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MEMORANDUM

To: Scott Smith, City of Norfolk Public Works; Niklas Hallberg, David Schulte, and Alicia Logalbo, USACE Norfolk District

From: Astrid Vargas, Kevin Hanegan, and Brian Joyner

Date: August 3, 2017

Subject: Preliminary Water Quality Assessment Results –Broad Creek

M&N Job No.: 9169-20

1 INTRODUCTION

Moffatt & Nichol (M&N) has been engaged by the City of Norfolk (City) to perform hydrodynamic modeling and water quality evaluations to support the Federal Coastal Storm Risk Management (CSRM) study. Consistent with the proposed scope of work, M&N is performing hydrodynamic simulations for Broad Creek without explicitly modeling important water quality constituents and processes. Instead, hydrodynamic results are analyzed to determine CSRM project impacts to salinities, flushing, and freshwater residence time (water age), which can collectively be used to qualitatively assess potential impacts to water quality.

The purpose of this memorandum is to present preliminary results related to the water quality assessment as an example of what figures and analyses are being performed. Note that the presented results are preliminary and may be revised during formal report writing.

2 DELFT3D HYDRODYNAMIC AND SALINITY MODELS

2.1 BROAD CREEK

M&N has developed a three-dimensional (3D) Hydrodynamic model (HD) of the Elizabeth River and Broad Creek, which covers the Elizabeth River mouth at Sewell's Point, and its western, southern, and eastern Branches. The modeling domain was discretized into a curvilinear grid, with a horizontal resolution that increases from its open boundary to the Eastern Branch and Broad Creek areas (Figure 1). The vertical domain is discretized into, six equally-spaced sigma layers.

Figure 2 depicts the model bathymetry for the Elizabeth River/Broad Creek Model. The model has been calibrated against water level and salinity measurements available at different locations of the model domain.

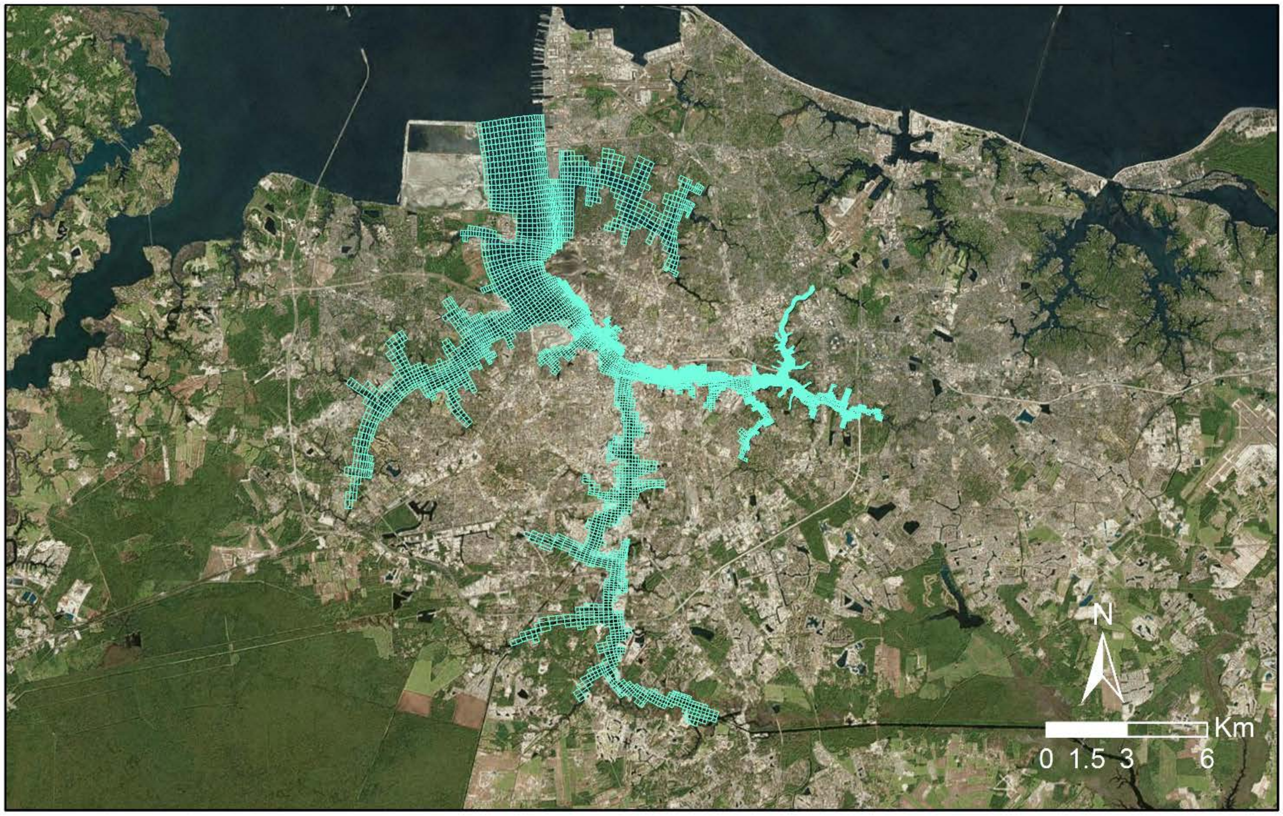


Figure 1 Computational Domain for the Elizabeth River/Broad Creek Model

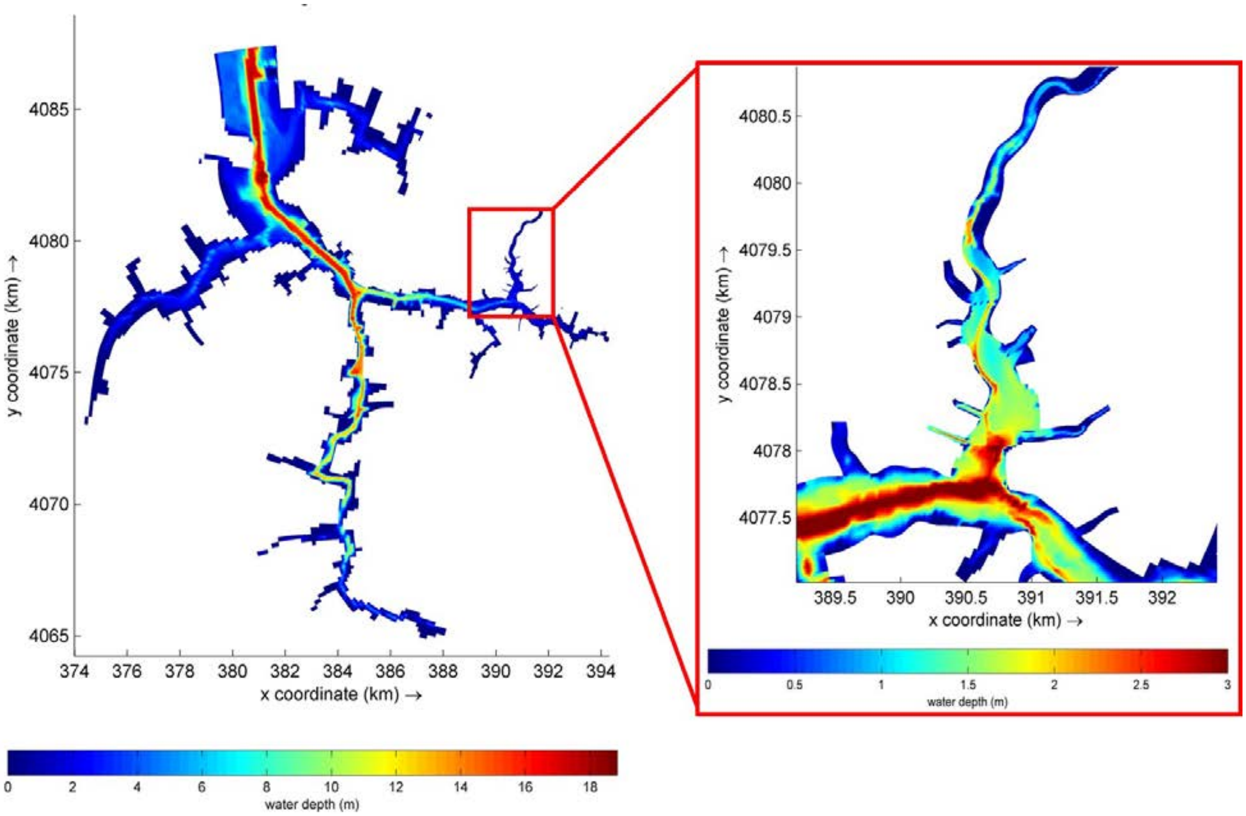


Figure 2 Model Bathymetry (NAVD88)

3 WATER QUALITY ANALYSIS SETUP

3.1 INTRODUCTION

Potential impacts of the proposed flood control structure (Project, Figure 3) to circulation and water quality in Broad Creek are evaluated with two sets of hydrodynamic simulation scenarios representing typical late-summer conditions and post-storm conditions.

Simulation of late-summer conditions are intended to provide insight of Project impacts on typical tidal flushing times, fresh water age and salinity during late-summer, when water quality is usually at its lowest. Simulation of post-storm conditions are intended to reflect potential project impacts on recovery time to typical water levels, circulation and salinity when the gates of the flood control structure re-open following a storm.

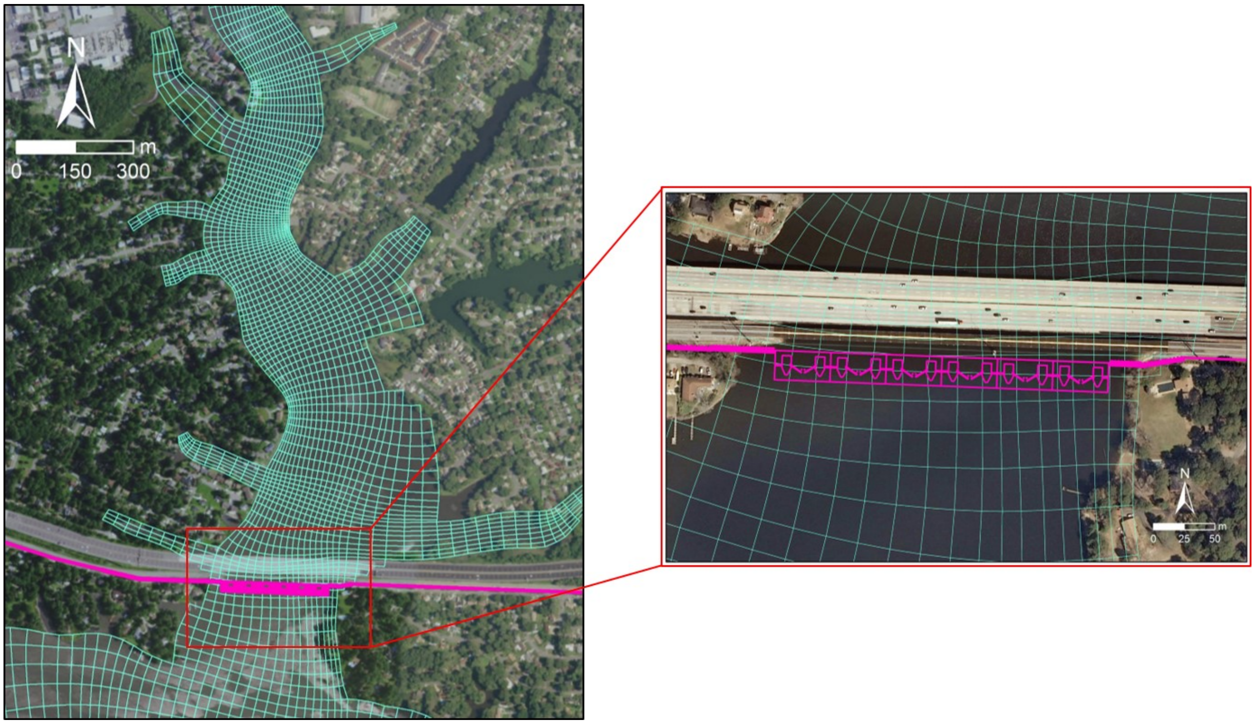


Figure 3 Proposed Flood Control Structure

3.2 METHODOLOGY

3.2.1 Typical Average Late-Summer Conditions

M&N is assessing potential project impacts on water quality for the long-term average conditions without explicitly modeling water quality constituents and processes. Instead, a modeling and post-processing framework has been developed that uses conservative and decaying tracer concentrations to derive the flushing time for a particular area of interest and the tidally-averaged freshwater age and salinity for all areas within Broad Creek. Model boundary conditions are set up such that the hydrodynamics, and salinity have reached a dynamic steady-state prior to tracer simulation. In this context, dynamic steady-state means that a parameter value will vary over the tidal cycle but will remain relatively constant at a given spatial location and for a particular phase of the tidal cycle.

The methodology for computing specific water-quality proxy quantities from model results are described below:

- **Bay flushing time**: The term *bay* is used to represent the interior domain on the protected side of the flood control structures. An initial conservative tracer concentration was set to a constant value throughout the bay and zero outside of the bay and at all boundaries. The model was run long enough to flush out most of the tracer. Tracer concentrations over time were used in post-processing to compute flushing time. Tracer concentration decreases exponentially with time at a rate that is equivalent to the inverse of the flushing time. Thus, by plotting the log of the tracer concentration versus time, flushing time was computed as the inverse of the slope of the curve. Ideally the curve is a straight line, but in practice it often isn't. Thus, a linear best fit was used to determine the slope and thus the flushing time.

  Tracer concentrations were averaged over space at specific output times for the entire bay and for various regions of the bay, such as the upper bay. The time series of these spatially-averaged concentrations were used to determine the flushing time for the bay regions. Flushing times were compared among scenarios. The flushing time is actually the first flushing period, referred to as the e-folding time, where approximately 63 % of the initial water in the bay region of interest has been flushed out.

- **Salinity**: Salinity reached a dynamic steady-state, which means varied over the tidal cycle, but values were close to the same at a given spatial location and phase of the tidal cycle. Output salinity was averaged for each computational cell over a lunar month (tidally averaged) after reaching dynamic steady-state. Tidally averaged salinity for the computational cells was averaged spatially over specific regions (e.g., entire bay, upper bay, etc.) and compared among scenarios. Additionally, color shaded spatial maps and difference maps of tidally averaged salinity were developed.

- **Fresh water residence time**: Tracer studies were performed to determine the residence time of the freshwater inflows. After dynamic steady-state spin-up, the model was run with initial conditions of zero tracer concentrations. Tracer concentrations at the most upstream freshwater source were set to a constant value, and tidal boundary tracer concentrations were set to zero. The model was allowed to run until dynamic steady-state conditions for tracer concentrations throughout the bay were reached. A tracer pair, one conservative and one decaying, was used to obtain dynamic, steady-state water age, or residence time, for freshwater sources. The decay rate was set to the reciprocal of the bay flushing time. Similar to salinity, freshwater age was tidally averaged over the lunar month producing tidally averaged fresh water age (residence time) for every computational cell. Color shaded spatial maps of tidally average freshwater residence time was produced allowing comparison among scenarios

3.2.2 Post Storm Recovery

A major rainfall event was imposed on the system with sea levels, tides, and wind conditions that are typically coincident with a major storm, such as a hurricane. The sea level and tides had storm surge characteristics that would cause flooding in the bay, necessitating closure of the barrier's gates. The model was started with the dynamic, steady-state, typical conditions described above and run long enough to capture not only the storm runoff and surge event, but the weeks following the event to allow enough time to restore the system to pre-storm conditions in terms of water levels and salinity, plus enough time to determine flushing time characteristics. In the *with Project* condition, the gates of the proposed structure were closed at the beginning of the storm event, remained closed during the storm and were re-opened once the water levels have receded to typical tidal conditions. The *with* and *without Project* scenarios were time referenced for comparing the two conditions. The time reference, or time zero, was established as the beginning of the rainfall-runoff hydrograph.

- **Freshwater tracers:** Two types of tracers were introduced in the freshwater inflows, a conservative and decaying tracer. These are two separate tracer variables and are not related to tracer pairs used for modeling water age in the typical average simulations (above section 3.2.1). The decay rate used for the non-conservative tracer was 0.5 per day. Initial concentrations for the tracers were specified to zero throughout the model domain, and to a constant value at all freshwater sources within the bay throughout the runoff hydrograph imposed during the storm. Tracer concentrations were tracked over time at various locations, such as an upstream location and at the structure exit in the main channel. Tracer concentrations versus time was compared for *with* and *without Project* conditions. The model was run long enough to flush out most of the tracers.

  Freshwater tracers will not reach a dynamic steady-state, since inflow to the bay is not constant through time; therefore, freshwater age cannot be derived. Instead, tracer concentrations were tracked over time at relevant locations.

- **Salinity**: Time series of output salinity was compared among scenarios for point locations. Salinity was monitored to gain insight on the recovery time for the system, i.e. the time required for restoration of pre-storm conditions.

3.3 MODEL SCENARIOS

For each of the hydrodynamic scenarios described above the following simulations were conducted:

- ***Without Project* case**: Simulations without the proposed flood control structure were carried out to establish the base condition for the evaluation of Project
- ***With Project, Alternative 1***: These simulations evaluate permanent Project impacts by incorporating the proposed flood control structure to the computational grid. All of the structure's gates (i.e., 6 gates) are open during the late-summer conditions, and are operated as necessary during the post-storm recovery simulations.
- ***With Project, Alternative 2***: These simulations include a flood control structure with only two central gates open for the late-summer and following the storm in the storm-recovery scenarios.

Flood control structures were incorporated to the computational domain by specifying thin dams, i.e. infinitely thin features which prohibit flow exchange between two adjacent computational cells without reducing the total wet surface and volume of the model. Figure 4 illustrates the defined thin dams for alternatives 1 and 2 of the *with Project* simulations. A sill elevation of -7 feet (2.1 m NAVD88) was set throughout the structure's footprint.

With and *without Project* simulations described above are also conducted for existing and future conditions as described below:

- **Existing conditions:** These simulations involve present-day water levels and bathymetry in the Elizabeth River. Essentially, tidal and discharge boundary conditions, as well as water depths were input to the model as available in different publicly available data sources.
- **Future conditions**: These simulations are intended to incorporate effects of future water levels and physical modifications to the Elizabeth River system.

  As directed by USACE, an expected sea level rise of 1.6 feet (0.48 m) is assumed for the end-of-plan year 2076. Imposed water levels at the open boundary of the model are adjusted accordingly.

It is assumed that Broad Creek bathymetry will be identical between the Existing and Future conditions. However, modifications to the Elizabeth River navigation channel due to Federal Channel Deepening Project are assumed. Such modifications are based on the assumed deepening in the *Norfolk Harbor / Southern Branch Elizabeth River Deepening Federal Feasibility Studies*, recently completed by the Virginia Institute of Marine Science (VIMS). Figure 5 shows the assumed channel deepening for the Future conditions simulations.

