FINAL FEASIBILITY REPORT AND INTEGRATED ENVIRONMENTAL ASSESSMENT

Appendix A

LYNNHAVEN RIVER BASIN ECOSYSTEM RESTORATION

VIRGINIA BEACH, VIRGINIA

U.S. Army Corps of Engineers
Norfolk District
803 Front Street
Norfolk, Virginia 23510-1096

July 2013

APPENDIX A

ENGINEERING, DESIGN, AND COST ESTIMATES

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ENGINEERING, DESIGN, AND COST ESTIMATES

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1	DEVELOPMENT OF THE HYDRODYNAMIC AND WATER QUALITY MODELS FOR THE LYNNHAVEN RIVER SYSTEM
2	NUMERICAL MODELING SCENARIO RUNS TO ASSESS TSS AND CHLOROPHYLL REDUCTIONS CAUSED BY ECOSYSTEM RESTORATION, LYNNHAVEN RIVER

INTRODUCTION

This Engineering Appendix outlines the engineering and design work to support the preparation of the Lynnhaven River Basin Environmental Restoration, Virginia Beach, Virginia.

Background

The study area covers the entire 64 square mile drainage area of the Lynnhaven River Basin which contains mostly developed neighborhoods and shopping centers. The Lynnhaven River complex, which includes the mainstem, the Eastern Branch, the Western Branch, and Broad Bay/Linkhorn Bay, is located in the city of Virginia Beach, along the southern shore of the Chesapeake Bay, between Cape Henry and the city of Norfolk.

The Lynnhaven River is the largest tidal estuary in the city and lies in the heart of the urbanized northern half of the city. This resource has 150 miles of shoreline and hundreds of acres of marsh, mudflat, and shallow water habitats. The river supports a tremendous level of recreational boating and fishing, crabbing, ecotourism, and general environmental observation. The navigational needs of the residents and users of the river are an integral part of the river's attraction. However, the river has become increasingly stressed over the past 30-plus years, as the watershed has experienced a shift from a predominantly rural to a predominantly urban/suburban land use pattern. This conversion has subjected the river to the expected accompanying development pressures related to the concurrent loss of natural buffers and increases in population and density.

Project Objective

The project objective is to develop a National Ecosystem Restoration (NER) Plan that reasonably maximizes environmental restoration benefits compared to costs, consistent with the Federal objectives. The selected plan will be shown to be cost-effective and justified to achieve the desired level of output.

HYDRODYNAMIC AND WATER QUALITY MODELING

Biological, topographical, and hydrological data were collected (as well as laboratory experiments) and used to support the development of a hydrodynamic and water quality model used to characterize existing conditions and model the future-without-project scenarios as well as future-with-project scenarios. The numerical modeling framework involves an integrated approach that combined several different processes such as hydrodynamic, water quality, nutrient, sediment processes in order assess nutrient load reductions for the Lynnhaven River system. Whereas the CE-QUAL-ICM (Corps of Engineers integrated compartment water quality model) is the central processing model, it depends, heavily upon the other models with which it interacts, such as the UnTRIM (Unstructured Tidal, Residual, and Intertidal Mudflat) hydrodynamic model for mass and volume transport, the HSPF (Hydrological Simulation Program – FORTRAN) watershed model for freshwater discharge and nutrient loadings, and the sediment model for sediment flux information.

The hydrodynamic model UnTRIM was used in this study as well as an ecological benefits model described in Chapter 9 of the main report. UnTRIM is a semi-implicit, finite difference (volume) model based on the three-dimensional shallow water equations as well as on the three-dimensional transport equation for salt, heat, dissolved matter, and suspended sediments. UnTRIM is governed by the equations of motion, the equation of continuity, and the transport equation. The model is intended to develop a methodology to assess the impact of proposed restoration plans, including Sub-Aquatic Vegetation (SAV), scallops, and fish reefs (including oyster reefs), on the Total Suspended Solids (TSS) and chlorophyll levels near these restoration sites. Final results of the modeling efforts are included in attachments 1 and 2 to this appendix.

SURVEY DATA

Hydrographic survey data was collected within the study area as part of the USACE Federal Navigation Channel maintenance in addition to the specific bathymetric surveys that was carried out in potential restoration areas. Topographic elevations were obtained from LiDAR data processed into a DEM provided to the Corps by the study Sponsor. All surveys are referenced to North American Datum (NAD) 1983 for horizontal and North American Vertical Datum (NAVD) 1988 for vertical elevations.

FLOOD RISK

The coastal areas of Virginia Beach are vulnerable to tidal flooding from major storms commonly referred to as hurricanes and northeasters. Both types of storms produce winds that push large volumes of water against the shore. Hurricanes, with their high winds and heavy rainfalls, are the most severe storms that hit the area. The term “hurricane” is applied to an intense cyclonic storm originating in tropical or subtropical latitudes in the Atlantic Ocean just north of the equator. A study of the tracks of all tropical storms for which there is a record indicates that, on an average of once a year, a tropical storm of hurricane force passes within 250 miles of the area and poses a threat to Virginia Beach. While hurricanes can affect the area from May through November, nearly 80 percent occur in the months of August, September, and October, with approximately 40 percent occurring in September. The most severe hurricane to strike the area occurred in August 1933. Other notable hurricanes that caused significant flooding in Virginia Beach were those of September 1933, September 1936, September 1960 and Hurricane Isabel 2003.

Another type of storm that can cause severe damage to the city is the northeaster. This is also a cyclonic-type storm and originates with little or no warning along the middle and northern Atlantic Coast. Northeasters occur most frequently in the winter, but can occur at any time. Accompanying winds are not of hurricane force, but are persistent, causing above-normal tides for long periods of time. The March 1962 northeaster was the worst to hit the study area. Other northeasters that caused significant flooding in Virginia Beach include those of March 1927, October 1948, April 1956, and November 2009. The depth of flooding during hurricanes and northeasters depends upon the velocity, direction, and duration of the wind; the size and depth of the body of water over which the wind is acting; and the astronomical tide. For instance, strong and persistent northerly and easterly winds will cause flooding of the shorelines of the Chesapeake Bay, the Atlantic Ocean, and their connecting inland waterways. Flooding in the Back Bay and North Landing River areas is caused by strong winds from a southerly direction. As would be expected, because of the larger size of the water bodies involved, flooding along the shorelines of the Chesapeake Bay, the Atlantic Ocean, and the Elizabeth River occurs in greater depth than flooding in the southern portion of the city.

Simultaneous flooding of both the outer coastal areas and southern bay areas of the city does not occur except in rare events when the surge-producing forces cause either the destruction or overtopping of the barrier dunes that separate the Atlantic Ocean from the inland waters in the southern portion of the city. The duration of the flooding depends upon the duration of the tide producing forces. Floods caused by a hurricane are usually of much shorter duration than the ones caused by a northeaster. Flooding from hurricanes rarely lasts more than one tidal cycle, whereas flooding caused by northeasters can last several days, during which the most severe flooding takes place at the time of the peak astronomical tide. The timing or coincidence of the maximum storm surge with the normal high tide is an important factor in the consideration of flooding from tidal sources. Tidal waters in the study area normally fluctuate twice daily about 3 feet in the Atlantic Ocean and approximately 2 feet in the Lynnhaven River. The range of fluctuations is somewhat less in most of the connecting interior waterways. There are no measurable astronomical tides in Back Bay or the North Landing River that is minimally connected hydraulicallywell to the south of this study. Flooding can occur as a result of an intense rainfall produced by local summer thunderstorms, or tropical disturbances, such as hurricanes, that move into the area from the Gulf of Mexico or Atlantic Coast. Flood heights on these streams can rise from normal to extreme flood peaks in a relatively short period of time. The duration of flooding depends on the duration of runoff producing rainfall. In some cases, floods may last for a couple of days, whereas floods occurring as a result of short duration summer thunderstorms usually rise to a maximum peak stage and subside to near normal levels in less than a day. The following table lists tidal flood elevation values from the Lynnhaven River flood insurance study.

