moffatt & nichol

800 World Trade Center
Norfolk, VA 23510

(757) 628-8222 Fax (757) 628-8244
www.moffattnichol.com

MEMORANDUM

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

From: Zhanxian Wang, Kevin Hanegan, and Brian Joyner

Date: August 03, 2017

Subject: Preliminary Water Quality Assessment Results – Pretty Lake

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 Pretty Lake without explicitly modeling important water quality constituents and processes. Instead, hydrodynamic results are analyzed to determine CSRM project impacts to salinities, flushing, and 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

The Delft3D model development for Pretty Lake was discussed in details in a previous submitted memo titled as "Pretty Lake Delft3D Model Development and Calibration", thus it will not be repeated here. The model grid and bathymetry for the existing condition are presented in Figure 1 and Figure 2, respectively. For the 3D modeling in this study, the sigma-model with six uniform layers was applied in the vertical direction. Physical processes included in the study are: tide/surge, wind, salinity, conservative and non-conservative constituents (called "tracer" hereafter). Due to lack of salinity data within Pretty Lake model domain, the model was only calibrated to water level measurements.

Figure 1 Computational grid for the Pretty Lake model

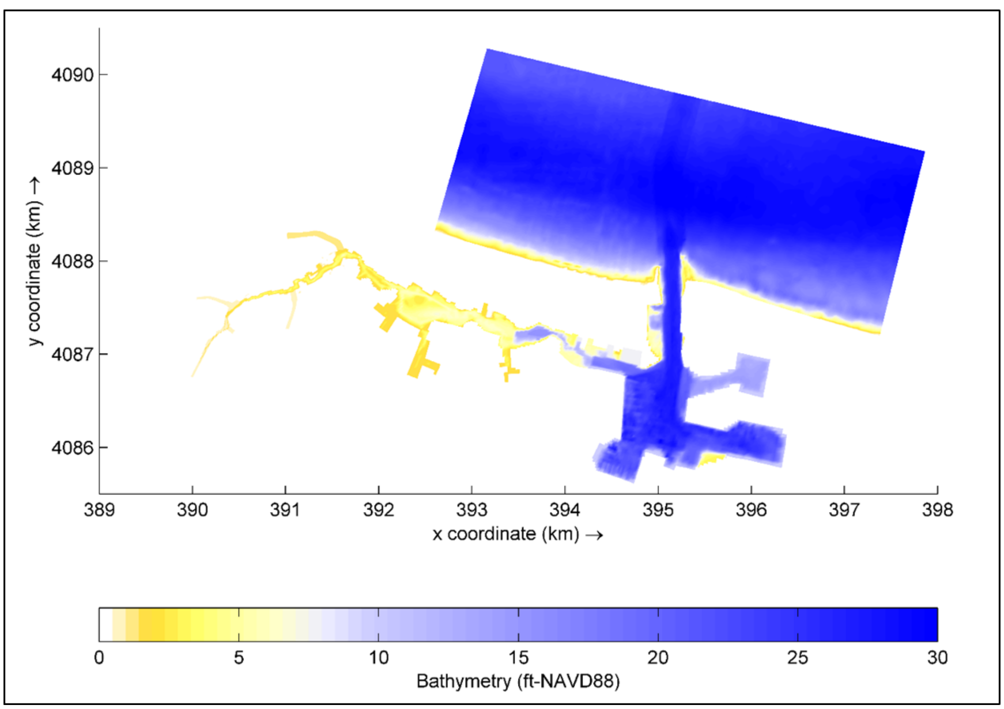


Figure 2 Model bathymetry

3 WATER QUALITY ANALYSIS SETUP

3.1 INTRODUCTION

Potential impacts of the proposed flood control structure (Project) to circulation and water quality in Pretty Lake 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.

3.2 METHODOLOGY

3.2.1 Typical Average Late Summer Conditions

M&N is assessing potential project impacts to water quality for the long-term average condition 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 within interested areas. Model boundary conditions are set up such that the hydrodynamics, salinity, and tracer concentrations reach 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 and lower 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 flushing out.

- **Salinity**: Salinity reached a dynamic steady-state, which means it will vary 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, lower 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 are 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 were produced allowing comparison among scenarios. Additionally, tidal-averaged freshwater age was averaged spatially over specific regions (e.g., entire bay, upper bay, lower bay, etc.). The tidal- and spatial-averaged freshwater age was compared 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 such 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 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 were 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 trough time, therefore freshwater age cannot be derived. Instead, tracer concentrations were tracked over time at relevant locations.

- **Salinity**: Time series of output salinity were 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:

- **No project case (*without Project*)**: Simulations without the proposed flood control structure were carried out to establish the base condition for the evaluation of Project

- ***With Project***: These simulations evaluate permanent Project impacts by incorporating the proposed flood control structure to the computational grid. The structure's single operable gate is open during the late-summer conditions and is operated as necessary during the post-storm recovery simulations.

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. A sill elevation of -8 feet (2.4 m) NAVD88 was set throughout the structure's footprint.

Simulations *with* and w*ithout Project* 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 discharge and water depth data was 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 the bathymetry of Pretty Lake and adjacent waters in the model domain will be identical between the Existing and Future conditions.

3.4 TYPICAL AVERAGE LATE SUMMER 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 or water age 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), 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.

3.4.1 Water Level Boundary

The offshore model boundaries were forced with astronomical constituents established at nearby NOAA tide gage – the Chesapeake Bay Bridge Tunnel (CBBT) (8638863) for the Pretty Lake Model. Table 1 lists the first 10 tidal constituents based on their amplitudes.

Table 1: Tidal constituents at NOAA 8638863

Name	Amplitude (ft)	Phase (degree)	Description
M2	1.25	21.0	Principal lunar semidiurnal constituent
N2	0.30	1.4	Larger lunar elliptic semidiurnal constituent
S2	0.23	45.8	Principal solar semidiurnal constituent
K1	0.19	184.9	Lunar diurnal constituent
SA	0.18	152.0	Solar annual constituent
O1	0.15	208.9	Lunar diurnal constituent
SSA	0.14	34.0	Solar semiannual constituent
NU2	0.06	359.2	Larger lunar evectional constituent
P1	0.06	188.1	Solar diurnal constituent
K2	0.06	46.4	Lunisolar semidiurnal constituent

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 the Virginia Institute of Marine Science (VIMS) from their EFDC-HEM3D model (Shen *et al.*, 2017) of the Chesapeake Bay, and it comprises the period between January 2010 and December 2013. Results at model boundary show variation in both the depth-averaged values and the degree of vertical stratification through time; however, an analysis of the four years of model results showed that salinities during the late summer period varied quite a bit among years. 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 3. A linear vertical variation of salinity along the offshore boundaries was adopted.

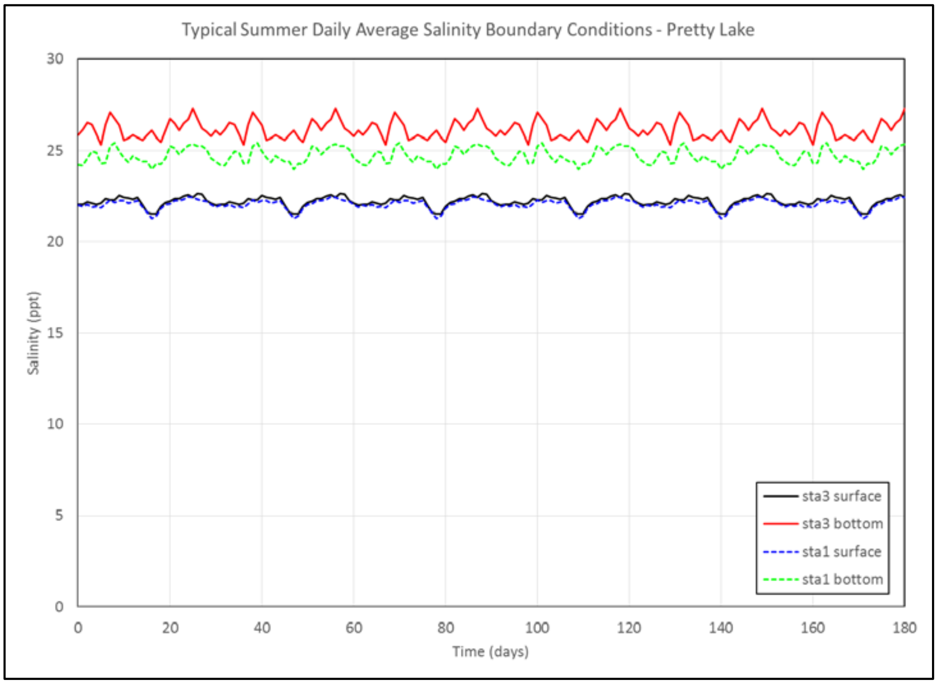


Figure 3: Surface and bottom daily average salinities for late summer period at Pretty Lake model offshore boundary

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. Figure 4 presents the freshwater discharge values (in cubic feet/hour) developed.

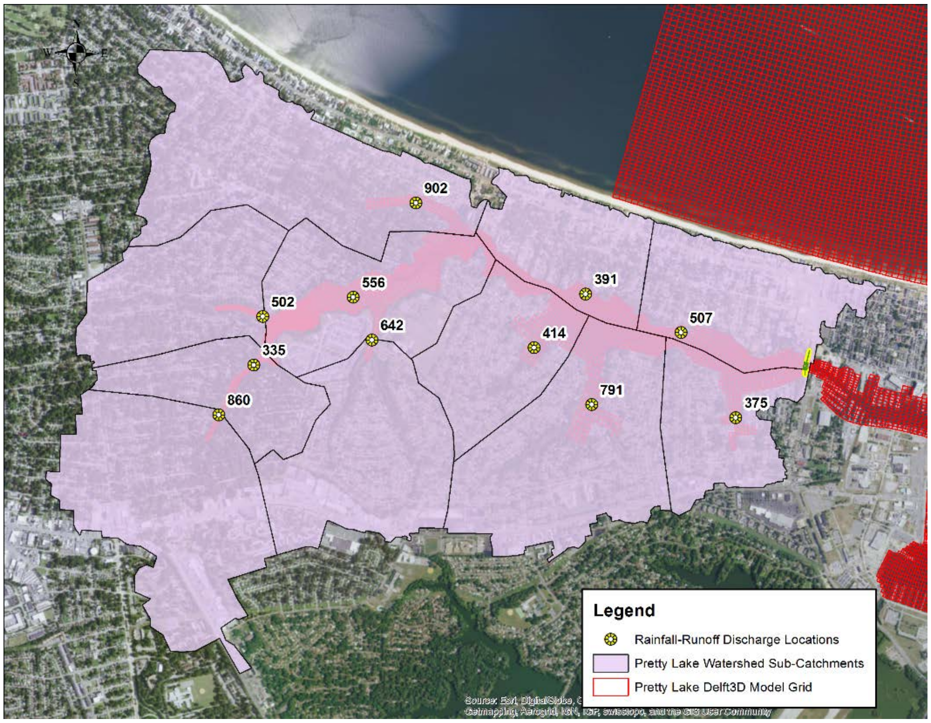
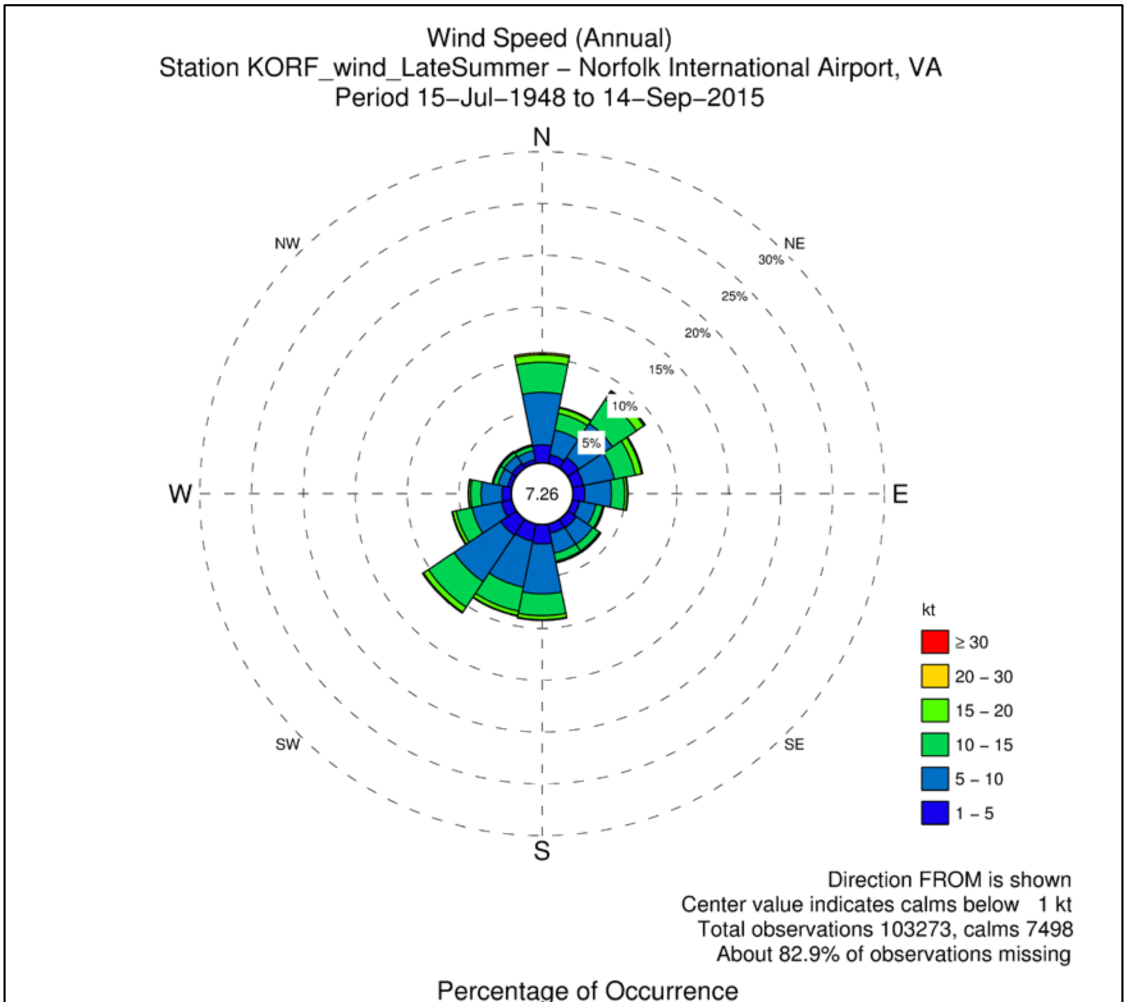


Figure 4: Freshwater inflows for the late summer condition

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 5 shows a wind rose of Norfolk International Airport wind derived from measurements 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
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 5: Norfolk International Airport wind rose for late summer period only (mid-July – mid-September)

3.4.5 Water Quality Tracers

Different constituents (tracers) were used for the evaluation of potential impacts on water quality in Pretty Lake.

For flushing time analysis, one conservative tracer was used for each region of interest (whole bay and upper bay). The offshore and inflow boundary conditions were set to zero concentration.

For the determination of freshwater residence time (water age), a tracer pair, one conservative tracer and one decaying tracer, were used. The decay rate of the decaying tracer was set to approximately the inverse of the flushing time determined from the flushing time analysis. At the most upstream freshwater source, the tracer pair concentrations were set to 100 mg/L. The concentrations were set to zero at the offshore and other inflow boundaries.

3.4.6 Initial Conditions

For the hydrodynamic and salinity initial conditions, a separate spin-up run was conducted for each simulation scenario using the input developed above. After the model reached dynamic steady state, salinity and hydrodynamic results (water levels and horizontal velocities) were extracted at one time step to be used to construct the initial conditions.

The initial conservative tracers' concentrations for the flushing time calculations were set to 100 mg/L in the study regions and 0 elsewhere. For the tracer pair used to calculate the freshwater residence time, the initial concentrations were set to 0.