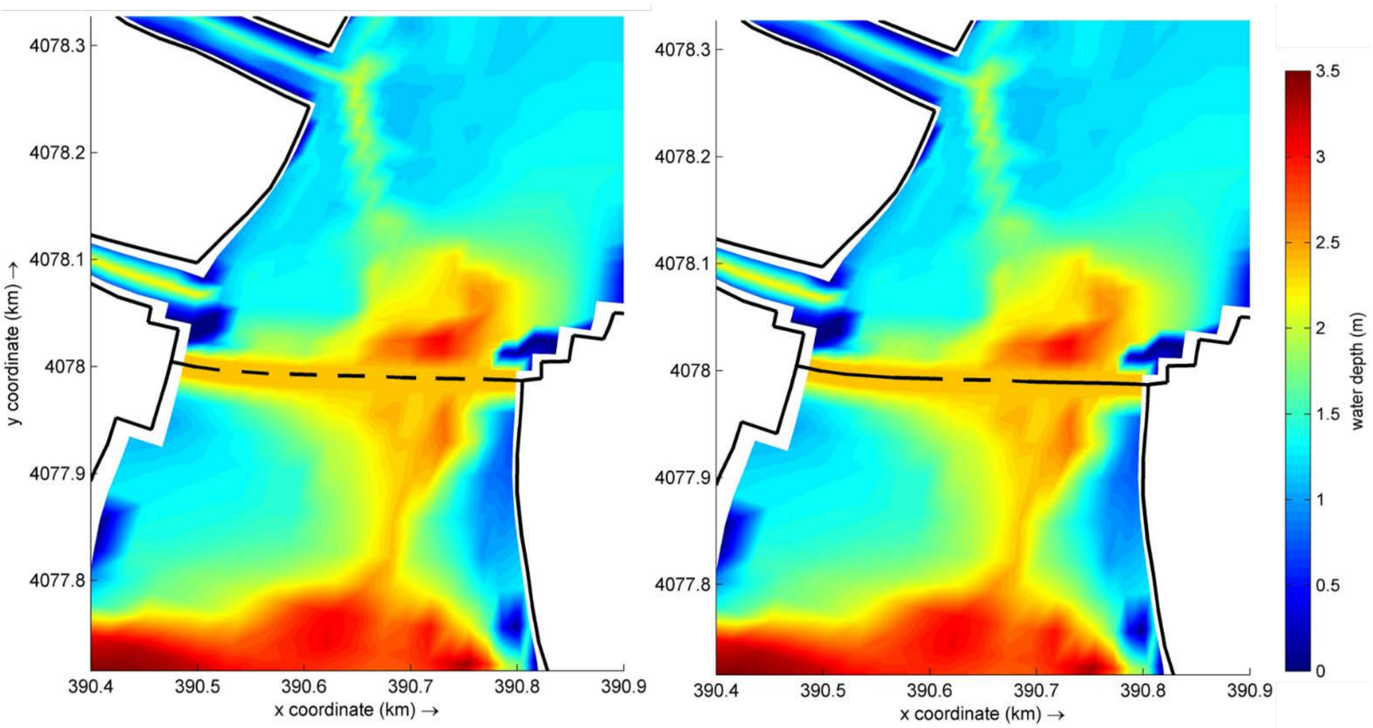


Figure 4 Thin Dams for the With Project Simulations:
Alternative 1 (*Left*) and Alternative 2 (*Right*)

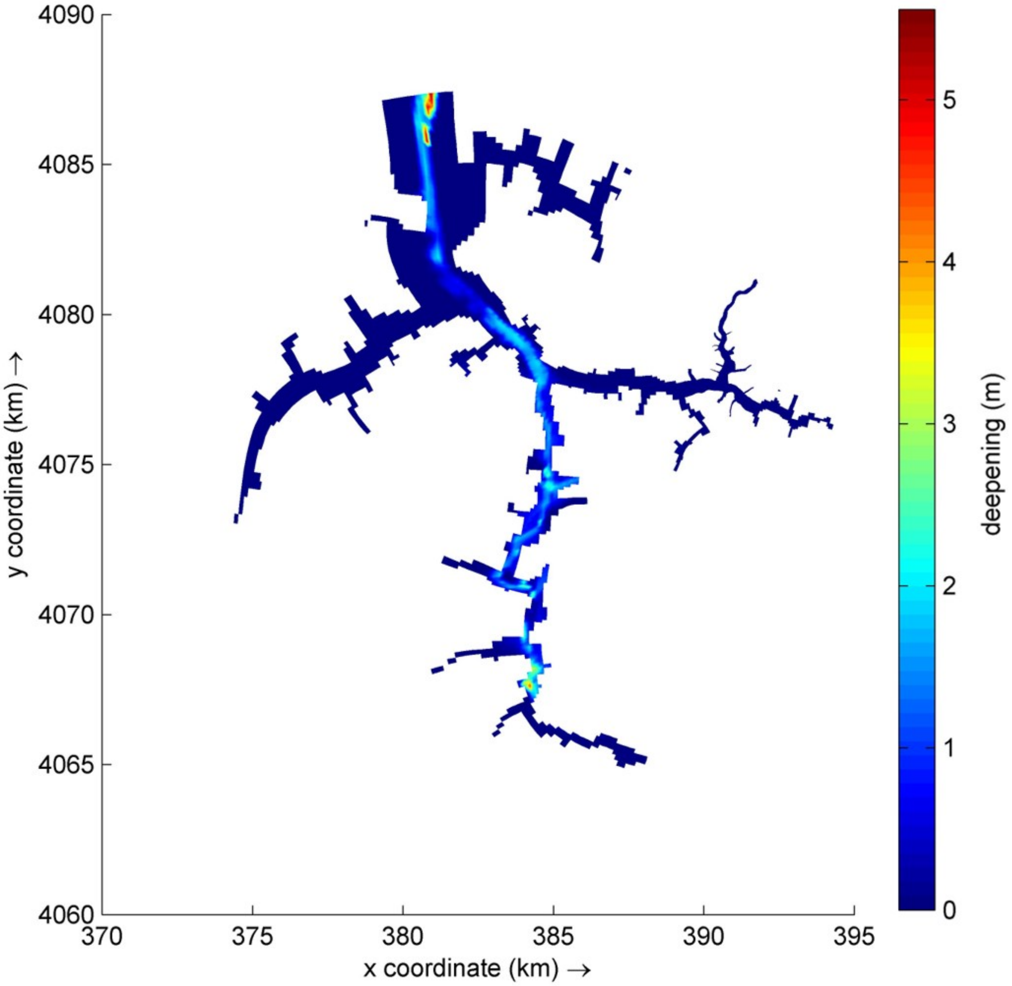


Figure 5 Assumed Channel Deepening for the Future Conditions Simulations

3.4 LATE-SUMMER TYPICAL CONDITIONS RUN SETUP

To determine the potential long-term impacts of the CSRM project on water quality, M&N relied on calculating *with* vs. *without Project* values for flushing time, salinity, and fresh water residence time under dynamic steady-state conditions. For the hydrodynamics to reach a dynamic steady-state condition, the model needs to be forced with boundary conditions that do not vary significantly at frequencies lower than that of the tidal cycle. The boundary conditions were derived to represent the typical conditions during the late summer (approximately July 15 through September 15^{h}), when water quality is most critical. The effects of any short-term events such as storms that could interrupt the dynamic steady state conditions were excluded. The model simulation duration for the typical summer condition was six (6) months.

Prior to specification of tracer concentrations for typical conditions water quality evaluation, the Elizabeth River/Broad Creek model is spin up to reach a hydrodynamic and salinity steady state. Boundary conditions to force the model are imposed as follows.

3.4.1 Water Level Boundary

The amplitude and phase of 37 harmonic constituents, as derived by NOAA-CO-OPS for station 8638610 (Sewell's Point), were specified to create a purely astronomical tidal boundary condition. The generated water level time series at the model open boundary, encompassing the summer months, is depicted in Figure 6.

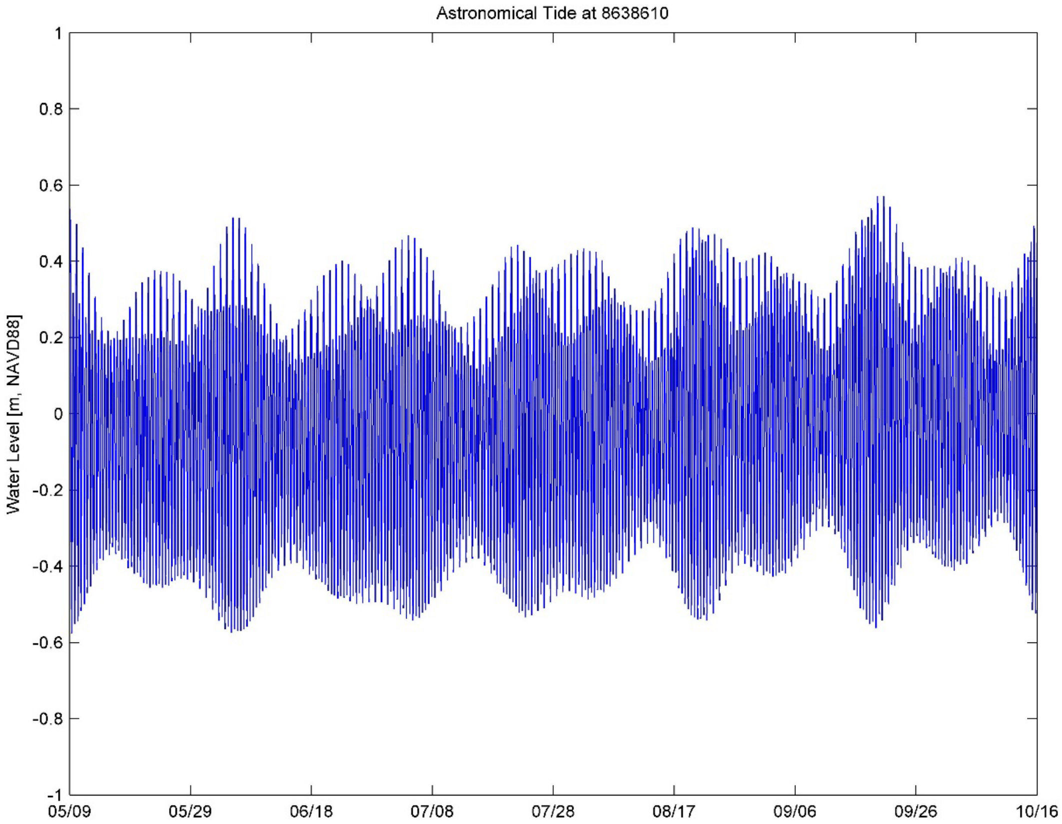


Figure 6 Astronomical Water Level Boundary Condition

3.4.2 Salinity:

A late-summer salinity time series was derived from a simulated 3D salinity data set at the model open boundary. The simulated data was provided by VIMS from their EFDC-HEM3D model (Shen *et al.*, 2017) of the Chesapeake Bay, and it comprises the period between January 2010 to December 2013. Because no year can be described as "typical", this approach was taken: daily salinity values were averaged over the four years' late-summer periods (i.e. mid-July to mid-September) included in the simulated salinity data set to obtain a one-month 3D salinity time series. This condition was consecutively repeated over the simulation period, as shown in Figure 7. A linear vertical variation of salinity along the offshore boundaries was adopted.

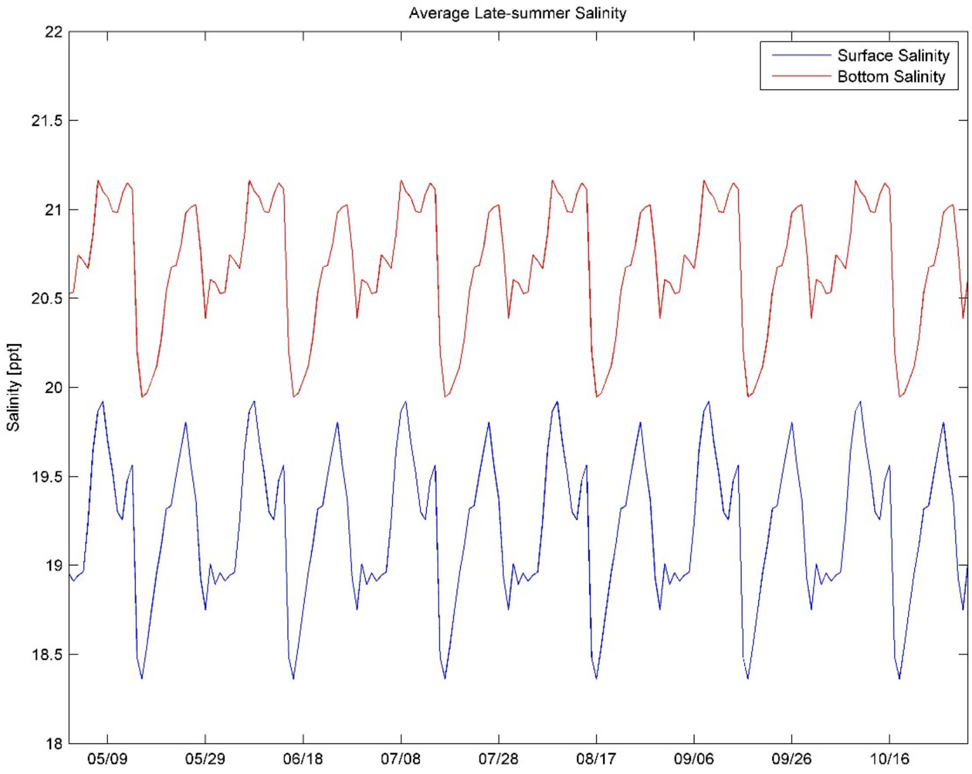


Figure 7 Late-summer Salinity Boundary Condition

3.4.3 Freshwater Inflows:

Approximately 15 years (1990 – 2015) of rainfall-runoff outputs were available for the project area from the Virginia Department of Environmental Quality (VADEQ) statewide watershed model hindcast. To determine representative late summer runoff conditions, the relevant runoff time series were averaged using only data from July 15 through September 15 of each year and excluding the runoff from major storms where daily precipitation was greater than 2 inches. These average values were imposed as constant freshwater discharges within the model for the six-month simulation to represent steady state runoff conditions for the period of interest. The locations of the freshwater inflow sources in the model domain are shown in Figure 10.

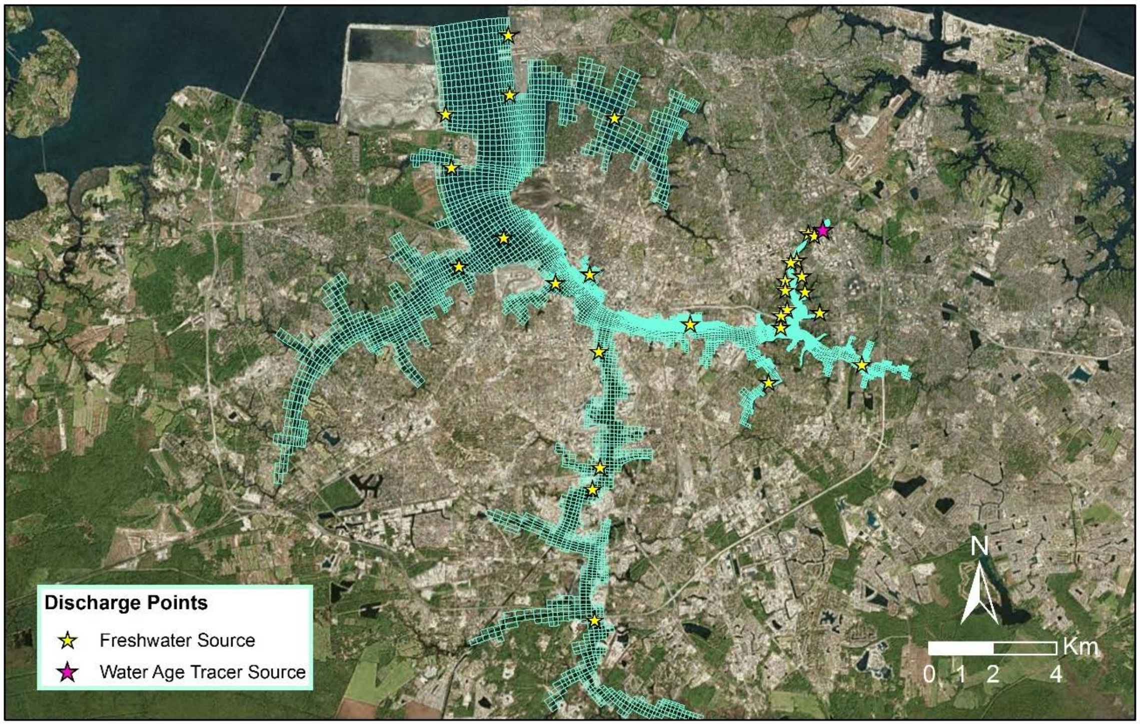
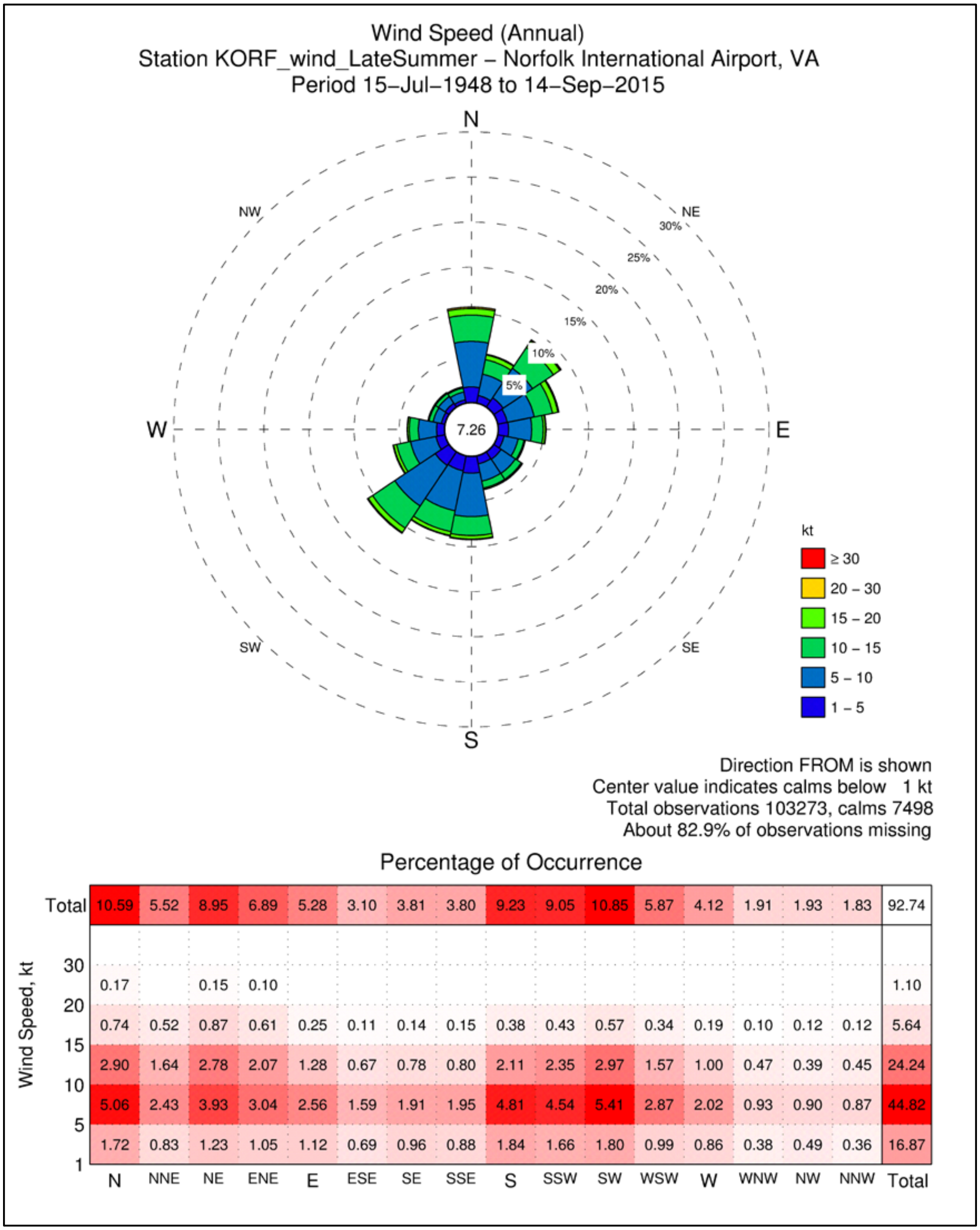


Figure 8 Freshwater Sources in the Computational Domain

3.4.4 Wind

As with the freshwater inflows, a constant wind speed and direction in space and time was imposed to represent typical late summer values while maintaining dynamic steady state conditions. Measurements from the Norfolk International Airport were used to derive both a scaler average wind speed (7.6 knots) and dominant wind direction (Southwest) for only the late summer period. This constant wind was applied for the full simulation period at the corresponding dominant direction. Figure 9 shows a wind rose from Norfolk International Airport limited to the late summer period each year.



Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	10.59	5.52	8.95	6.89	5.28	3.10	3.81	3.80	9.23	9.05	10.85	5.87	4.12	1.91	1.93	1.83	92.74
≥ 30																	
20 – 30	0.17		0.15	0.10													1.10
15 – 20	0.74	0.52	0.87	0.61	0.25	0.11	0.14	0.15	0.38	0.43	0.57	0.34	0.19	0.10	0.12	0.12	5.64
10 – 15	2.90	1.64	2.78	2.07	1.28	0.67	0.78	0.80	2.11	2.35	2.97	1.57	1.00	0.47	0.39	0.45	24.24
5 – 10	5.06	2.43	3.93	3.04	2.56	1.59	1.91	1.95	4.81	4.54	5.41	2.87	2.02	0.93	0.90	0.87	44.82
1 – 5	1.72	0.83	1.23	1.05	1.12	0.69	0.96	0.88	1.84	1.66	1.80	0.99	0.86	0.38	0.49	0.36	16.87

Figure 9 Norfolk International Airport wind rose for late summer period only (mid-July – mid-September)

3.4.5 Flushing Time Tracers:

Initial concentrations for two type of tracers were specified as depicted in Figure 10. The concentration at the model open boundary and freshwater sources is set to zero.