Table 1. SUMMARY OF STILLWATER ELEVATIONS (NAVD 88)

LOCATION	10 Percent	2 Percent	1 Percent	0.2 Percent
LYNNHAVEN BAY	4.9	6.2	6.8	8.2
LYNNHAVEN RIVER	4.9	6.2	6.8	8.2
BROAD BAY	4.3	5.4	5.9	7.1
LINKHORN BAY	4.3	5.4	5.9	7.1

All of the alternatives considered in the study have the potential to be impacted by intense storm events such as hurricanes or northeasters. The degree of damage and the length of recovery time depend mainly on the duration, magnitude and direction of wind-driven waves. The probability of complete habitat loss for each alternative is relatively low because the wetlands are located in sheltered creeks or protected with riprap. The most likely damage would come from “rack” debris covering wetland plants. Storm impacts to the reef habitat sites are not considered significant because these sites are submerged under several feet of water. The SAV sites are susceptible to storm wave degradation; however these areas should recover after several growing seasons.

Tides

Tides in the Lynnhaven have been extensively studied and sufficient data exists to describe the general tidal pattern in the estuary. The tidal range reported at the Chesapeake Bay Bridge Tunnel north of the inlet in Chesapeake Bay, is approximately 3 feet. The range reported for Lynnhaven Inlet is 2 feet as this constricted inlet controls tides throughout the basin, which are generally 2 feet or less. Tidal data assembled by the Virginia Institute of Marine Science shows that the Long Creek Channel project of the mid-1960's was successful in achieving its goal of increased tidal flushing of Broad and Linkhorn Bays. These increases were predicted fairly accurately by the USACE study of 1952 (presented in USACE 1962), using fixed and movable bed models. Tidal amplitude has increased in Broad Bay from 0.2 feet to 0.95-1.2 feet, and in Linkhorn Bay from 0.2 feet to 1.01-1.3 feet. Additionally, the phase lag between tides at the inlet and in the bays has been reduced some 2 hours in Broad Bay and 1.5 hours in Linkhorn Bay. Tidal amplitude in the East and West Branches was measured as 2.1 and 1.95 feet, respectively, in 1947, and as 2.0 and 2.0 feet in 1973; this is not a significant change. Virginia Institute of Marine Science, reports that tide ranges are fairly uniform in the branches, even in upstream reaches. Mean tide ranges in the vicinity of the Lynnhaven River are listed below.

Table 2. TIDE RANGES (ft) IN THE VICINITY OF THE STUDY AREA

Location	Tide range
Chesapeake Bay Bridge Tunnel	2.55
Lynnhaven Inlet	2.22
Broad Bay Canal	1.38
Long Creek	1.68

*NOAA Tide Chart

Sea Level Rise. Data collected by the Sewells Point tide gauge in Virginia was used to project SLR for the Lynnhaven Project. This particular gauge has been collecting tide and sea level change information since 1927. As required by USACE policy (EC 1165-2-211 - Incorporating Sea-Level Change Considerations in Civil Works Programs) increases in sea level were calculated for three different accelerating eustatic sea level rise (SLR) scenarios - low, intermediate and high. Sea level is projected to rise by 0.73 ft within fifty years if the rate of increase remains consistent with historic trends as described in the low scenario. The intermediate scenario predicted a 1.14 ft increase in the sea level, while the high scenario forecasted that sea level will increase 2.48 ft over the 50-year life span of the project.

Table 3. PROJECTED INCREASE IN SEA LEVEL FROM INITIAL CONSTRUCTION, 2014 THROUGH THE 50 YEAR LIFE SPAN OF THE LYNNHAVEN RIVER BASIN ECOSYSTEM RESTORATION PROJECT

Year	Low Scenario (ft)	Intermediate Scenario (ft)	High Scenario (ft)
2014	0	0	0
2019	0.07	0.10	0.17
2024	0.15	0.20	0.36
2029	0.22	0.30	0.57
2034	0.29	0.41	0.79
2039	0.36	0.52	1.03
2044	0.44	0.64	1.29
2049	0.51	0.76	1.56
2054	0.58	0.88	1.85
2059	0.66	1.01	2.15
2064	0.73	1.14	2.48

The two elements of the Lynnhaven Study that will be most influenced by sea level rise are SAV and wetland restoration, while SLR will have little or no effect on reef habitat and bay scallops. Although bay scallops prefer SAV habitat, they are also associated with sand and muddy bottoms and will persist without SAV. If the locations of the SAV beds shift due to the effects of SLR, the bay scallop population will adjust with the SAV beds. As sea level rises, the depth of the reef balls will increase; however, the fish and invertebrates within the basin will continue to utilize the structures. SLR may limit the amount of algae that depends on light transmission using the reef habitat.

Two recent studies have investigated the impact of SLR on the tidal wetlands of the Virginia Beach area. In the first, the U.S. Climate Change Science Program (Cahoon et al., 2009) assessed wetlands of the mid-Atlantic Region, and the second was completed by VIMS and concentrated specifically on tidal marshes in the Lynnhaven Basin (Berman and Berquist, 2009).

The U.S. Climate Change Science Program study predicted wetland survival using three different scenarios, twentieth century rates of SLR, a 2 mm/yr (0.007 ft/yr) acceleration of SLR, and a 7 mm/yr (0.02 ft/yr) increase (Cahoon et al., 2009). The study concluded that wetlands in the Virginia Beach area would keep pace with increases to ocean levels predicted in Scenario 1, but would not survive and would be converted to open water if sea level increased at the rate described by Scenario 3. The fate of local wetlands could not be determined at the Scenario 2 rate of increase and would be dependent on hydrology and sediment supply.

The VIMS wetland study also assessed SLR at three different rates (Berman, 2009). The most conservative prediction used an increase of 4.1 mm/yr (0.01 ft/yr), a rate similar to the historic SLR observed at the Sewell’s Point, VA tide gauge. This scenario predicted increases in sea height by 102.50 mm (0.40 ft) and 205 mm (0.67 ft) at years 2032 and 2057 respectively, resulting in the loss of nearly 30 percent of all wetlands in the Lynnhaven Basin over the next 50 years. Two more aggressive rates, 7.35 mm/yr (0.02 ft/yr) and 17.20 mm/yr (0.06), were used to project SLR out to year 2100. Increases in sea level of 683 mm (2.24 ft) and 1600 mm (5.25 ft) were calculated for the medium and high accelerated rates, resulting in the loss of 95 percent and 100 percent of all wetlands.

GEOLOGY

Soils in the watershed are generally loams and sandy loams, which overlie deep deposits of unconsolidated stratified lenticular sand and silt with some gravel and clay. Soils are easily erodible when cleared of vegetation. Generally, soils are permeable, and Chipman (1948) reports that there is very little surface drainage, and much of the fresh water resulting from rains enters by percolation through the porous subsoils of the banks. As the watershed becomes developed, paved, and ditched, rain waters increasingly enter the estuary as storm water runoff. Stream flow data for tributaries of the Lynnhaven system are unavailable, as there are no gauged streams in the vicinity.

Watershed areas for tributary streams are small, and stream flow is greatly reduced during dry periods. This is evidenced by salinity data, which indicate nearly isohaline conditions throughout the estuary following periods of little precipitation. Generally, salinity increases toward the inlet and decreases in upstream reaches. During hot dry periods, a reverse salinity gradient can develop in the estuary, where, due to evaporation, limited flushing, and low fresh water input, upper reaches may become more saline than areas closer to the inlet. Tidal exchange has increased in Broad and Linkhorn Bays since the completion of the Long Creek project, but it is not clear how the Eastern and Western Branches were affected by these changes.