3.5 Post Storm Recovery Run Setup

For post-storm recovery investigation, model simulations were begin with initial conditions derived from the long-term run described previously, where conditions reached 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 recede to normal levels, the model forcing conditions 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 was at low tide and approximately 12:00 pm on September 17, and reopened at 12:00 pm on September 21 when the tide level returned to normal conditions. After a 4-day (96 hour) simulation period, when water levels receded to typical elevations, flood gates would be re-opened and 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

The water level boundary conditions for Isabel at the offshore were developed using the measurements at NOAA gage CBBT. Because the storm simulations were hot-started from the typical summer condition results and also followed by the typical summer conditions to simulate the recovery, the measured Isabel water levels were not used directly in this study. Instead, the surge levels were first extracted by subtracting the predicted tide levels from the measured water levels during Isabel, and then they were superimposed onto the typical summer condition tide levels to form the water level boundary conditions for the storm period. Figure 6 presents the storm water level condition for the storm period simulations.

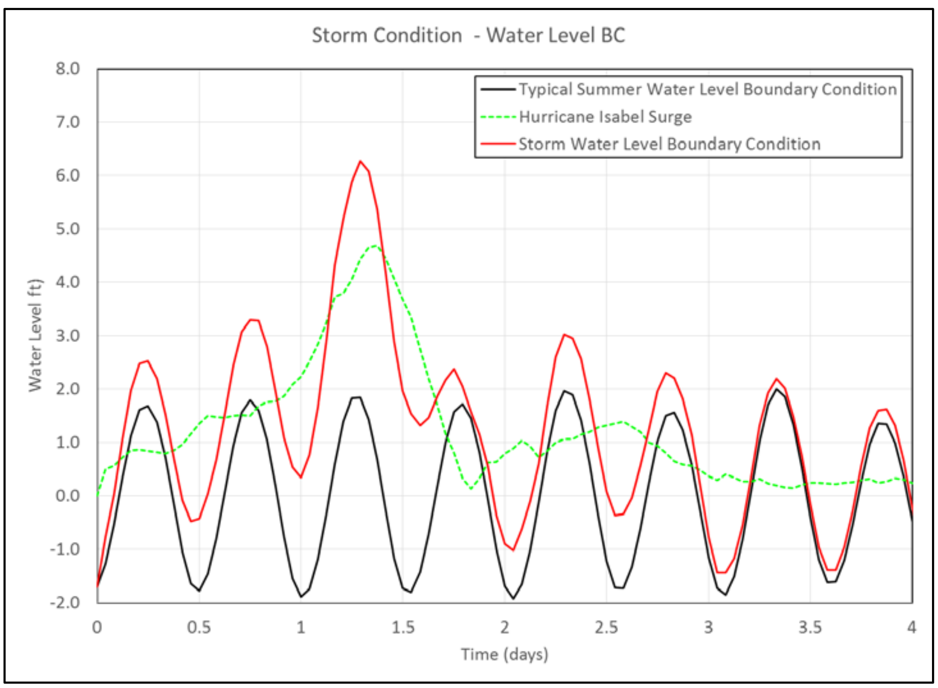


Figure 6: Water level boundary condition for the storm period simulations

3.5.2 Salinity

The salinity boundary condition at the offshore during the storm period was developed using the measured water temperature and conductivity at NOAA gage CBBT during Hurricane Isabel. The resulted salinity values are for the surface water layer only. The salinity difference between the bottom layer and the surface layer was assumed to be the same as the typical summer condition (3.3 ppt). Similarly, a linear salinity variation profile was adopted. Figure 7 shows the surface and bottom salinity boundary conditions for the storm period simulation.

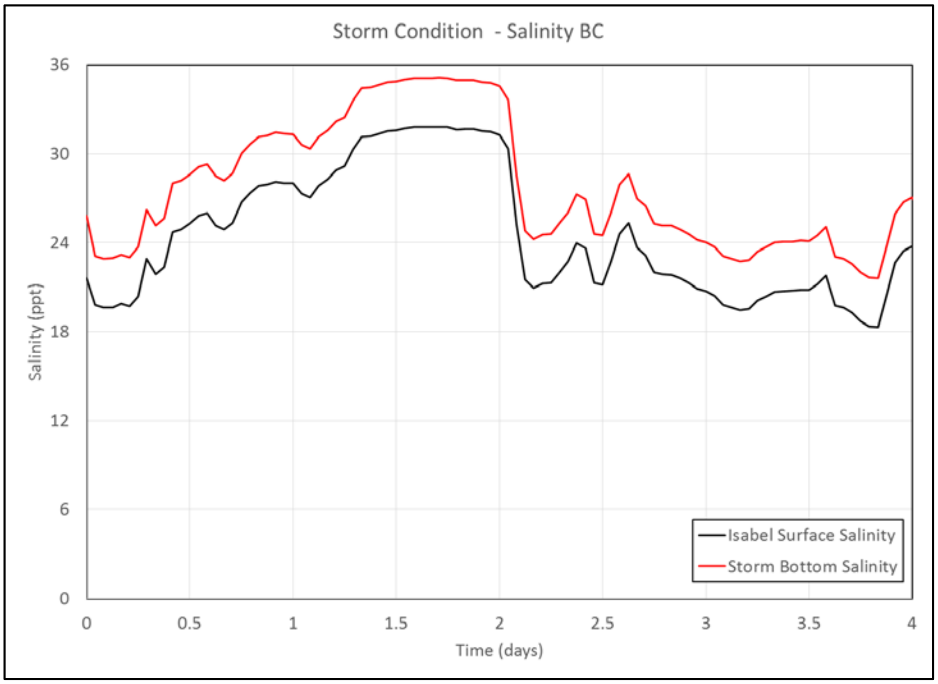


Figure 7: Salinity boundary condition for the storm period simulations

3.5.3 Freshwater Inflows

The daily rainfall-runoff caused by Hurricane Isabel was available for the project area from the VADEQ statewide watershed model hindcast. Based on the VADEQ model, storm total rainfall depths range from 3.2” to 5.4” over the region. According to NOAA Atlas 14, this puts Isabel rainfall at 2-yr to 10-yr return periods for a 24-hour storm.

3.5.4 Wind

The wind inputs for the storm period simulations were obtained from measured wind data at NOAA-COOPS station 8638863 (Chesapeake Bay Bridge Tunnel) during Hurricane Isabel. The wind records were smoothed by a 3-hour moving average method to prevent potential model instability issues due to dramatic changes in both wind speed and 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. Figure 8 presents the wind inputs for the storm period.

Figure 8: Wind conditions for the storm period simulations

3.5.5 Water Quality Tracers

For the two freshwater tracers, their concentrations at the offshore boundaries were set to zero, as well as their initial conditions. The concentrations from the freshwater sources were set to 100 mg/L during the 4-day storm period, and then set to zero for the recovery period.

4 Typical Conditions Results

4.1 Existing Conditions Results

Flushing time, tidally-averaged salinity, and tidally-averaged freshwater age were computed for the full Pretty Lake (Whole Bay) area and Upper Bay region as defined in Figure 9.

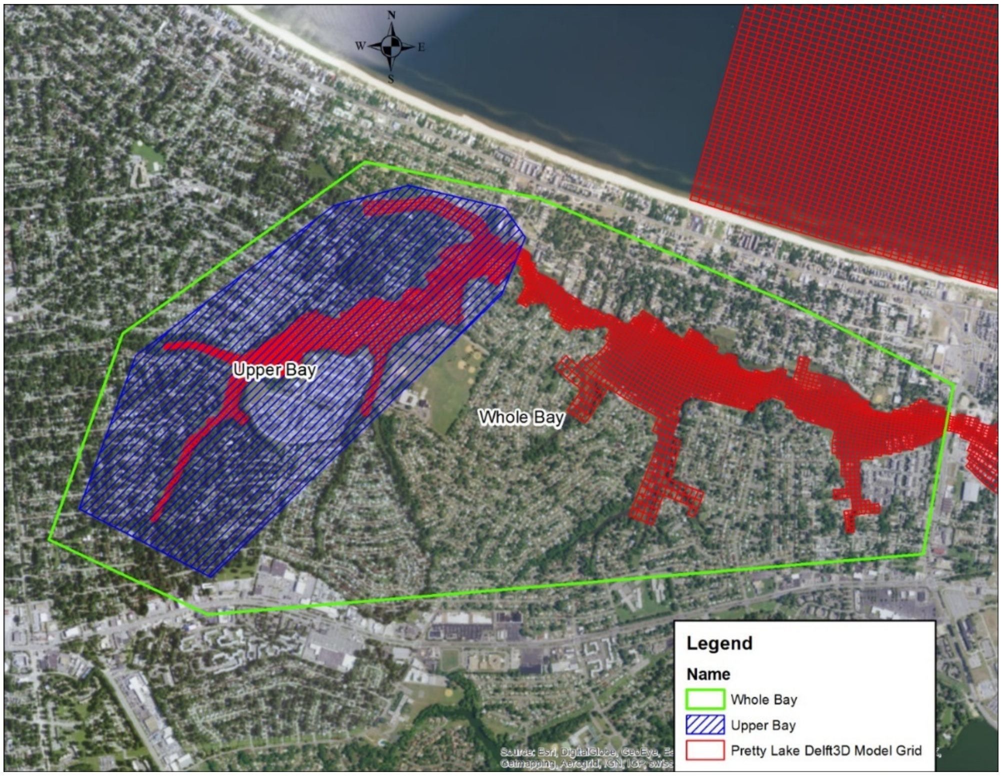


Figure 9: Pretty Lake water quality analysis regions

4.1.1 Flushing Time

Figure 10 plots the spatially-averaged, depth-averaged conservative tracer concentration through time for the Whole Bay and Upper Bay regions of Pretty Lake under the existing condition. The first 20 days of results after achieving dynamic stability are used in the flushing time analysis (see Figure 11 to Figure 14), where the inverse slope of a linear fit of the natural log of concentration corresponds to the flushing time.

The flushing time under the existing condition *without Project* is 9.5 days and 12.3 days for the whole bay and upper bay, respectively. *With Project* (gate open), the flushing time becomes 8.6 days sand 11.0 days respectively. The results indicate that the project has a practically negligible effect on flushing times. However, there is a definite trend that suggests that the project could result in a slightly greater flushing rate (lower flushing time), which seems counter-intuitive. Less cross-sectional area for flow due to the gate structure restriction will result in higher entrance/exit velocities 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.

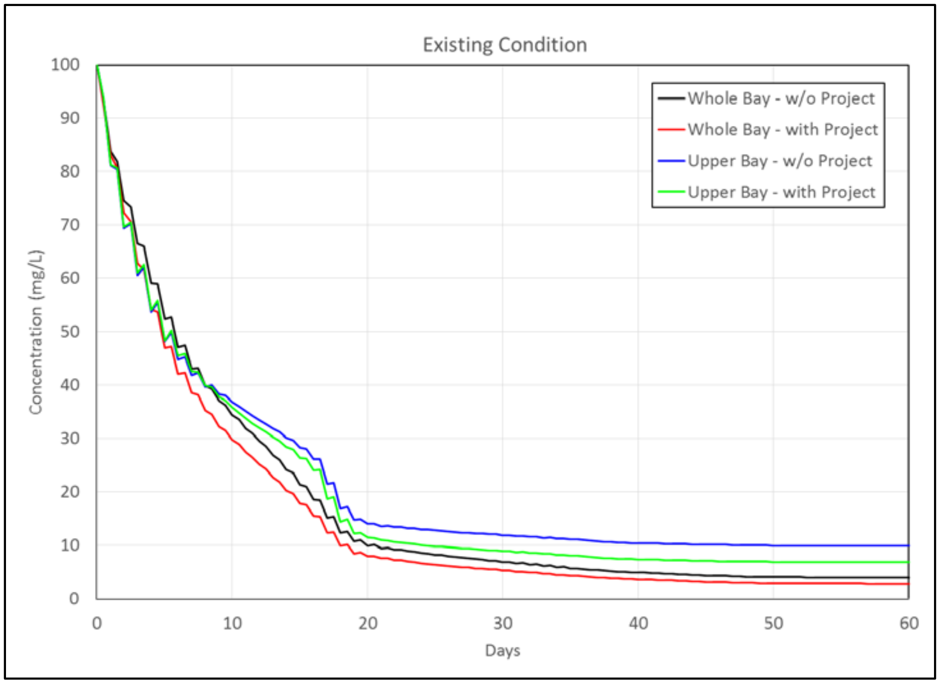


Figure 10:Spatially-averaged conservative tracer concentration through time in the Whole Bay and Upper Bay regions of Pretty Lake – existing condition

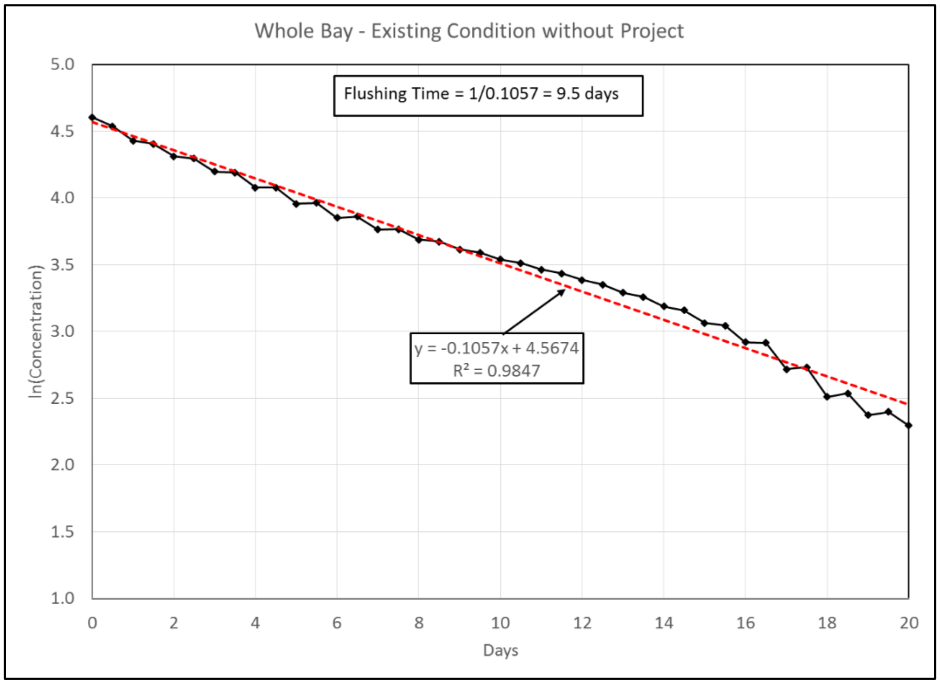


Figure 11:Existing Conditions *without Project* Whole Bay region flushing time

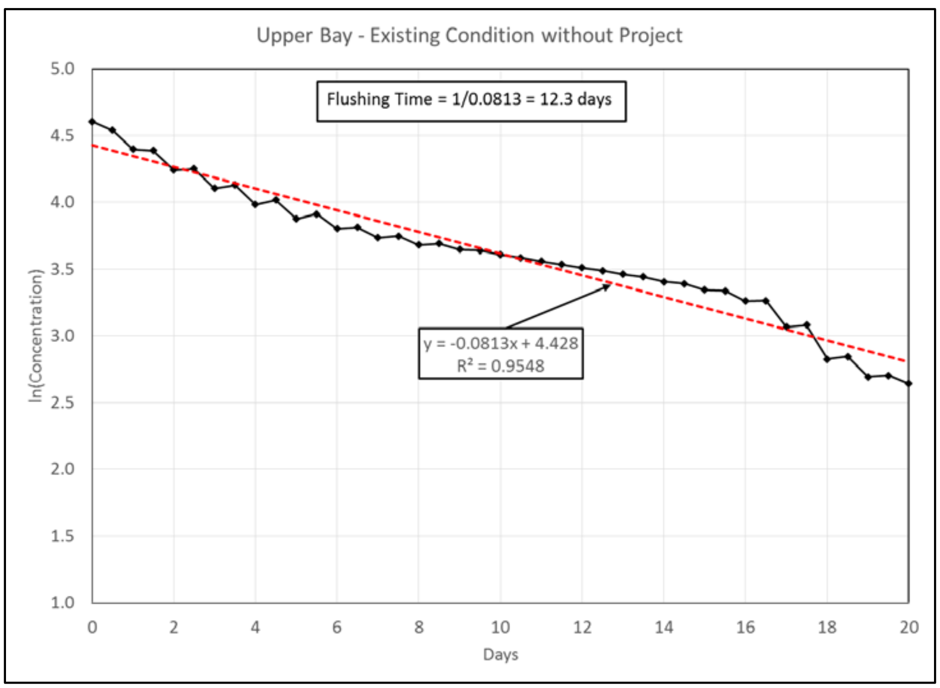


Figure 12:Existing Conditions *without Project* Upper Bay region flushing time

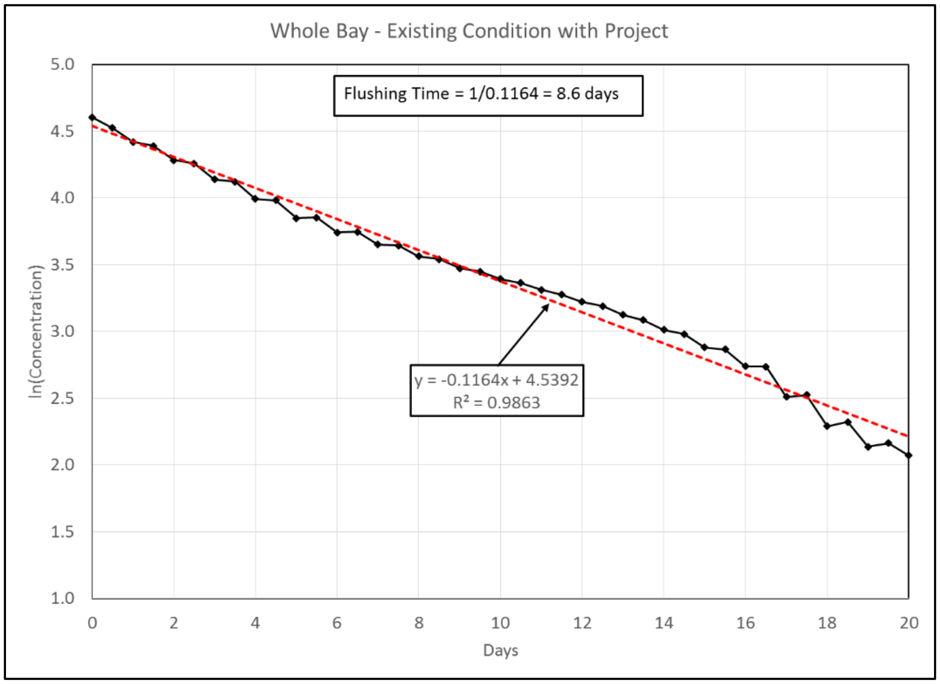


Figure 13:Existing Conditions *with Project* <u>Whole Bay</u> region flushing time