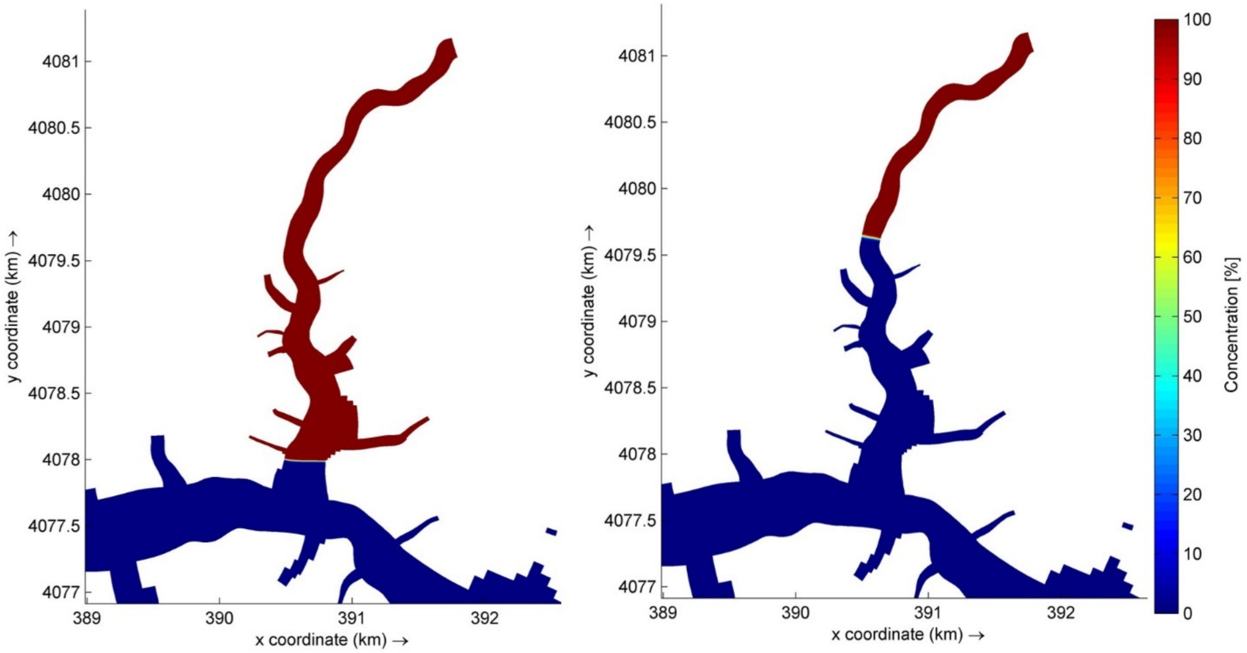


Figure 10 Initial Concentrations for Flushing Time Tracers: Whole Bay (*Left*) and Upper Bay (*Right*)

3.4.6 Water age tracers:

Water age tracer concentrations are set to a constant value (i.e. 100 mg/L (g/m^3)) throughout the simulation period, at the most upstream freshwater source within the Bay (Figure 8) and are set to zero for the rest of the discharge sources and model open boundary.

3.5 POST STORM RECOVERY RUN SETUP

For post-storm recovery investigation, model simulations were started with initial conditions derived from the long-term run described previously, where conditions reach a dynamic steady state. The *with Project* gates started in the closed position, while a gradual surge event was imposed at the water level boundary. Concurrently, a rainfall event discharge hydrograph associated with such surge event was routed into the basin through freshwater sources.

After the water level recedes to typical elevations, the surge barrier gates were opened, and the simulations proceeded for another few weeks (or longer as necessary) to capture the post-storm and closure event recovery period. After the storm surge and extreme rainfall hydrograph receded to normal levels, the model forcing conditions were reverted to the typical late summer conditions values as described above.

USACE advised M&N to use historical Hurricane Isabel in 2003 as the design storm. The barriers would be closed the day before the storm hit the area, which is at low tide and approximately 12:00pm on September 17, and reopened at 12:00pm on September 21 when the tide level returned to normal conditions. After gate re-opening, the imposed model boundary salinity, wind, and freshwater discharge were reverted to the typical late-summer conditions described above.

The model boundary condition and other inputs are discussed below for the storm period only. The inputs during the post storm recovery periods are the same as the typical summer conditions described in previous section and are not repeated here.

3.5.1 Water Level Boundary

The meteorological tide from Hurricane Isabel at the model open boundary was derived by subtracting the observed water levels to the predicted tide at NOAA CO-OPS station 8638610 (Sewell's Point) The resulting storm surge is depicted by the green curve in Figure 11. The peak surge at Sewell's Point occurred on September 18, 2003 and was approximately 1.6 feet (1.7 m). This peak surge coincides with the high astronomical water levels and results in total water levels of up to 2.1 m at the model open boundary, as depicted in Figure 11.

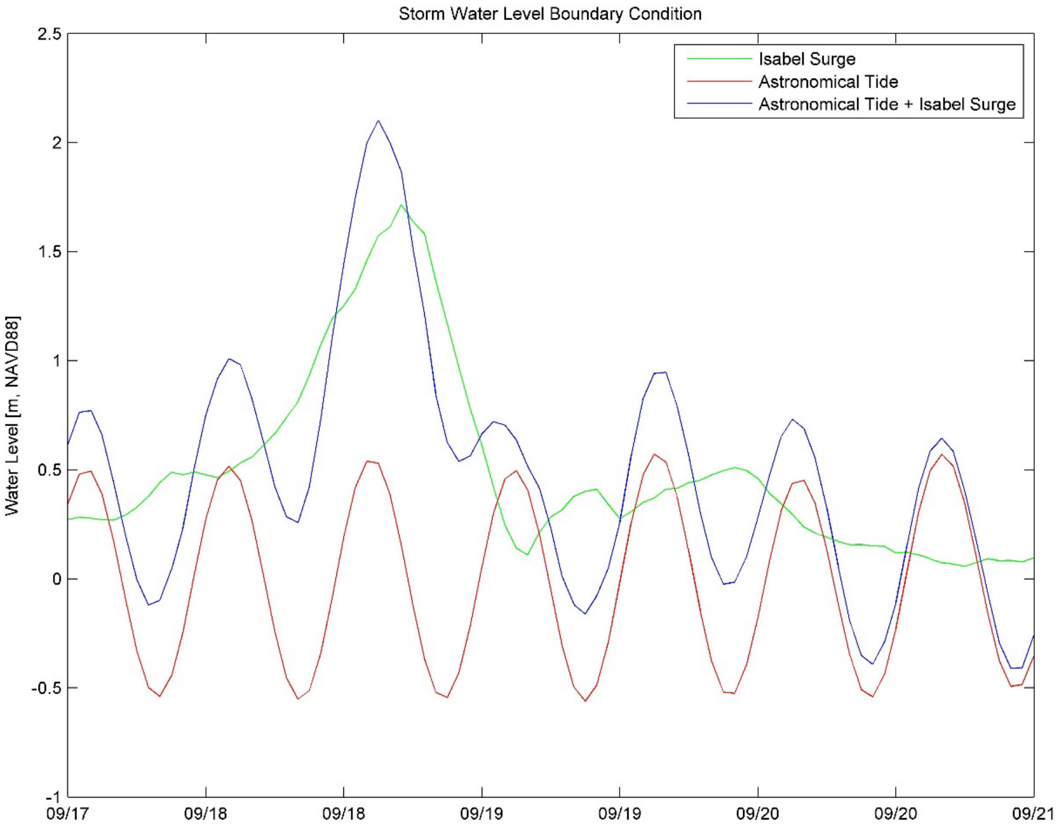


Figure 11 Storm Water Level Boundary Condition

3.5.2 Salinity

Surface salinity data for the Isabel storm period was derived from surface water temperature and conductivity data available from Sewell’s Point Station. The derived salinity data set indicated that the Sewell’s Point area had already freshened by the start of the storm simulation period (i.e., September 17). In order to avoid significant differences between boundary and initial salinity conditions (which had already reached a dynamic steady state), the derived salinity data set was adjusted to reproduce the variation in salinity values observed during the storm period (i.e., an increase followed by a more rapid decrease) with respect to the mean value for the late-summer salinity boundary condition. A linear salinity profile was assumed, with a constant gradient of 1.5 ppt (Figure 12), equivalent to the average salinity gradient imposed in the late-summer boundary condition.

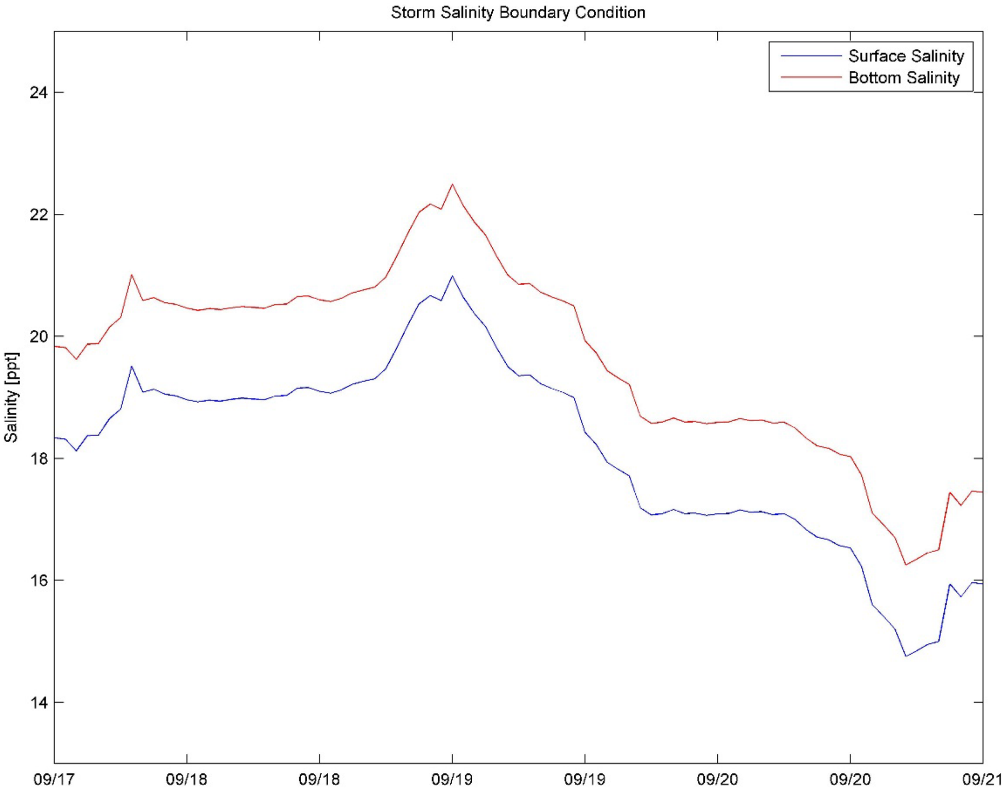


Figure 12 Storm Salinity Boundary Condition

3.5.3 Freshwater Inflows

Daily rainfall run-off data for the Isabel storm period, available from the VADEQ hindcast model was imposed to the freshwater sources in the model domain (Figure 8). Total rainfall depths from Isabel ranged from 3.2” to 5.4” over the region, which corresponds to a 2-yr to 10-yr return period rainfall (for a 24-hour storm).

3.5.4 Wind

Wind records for the full Isabel storm period are available from NOAA-COOPS station 8638863 (Chesapeake Bay Bridge Tunnel). The data set was smoothed by a 3-hour moving average (Figure 13) in order to avoid instabilities related to sudden significant changes in wind speeds and/or wind direction. The wind data from the Norfolk International Airport have gaps during Isabel, thus they are not used for the storm simulation in this study.

3.5.5 Freshwater tracers

Freshwater tracer concentrations are set to a constant value (i.e., 100 g/m^3) at freshwater sources within the bay (and set to zero for all other discharge points) during the storm simulation period. Following the gates re-opening, tracer inflow concentrations are set to zero.

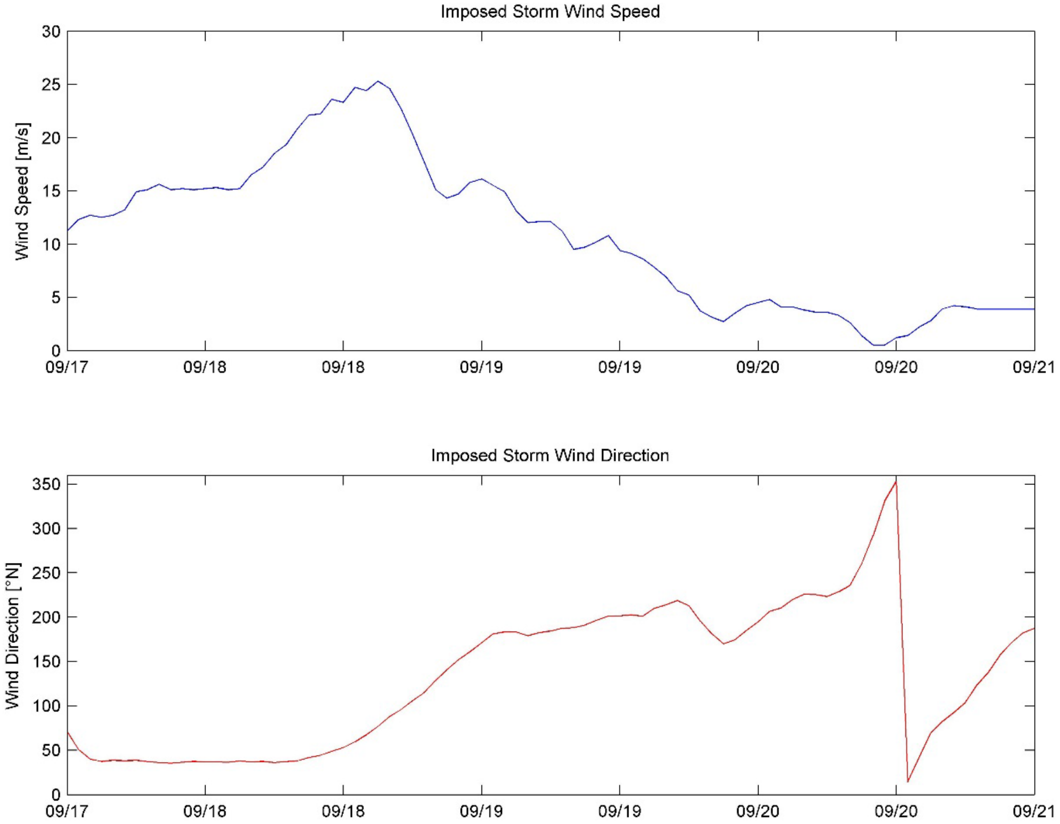


Figure 13 Imposed Wind Condition

4 TYPICAL CONDITIONS RESULTS

4.1 EXISTING CONDITIONS RESULTS

Flushing time, tidally-averaged salinity, and tidally-averaged freshwater age were computed for the full Broad Creek (Whole Bay) area and Upper Bay region as defined in Figure 14.

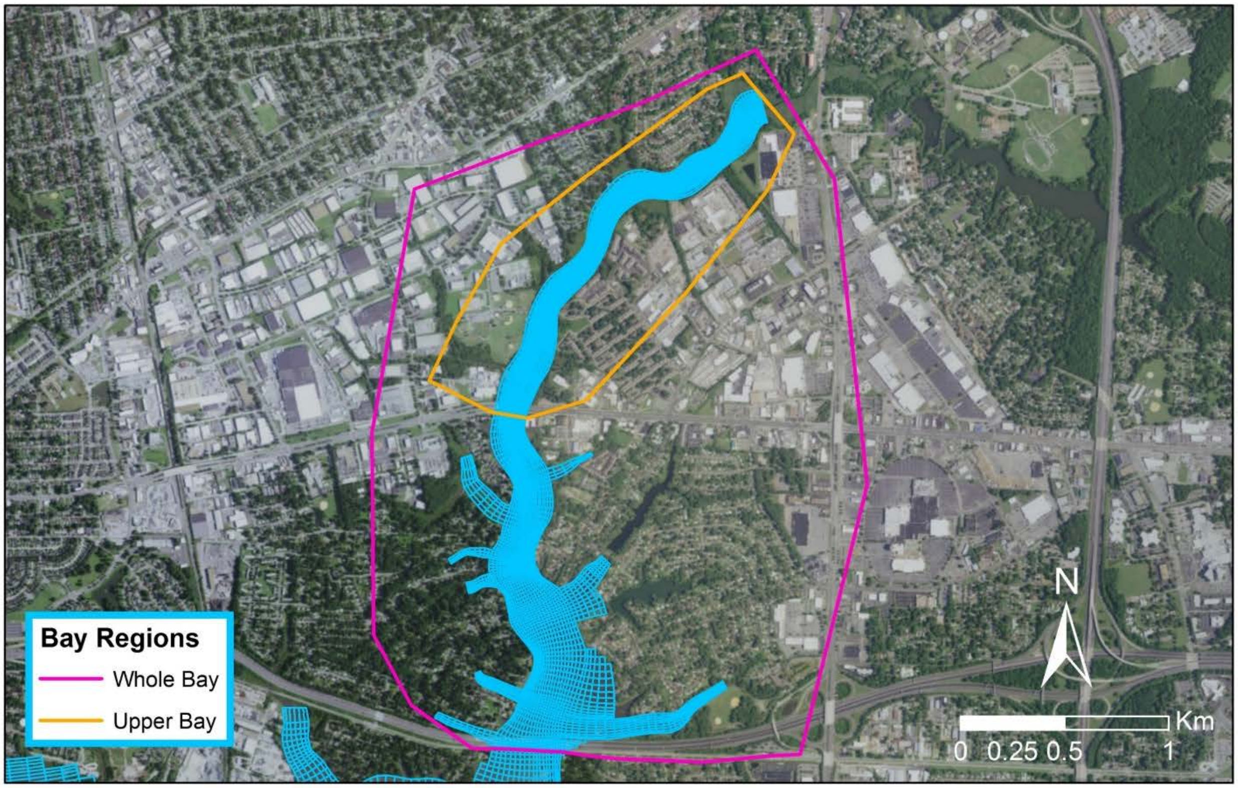


Figure 14 Broad Creek Water Quality Analysis Regions

4.1.1 Flushing Time

Figure 15 plots the spatially-averaged tracer concentration through time for the Whole Bay and Upper Bay regions of Broad Creek. The first 20 days of results after achieving dynamic stability are used to determine flushing times. As shown in Figure 16 and Figure 17, a linear regression is applied to the natural logarithm of the tracer concentrations. The inverse slope of such curve corresponds to the flushing time.

