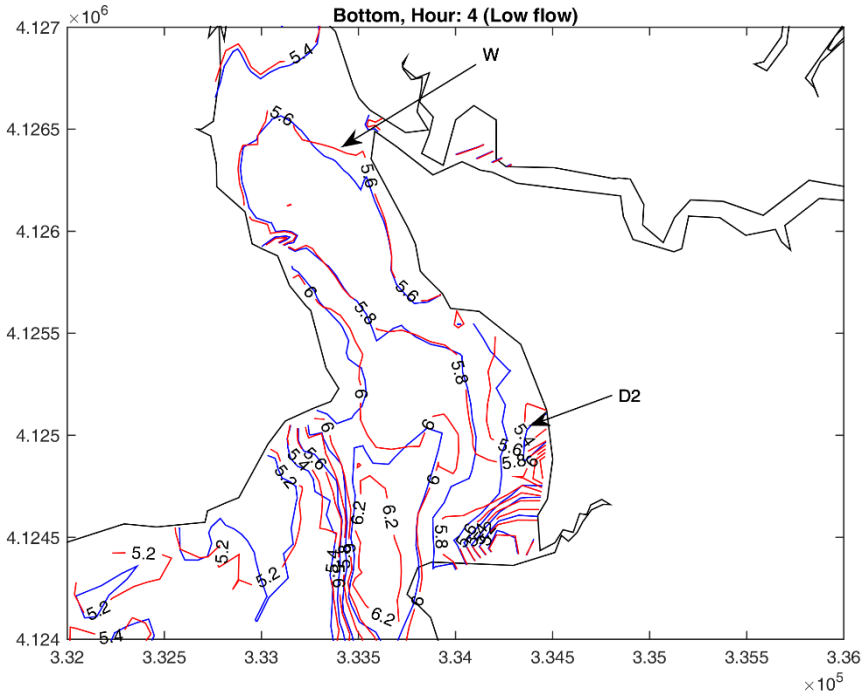


Figure 4-6-5. Comparison of surface salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).


Bottom, Hour: 1 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 2 (Low flow)
W
D2
×10^6
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^5


Bottom, Hour: 3 (Low flow)
W
D2
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5


Bottom, Hour: 4 (Low flow)
W
D2
4.127
4.1265
4.126
4.1255
4.125
4.1245
4.124
3.32
3.325
3.33
3.335
3.34
3.345
3.35
3.355
3.36
×10^6
×10^5