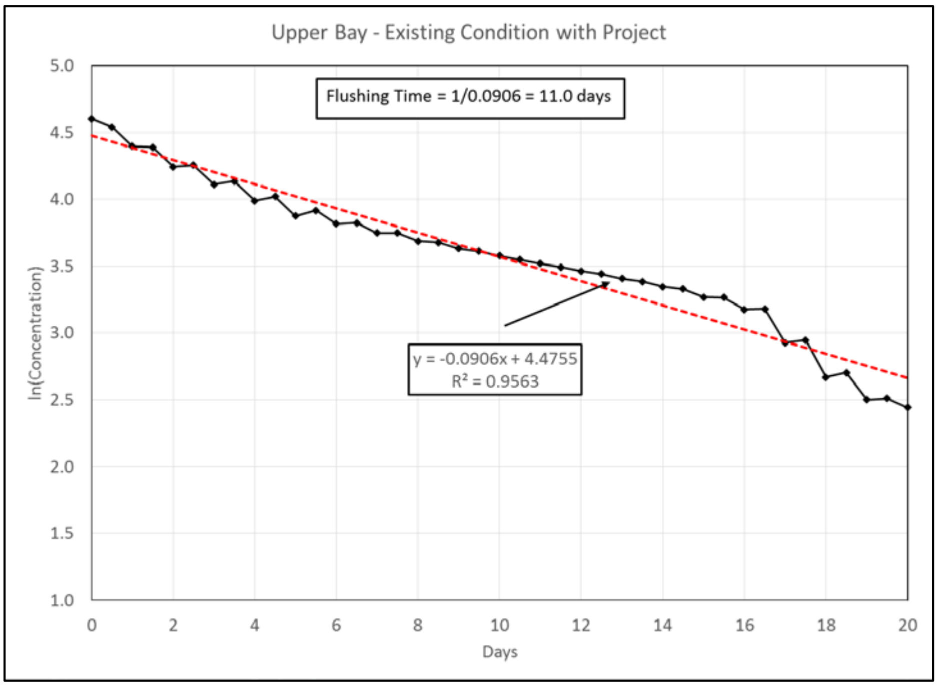


Figure 14:Existing Conditions *with Project* <u>Upper Bay</u> region flushing time

4.1.2 Salinity

Tidally averaged, depth-averaged salinity at each model computational cell-column is calculated after salinity reaching dynamic steady state. Figure 15 and Figure 16 present spatial variation in the steady-state, tidal-averaged salinity for *without Project* and *with Project*, respectively, under the existing condition. Figure 17 shows the spatial variation in tidally averaged, depth-averaged salinity deviation (*with Project* minus *without Project*). The tidally averaged, depth-averaged salinity *without Project* is about 21.9 ppt and 19.9 ppt in the whole bay and upper bay region, respectively. These values *with Project* become 22.0 ppt and 19.9 ppt, respectively. These results indicate the project effect on the salinity is negligible.

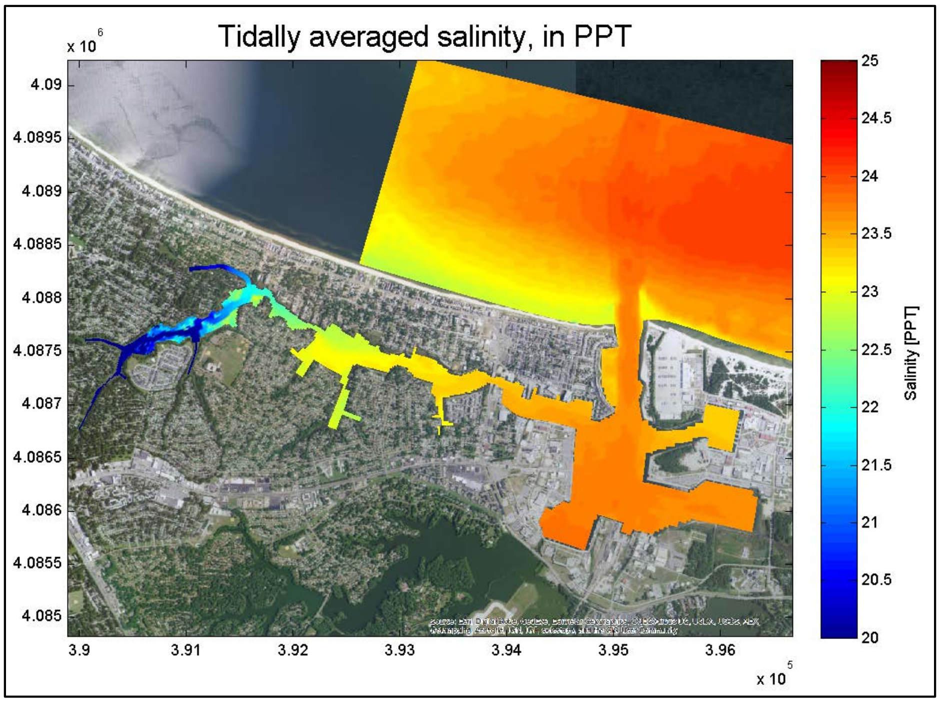


Figure 15:Existing condition *without Project* steady-state, tidally-averaged salinity

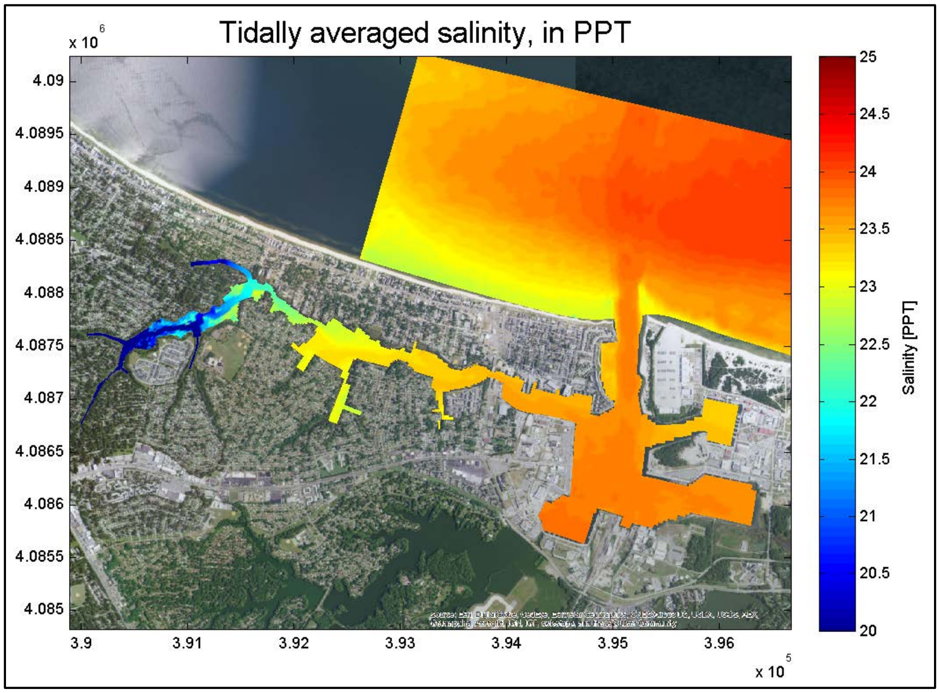


Figure 16:Existing condition *with Project* steady-state, tidally-averaged salinity

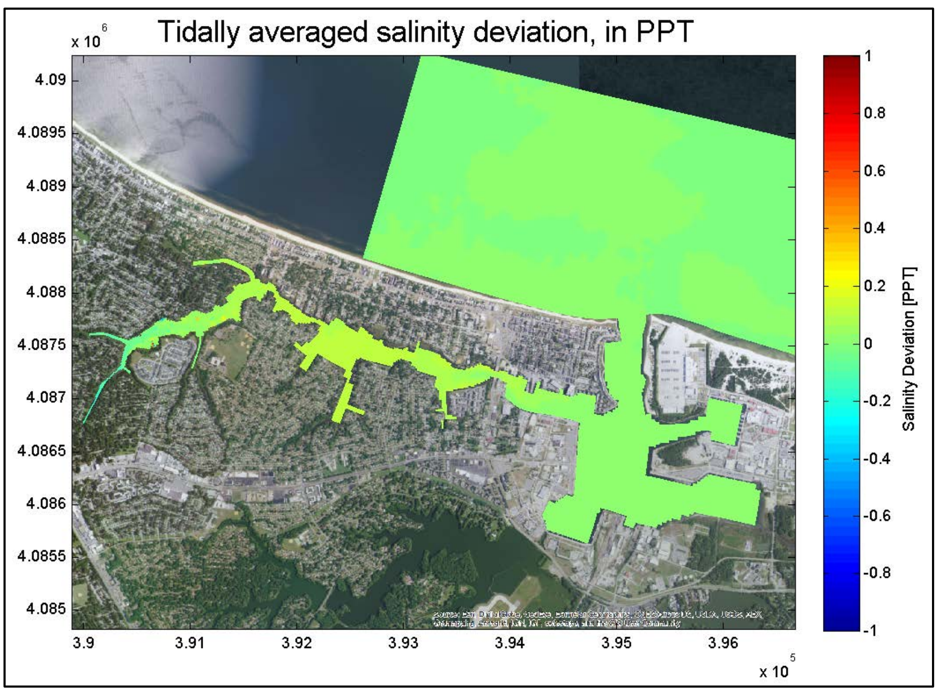


Figure 17:Steady-state, tidally-averaged salinity deviation (*with Project* minus *without Project*) for existing conditions

4.1.3 Freshwater Residence Time

The freshwater residence time was computed from the relative concentrations of a conservative and decaying tracer released at the most upstream freshwater source. After the concentrations reached a dynamic steady-state, they were depth-averaged for every computational cell-column at every time step. The depth-averaged concentrations were then used to calculate the freshwater residence time (water age) at each cell-column at every time step. Finally, the freshwater residence time was tidally-averaged for every computational cell-column in the area of interest. Figure 18 and Figure 19 present spatial variation in the steady state, tidally averaged, depth-averaged freshwater residence time for *without Project* and *with Project*, respectively under the existing condition. Figure 20 shows spatial variation in the residence time deviation (*with Project* minus *without Project*). The tidally averaged, depth-averaged freshwater residence time *without Project* is about 14.6 days and 11.6 days in the whole bay and upper bay region, respectively. These values *with Project* become 14.4 days and 11.5 days, respectively. These results indicate the project effect on the freshwater residence time is negligible.

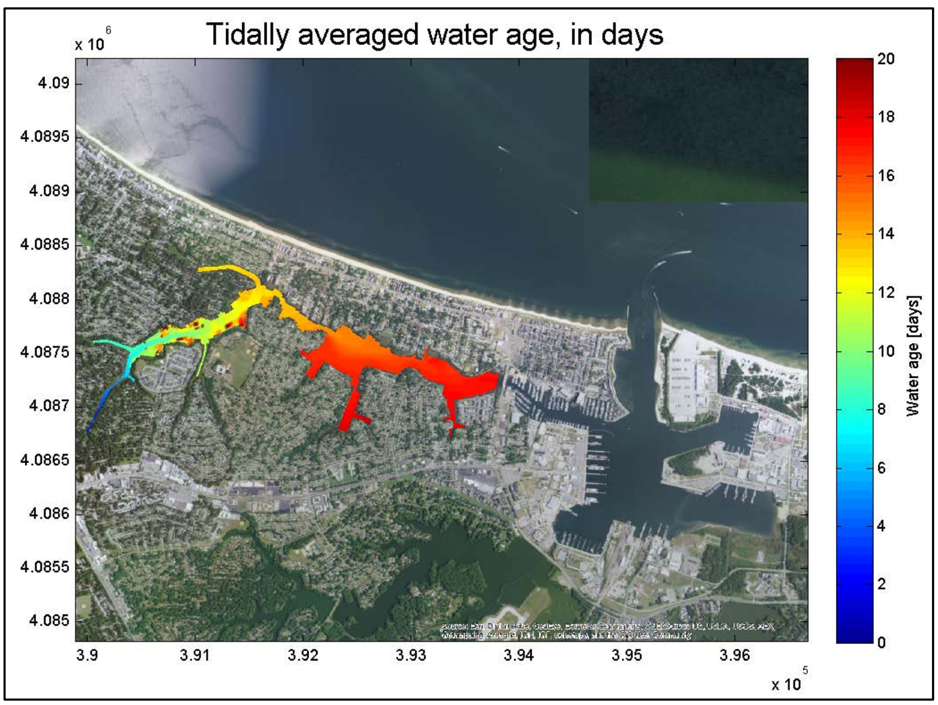


Figure 18:Existing condition *without Project* steady-state, tidal-averaged, depth-averaged freshwater residence time

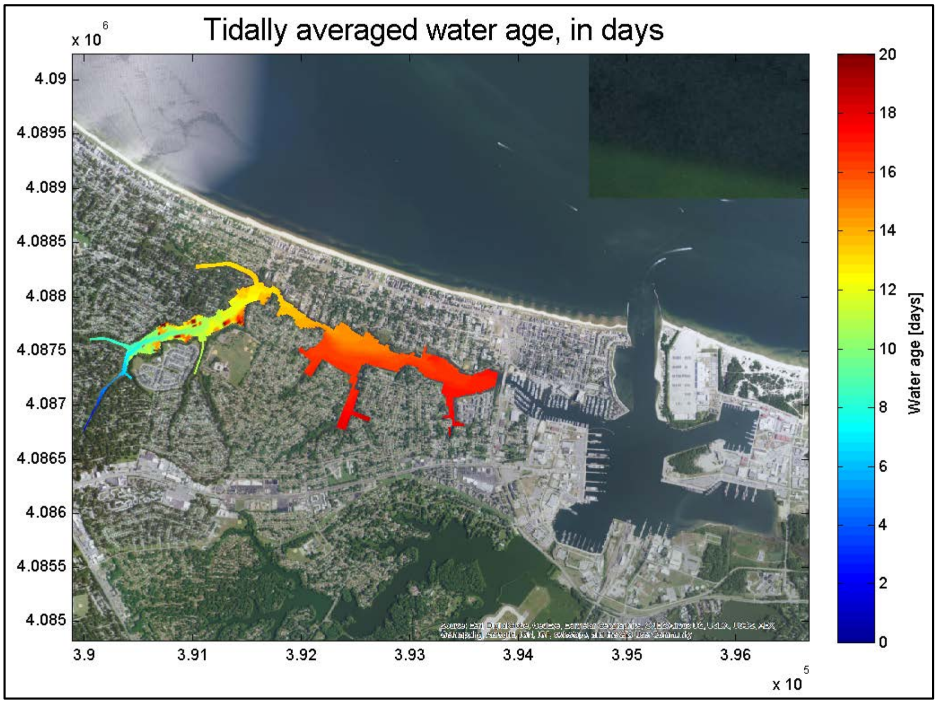


Figure 19:Existing condition *with Project* steady-state, tidal-averaged, depth-averaged freshwater residence time