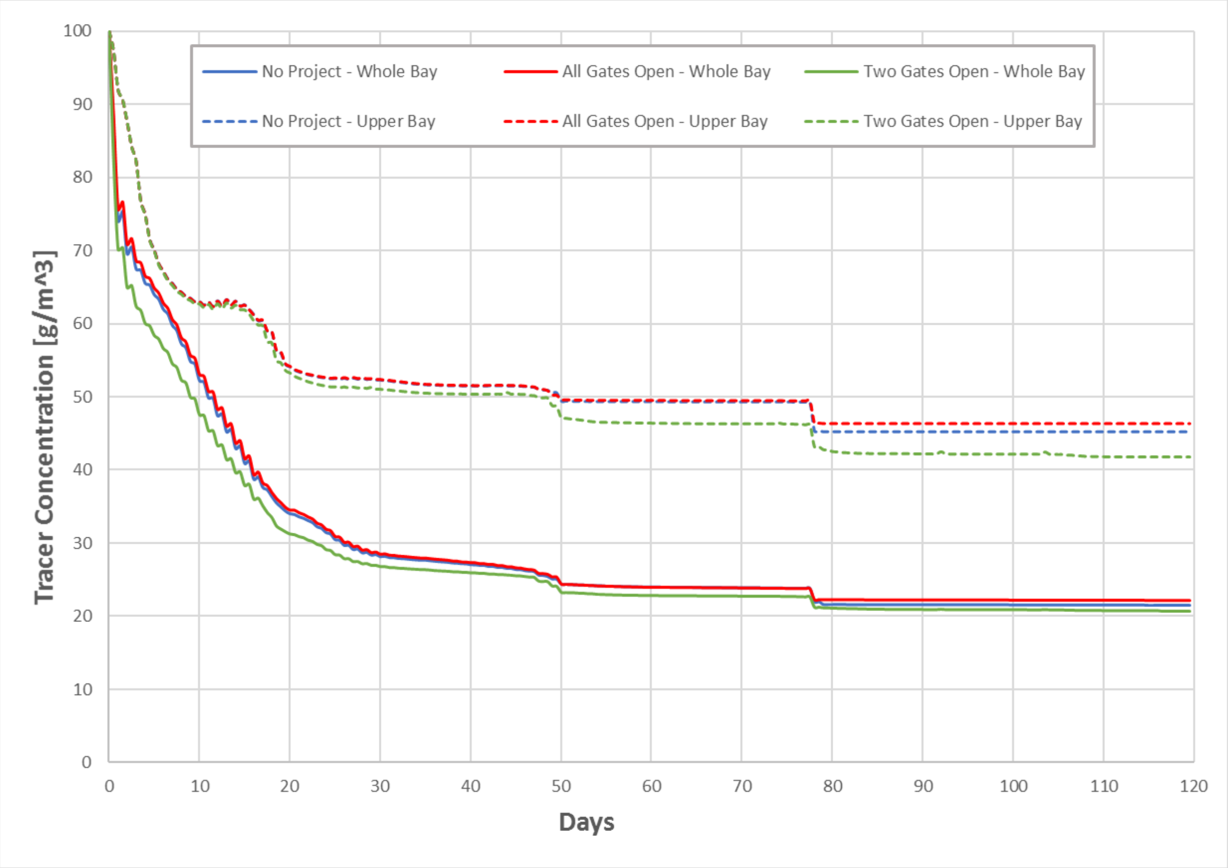


Figure 15 Existing Conditions: Spatially-Averaged Conservative Tracer Concentration Over Time in the Whole Bay and Upper Bay Regions of Broad Creek

Whole Bay flushing time was estimated at 22.2 days for the *without Project* case, 22.3 days for the *with Project Alternative 1* – all gates open case, and 21.7 days for the *with Project Alternative 2* – two gates open case. Flushing time for the Upper Bay tracer is 43 days *without Project*, 43.1 days with all gates open, and 41.0 days for the two gates open case

Due to the degree of precision of the followed approach (i.e., required regression analysis), these differences in flushing times between *with* and *without Project* cases are considered to be negligible. However, there is a definite trend that suggests that less gate opening could result in a slightly greater flushing rate (lower flushing time). Less flow area due to fewer gate openings, will result in higher entrance/exit velocities (see with possibly no reduction in tidal prism volume exchange. Higher velocities could induce greater secondary circulation, such as Stokes Drift, which could enhance mixing, thus reducing flushing time slightly.

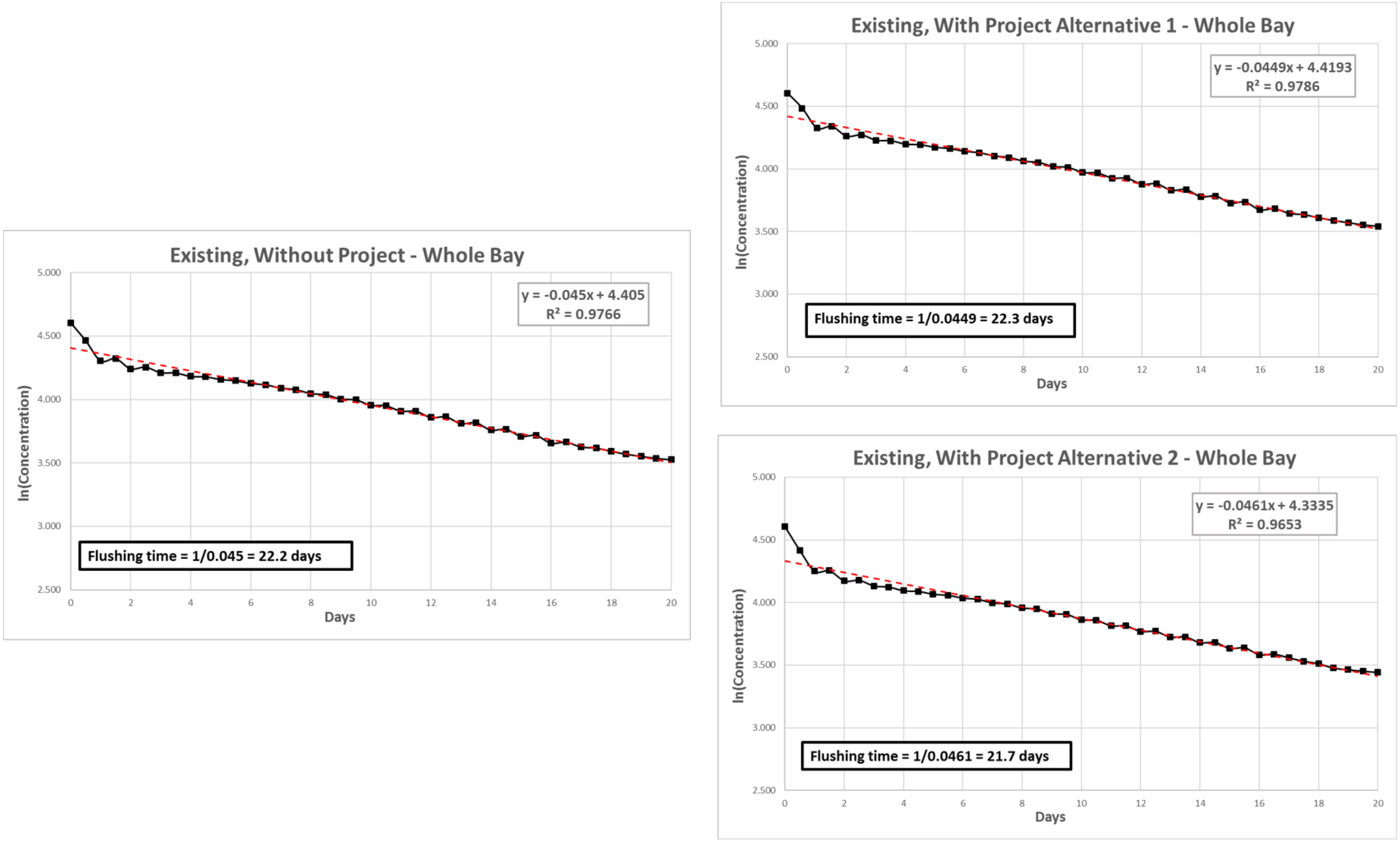


Figure 16 Existing Conditions Whole Bay Region Flushing Time Analysis

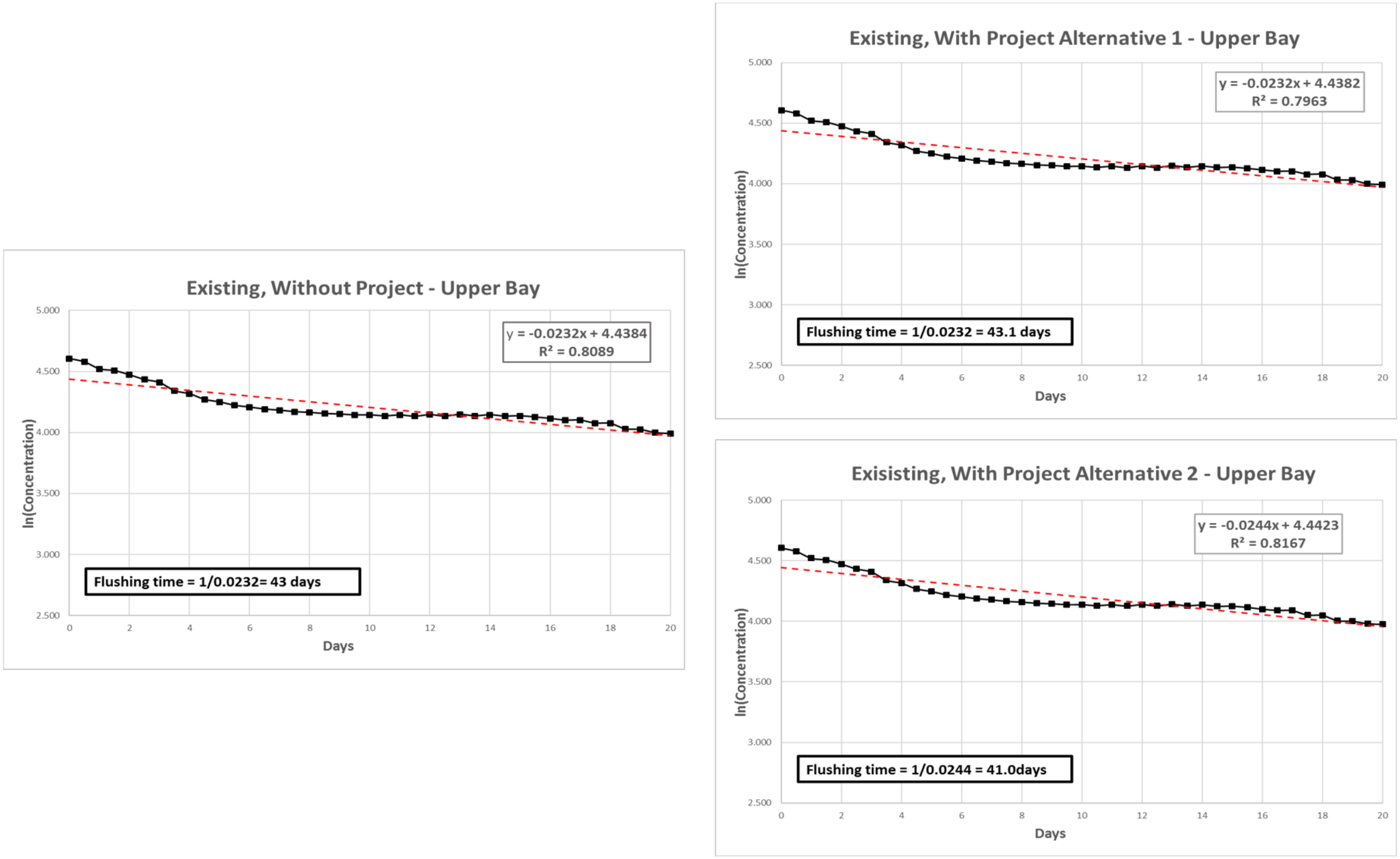


Figure 17 Existing Conditions: Upper Bay Region Flushing Time Analysis

4.1.2 Freshwater Age

The freshwater age was computed from the relative concentrations of a conservative and decaying tracer released at the most upstream freshwater source (Figure 8). After the concentrations reached a dynamic steady-state, they were tidally-averaged for every computational cell in the area of interest. Figure 18 plots spatial variation in the steady-state, tidal-averaged freshwater age for the *with* and *without Project* simulations. The freshwater age deviation is depicted in Figure 19.

Averaged over the Whole Bay, freshwater age is 10.3 days *without Project*, 10.4 days *with Project Alternative 1* (all six potential gates), and 10.1 days *with Project Alternative 2* (two central gates). Upper Bay water age was estimated at 3.3 days *without Project*, 3.2 days *with Project Alternative 1*, and 3.8 days *with Project Alternative 2*. These results indicate that water age is affected very little if at all by the Project under existing conditions.

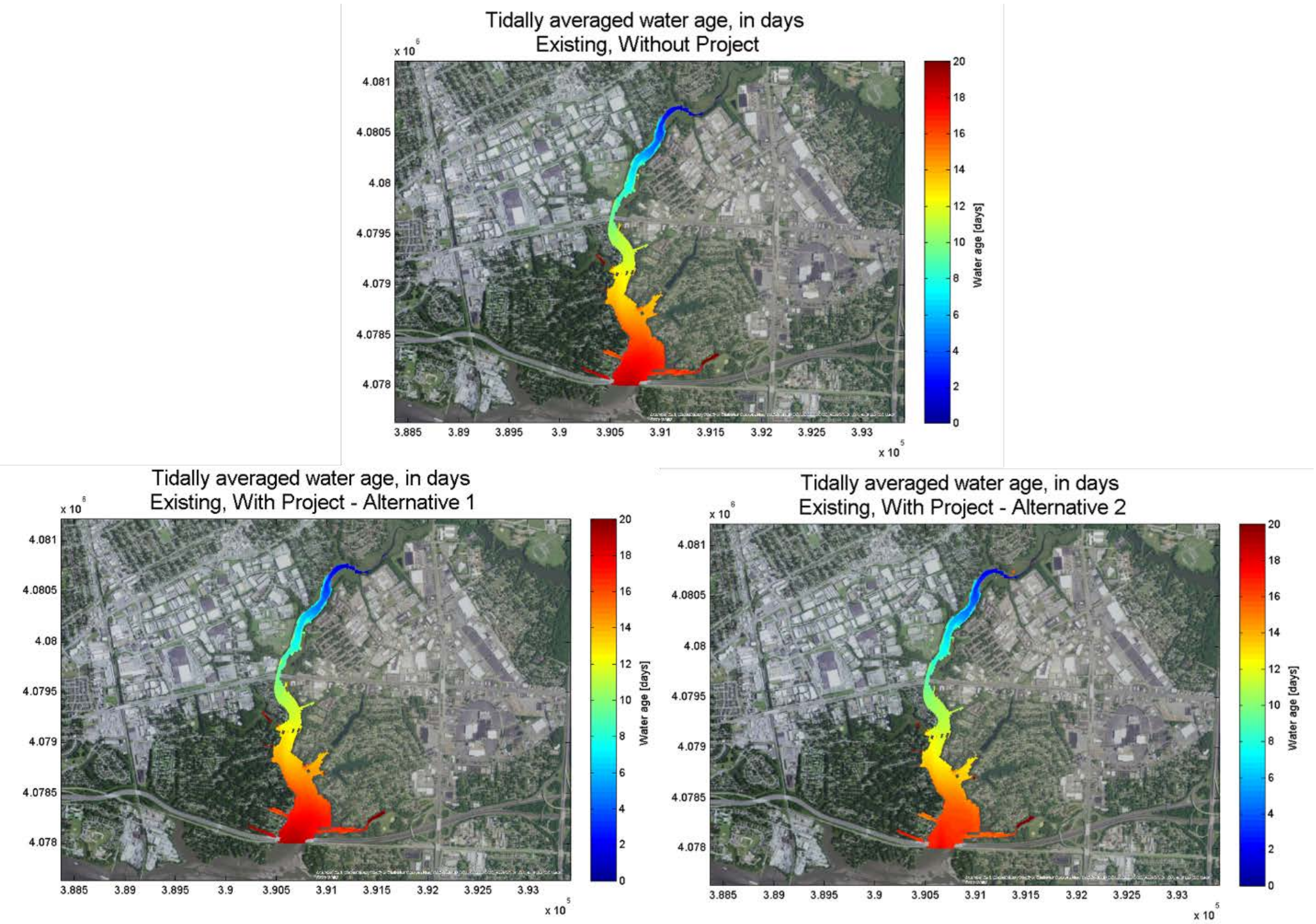


Figure 18 Existing Conditions: Steady State, tidal-averaged freshwater age for No project (*Top*), With Project-Alternative 1 (*Bottom Left*), and With Project-Alternative 2 (*Bottom Right*)

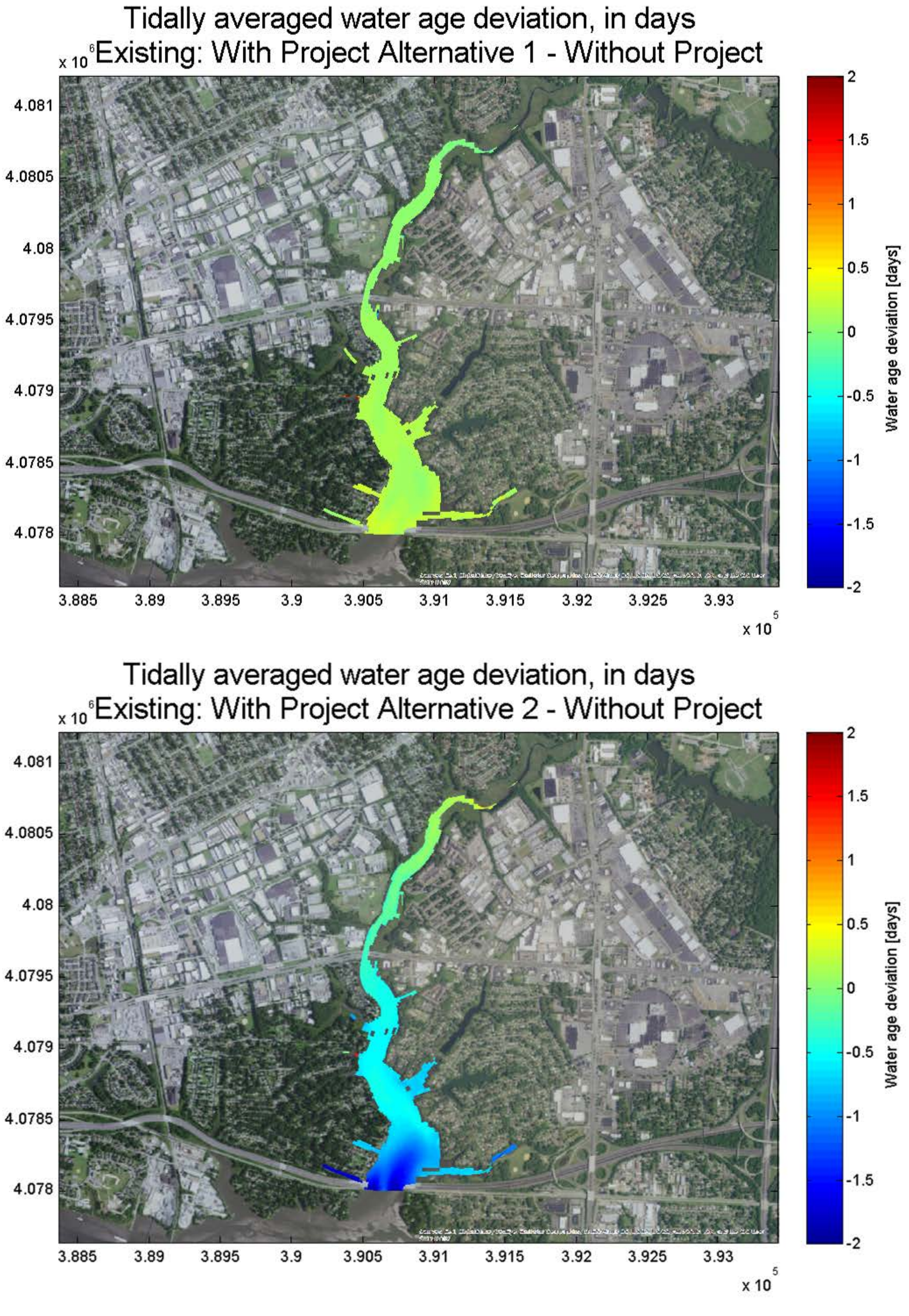


Figure 19 Existing Conditions Freshwater Age Deviation from Without Project: With Project Alternative 1 (*Top*) and With Project Alternative 2 (*Bottom*)

4.1.3 Salinity

Depth and tidal-averaged salinity was computed at each computational cell once salinity had reached a dynamic steady state. Figure 20 and Figure 21 present the spatial variation in the steady-state, tidal-averaged salinity for *with* and *without Project* simulations under existing conditions.

Small differences in the spatially averaged salinities are observed between simulation cases. Averaged over the whole bay the estimated salinity is 5.4 ppt for the *without Project* case, 5.2 ppt with *Alternative 1*, and 6.2 ppt with *Alternative 2*. Further from the structure, Upper Bay salinities were estimated at 1.6 ppt, 1.5 ppt, and 2.8 ppt, respectively. Although more obvious salinity deviations are observed between the *without Project* and two gates open (*Alternative 2*) cases, deviation values remain low (below 1 ppt) and can be considered negligible.