GEOTECHNICAL INVESTIGATIONS

Norfolk District conducted a subsurface investigation in November 2009 to determine the extent of sandy bottom conditions at various locations throughout the Lynnhaven River system (see Plate 1). Vibracore sampling was conducted from a shallow draft sectional barge utilizing a Trimble Model 132 DGPA unit with submeter accuracy for location determination and a hydraulically operated four point mooring system to position and stabilize the barge while sampling. The vibracore equipment was deployed using a 5,000 lb. capacity hydraulic winch and cable, routed through a 40-foot articulated mast in the middle of the barge. Refer to the following figures for results and boring locations. Samples collected during the subsurface investigation were approximately 10 in length and visually classified according to the Unified Soils Classification System. Boring logs and grain size distribution graphs results are available upon request.

Table 4. SUBSURFACE INVESTIGATION RESULTS

Pt Num	Pt Name	X	Y	Lat	Long	Depth of Water	Fines	Sands	Depth to Sand	Bottom MLLW	Sand Elevation	
1	1 as-built	12183762.15	3493581.96	36.89322808	-76.10315105	6.9	2.6 - 3	0 - 2.6, 3 - B.O.H.	3	-5.1	-8.1	
2	2 as-built	12184261.36	3494167.86	36.89480198	-76.10139361	3.6		0 - B.O.H.	0	-1.8	-1.8	
3	3 as-built	12184265.92	3493695.69	36.89350521	-76.10141904	5.2		0 - B.O.H.	0	-3.4	-3.4	
4	4 as-built	12184768.18	3494168.33	36.89476789	-76.09966099	4.6		0 - B.O.H.	0	-2.9	-2.9	HILL POINT
5	5 as-built	12184756.27	3493674.48	36.89341275	-76.09974464	4		0 - B.O.H.	0	-1.8	-1.8	
6	6 as-built	12185264.12	3494179.50	36.89476392	-76.09796463	2.9		0 - B.O.H.	0	-1.4	-1.4	
7	7 as-built	12185273.99	3493794.90	36.89370723	-76.09796435	4		0 - B.O.H.	0	-2.3	-2.3	
8	8 as-built	12185769.47	3494167.88	36.89469669	-76.09623808	3.5		0 - B.O.H.	0	-2.3	-2.3	
9	9 as-built	12185597.63	3493945.82	36.89409899	-76.09684485	5	0.8 - B.O.H.	0 - 0.8	4.2	-3	-7.2	
10	10 as-built	12192168.26	3492931.43	36.89085227	-76.07447239	3.3		0 - B.O.H.	0	-1.8	-1.8	
13	13 as-built	12192962.80	3491808.47	36.88771286	-76.07185514	5.5	0 - 5.6	5.6 - B.O.H.	5.6	-4.4	-10	
14	14 as-built	12193242.30	3491395.96	36.88656049	-76.07093604	4	0 - 1	1 - B.O.H.	1	-3.8	-4.8	
16	16 as-built	12193820.85	3490575.75	36.88426753	-76.06903069	3	2 - 3.5	0 - 2, 3.5 - B.O.H.	3.5	-1	-4.5	
17	17 as-built	12193977.76	3490142.83	36.88306777	-76.06853249	3		0 - B.O.H.	0	-0.2	-0.2	BROCK COVE
19	19 as-built	12193672.91	3491649.14	36.88722520	-76.06944187	4	0 - 1	1 - B.O.H.	1	-2.4	-3.4	
23	23 as-built	12193315.88	3493060.80	36.89112644	-76.07053806	3	0 - 4.5	4.5 - B.O.H.	4.5	-1.8	-6.3	
25	25 as-built	12193810.96	3492353.14	36.88914841	-76.06890801	4	0 - 3	3 - B.O.H.	3	-2.1	-5.1	
26	26 as-built	12194108.12	3491930.78	36.88796772	-76.06792944	3.4	0 - 0.5	0.5 - B.O.H.	0.5	-0.6	-1.1	
29	29 as-built	12194152.29	3493255.02	36.89160056	-76.06766181	1.5	3 - B.O.H.	0 - 3*	0	-0.8	-0.8	3' of sand on top
30	30 as-built	12194469.19	3492790.83	36.89030361	-76.06661944	2	0 - 0.5, 4 - B.O.H.	0.5 - 4*	0.5	-1.6	-2.1	3.5' of sand at 0.5' depth
36	36 as-built	12194082.30	3486839.30	36.87398987	-76.06846607	4	0 - 5	5 - B.O.H.	5	-3.2	-8.2	
39	39 as-built	12194561.90	3486949.52	36.87425856	-76.06681728	3.5	0 - 2.5	2.5 - B.O.H.	2.5	-2.4	-4.9	
40	40 as-built	12194621.21	3486671.57	36.87349120	-76.06663908	3	0 - 4.5	4.5 - B.O.H.	4.5	-1.9	-6.4	
42	42 as-built	12195167.62	3486580.56	36.87320262	-76.06477973	3.5	0 - 7	7 - B.O.H.	7	-1.9	-8.9	BROWN COVE
45	45 as-built	12194832.03	3488041.24	36.87723697	-76.06579787	5.9	0 - 5	5 - B.O.H	5	-3.6	-8.6	
47	47 as-built	12195429.10	3487664.16	36.87615933	-76.06379052	3	0 - 1.0	1.0 - B.O.H.	1	-0.7	-1.7	
53	53 as-built	12196110.12	3486285.18	36.87232478	-76.06158479	4	0 - 4	4 - B.O.H	4	-1.1	-5.1	
56	56 as-built	12206236.72	3494021.86	36.89284370	-76.02628460	13.1	0 - 1	1 - B.O.H.	1	-10.6	-11.6	
57	57 as-built	12206350.34	3494928.61	36.89532516	-76.02581495	11.5	0 - 1.4	1.4 - B.O.H.	1.4	-9.6	-11	
58	58 as-built	12206450.58	3494359.23	36.89375461	-76.02552331	12	0 - 3.3	3.3 - B.O.H.	3.3	-9.8	-13.1	
59	59 as-built	12206651.43	3493770.97	36.89212499	-76.02488946	10.5	0 - 4.2	4.2 - B.O.H.	4.2	-9	-13.2	BROAD BAY
60	60 as-built	12206778.23	3494118.87	36.89307107	-76.02442482	11.1	0 - 3	3 - B.O.H.	3	-9.5	-12.5	
61	61 as-built	12206696.50	3494782.28	36.89489846	-76.02464472	12	0 - 1.3	1.3 - B.O.H.	1.3	-9.6	-10.9	
62	62 as-built	12207039.20	3494488.98	36.89406847	-76.02349952	7.5		0 - B.O.H.	0			
P1	P1 as-built	12188143.00	3498134.00	36.90542026	-76.08777760	12		0 - B.O.H.	0			
P11	P11 as-built	12188431.00	3497568.00	36.90384597	-76.08684240	3	0 - 0.4	0.4 - B.O.H.	0.4			
P13	P13 as-built	12188143.00	3497979.00	36.90499468	-76.08779114	4		0 - B.O.H.	0			
P2	P2 as-built	12188187.00	3498049.00	36.90518379	-76.08763459	7		0 - B.O.H.	0			
P3	P3 as-built	12188236.00	3497952.00	36.90491402	-76.08747554	3.3		0 - B.O.H.	0			
P4	P4 as-built	12188212.00	3497825.00	36.90456699	-76.08756869	3.5		0 - B.O.H.	0			PILOT ISLAND
P5	P5 as-built	12188268.00	3498150.00	36.90545542	-76.08734883	3.3		0 - B.O.H.	0			
P6	P6 as-built	12188810.00	3497329.00	36.90316314	-76.08556753	9.2		0 - B.O.H.	0			
P7	P7 as-built	12188684.00	3497593.00	36.90389685	-76.08597523	3		0 - B.O.H.	0			
P8	P8 as-built	12188530.00	3497376.00	36.90331185	-76.08652072	3.6		0 - B.O.H.	0			
P9	P9 as-built	12188803.00	3497918.00	36.90478085	-76.08553995	3.6		0 - B.O.H.	0			
	Hill Point		Brock Cove		Brown Cove		Broad Bay		Pilot Island			