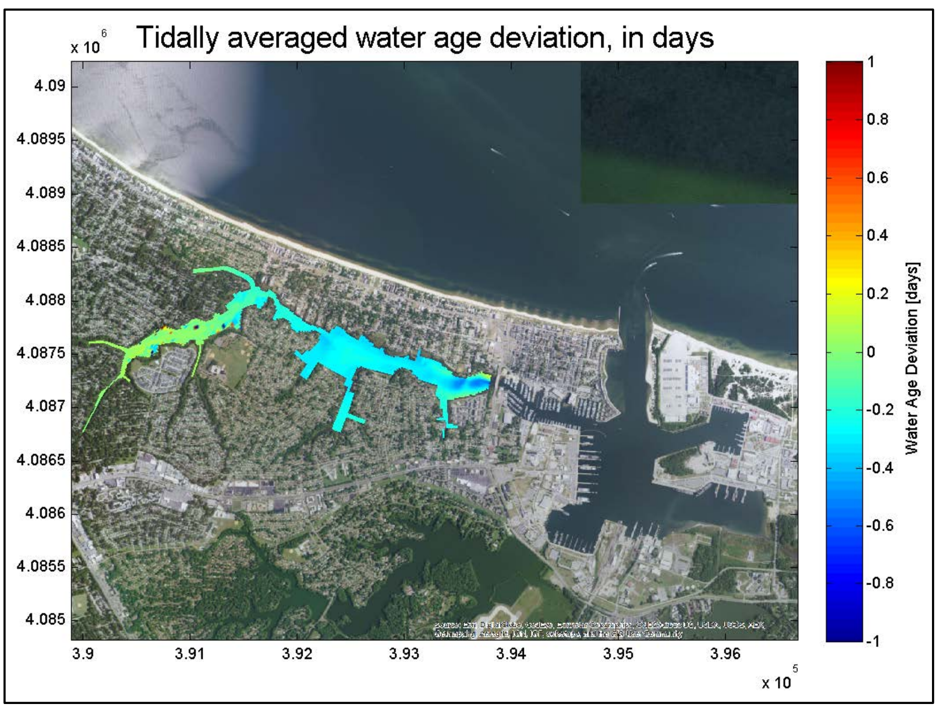


Figure 20:Steady-state, tidal-averaged, depth-averaged freshwater residence time deviation (*with Project* minus *without Project*) for existing conditions

The time series of depth-averaged freshwater residence time at four locations (see Figure 21) are also presented in Figure 22. Dynamic steady state conditions are reached after 40 days. The differences in freshwater residence time at all locations are very small.

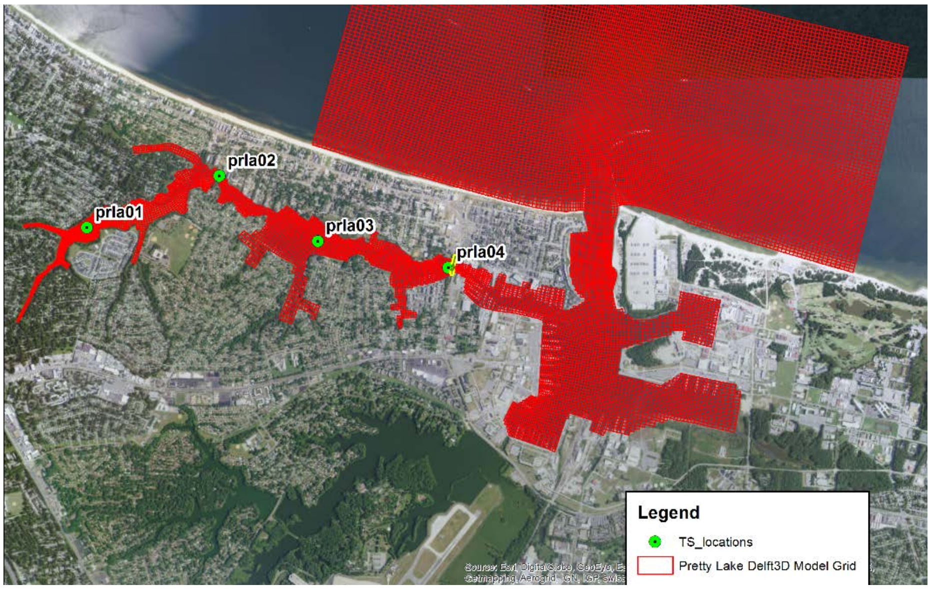


Figure 21: Locations for time series demonstration

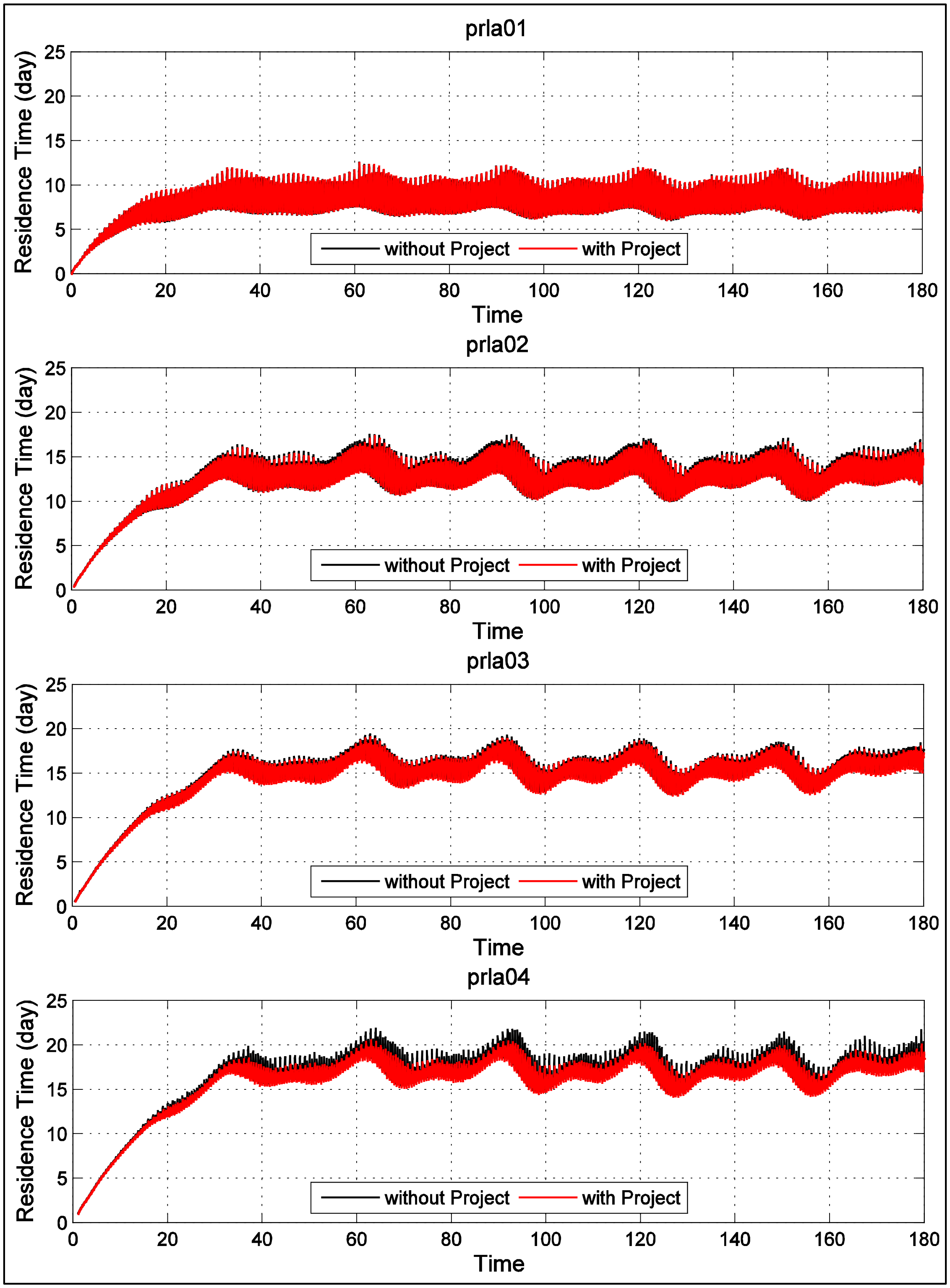


Figure 22: Time series of freshwater residence time under existing condition

4.2 Future Conditions Results

Flushing time, tidally-averaged salinity, and tidally-averaged freshwater age for the full Pretty Lake (Whole Bay) area and Upper Bay region as defined in Figure 9 were computed for future conditions.

4.2.1 Flushing Time

Figure 23 plots the spatially-averaged, depth-averaged conservative tracer concentration through time for the Whole Bay and Upper Bay regions of Pretty Lake under the future condition *with* and *without Project*. Similar to the existing condition, the first 20 days of these results are used in the flushing time analysis (see Figure 24 to Figure 27), where the inverse slope of a linear fit of the natural log of concentration corresponds to the flushing time (e-folding time).

The flushing time under the future condition *without Project* is 8.7 days and 7.3 days for the whole bay and upper bay, respectively. With the proposed project (gate open) in place, the flushing time becomes 7.8 days sand 7.0 days respectively. The results indicate that the flushing times are affected very little by the project, and are actually reduced slightly. Future conditions of sea level rise cause more rapid flushing than existing conditions.

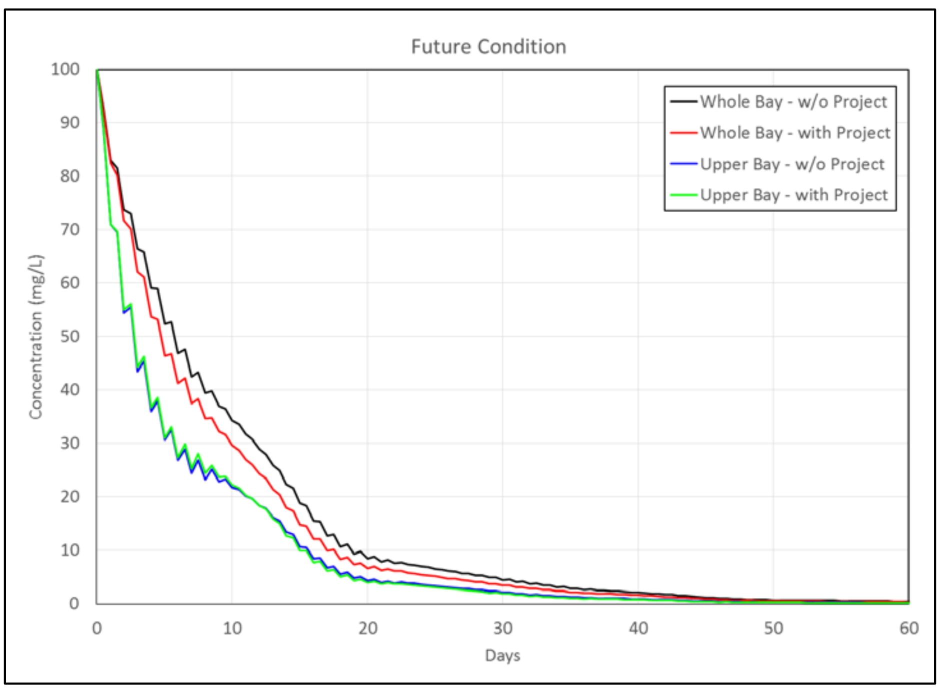


Figure 23:Spatially-averaged conservative tracer concentration through time in the Whole Bay and Upper Bay regions of Pretty Lake – future condition

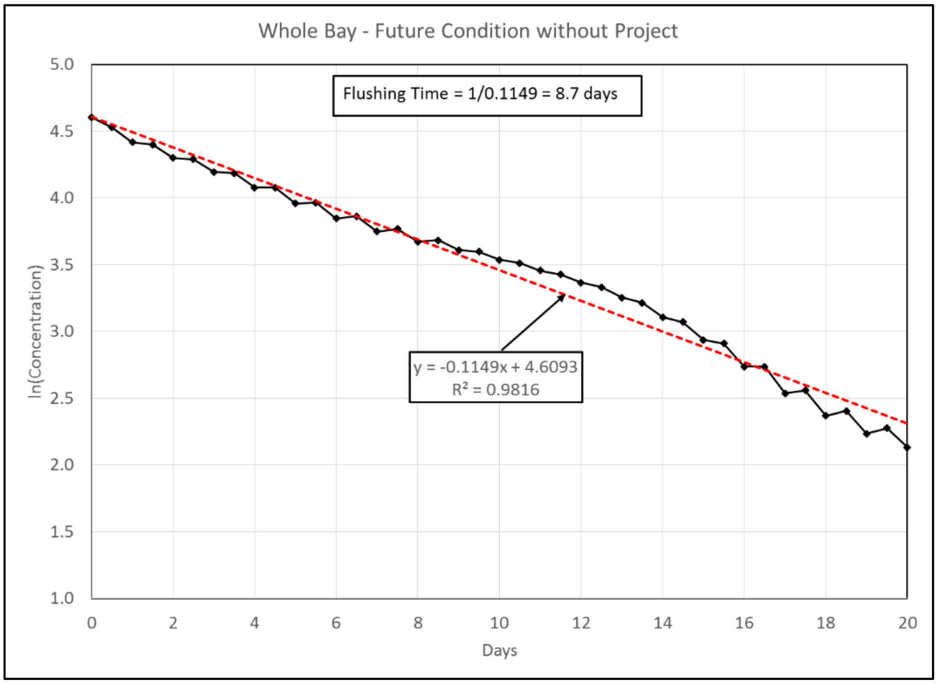


Figure 24:Future Conditions *without Project* <u>Whole Bay</u> region flushing time

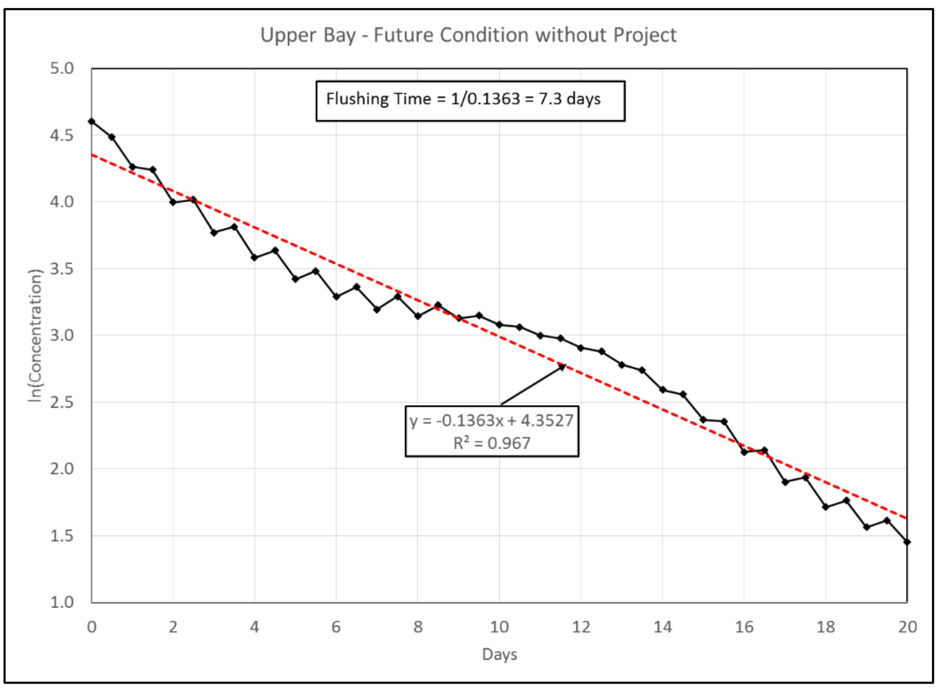


Figure 25:Future Conditions *without Project* <u>Upper Bay</u> region flushing time