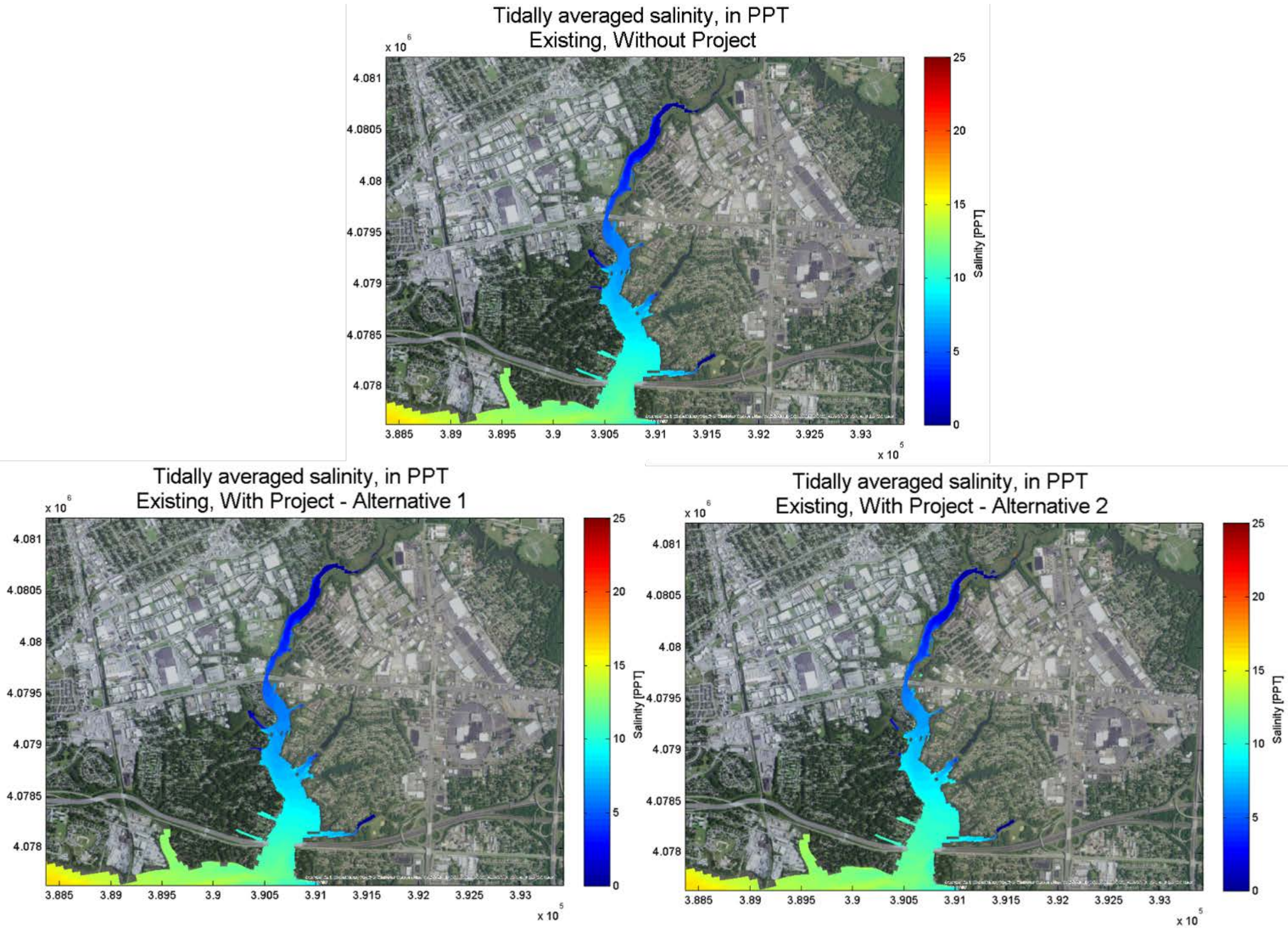


Figure 20 Existing Conditions: Steady State, tidal-averaged Salinity for No project (*Top*), With Project-Alternative 1 (*Bottom Left*), and With Project-Alternative 2 (*Bottom Right*)

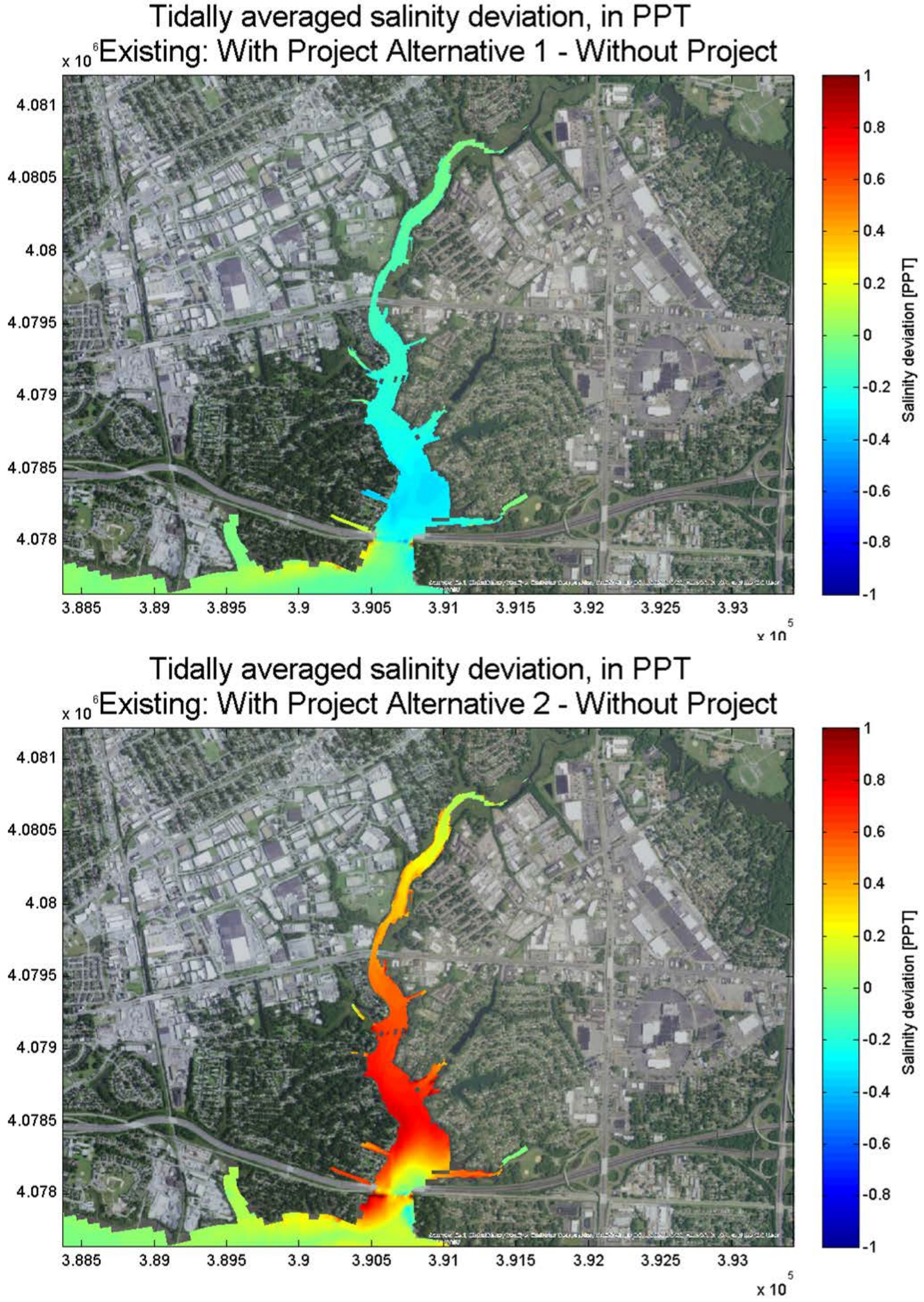


Figure 21 Existing Condition Salinity Deviation from Without Project: With Project Alternative 1 (*Top*) and With Project Alternative 2 (*Bottom*)

4.2 FUTURE CONDITIONS RESULTS

4.2.1 Flushing Time

Figure 22 plots the spatially-averaged tracer concentration through time for the Whole Bay and Upper Bay regions of Broad Creek. The figure shows that tracer concentrations under future conditions decrease more rapidly than under existing conditions.

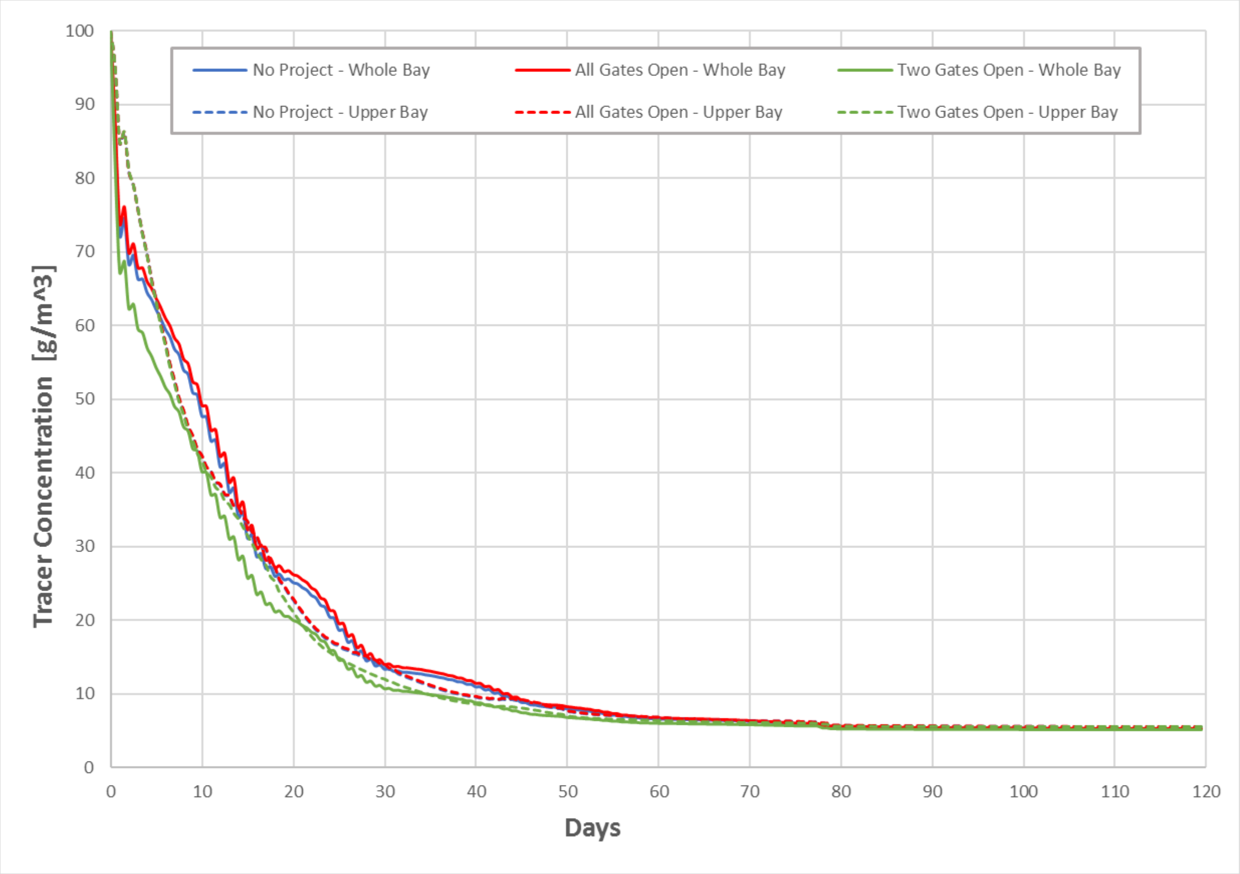


Figure 22 Future Conditions: Spatially-Averaged Tracer Concentration Over Time in the Whole Bay and Upper Bay Regions of Broad Creek

Flushing times were derived as described in Section 4.1.1. Linear regression plots are presented in Figure 23 and Figure 24. Flushing times are reduced when compared to existing conditions. Without the flood control structure, Whole Bay flushing time is estimated at 15.7 days. With all of the structure gates open, the flushing time is estimated at 16.0 days, and for only two of the gates open the flushing time is 14.0 days. Upper Bay flushing was estimated at 14.5 days for the *without Project* and *with Project – Alternative 1*, and at 13.6 days for the *with Project –Alternative 2 case*. The project is expected to have very minor to no impacts on bay flushing times.

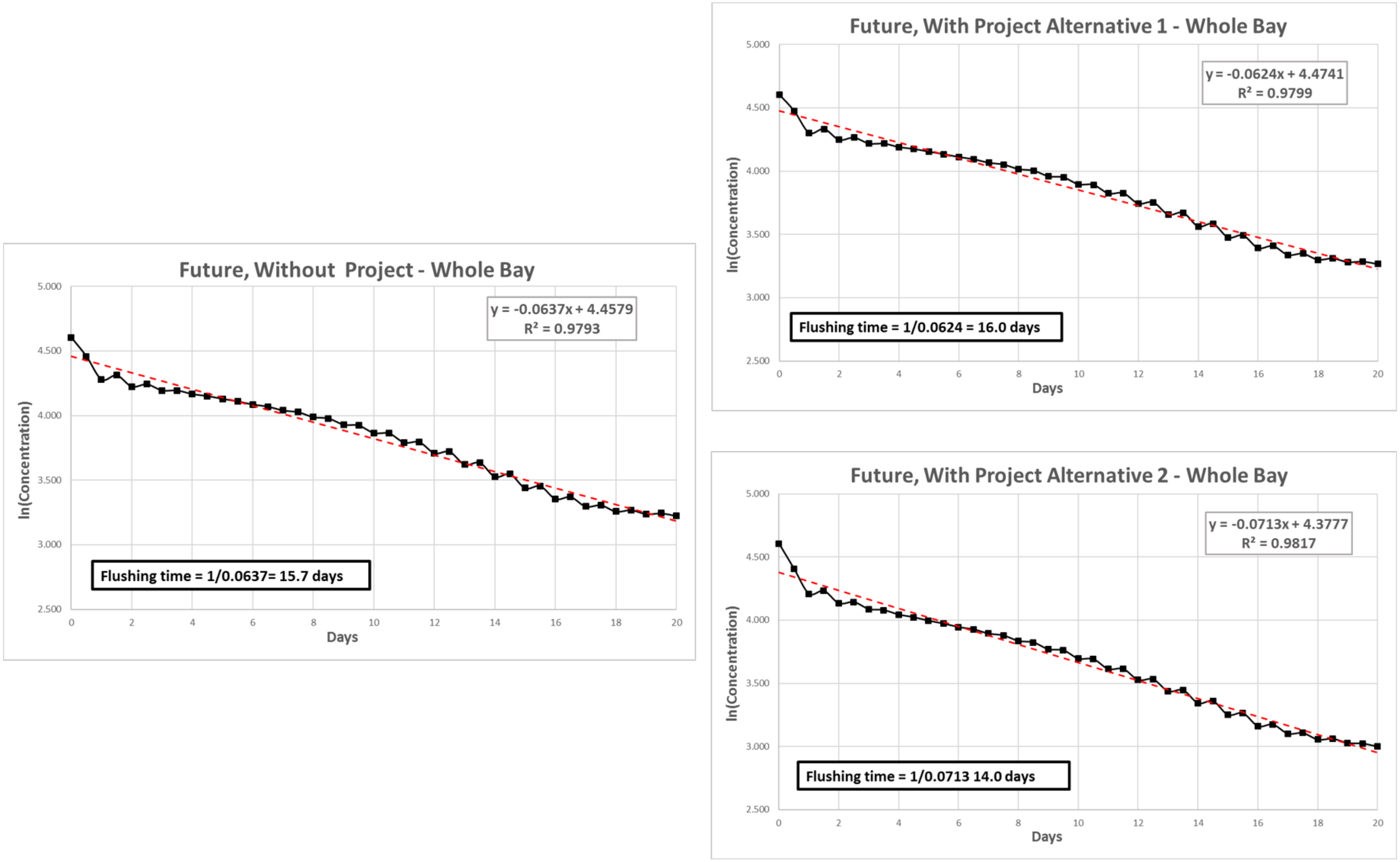


Figure 23 Future Conditions: Whole Bay Region Flushing Time Analysis

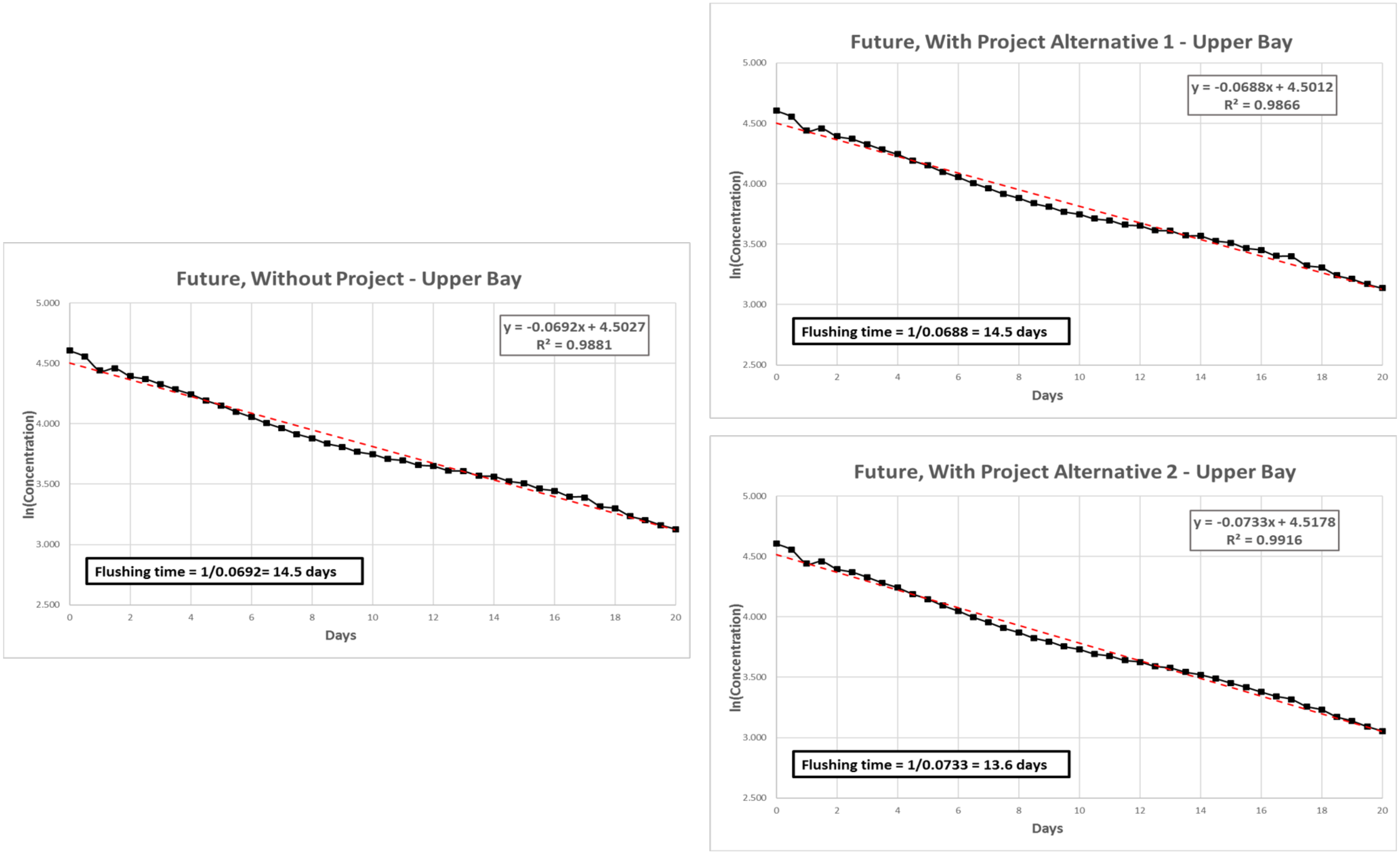


Figure 24 Future Conditions: Upper Bay Region Flushing Time Analysis

4.2.2 Freshwater Age

Compared to existing conditions (present day) simulations, a general increase in water age in Broad Creek is observed in future conditions simulations, as shown in Figure 25Figure 23 and Figure 26. Averaged over the Whole Bay, freshwater age is 16.8 days *without Project*, 17.0 days *with Project Alternative 1* and 15.7 days *with Project Alternative 2*. Upper Bay water age was estimated at 9.3 days *without Project*, 9.4 days *with Project Alternative 1*, and 8.9 days *with Project Alternative 2.* The conclusion is similar between existing and future conditions: little to very minor impacts on freshwater age are expected from the Project.