Figure 1. CORE LOCATIONS PILOT ISLAND

Pilot Island As-Built Core Locations
Note: NOAA S57 background chart is approximate, actual core locations plotted
Grid System: NAD83, VA South State Plane, US Survey Feet

Pilot Island

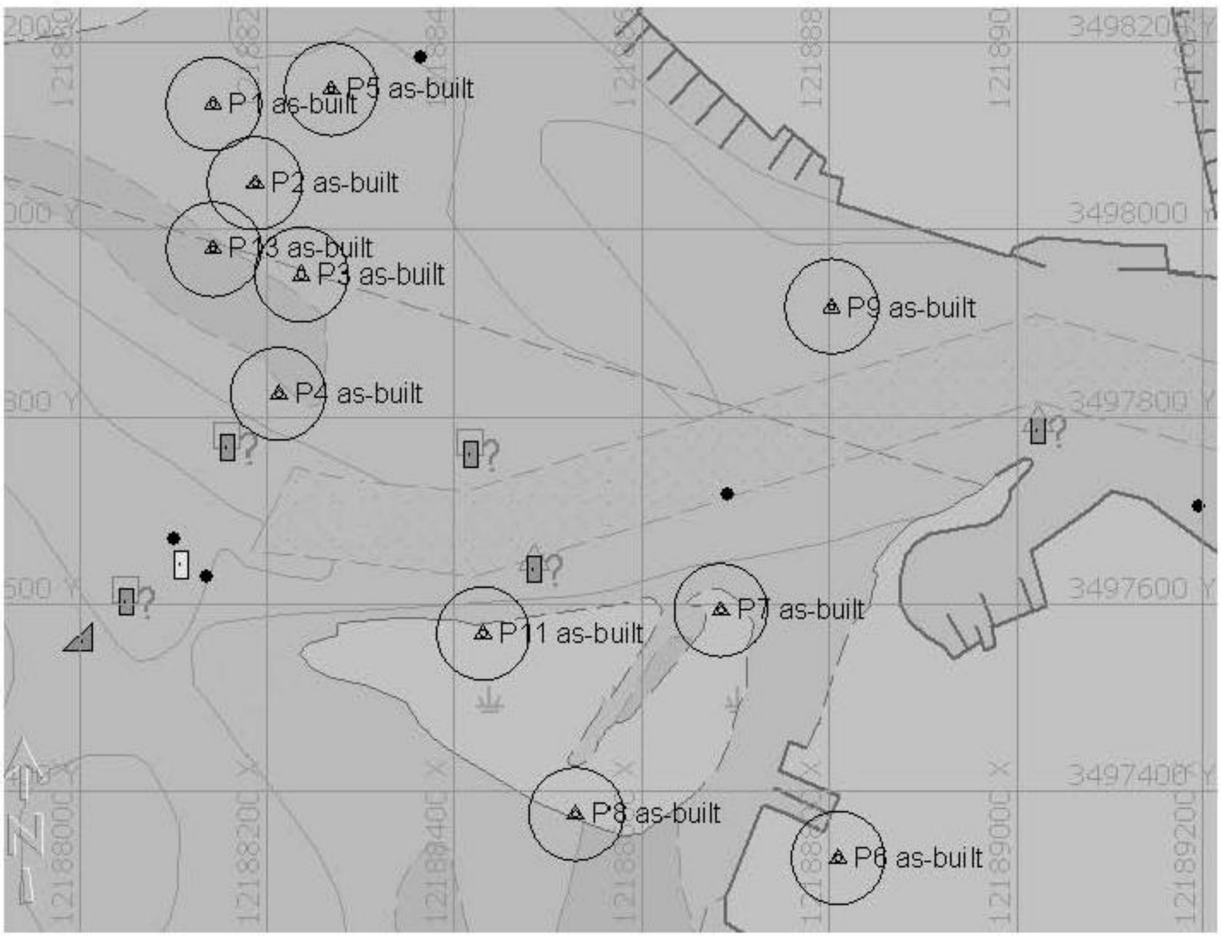


Figure 2. CORE LOCATIONS BROAD BAY

Broad Bay As-Built Core Locations
Note: NOAA S57 background chart is approximate, actual core locations plotted
Grid System: NAD83, VA South State Plane, US Survey Feet

Broad Bay

Figure 3. CORE LOCATIONS BROWN COVE

Brown Cove As-Built Core Locations
Note: NOAA S57 background chart is approximate, actual core locations plotted
Grid System: NAD83, VA South State Plane, US Survey Feet

Brown Cove

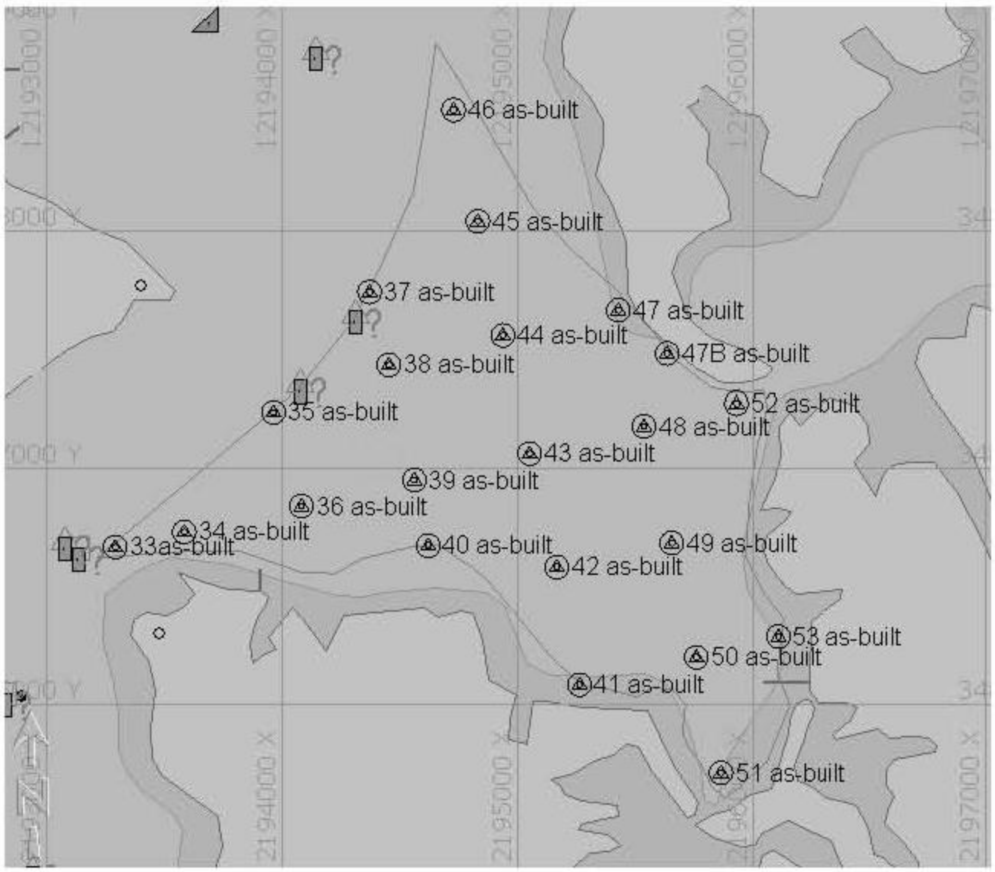


Figure 4. CORE LOCATIONS BROCK COVE

Brock Cove As-Built Core Locations
Note: NOAA S57 background chart is approximate, actual core locations plotted
Grid System: NAD83, VA South State Plane, US Survey Feet