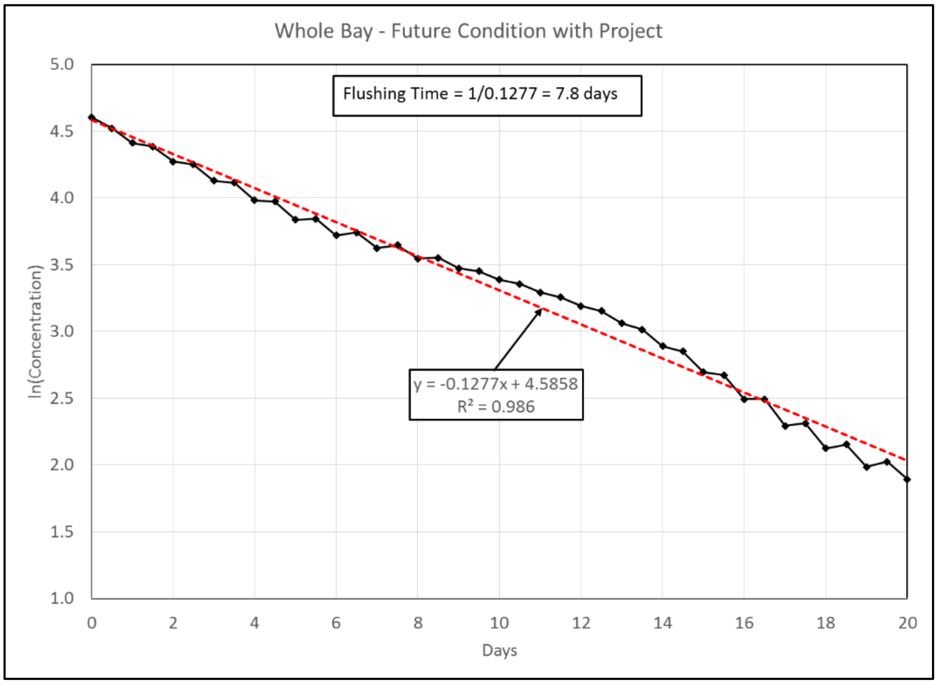


Figure 26:Future Conditions *with Project* <u>Whole Bay</u> region flushing time

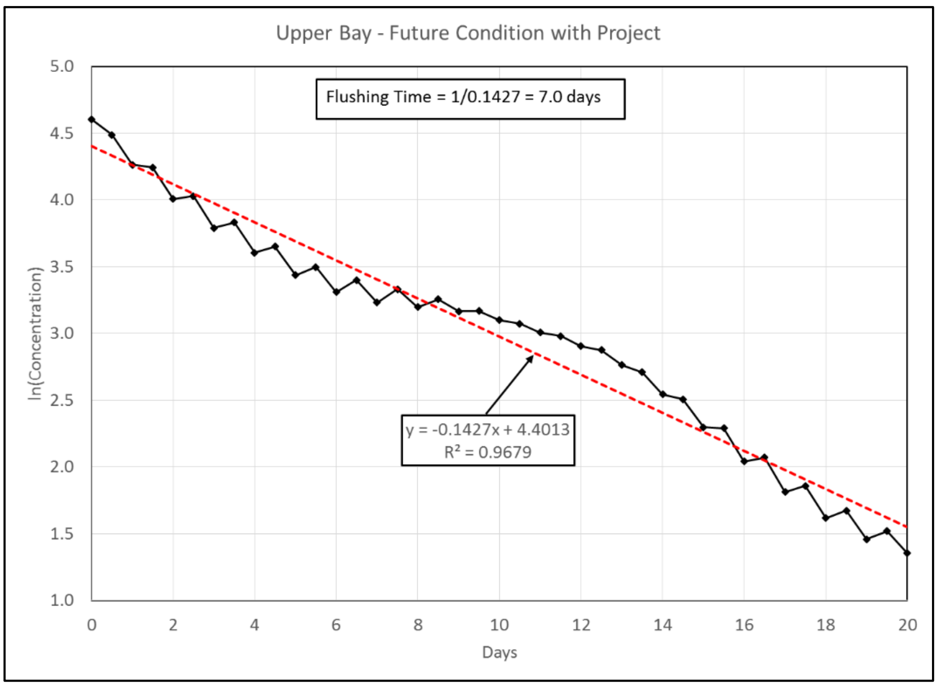


Figure 27:Future Conditions *with Project* <u>Upper Bay</u> region flushing time

4.2.2 Salinity

Figure 28 and Figure 29 present spatial variation in the steady-state, tidal-averaged, depth-averaged salinity for *without Project* and *with Project*, respectively, under the future condition. Figure 30 shows the spatial variation in salinity deviation (*with Project* minus *without Project*). The tidally averaged, depth-averaged salinity *without Project* is about 22.5 ppt and 21.5 ppt in the whole bay and upper bay region, respectively. These values *with Project* become 22.6 ppt and 21.5 ppt, respectively. These results indicate the project effect on the salinity is negligible for future conditions.

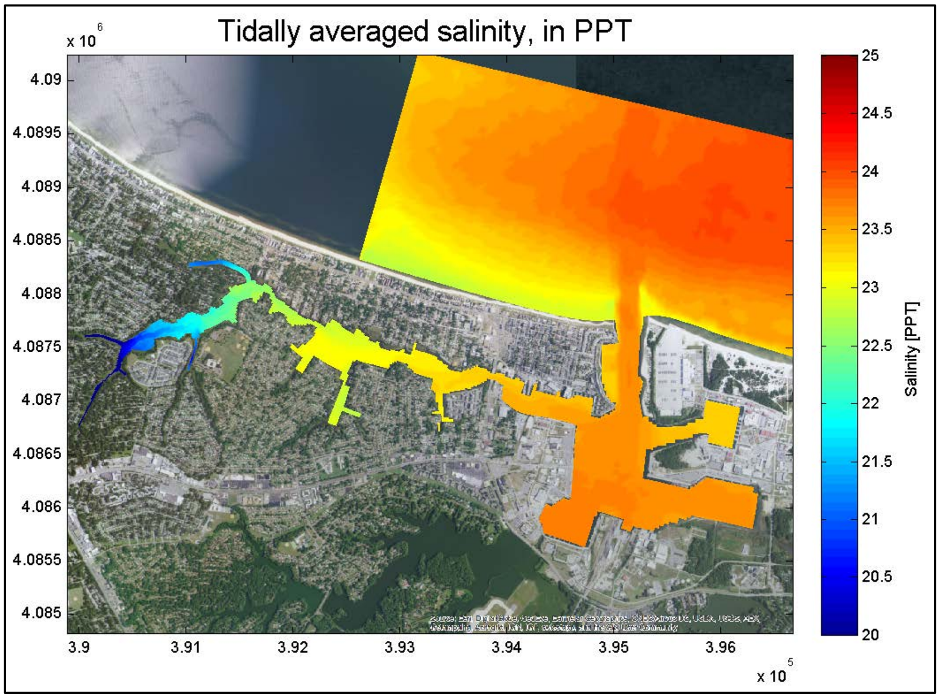


Figure 28:Future condition *without Project* steady-state, tidally-averaged, depth-averaged salinity

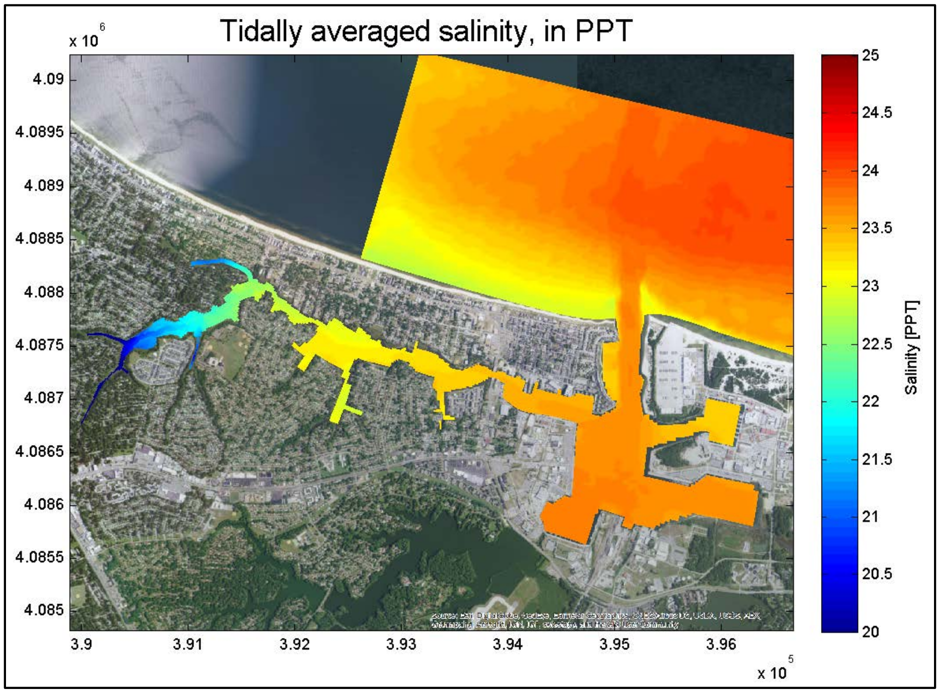


Figure 29:Future condition *with Project* steady-state, tidally-averaged, depth-averaged salinity

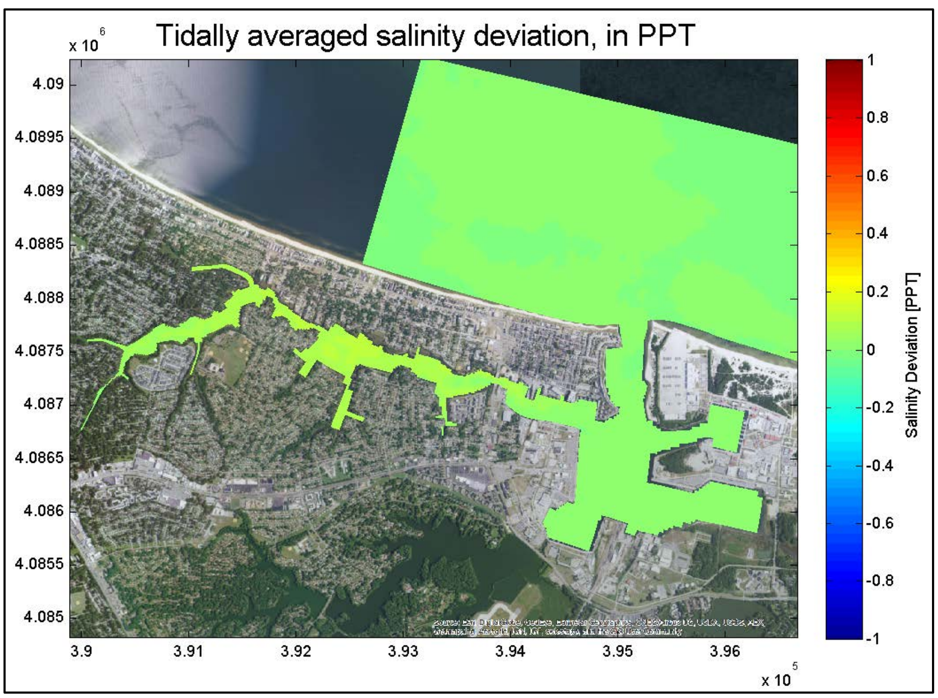


Figure 30:Steady-state, tidally-averaged, depth-averaged salinity deviation (*with Project* minus *without Project*) for future conditions

4.2.3 Freshwater Residence Time

Figure 31 and Figure 32 present spatial variation in the steady state, tidally averaged, depth-averaged freshwater residence time for *without Project* and *with Project*, respectively, under the future condition. Figure 33 shows spatial variation in the residence time deviation (*with Project* minus *without Project*). The tidally averaged, depth-averaged freshwater residence time *without Project* is about 13.9 days and 10.6 days in the whole bay and upper bay region, respectively. These values *with Project* become 13.6 days and 10.4 days, respectively. These indicate the project effect on the freshwater residence time is negligible. Freshwater residence times are reduced for future conditions compared with existing conditions.

The time series of depth-averaged freshwater residence time at four locations (see Figure 21) are presented in Figure 34. Dynamic steady state conditions are reached after 40 days. The differences in freshwater residence time at all locations are very small.

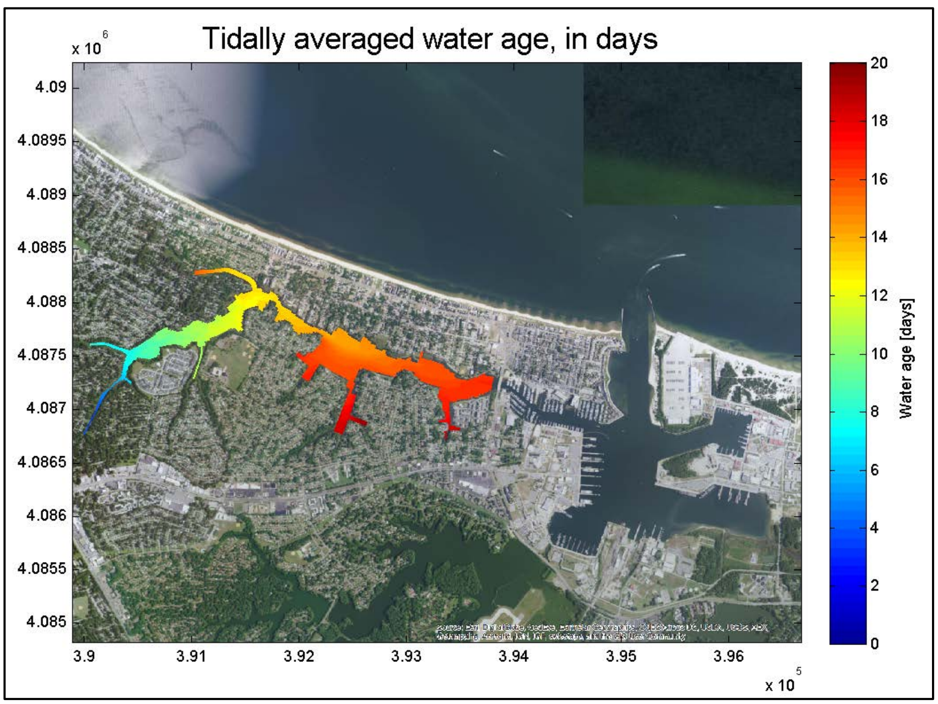


Figure 31:Future condition *without Project* steady-state, tidal-averaged freshwater residence time

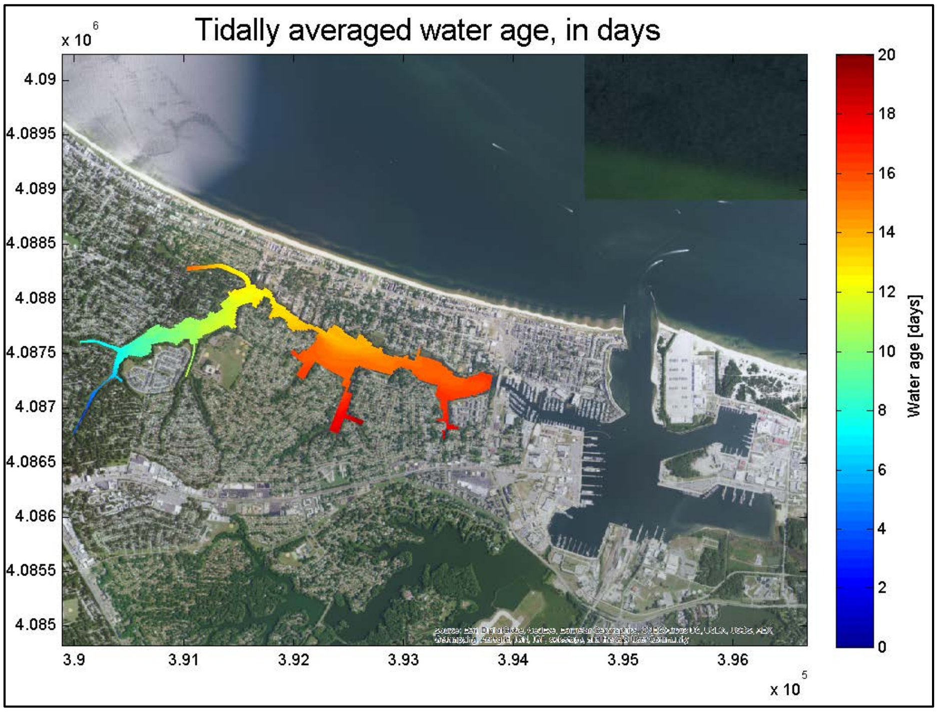


Figure 32:Future condition *with Project* steady-state, tidal-averaged freshwater residence time