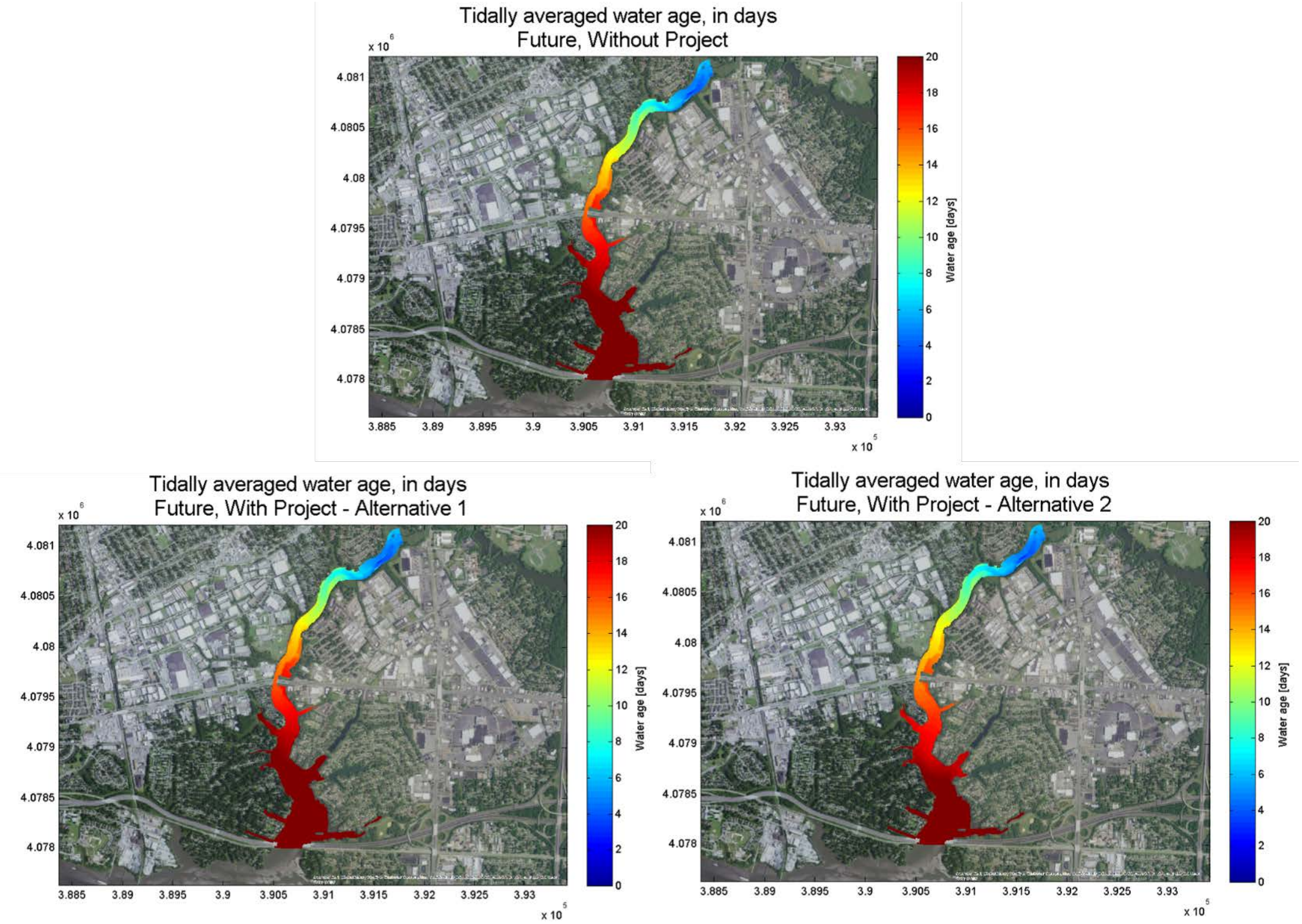
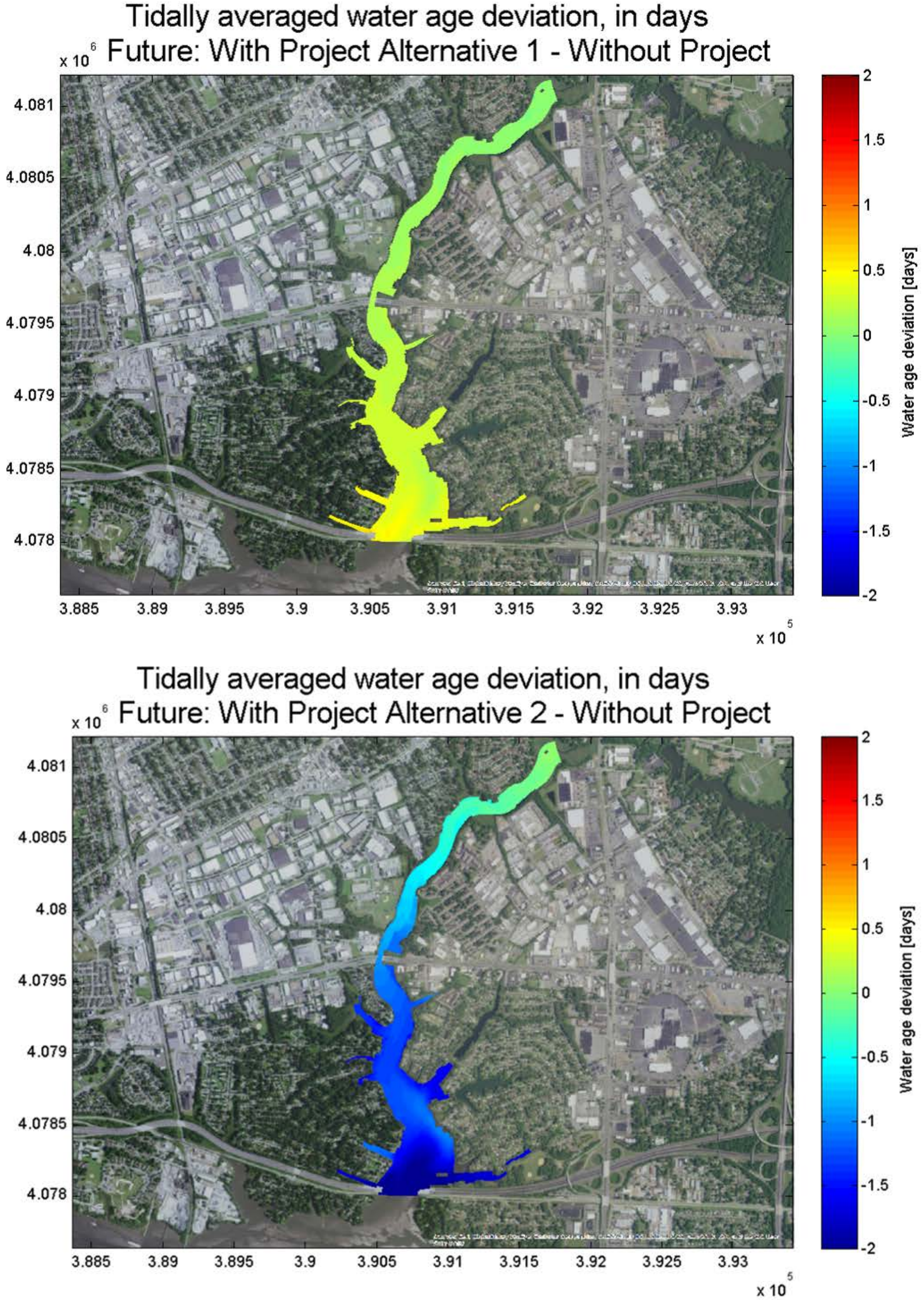


Figure 25 Future Conditions: Existing Conditions: Steady State, tidal-averaged freshwater age for No project (*Top*), With Project-Alternative 1 (*Bottom Left*), and With Project-Alternative 2 (*Bottom Right*)



Tidally averaged water age deviation, in days
Future: With Project Alternative 1 - Without Project

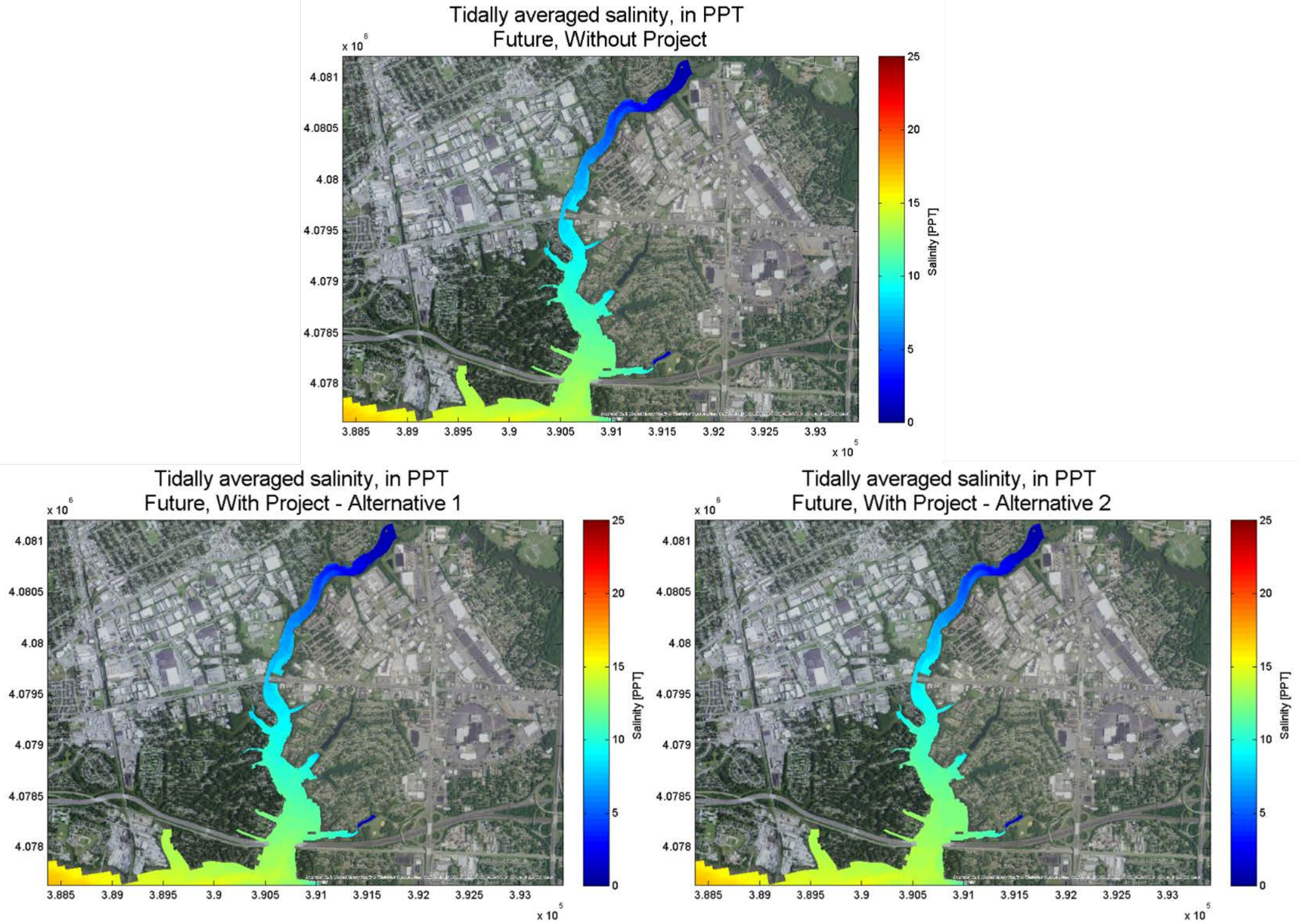
Tidally averaged water age deviation, in days
Future: With Project Alternative 2 - Without Project

Figure 26 Future Conditions Freshwater Age Deviation from Without Project: With Project Alternative 1 (*Top*) and With Project Alternative 2 (*Bottom*)

4.2.3 Salinity

Figure 27 and Figure 28 present the spatial variation in the steady-state, tidal-averaged salinity for *with* and *without Project* simulations under future conditions. A slight increase in salinity values is also observed with respect to the existing conditions cases.

Averaged salinities in the Whole Bay are estimated to be 8.4 ppt, 8.2 ppt, and 8.8 ppt *without Project*, *with Project Alternative 1*, and *with Project Alternative 2* scenarios, respectively. Upper Bay region averaged salinities are 4.5 ppt, 4.3 ppt, and 4.8 ppt respectively.



Tidally averaged salinity, in PPT
Future, Without Project

Tidally averaged salinity, in PPT
Future, With Project - Alternative 1

Tidally averaged salinity, in PPT
Future, With Project - Alternative 2

Figure 27 Future Conditions: Steady State Salinity for No project (*Top*), With Project-Alternative 1 (*Bottom Left*), and With Project-Alternative 2 (*Bottom Right*)

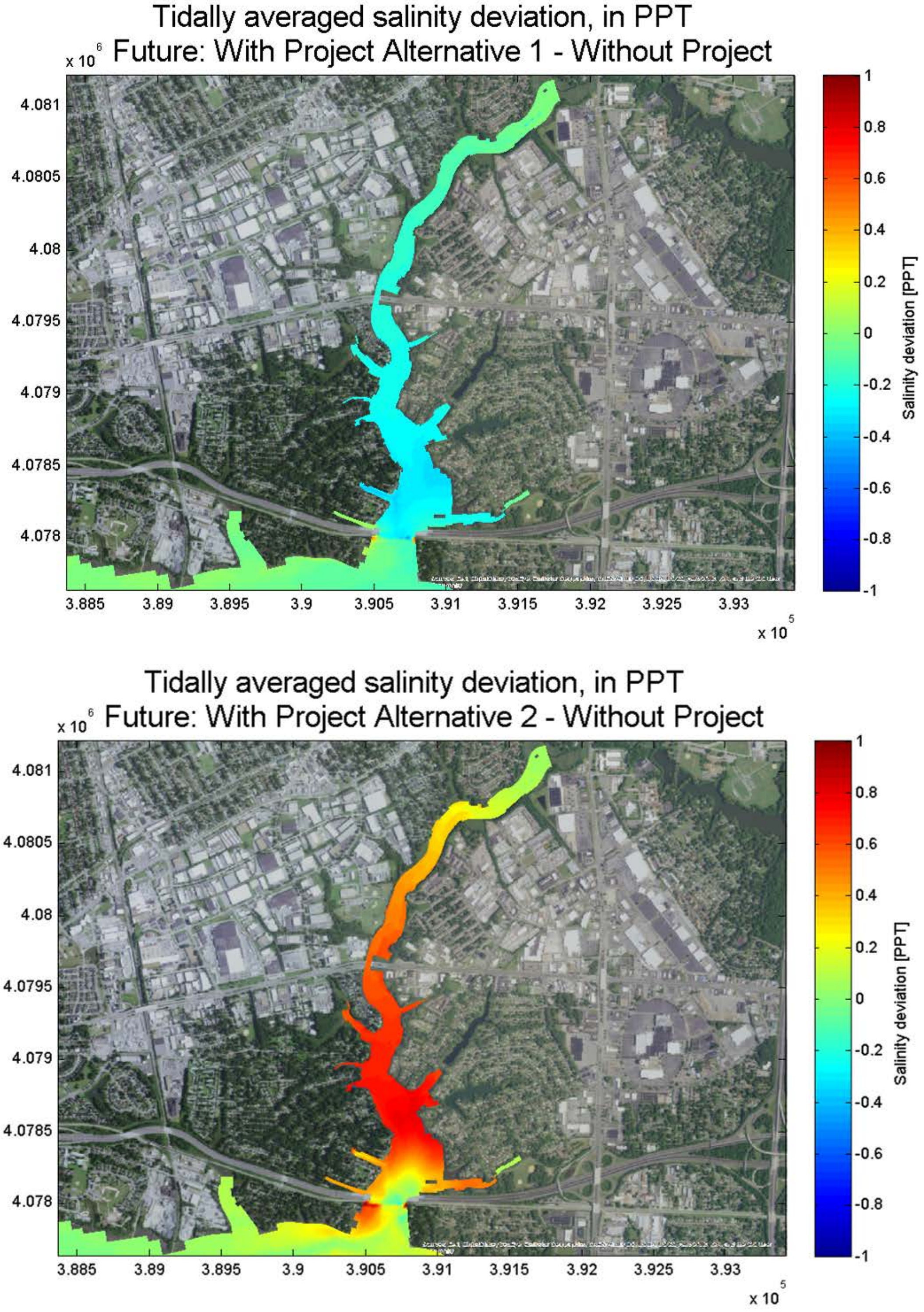


Figure 28 Future Condition Salinity Deviation from Without Project: With Project Alternative 1 (*Top*) and With Project Alternative 2 (*Bottom*)

4.2.4 Effects of Project on Flow Velocities

Results presented above indicate minor Project impacts on water quality parameters. As noted, *with Project Alternative 2* scenarios, present a trend of lower flushing time and freshwater age. This can be explained by looking at flow velocities at the gate alignment. While the same amount of flow is exchanged in and out of the bay, less flow area due to fewer gate openings results in higher entrance and exit velocities. Increased velocities induce secondary circulation patterns, and create a mechanism for enhanced mixing, thus slightly reducing flushing times and freshwater age.

Figure 29 and Figure 30 show depth averaged velocities at Peak Ebb and Flood for *with* and *without Project* scenarios under existing conditions. Flow velocities are significantly increased for the narrowest area of flow exchange (i.e. the *with Project Alternative 2* case). Similar response is expected under future conditions.

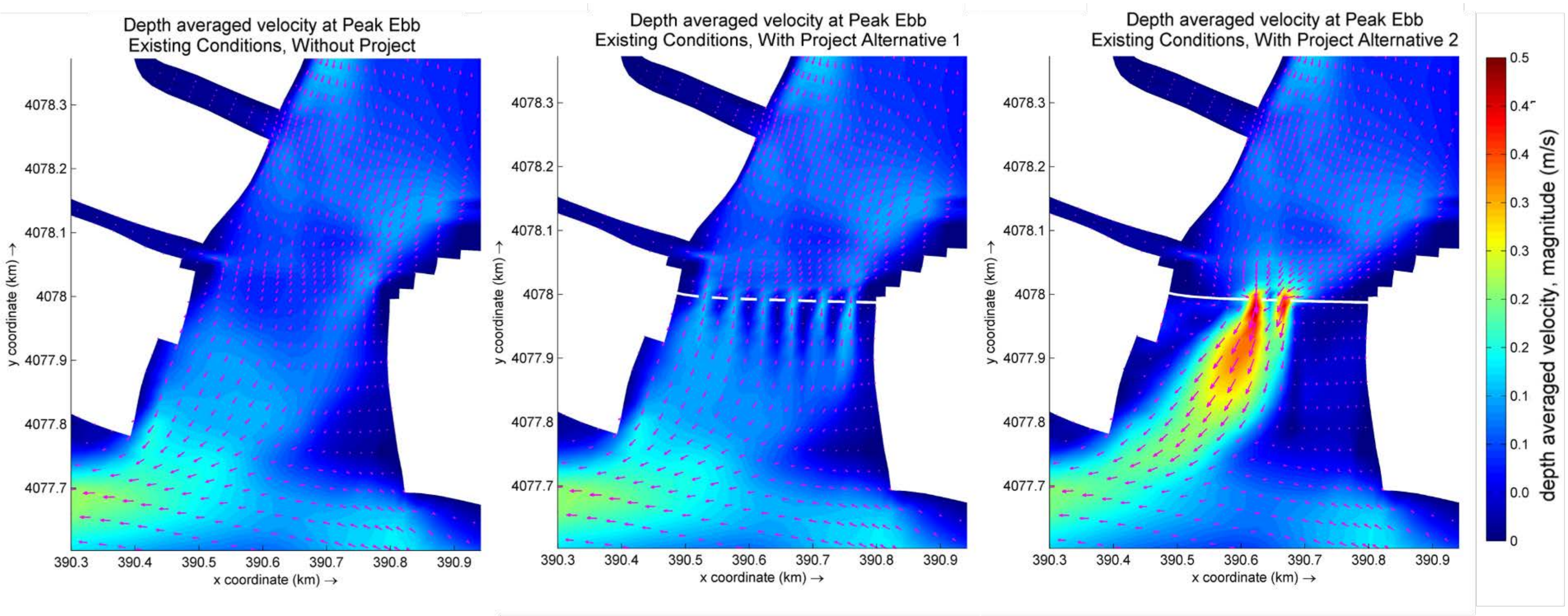


Figure 29 Depth Averaged Velocity at Peak Ebb for the Without Project (*Left*), With Project – Alternative 1 (*Center*), and With Project Alternative 2 (*Right*) simulations Under Existing Conditions