Brock Cove

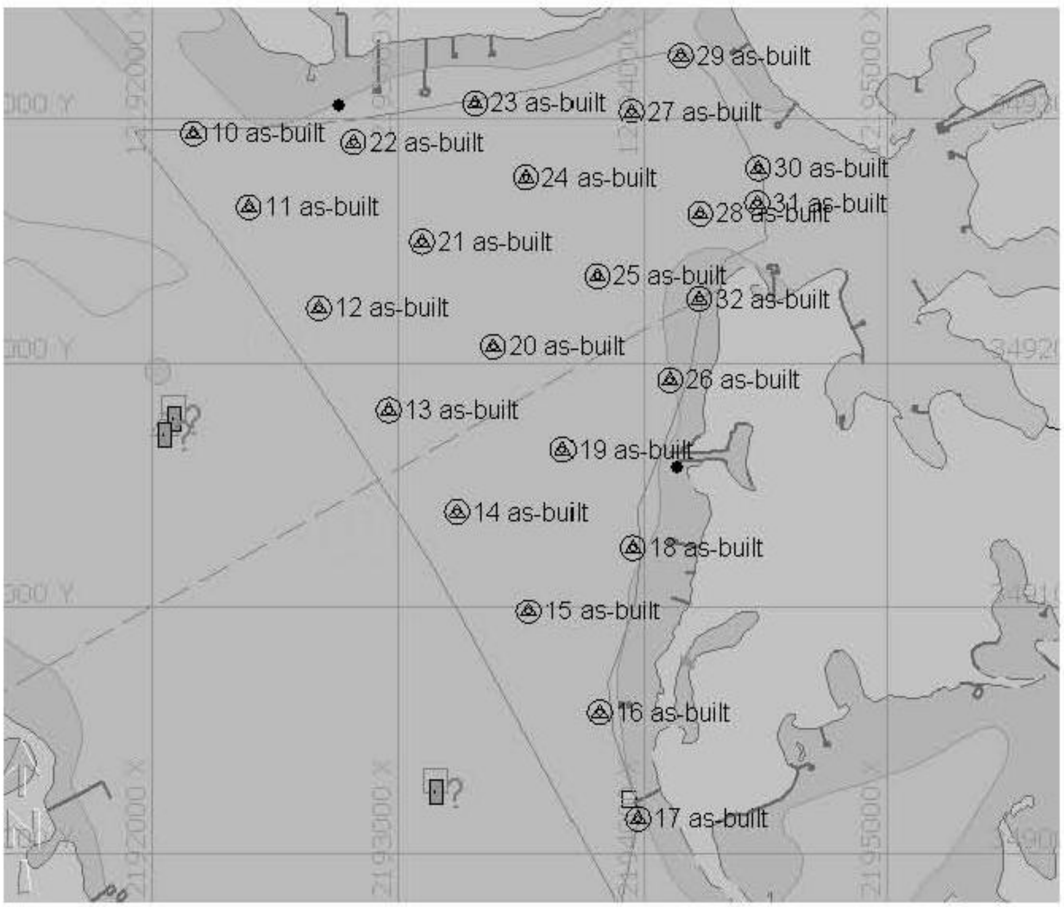
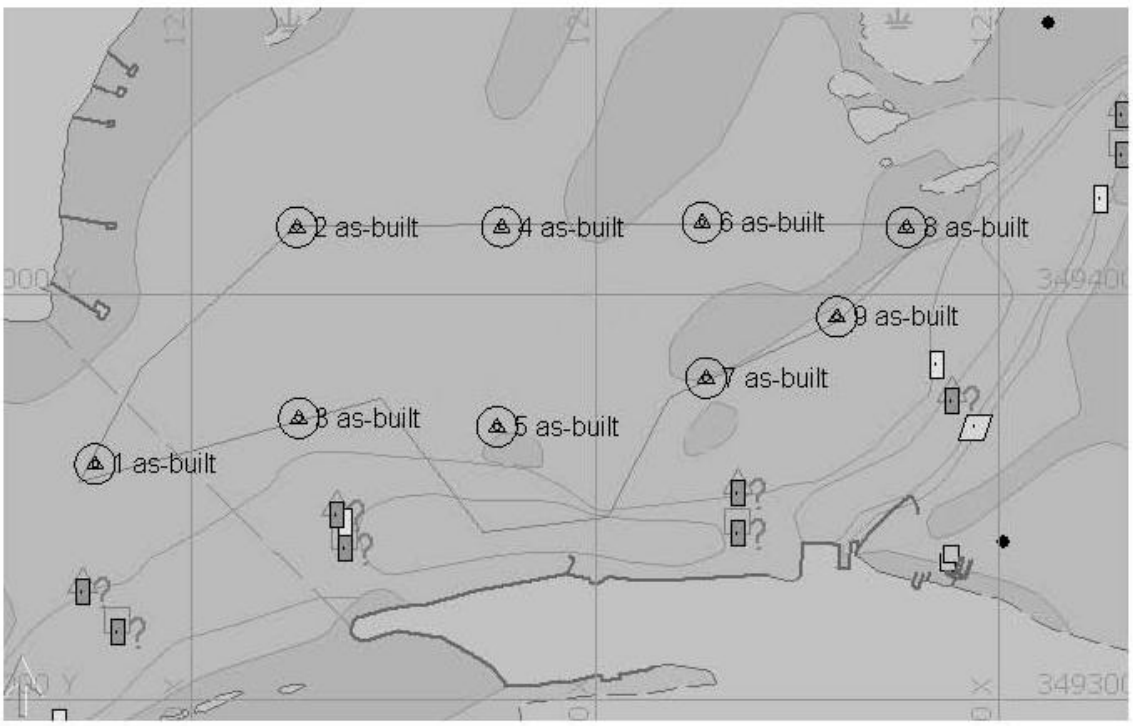


Figure 5. CORE LOCATIONS HILL POINT

Hill Point As-Built Core Locations
Note: NOAA S57 background chart is approximate, actual core locations plotted
Grid System: NAD83, VA South State Plane, US Survey Feet

Hill Point



CONCEPTUAL DESIGN ALTERNATIVES

General

Concept-level designs were developed for reef habitat, wetland creation and wetland restoration/diversification sites considered for evaluation. The SAVand bay scallop alternatives are explained in detail in the main report and are not included in this appendix with the exception that the information from the geotechnical investigations and the hydrodynamic modeling was used to identify potential sites based on bottom conditions and flow patterns.

Reef Habitat

There are nine sites identified for restoration of essential fish habitat utilizing reef balls within the Lynnhaven River. Four sites, totaling approximately 10.5 acres, were located for the construction of reef structure in the Lynnhaven mainstem. The restoration measure for these sites would involve placement of low relief reef balls that are approximately two feet in height. The five sites are in the Broad Bay/Linkhorn Bay complex and make up approximately 21 acres of potential fish reefs. Reef habitat (reef balls) designs were derived mainly from the website: reefball.org. Placement of high relief reef balls, up to 6 feet in height, was evaluated based on water depth and densities required for environmental benefits as described in the environmental appendix. An 8'x8'x12" geogrid mattress would be placed under reef ball in areas where soft bottom conditions exist. The selected plan locations are dispayed in plates 2 and 3 of the main report.