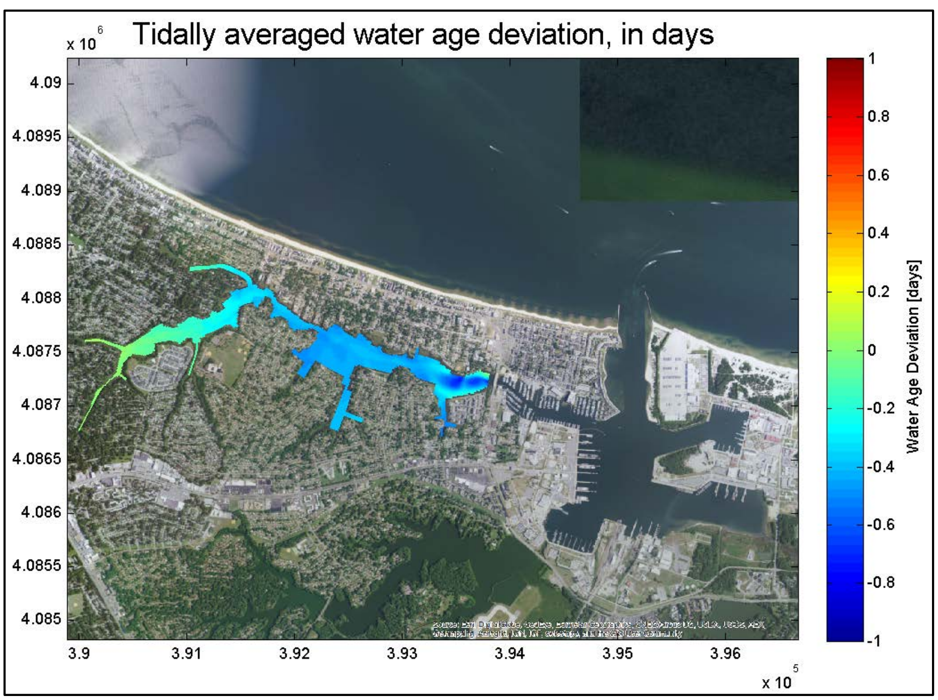


Figure 33:Steady-state, tidal-averaged, depth-averaged freshwater residence time deviation (*with Project* minus *without Project*) for future conditions

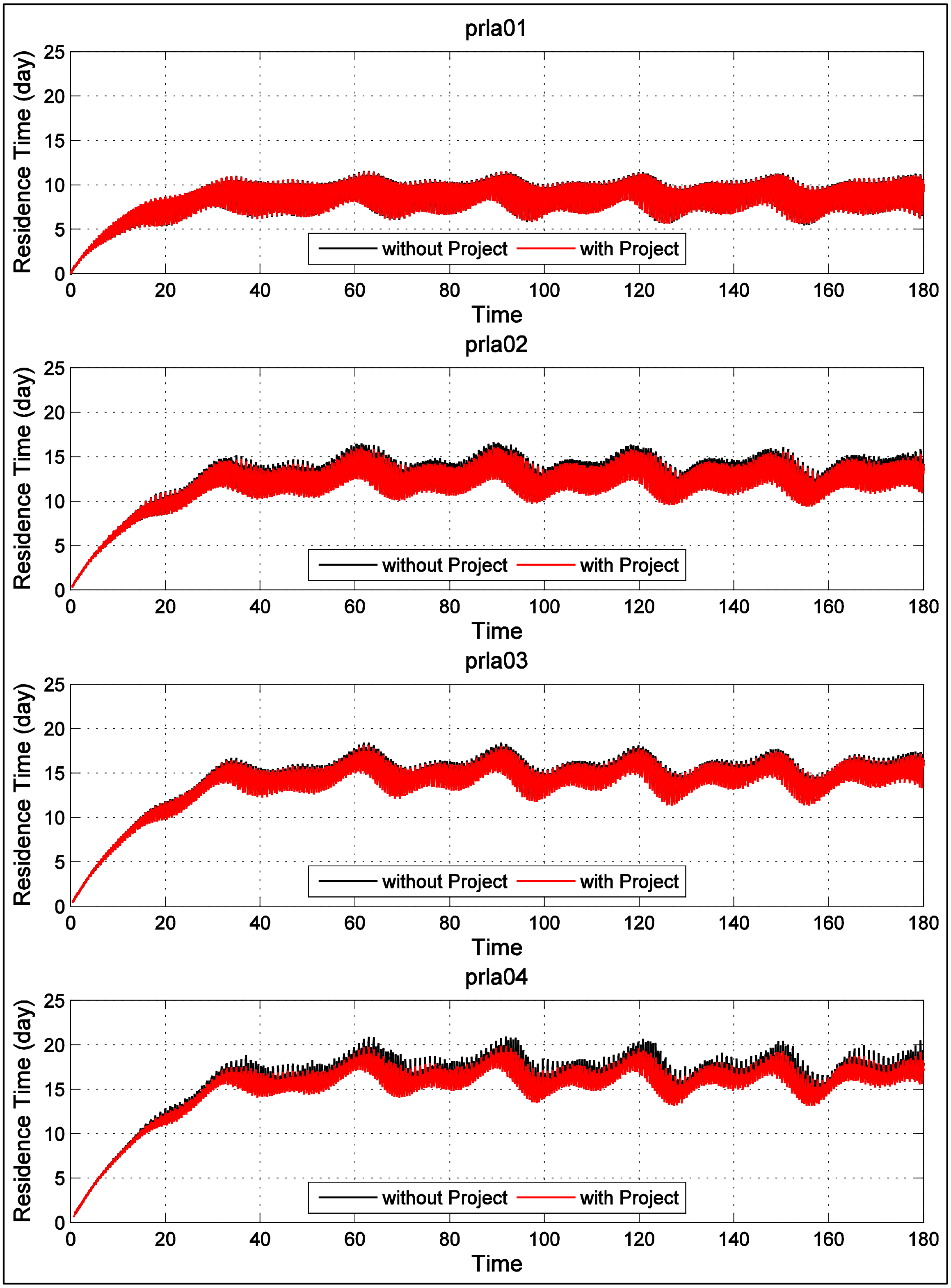


Figure 34: Time series of freshwater residence time under future condition

4.2.4 Project Effects on Flow Velocities

Results presented above indicate minor project impacts on water quality parameters. As noted, *with Project* scenarios present a trend of lower flushing time and freshwater age. This can be explained by looking at flow velocities at the gate alignment. Less cross-sectional area for flow due to the gate structure restriction will result in higher entrance/exit velocities with possibly no reduction in tidal prism volume exchange. Increased velocities induce greater secondary circulation patterns, and create a mechanism for enhanced mixing, thus slightly reducing flushing times and freshwater age.

Figure 35 and Figure 36 show depth averaged velocities at peak ebb and flood for *with* and *without Project* scenarios under the existing conditions. Flow velocities are significantly increased for the narrowest area of flow exchange *with Project* and downstream. Similar response is expected under future conditions.

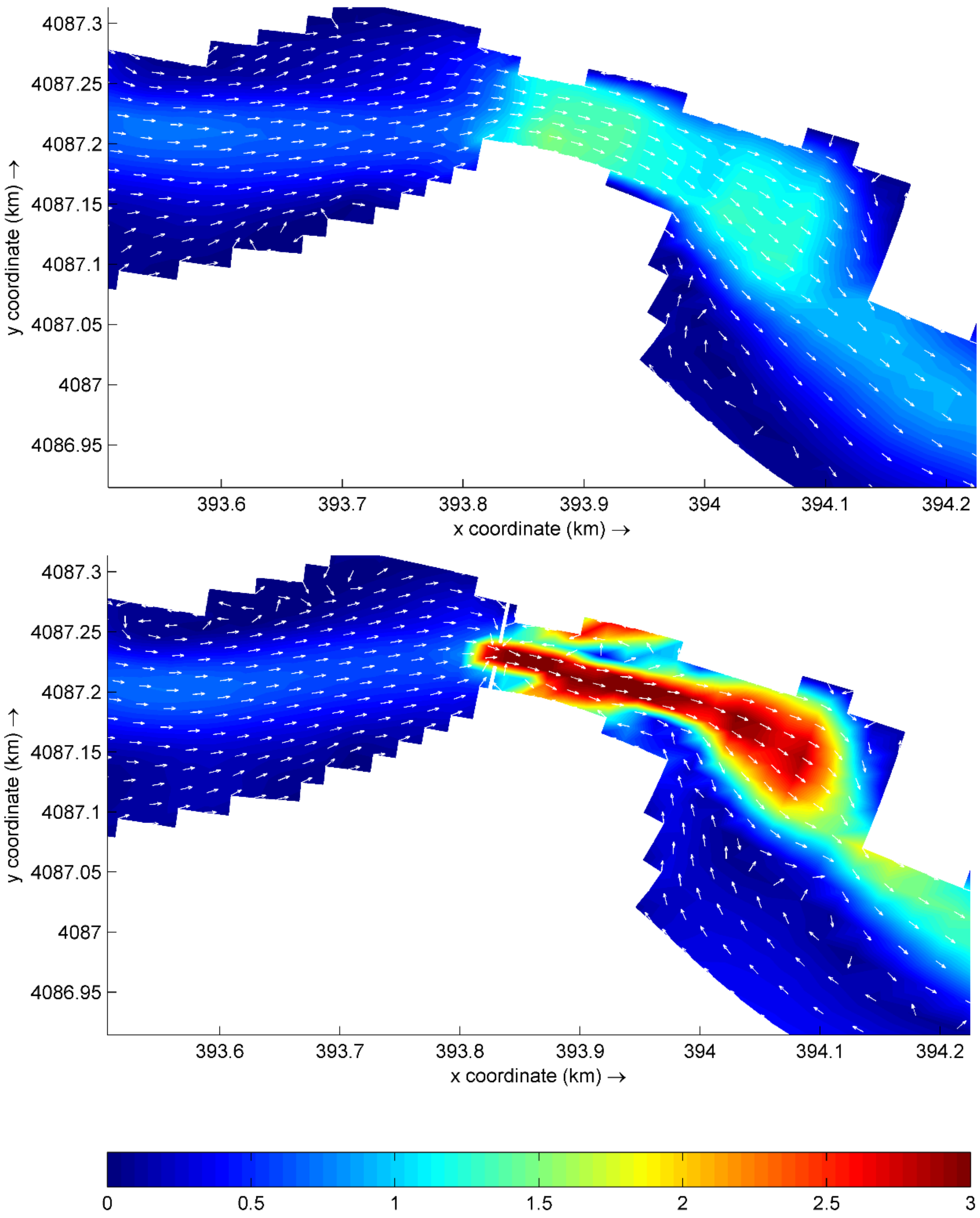


Figure 35:Depth averaged peak ebb velocities (in ft/s) for the *without Project* (top) and *with Project* (bottom) simulations under existing condition

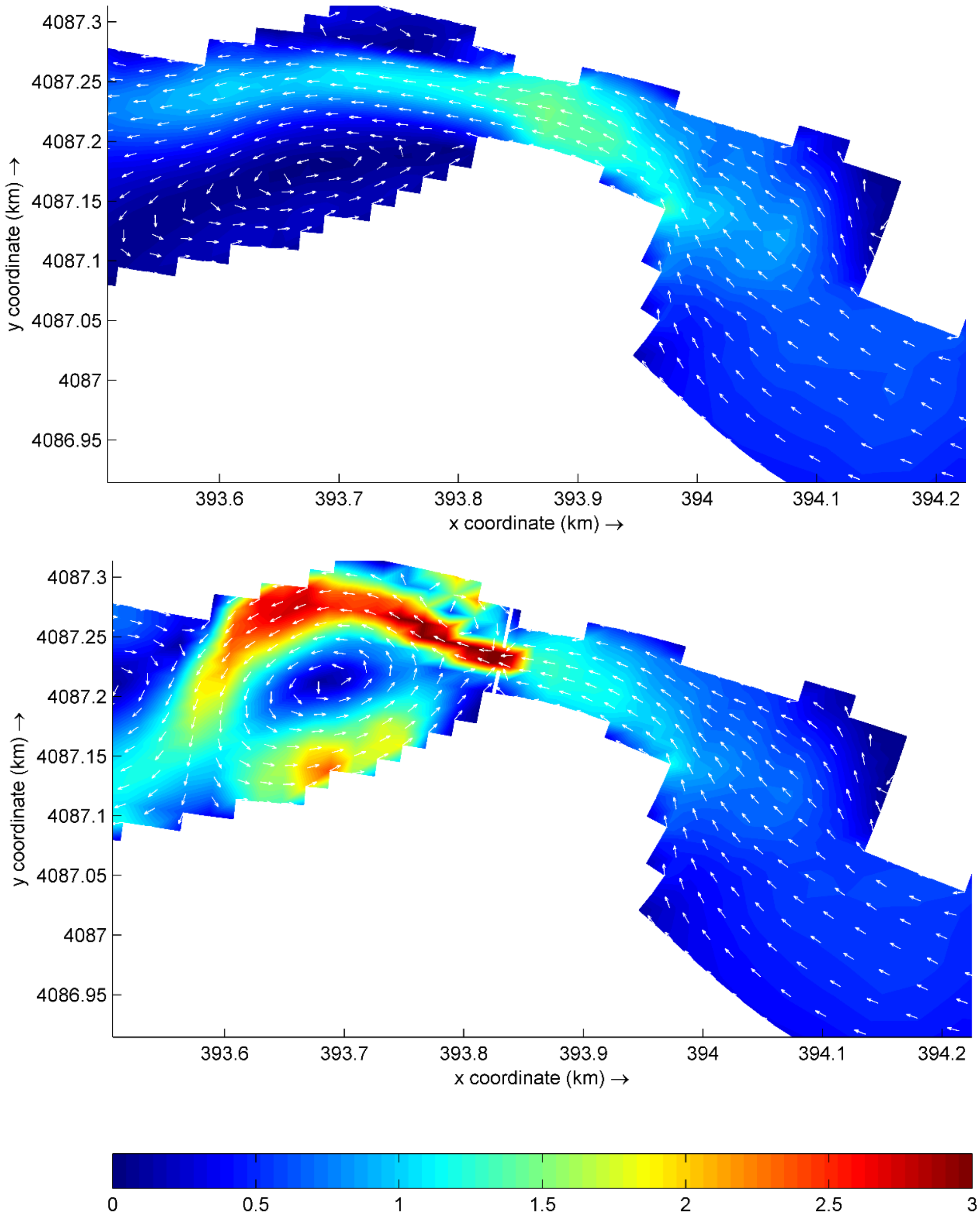


Figure 36: Depth averaged peak flood velocities (in ft/s) for the *without Project* (top) and *with Project* (bottom) simulations under existing condition

4.3 SUMMARY

Table 2 gives the summary of the spatially averaged model results of flushing time, tidally averaged freshwater residence time, and tidally averaged salinity under the typical summer conditions. The project impacts are negligible under both existing and future conditions. The very small, but quantifiable metrics in Table 2 indicate slightly increased flushing rates with the project, possibly due to increased secondary circulation associated with higher flow velocities through the gate structure.

Table 2: Summary of Pretty Lake typical summer condition results.

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*	9.5	14.6	21.9	12.3	11.6	19.9
Existing condition *with Project*	8.6	14.4	22.0	11.0	11.5	19.9
Future condition *without Project*	8.7	13.9	22.5	7.3	10.6	21.5
Future condition *with Project*	7.8	13.6	22.6	7.0	10.4	21.5

5 POST-STORM RECOVERY RESULTS

5.1 EXISTING CONDITIONS RESULTS

Time series of depth-averaged freshwater tracer concentrations and depth-averaged salinities at four locations upstream of the proposed project site (see Figure 21) are compared for the *without Project* and *with Project* conditions. Figure 37 to Figure 40 present the model results under the existing condition. Time "0" in the figures indicates the time of flood gate closing before the storm, and "Gate Open" on the time axes indicates the gate re-opening after the storm. The decay rate for the decaying tracer was set to 0.5 per day.