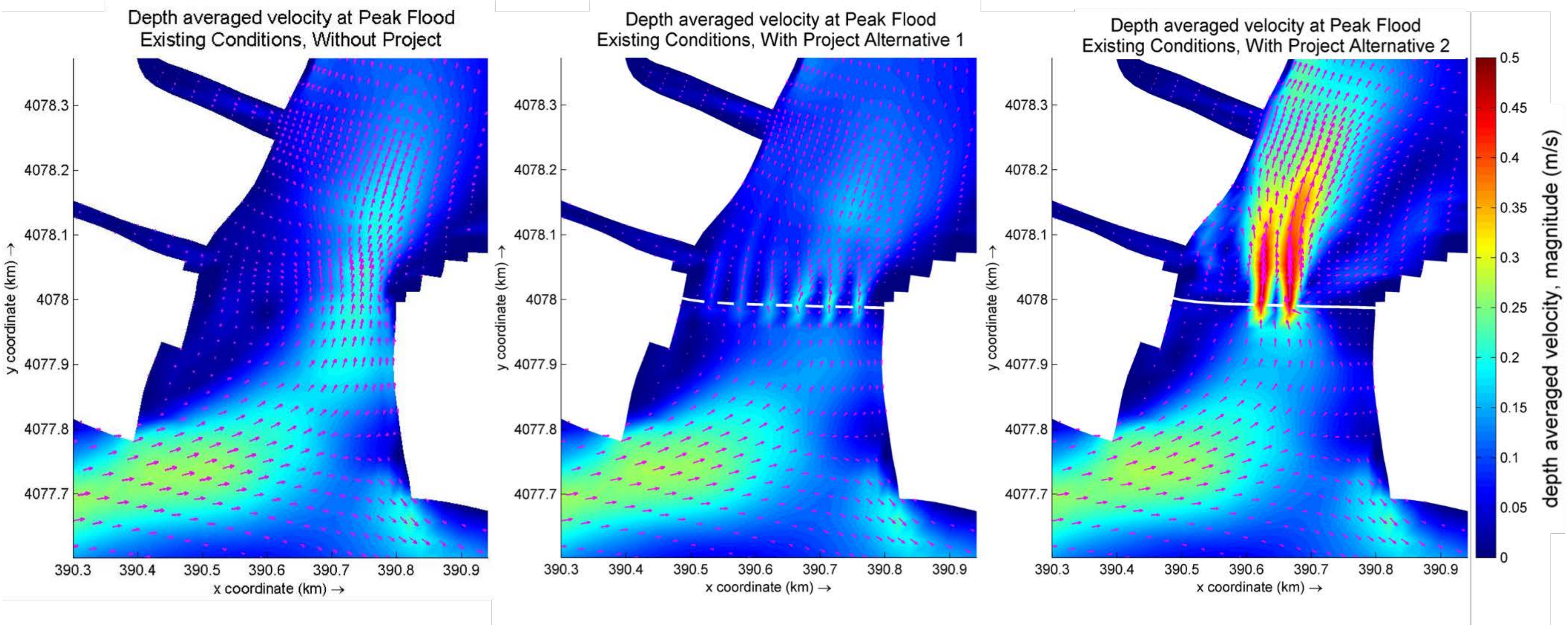


Figure 30 Depth Averaged Velocity at Peak Flood for the Without Project (*Left*), With Project – Alternative 1 (*Center*), and With Project Alternative 2 (*Right*) simulations Under Existing Conditions

4.3 SUMMARY

A summary of the findings in the typical late-summer conditions simulations is provided in Table 1. The estimated values for flushing time, freshwater age and salinity indicate negligible Project impacts on water quality under typical hydrodynamic conditions.

Table 1 Typical Conditions Simulation Results Summary

Scenario	Whole Bay			Upper Bay		
	Flushing Time (days)	Freshwater Age (days)	Salinity (ppt)	Flushing Time (days)	Freshwater Age (days)	Salinity (ppt)
Existing condition without project	22.2	10.3	5.4	43	3.3	1.6
Existing condition with project Alternative 1	22.3	10.4	5.2	43.1	3.2	1.5
Existing condition with project Alternative 21	21.7	10.1	6.2	41.0	3.8	2.8
Future condition without project	15.7	16.8	8.4	14.5	9.3	4.5
Future condition with project Alternative 1	16.0	17.0	8.2	14.5	9.4	4.4
Future condition with project Alternative 2	14.0	15.7	8.8	13.6	8.9	4.8

5 POST-STORM RECOVERY RESULTS

To evaluate post-storm recovery, time series of freshwater tracer concentrations and salinity at four locations upstream of the proposed flood control structure are presented in the following sections. Figure 31 depicts the location of the monitoring stations.

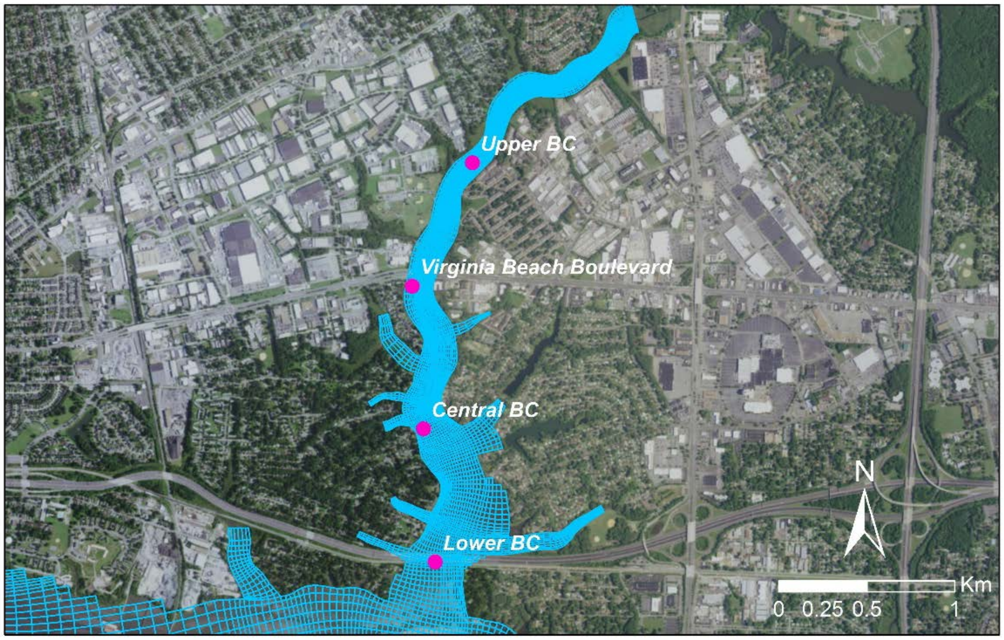


Figure 31 Monitoring Stations for Water Quality Evaluation

5.1 EXISTING CONDITIONS RESULTS

Depth averaged freshwater tracer concentrations and salinity are plotted through time in Figure 32 through Figure 35. Time *zero* in the plots corresponds to the time when the gates are re-opened for the *with Project* simulations. As stated previously, time zero for the simulation occurs when the storm runoff hydrograph commences.

With Project, and prior to gate re-opening, freshwater tracer concentrations exhibit higher values in the upstream area (Upper BC and Virginia Beach Boulevard stations), which is more influenced by runoff sources. For the *without Project* scenario, the non-interrupted flow exchange with the Elizabeth River system results in flushing of the freshwater tracers during the storm period, consequently exhibiting lower concentrations through time, when compared to the *with Project* scenarios.

After the gates re-open, conservative tracer concentrations for both the *with Project* scenarios are about the same and greater than those *without Project*, but eventually (i.e., after about 20 days in upstream stations) decrease to similar values of *without Project* concentrations. For the more downstream stations, conservative tracer concentrations reach the same low levels sooner. Flushing of the decaying tracers practically occurs at the same rate for the *with* and *without Project* scenarios at all stations.

The freshwater conservative tracer is almost completely flushed out after 30 days or less of gate re-opening for all simulated scenarios at all stations, while the decaying tracer has decayed and flushed after about 5 days or less.

In upstream stations (Upper BC and Virginia Beach Boulevard), an approximate period of 10 days after gate re-opening is required for salinity values in the *with Project* scenarios to coincide with those in the *without Project* scenario. Salinity coincidence occurs much faster for the downstream stations (almost immediately after gate re-opening for the Lower BC station). Steady-state, pre-storm salinity conditions are restored after an approximate period of 25 days for all scenarios and all stations.

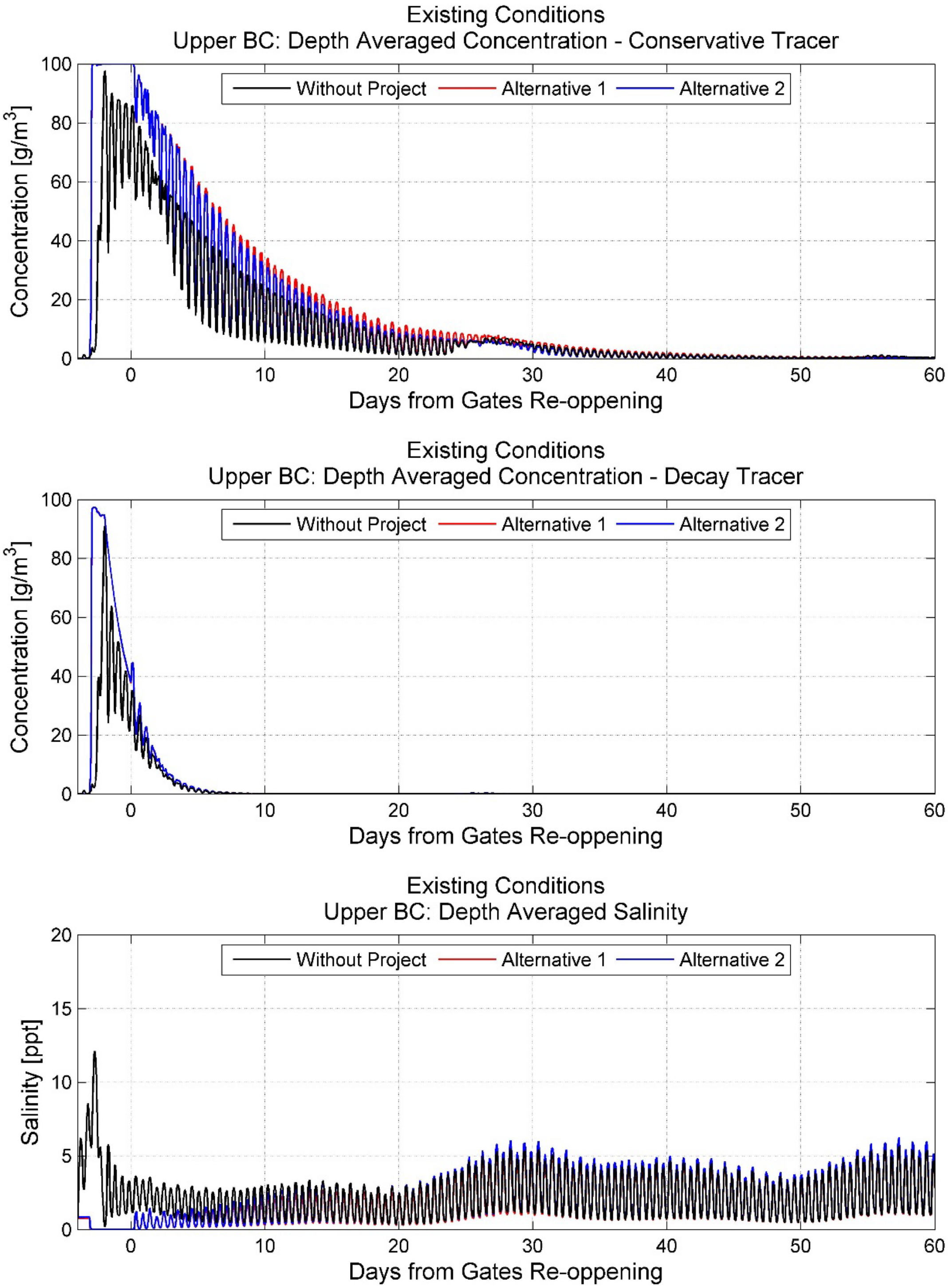


Figure 32 Existing Conditions: Depth Averaged Tracer Concentrations and Salinity at Upper BC Station

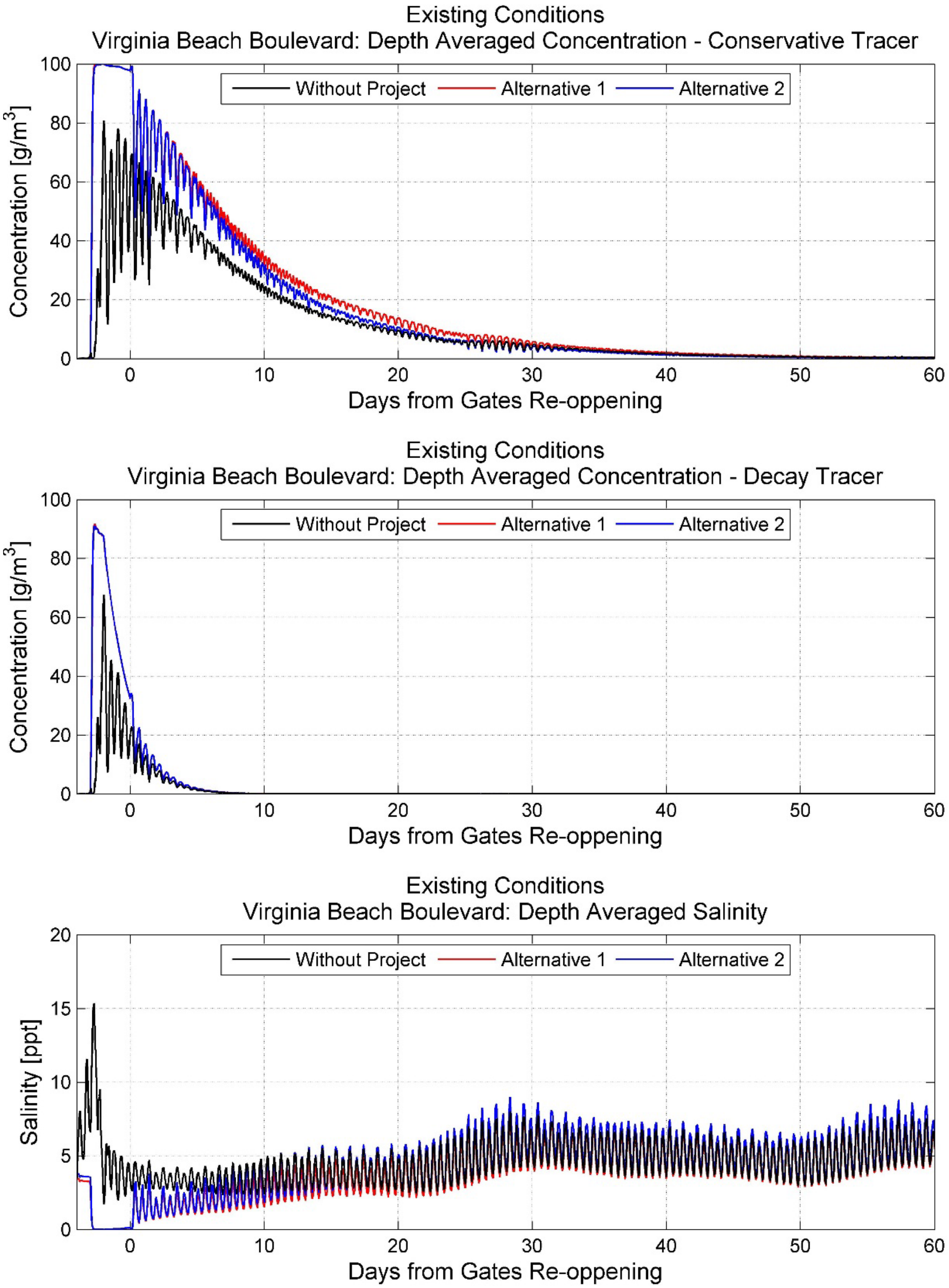
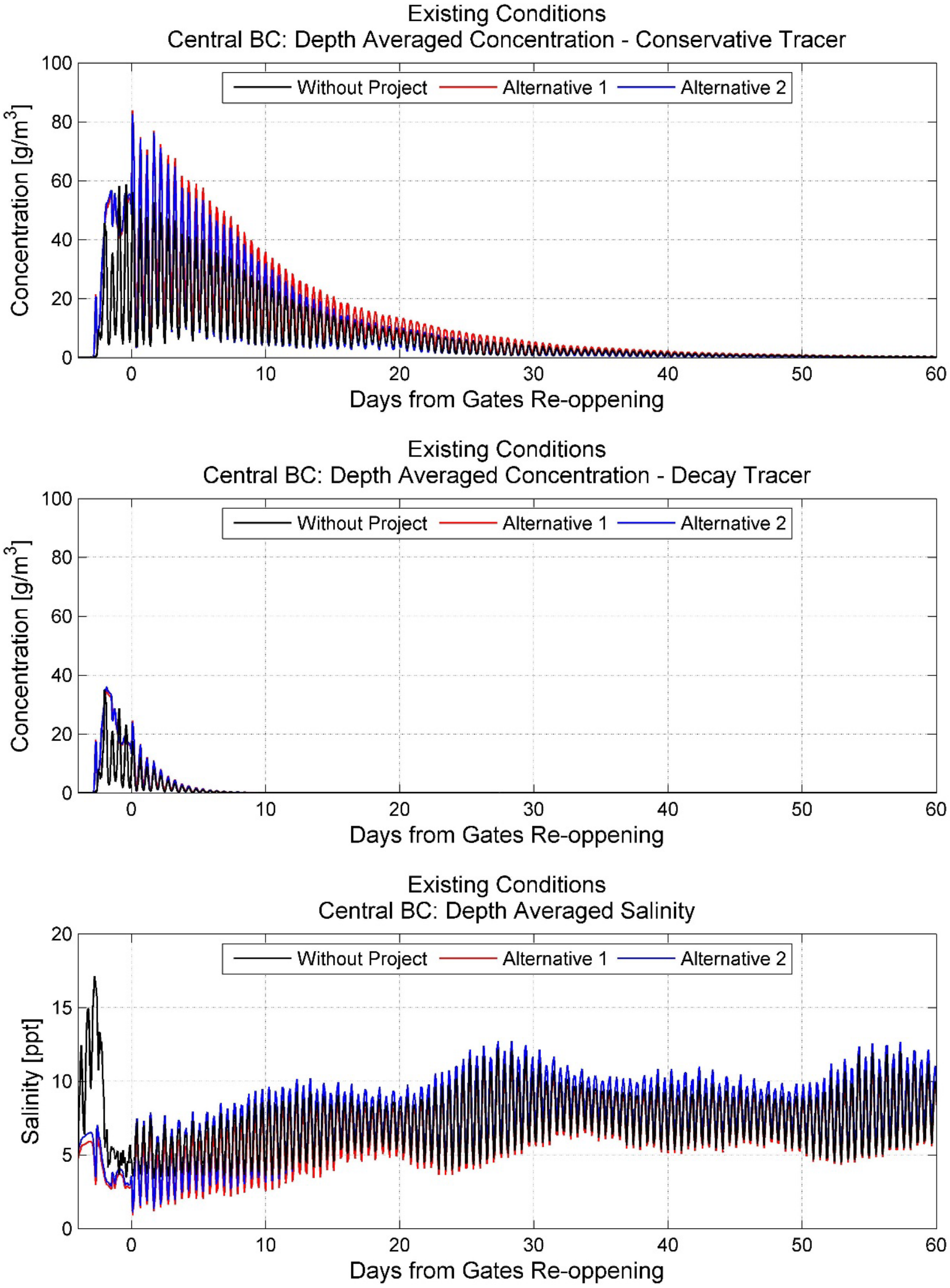


Figure 33 Existing Conditions: Depth Averaged Tracer Concentrations and Salinity at Virginia Beach Boulevard Station



Existing Conditions
Central BC: Depth Averaged Concentration - Conservative Tracer

Existing Conditions
Central BC: Depth Averaged Concentration - Decay Tracer

Existing Conditions
Central BC: Depth Averaged Salinity

Figure 34 Existing Conditions: Depth Averaged Tracer Concentrations and Salinity at Central BC Station