Table 4. REEF BALL PROPERTIES

Style	Width	Height	Weight	Concrete Volume	Surface Area	# Holes
Goliath	6 feet	5 feet	4,000-6,000 lbs.	1.3 yard3	230 ft2	25-40
Super Ball	6 feet	4.5 feet	4,000-6,000 lbs	1.3 yard3	190 ft2	22-34
Ultra Ball	5.5 feet	4.3 feet	3,500-4,500 lbs.	0.9 yard3	150 ft2	22-34
Bay Ball	3 feet	2 feet	375-750 lbs.	0.10 yard3	30 ft2	11-16

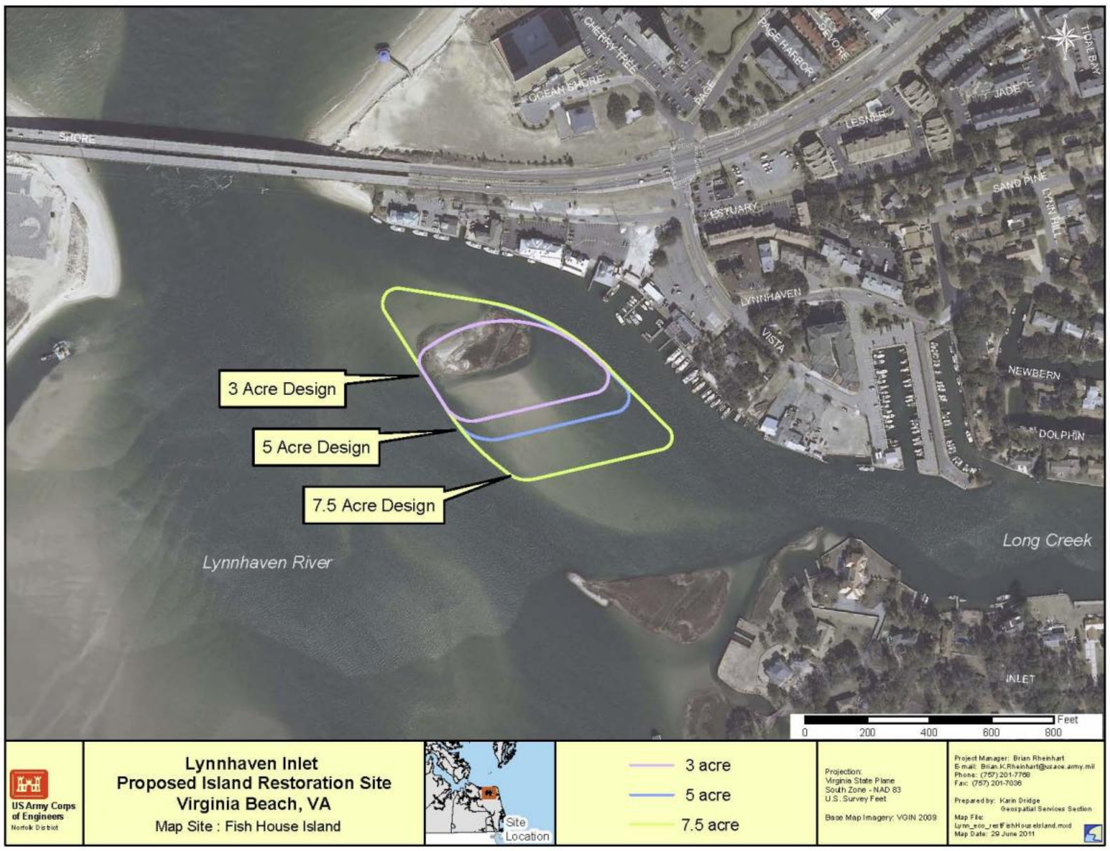
Figure 6. REEF BALL PHOTO

Wetland Creation

Three areas have been identified by the sponsor and resource agencies for wetland creation. The sites indentified are as follows: Fish House Island, Narrows to Rainey Gut and Lake Windsor. Wetland site size and shapes were largely dictated by the exiting site conditions such a bank type, depth of water, fetch and characteristics of adjacent shorelines. Proposed wetland plant elevations were determined by assessing elevations of nearby native plant areas. Coastal Engineering Design and Analysis System (CEDAS) was used to determine rocks sizes, structure dimensions and slopes.

Fish House Island (Figure 8) , located just inside the mouth of the Lynnhaven Inlet, is an example of an island within the Lynnhaven River Basin that has lost significant area and was determined to be a potential site for marsh restoration. Historical aerial photography shows that Fish House Island was approximately 10 acres in size in the 1930's, however the present area covers approximately 1.25 acres.

Figure 7. FISH HOUSE ISLAND



Some risk is associated with the restoration of Fish House Island. Erosion occurring on the island is due to swift currents experienced during maximum flood and ebb tides. The restoration of the island will not eliminate these currents and could increase the velocity of the currents due to a reduced cross section outside of the main channels. Even with that associated risks, this measure represents an opportunity to restore significant amounts of lost wetlands in the Lynnhaven watershed, so this site was carried forward in the study. Three different options were evaluated. These include the "small island" option that included 3 acres of restoration, the "medium island" option that would result in 5 acres of marsh and finally the "large island" option, which included 7.5 acres of restoration.

The Narrows to Rainey Gut (NR) site consists of an eroding fast-land bank ranging from 3 to 6 feet in height with an exposed berm at low tide approximately 20 feet wide. The shoreline is facing south –south west with an effective fetch of less than a mile to the south. The major design features include a trapezoidal stone riprap sill to protect wetland plants and stabilize the shoreline.

Figure 8. NARROWS TO RAINEY GUT STUDY AREA

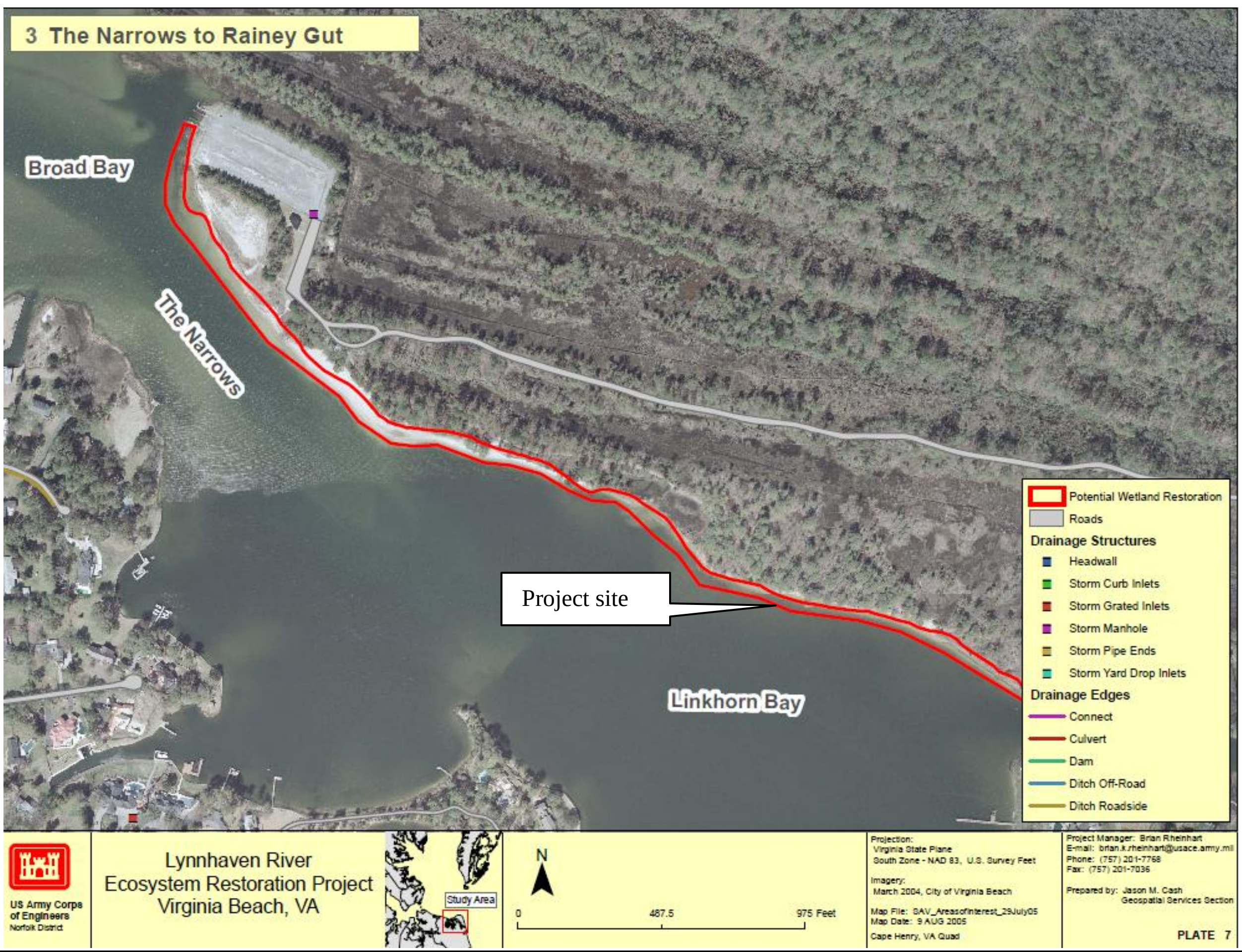
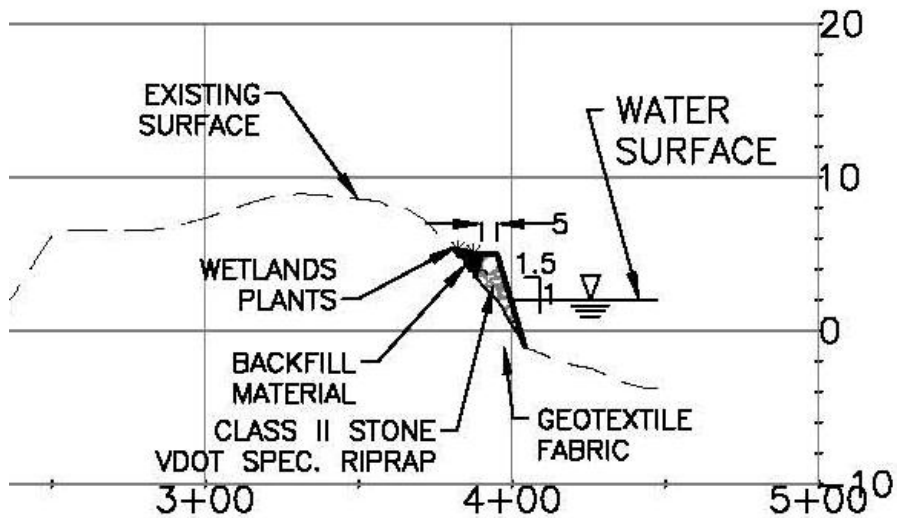