With Project, and prior to gate re-opening, freshwater tracer concentrations exhibit higher values in the upstream area, which is more influenced by runoff sources. For the *without Project* scenario, the non-interrupted flow exchange with the Little 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 the *with Project* scenarios are greater than those *without Project*, but eventually (i.e., after about 30 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 7 days or less.

In upstream stations, an approximate period of 25 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).

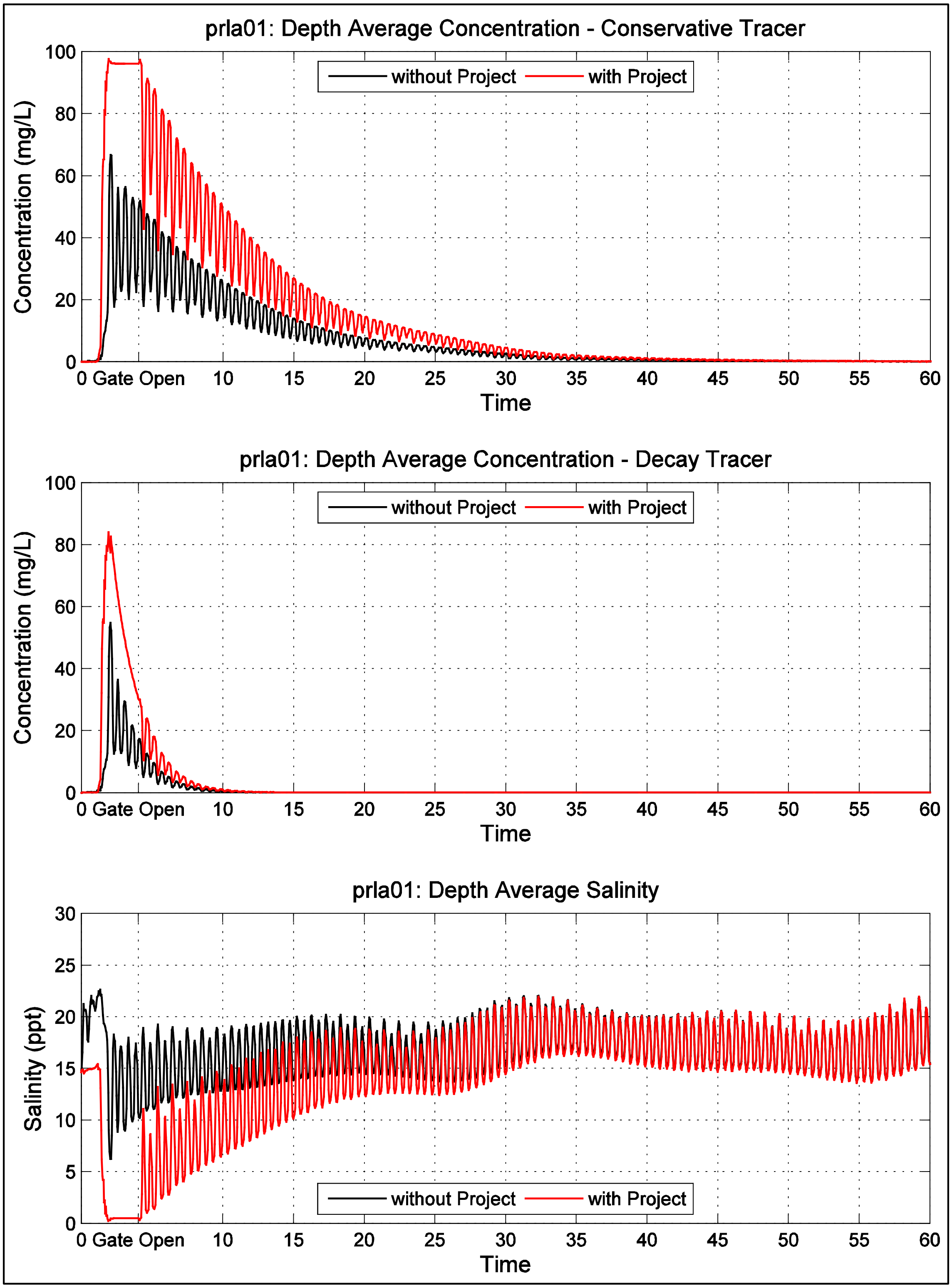


Figure 37: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla01 for a storm event under existing condition

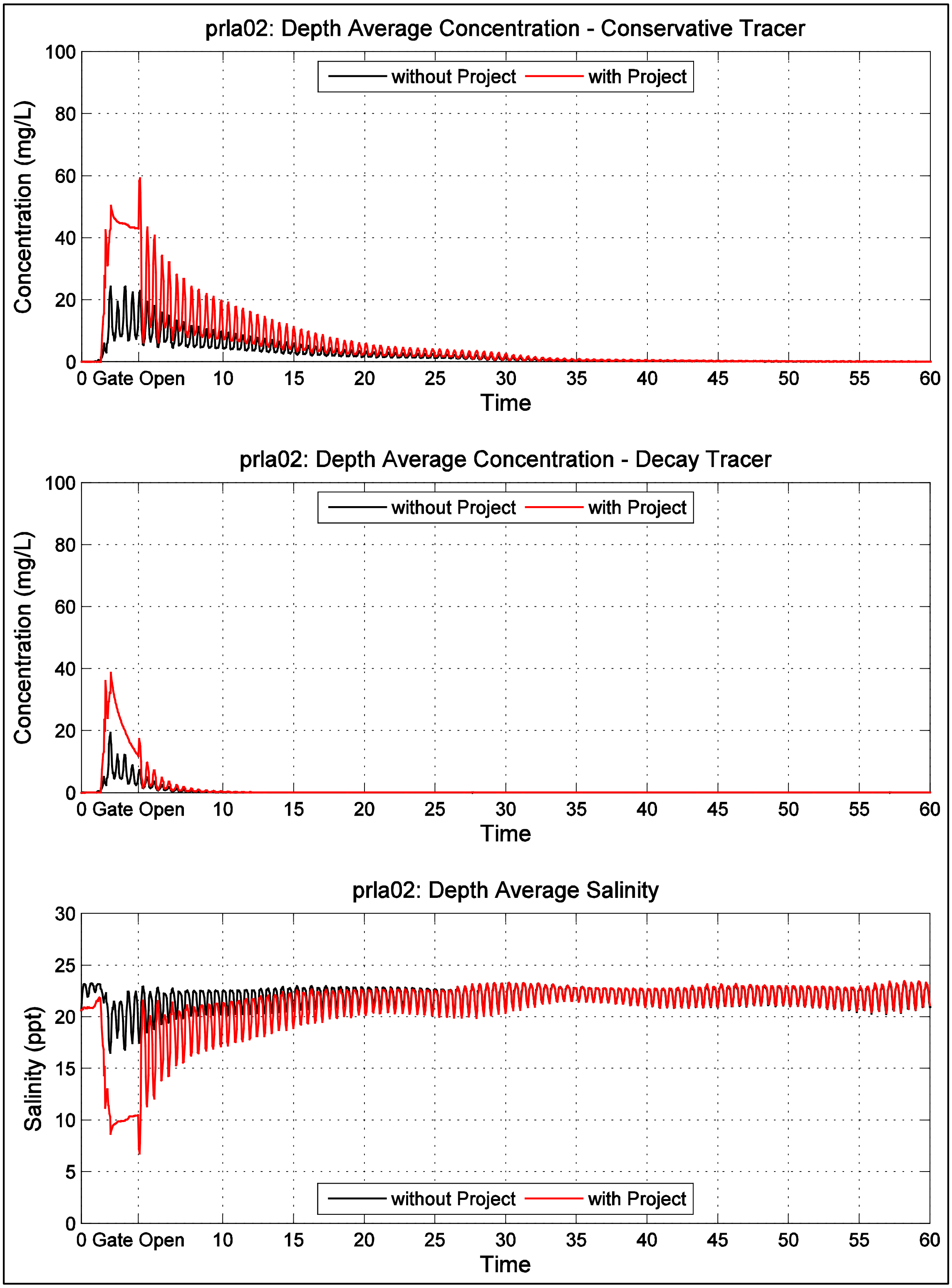


Figure 38: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla02 for a storm event under existing condition

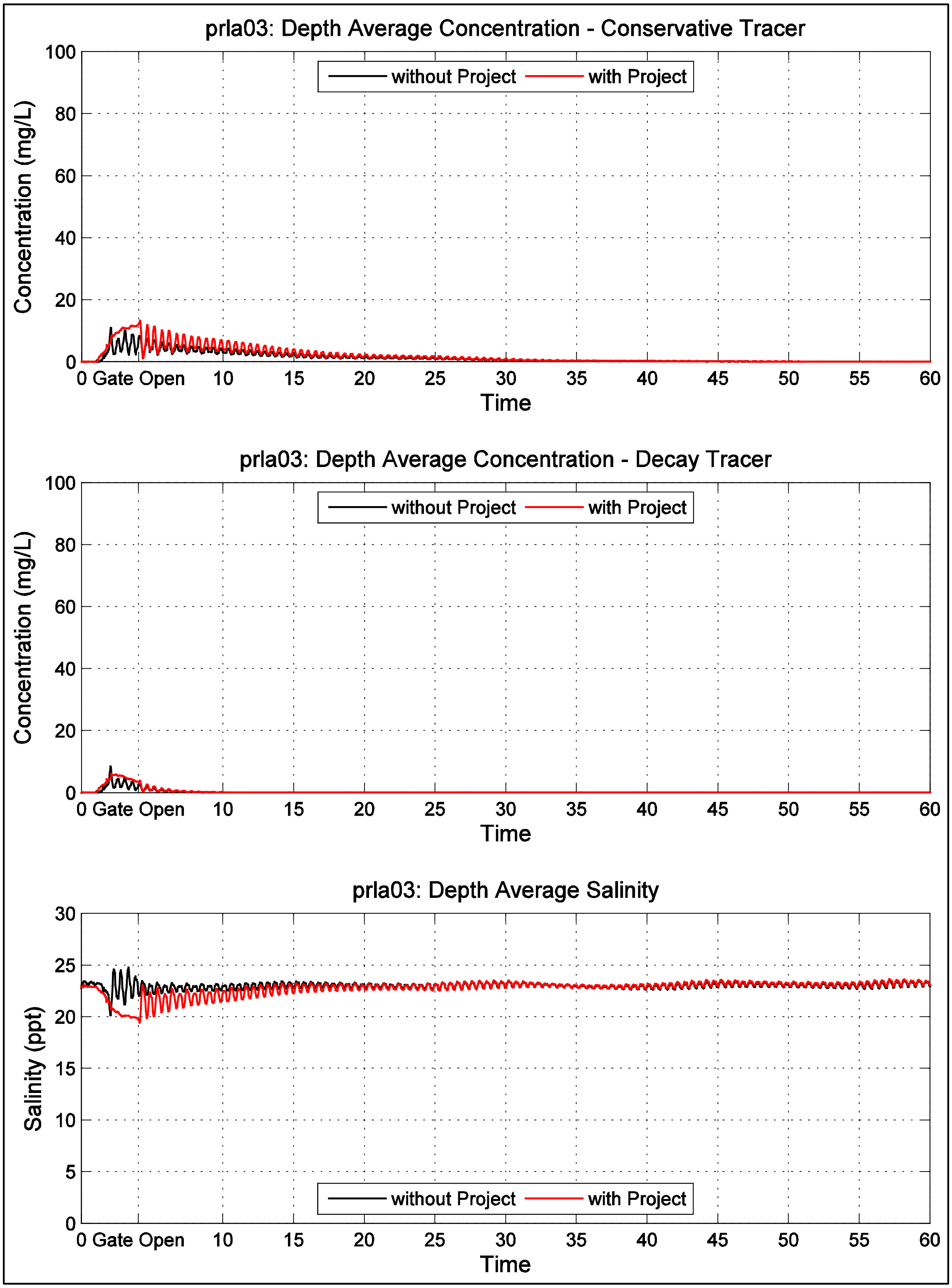


Figure 39: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla03 for a storm event under existing condition

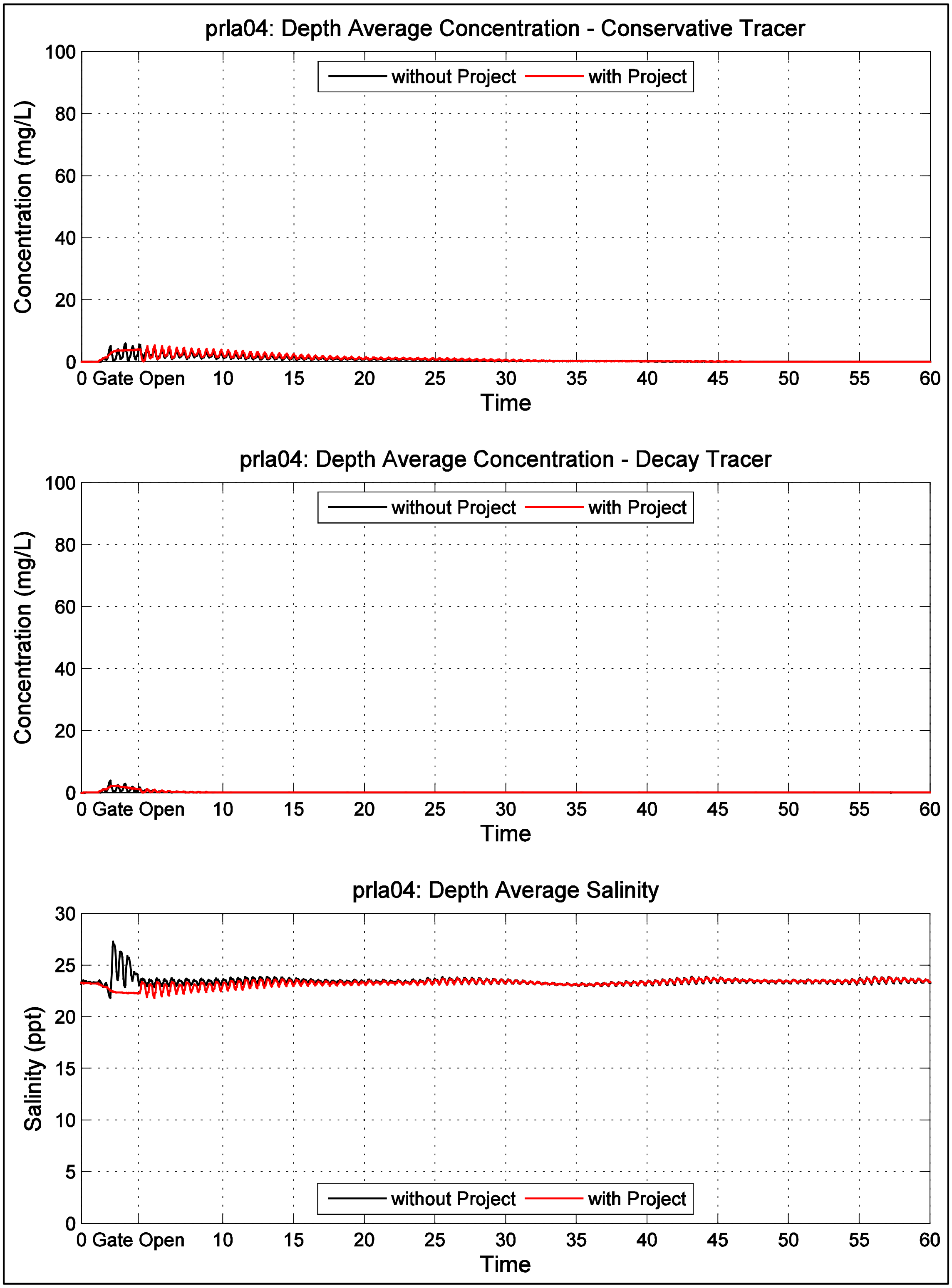


Figure 40: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla04 for a storm event under existing condition

5.2 FUTURE CONDITIONS RESULTS

Time series of depth-averaged freshwater tracer concentrations and depth-averaged salinities at four locations upstream of the proposed project site (see Figure 21) are compared for the *without Project* and *with Project* conditions. Figure 41 to Figure 44 present the model results under the future condition. Time “0” indicates the flood gate closing before the storm, and “Gate Open” on the time axes indicates the gate re-opening after the storm.