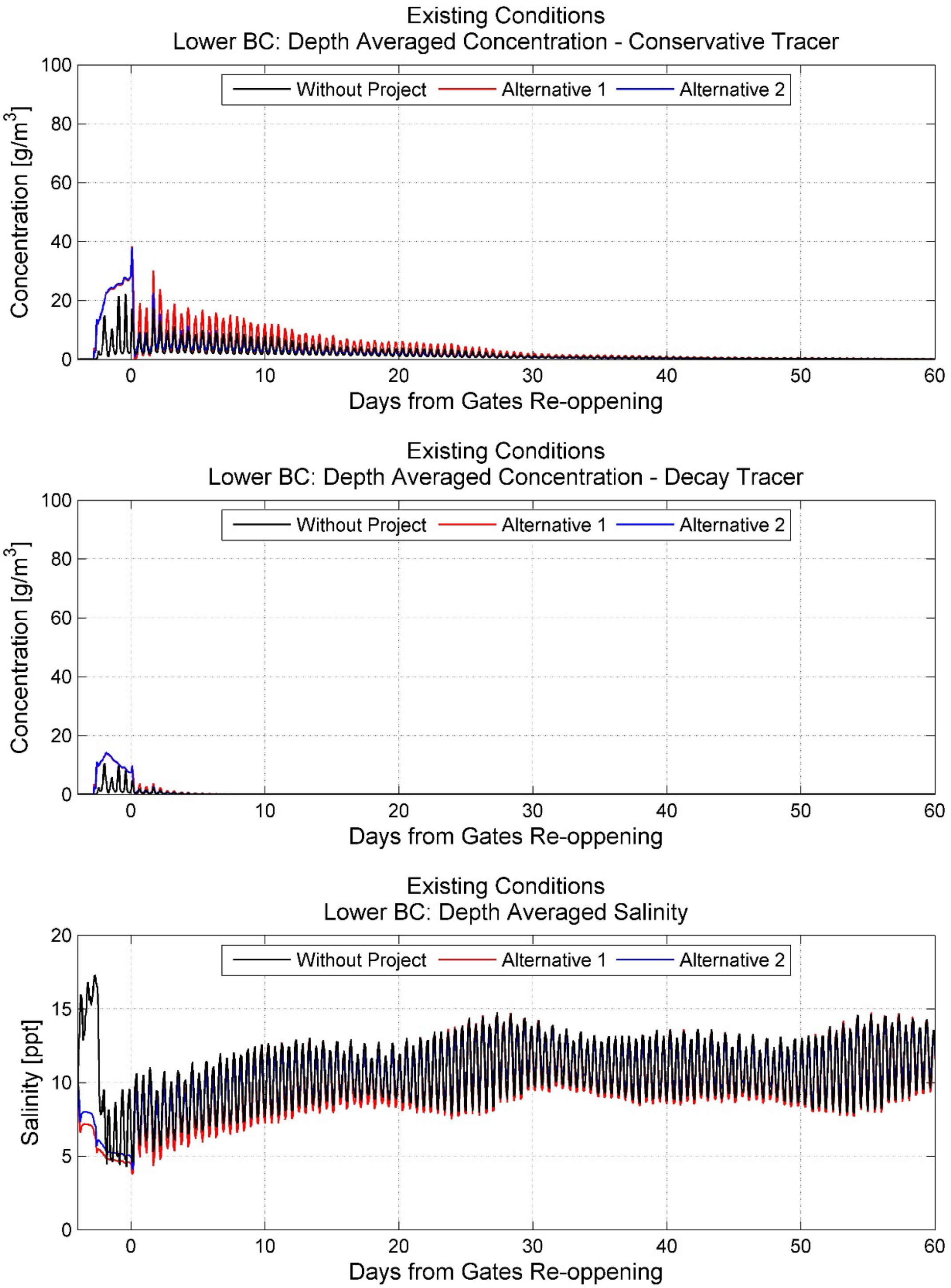


Figure 35 Existing Conditions: Depth Averaged Tracer Concentrations and Salinity at Lower BC Station

5.2 FUTURE CONDITIONS RESULTS

Under future conditions, the larger flow exchange in the bay with the Elizabeth River system, resulting from increased sea levels, is reflected in the higher deviation of tracer concentrations and salinity between the *with* and *without Project* scenarios at the moment of gate re-opening (Figure 36 through Figure 39), when compared to existing conditions.

Similar conclusions can be drawn for the flushing time response between the *with* and *without Project* scenarios, when compared to existing conditions. The time required for the conservative tracer to be almost completely flushed out of the bay is increased some (by about 10 days) for all stations and all future conditions scenarios due to the greater water volumes associated with higher water levels.

Response in salinity between the *with* and *without Project* scenarios is also similar to that observed under existing conditions.

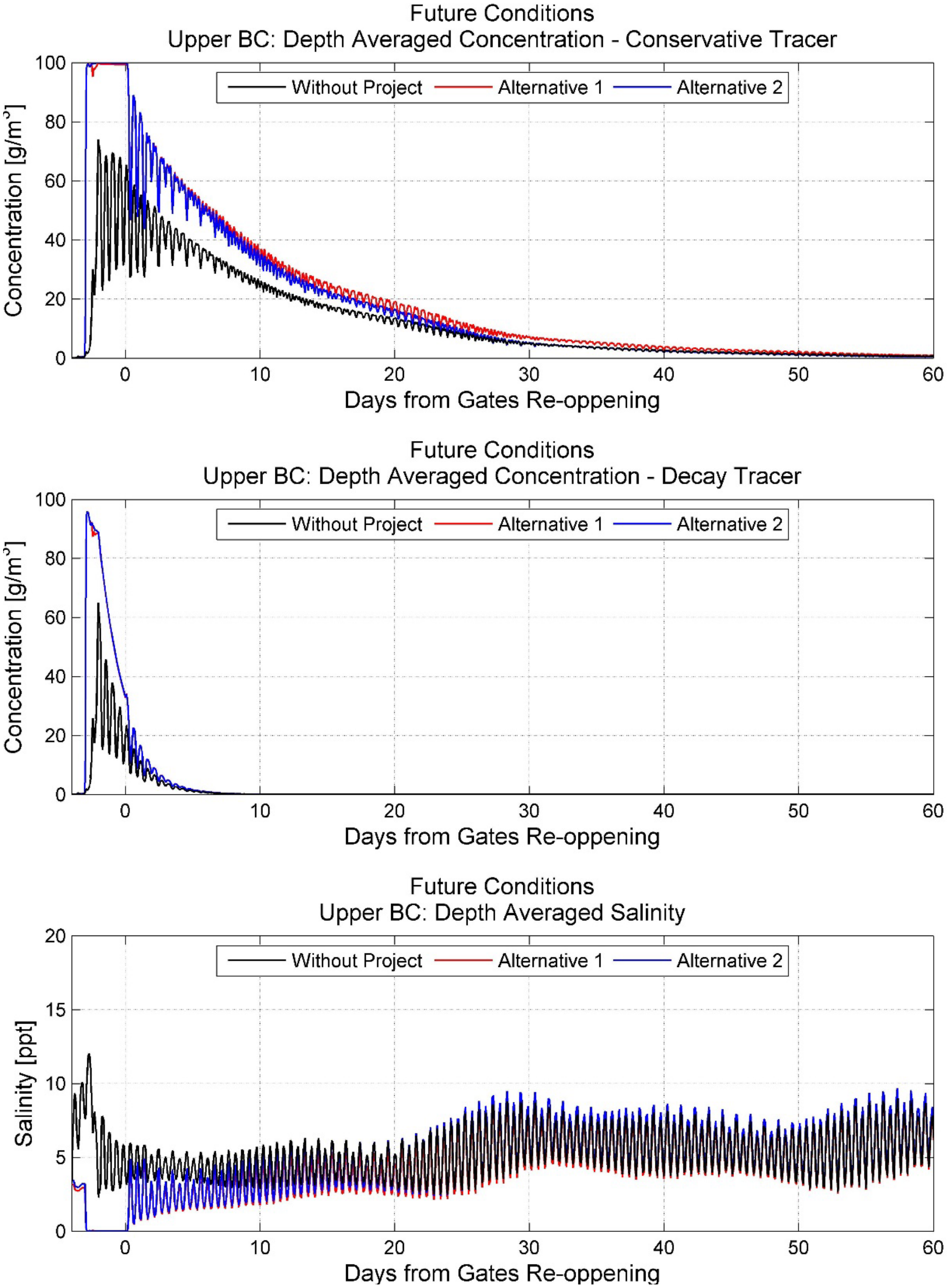


Figure 36 Future Conditions: Depth Averaged Tracer Concentrations and Salinity at Upper BC Station

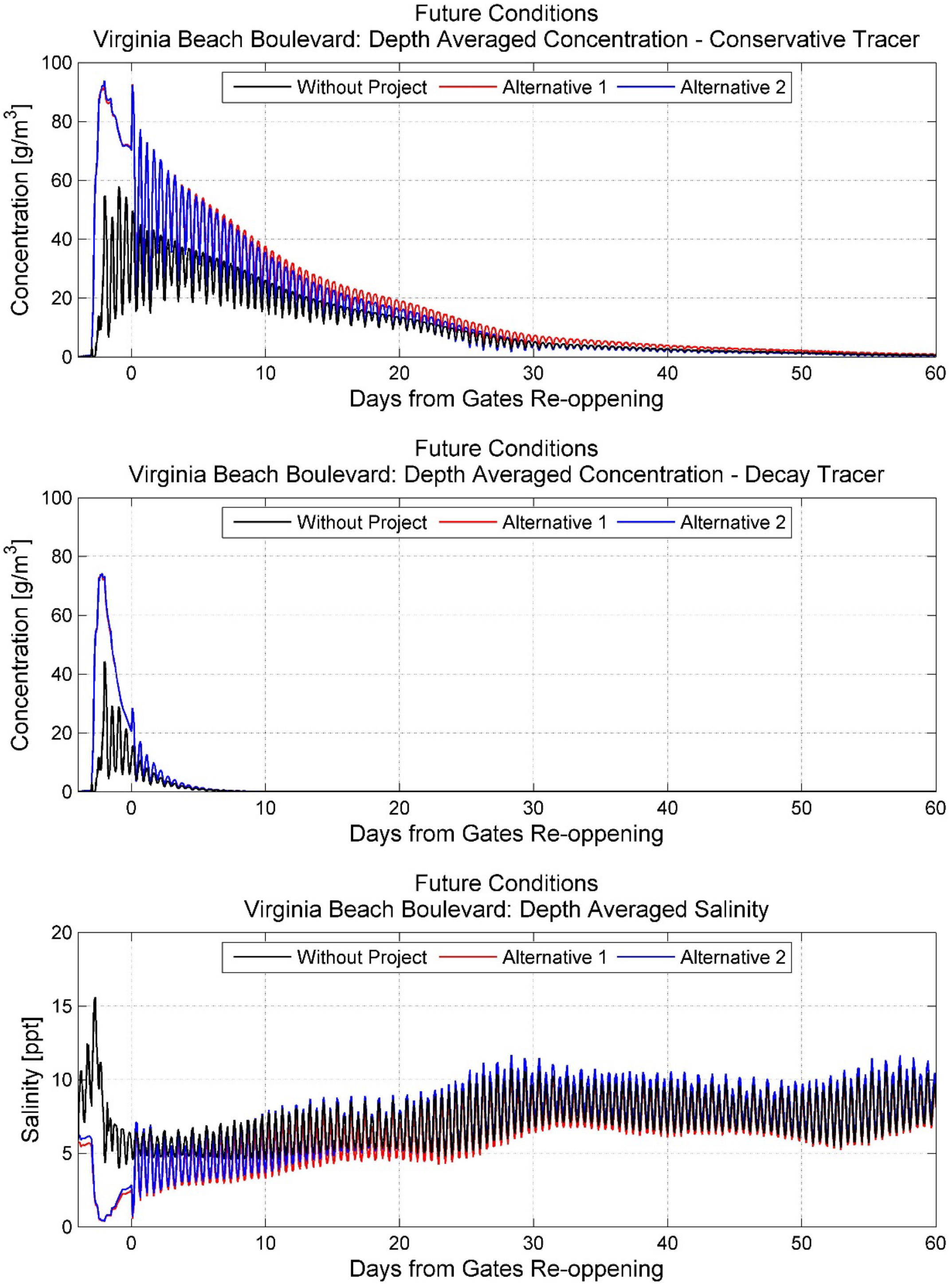


Figure 37 Future Conditions: Depth Averaged Tracer Concentrations and Salinity at Virginia Beach Boulevard Station

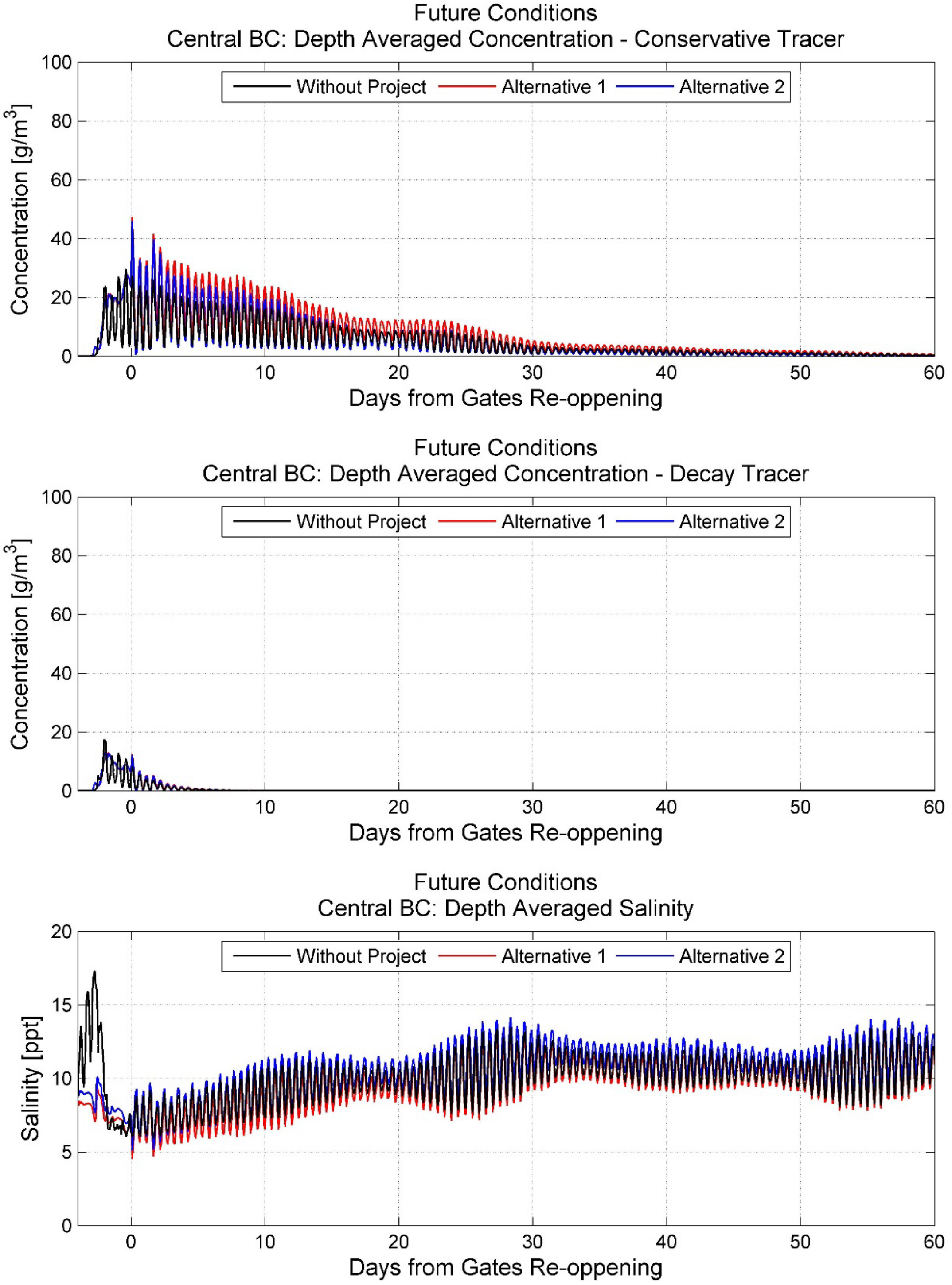
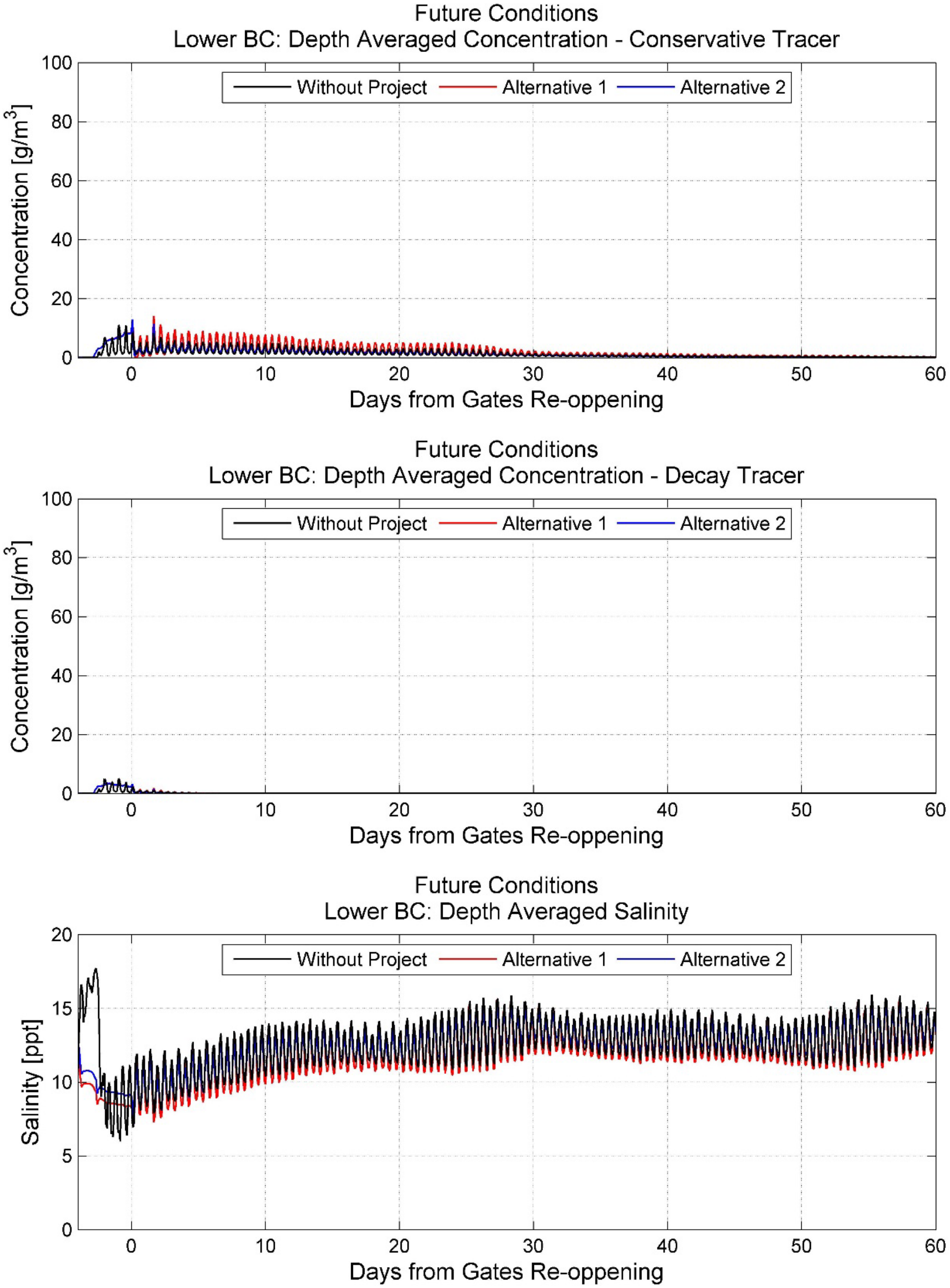


Figure 38 Future Conditions: Depth Averaged Tracer Concentrations and Salinity at Central BC Station



Future Conditions
Lower BC: Depth Averaged Concentration - Conservative Tracer

Future Conditions
Lower BC: Depth Averaged Concentration - Decay Tracer

Future Conditions
Lower BC: Depth Averaged Salinity

Figure 39 Future Conditions: Depth Averaged Tracer Concentrations and Salinity at Lower BC Station

5.3 SUMMARY

Results provided above suggest minor Project impacts on water quality recovery time after gate closure during storms and following re-opening. In summary:

- Recovery time decreases from upstream to downstream stations.
- Conservative tracer concentrations *with Project* are higher during and immediately following gate re-opening, but decline to *without Project* concentrations with 20 days (or less in downstream stations).
- All decaying tracer concentrations are gone in 5 days or less for all stations and all scenarios.
- Salinity for *with Project* coincides with salinity for *without Project* after about 10 days (or less in downstream stations).
- Salinity recovers to pre-storm conditions after about 25 days for all conditions and all stations.