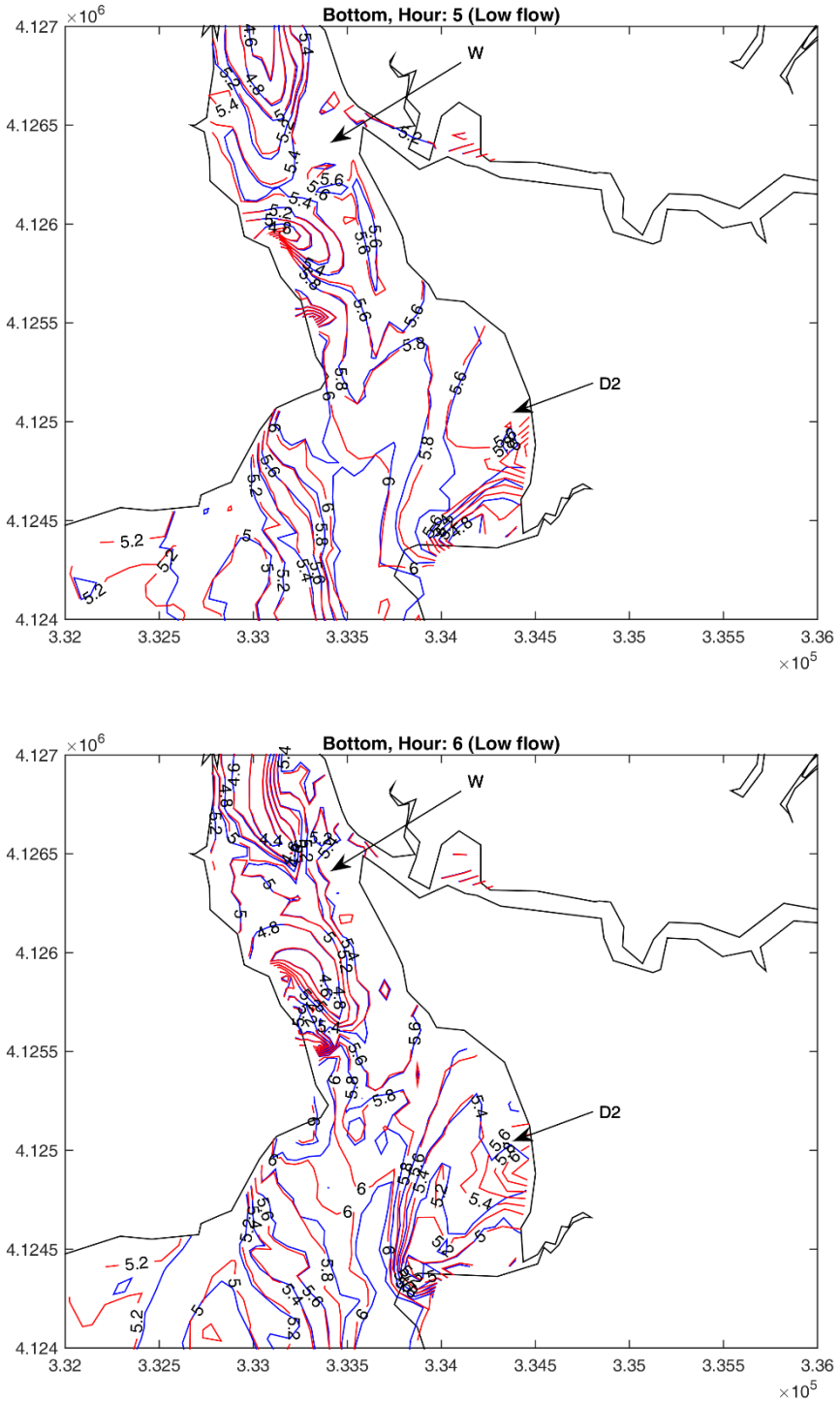


Figure 4-6-6. Comparison of bottom salinity distribution near the Chickahominy Riverfront Park withdrawal site and discharge site II for a tidal cycle during low flow period (blue lines are baseline condition, red lines are scenario runs, W is withdrawal site and D is discharge site).

5. Summary

A series of model simulations have been conducted with respect to two discharge locations located at Brickyard Landing and Chickahominy Riverfront Park. Discharge locations are located downstream of Brickyard Landing, and Chickahominy Riverfront Park. Two discharge locations near Chickahominy Riverfront Park are compared. The discharge and withdrawal presented are based on design flow of Phase II and Phase III. The salinity discharged from the discharge location is 4 times higher than that at the withdrawal sites. The year 2007 was used for the model simulations for different scenarios. The annual flow of 2007 comprises a low flow year. During spring and early summer, the flow, which is still high, results in very low salinity intrusion. During summer and fall, the salinity intrusion increases the high salinity up to 3 psu at the Chickahominy Haven, upstream of Brickyard Landing. This hydrological variation of 2007 is a good representation of the large seasonal salinity variation under different hydrological years. Three model simulations were conducted for each design phase: one experiment at Brickyard Landing, and two experiments at Chickahominy Riverfront Park with respect to two discharge locations.

The model simulations at Brickyard Landing show that salinity has a minor change at the withdrawal location. The change of salinity is less than 0.3 psu at the withdrawal location. The salinity increases at the discharge location. The large salinity change occurs during low flow period and the maximum salinity is about 1.2 and 1.7 psu at the bottom for Phase II and Phase III, respectively. The change can up to 28% for Phase III. The high increase of salinity occurred only locally. Because withdrawal flow and discharge also affect the dynamic condition, the horizontal distribution of salinity has a slight change.

Both an increase and a decrease of salinity occur during the tidal period and depend on the tidal phase. During flood tide, salinity increases a little. Salinity decreases during ebb tide. The change of salinity also depends on the flow condition. During a high-flow period, salinity intrusion increases. But salinity intrusion decreases during a low-flow period. Overall, migration of salinity is not very significant. Due to strong flow and tide mixing, no obvious local accumulation of salt occurred at the discharge location.

The model simulations at Chickahominy Riverfront Park at discharge location I were conducted. The model results show that minor changes of salinity at the withdrawal site for both Phases II and III due to a large water volume and tidal mixing. The maximum change of salinity at discharge location is about 1.59 and 2.03 psu at the bottom for Phase II and Phase III, respectively. Salinity increases and decreases occur at the discharge location, but salinity increase occurs for most of time. The horizontal distribution of salinity changes slightly during high flow period. More changes occur during low flow, especially toward the eastern shore near the discharge location. Away from the discharge location, there is no significant migration of the horizontal salinity distribution.

The model simulations at Chickahominy Riverfront Park at discharge location II were conducted. The model results show that a minor change of salinity at the discharge location is observed for both Phases II and III, respectively, due to a large water volume and tidal mixing.

The maximum change of salinity at discharge location is about 1.87 and 2.32 psu at the bottom for Phase II and Phase III, respectively. The change is about 21% and 26% of maximum salinity. Because this discharge location is near the eastern shore with relatively low flow and low mixing, the salinity discharged will accumulate near the discharge location resulting in an increase of salinity locally. Away from the discharge location, there is no significant migration of the horizontal salinity distribution.

References

Rice, K.C., Bennett, M.R., Shen, J., 2011. Simulated Changes in Salinity in the York and Chickahominy Rivers from Projected Sea-level Rise in Chesapeake Bay. USGS Open-File Report 2011e1191, 31 p.

Rice, K.C., Hong, B., and Shen, J. 2012. Assessment of salinity intrusion in the James and Chickahominy Rivers as a result of simulated sea-level rise in Chesapeake Bay, East Coast, USA. Journal of Environmental Management. 111, 61-69.

VA-DEQ. 2016.Bacteria TMDL Development for the Lower Chickahominy River Watershed Located in Charles City, James City, and New Kent Counties, VA. Virginia Department of Environmental Quality. http://www.deq.virginia.gov/Portals/0/DEQ/Water/TMDL/drftmdls/Chick_Report_BacTMDL_08aug2016.pdf

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