Under future conditions, the larger flow exchange in the bay with the Little Creek 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 when compared to the existing conditions.

Similar conclusions can be drawn for the flushing time and salinity responses between the *with* and *without Project* scenarios, when compared to the existing conditions.

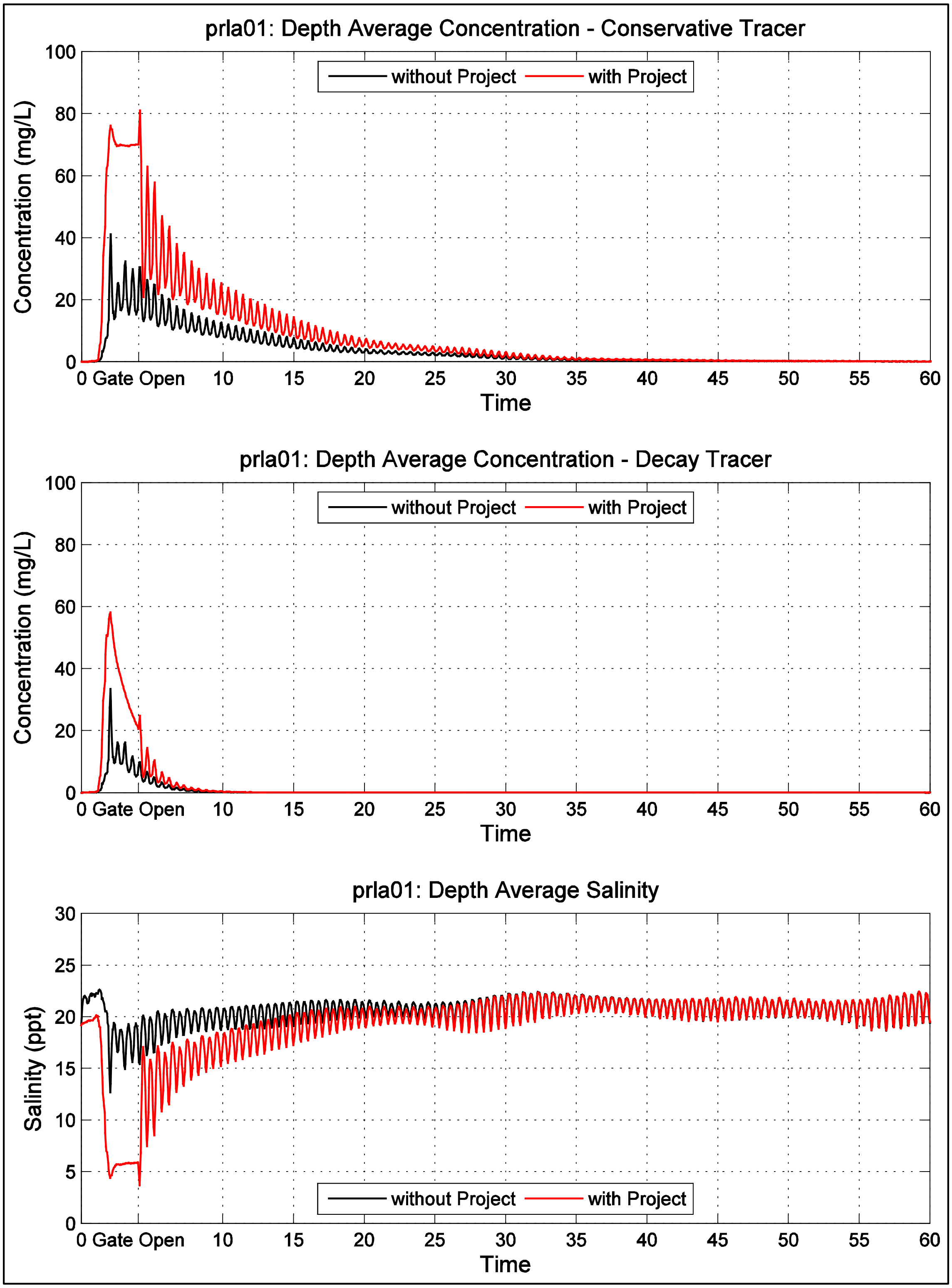


Figure 41: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla01 for a storm event under future condition

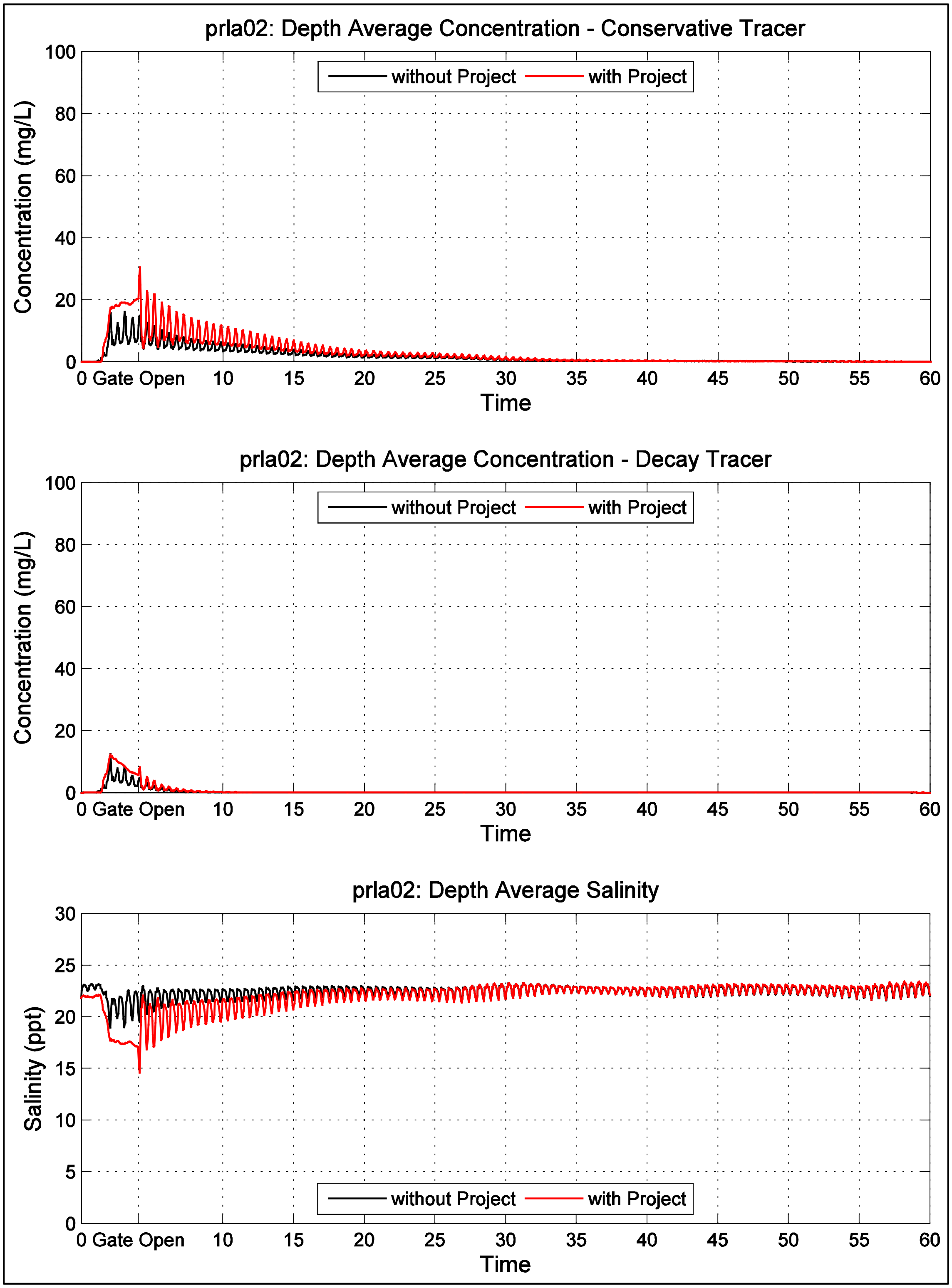


Figure 42: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla02 for a storm event under future condition

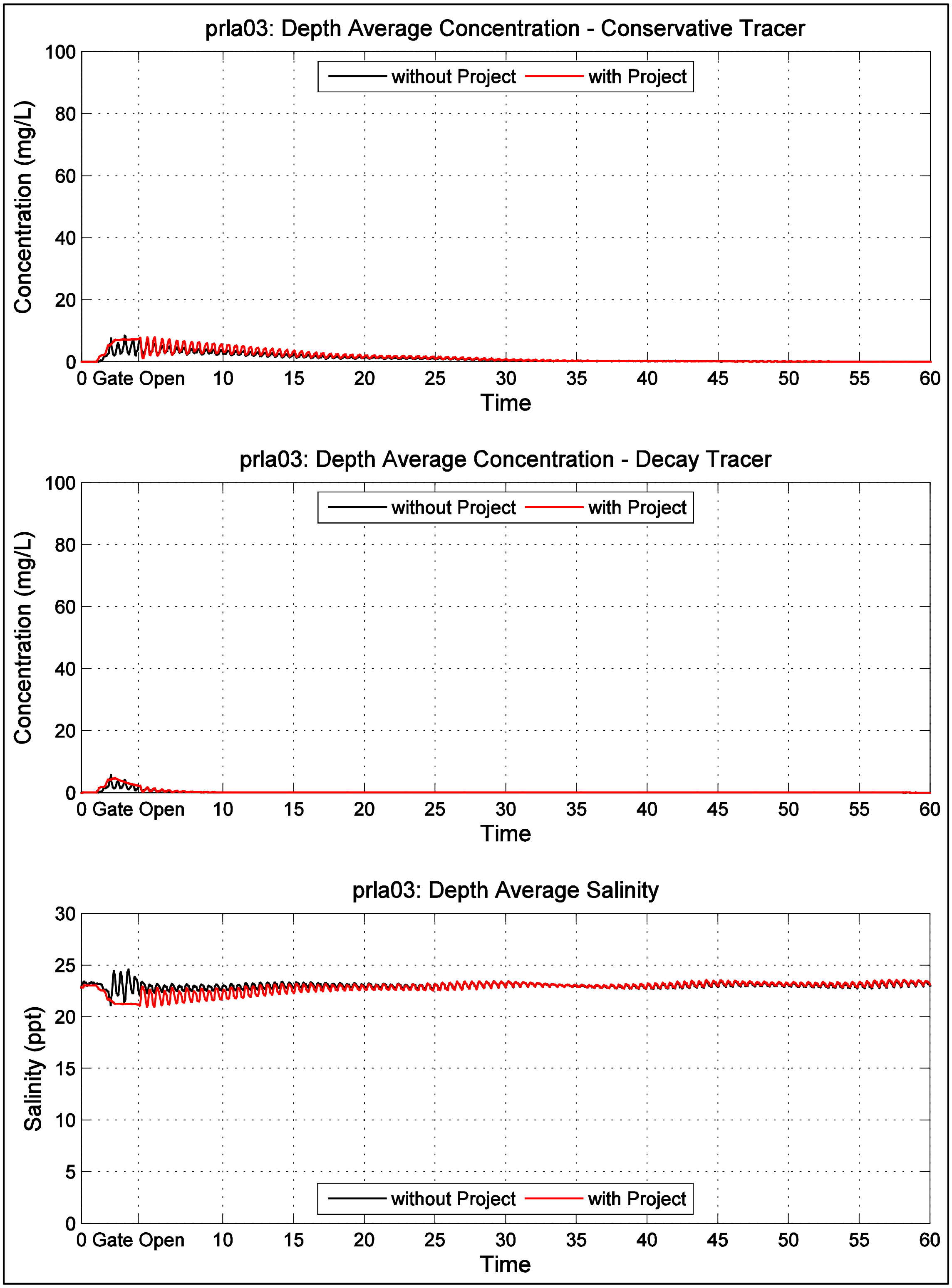


Figure 43: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla03 for a storm event under future condition

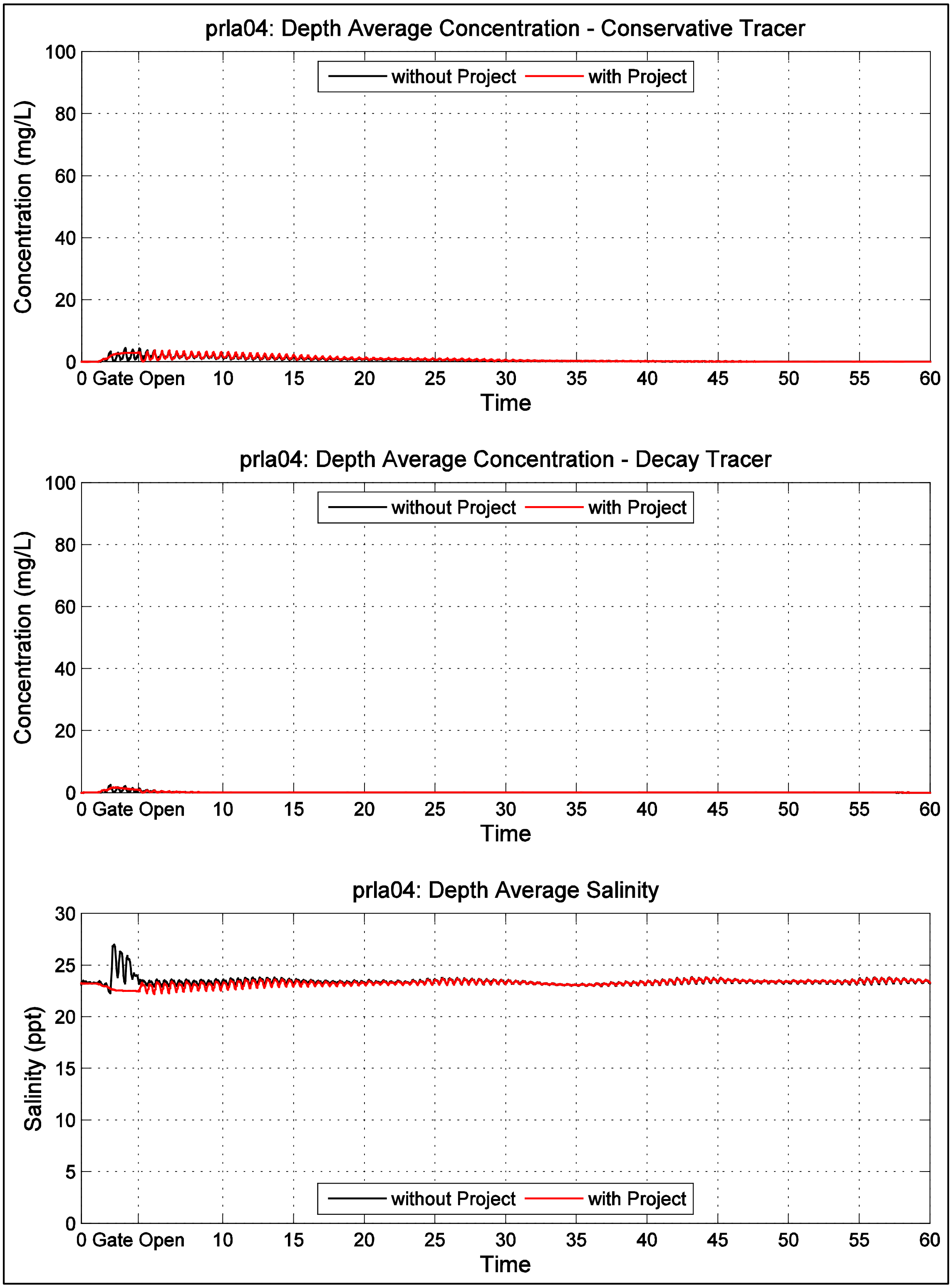


Figure 44: Time series of depth-average conservative tracer and decaying tracer concentrations and salinities at prla04 for a storm event under future condition

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 30 days (or less in downstream stations).
- All decaying tracer concentrations are gone in 7 days or less for all stations and all scenarios.
- Salinity for *with Project* coincides with salinity for *without Project* after about 25 days (or less in downstream stations).