Figure 9. NARROWS TO RAINEY GUT PROJECT SITE

Figure 10. NARROWS TO RAINEY GUT CROSS SECTION



The Lake Windsor (LW) site consists of an eroding fast-land bank ranging from 1 to 3 feet in height. The shoreline is facing south with an effective fetch of about 0.1 miles to the south. The major design features include a trapezoidal stone riprap sill to protect wetland plants and stabilize the shoreline.

Figure 11. LAKE WINDSOR STUDY AREA

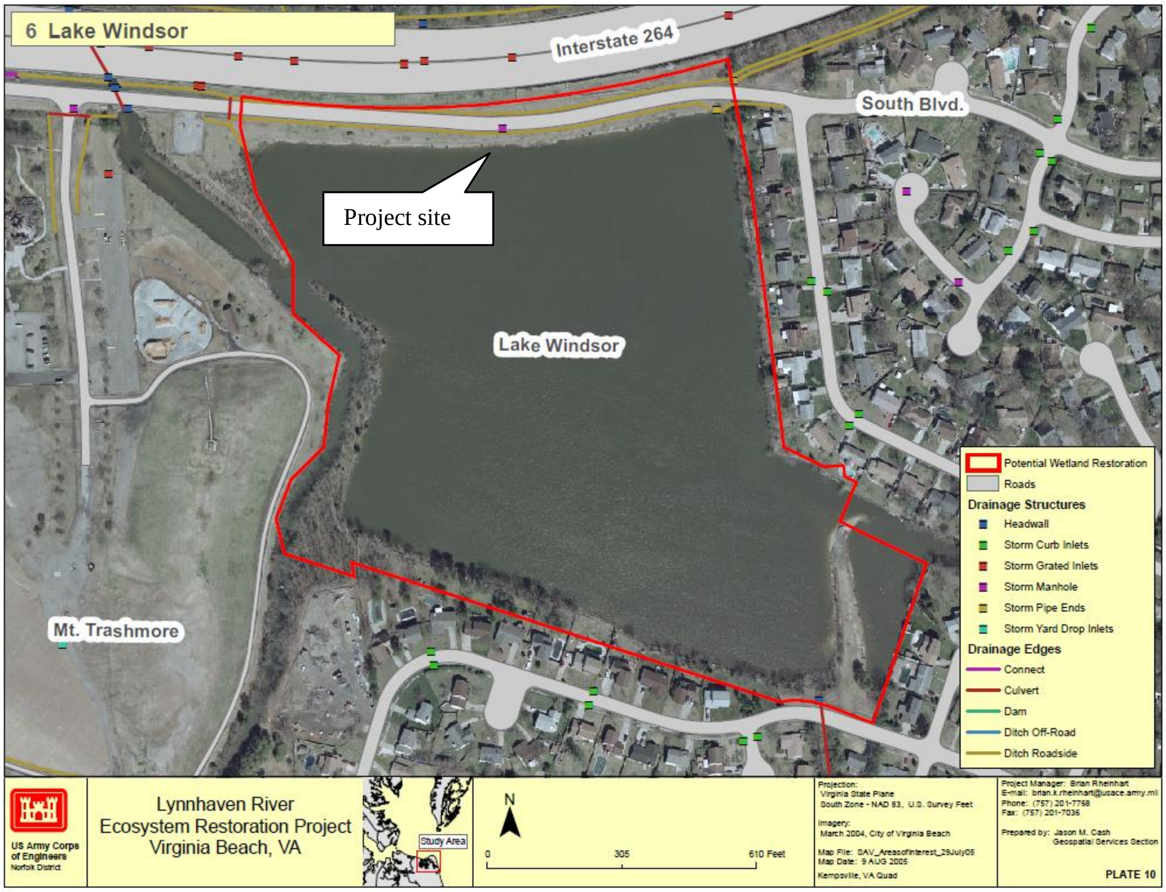


Figure 12. LAKE WINDSOR PROJECT LOCATION

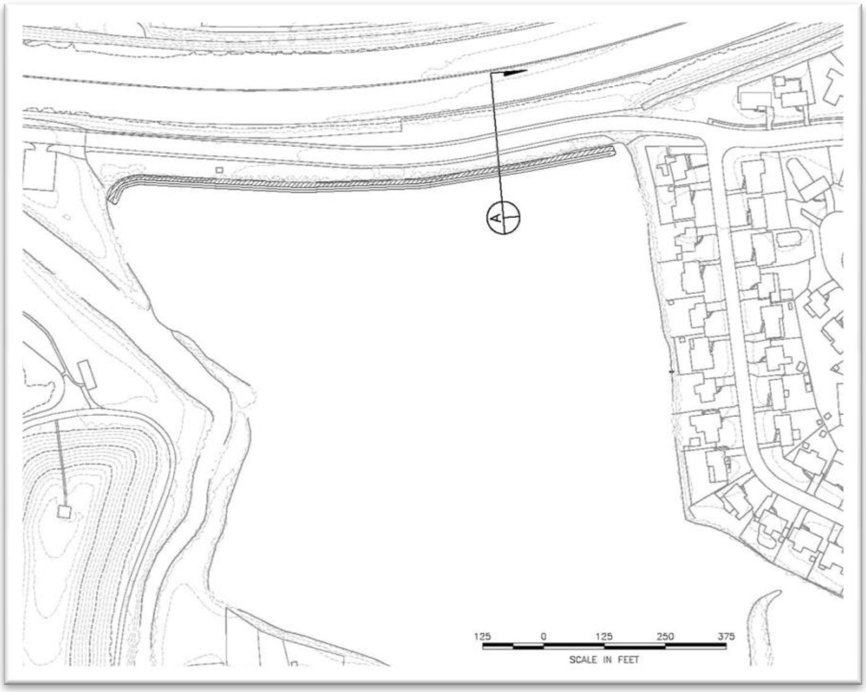
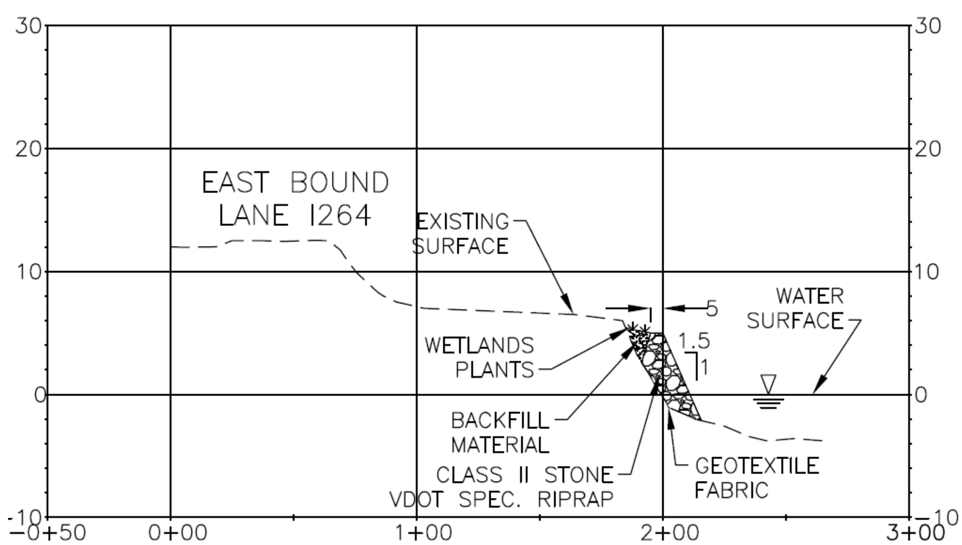


Figure 13. LAKE WINDSOR CROSS SECTION



Wetland Restoration/ Diversification Sites

Four sites within the Lynnhaven River Basin have been identified for restoration or diversification efforts in the Lynnhaven Restoration Project. Each site contains established stands for the nonnative, invasive, emergent plant, *P. australis*.

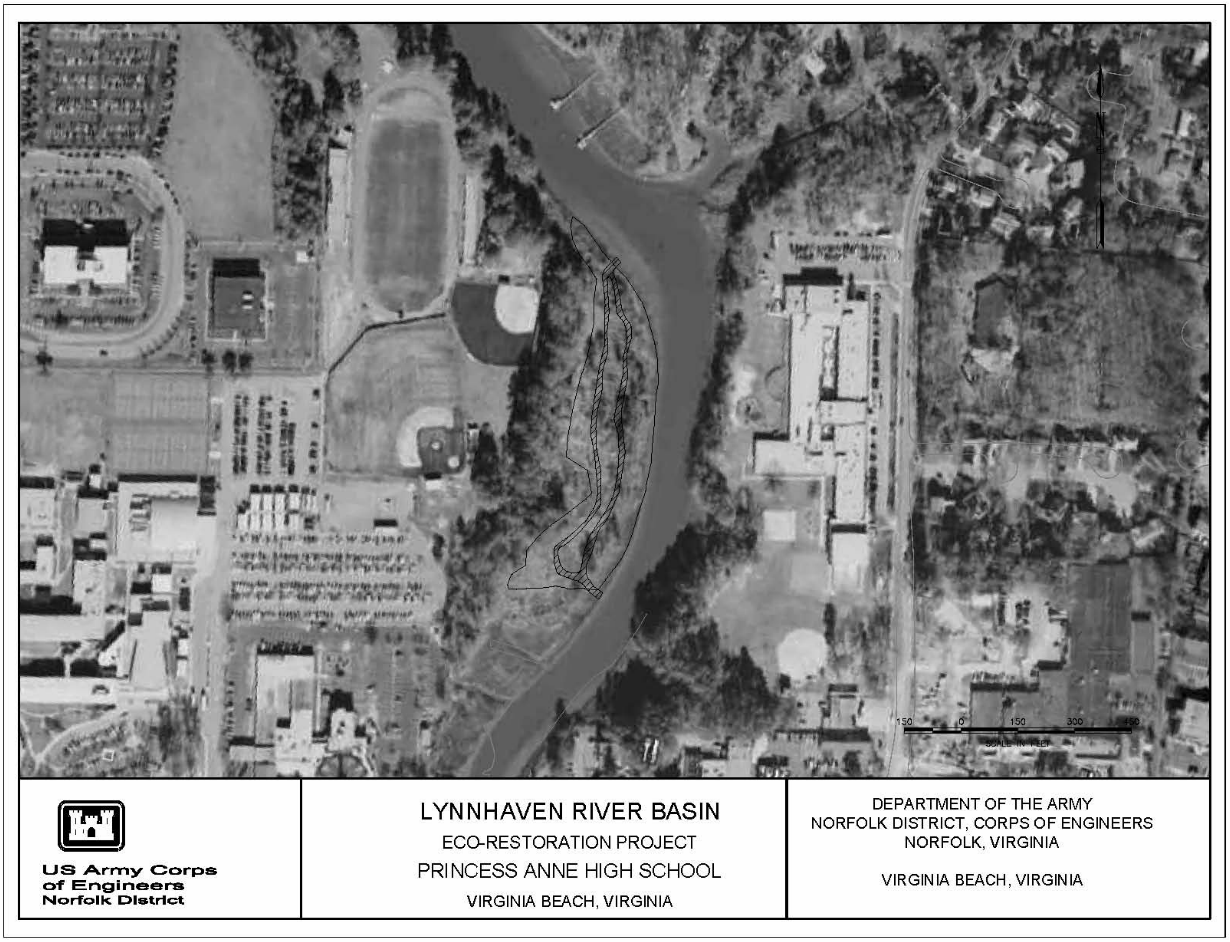
Princess Anne Site. The Princess Anne site (PA) is “half moon” shaped, with a fringe marsh, and approximately 3.82 acres in size (Figure 14). The site is located northeast of Virginia Beach Town Center, in a highly developed area of the city. The regions south and west of the site are highly urbanized, consisting of large, multistoried buildings and impervious surfaces, such as parking lots and roadways. The areas situated to the north and east of the PA site are made up of residential neighborhoods of single family housing units.

The western edge of the PA site flanks Princess Anne High School and Thalia Lynn Baptist Church. A 50 to 100-foot wide forested buffer zone separates the marsh from the large parking lots, buildings, and recreational fields of the school and church. Thurston Branch runs along the eastern edge of the site. On the opposite shore across from the PA site, a single line of trees separates Thurston Branch from Thalia Elementary School. The school property is comprised of numerous buildings, a parking lot, and maintained lawn. A drainage channel separates the PA site from another fragment of salt marsh approximately 1 acre on the site’s southern edge.

Thurston Branch runs along the entire eastern margin of the PA site, so tidal inundation is not restricted to the site. There is approximately 0.3 miles of shoreline, composed of a thin band of tidal flats and native vegetation, located along the site boundary. Immediately inland of the shoreline is a narrow, wooded, island that runs most of the length of the site. The area situated between the wooded island and the upland buffer, approximately 3 acres, is dominated entirely by *Phragmites austrialis*. The marsh running along the southern edge of the project site is vegetated with native salt marsh plants.

Figure 14. THE PRINCESS ANNE WETLAND RESTORATION SITE, VIRGINIA BEACH, VIRGINIA

Figure 15. THE PRINCESS ANNE WETLAND RESTORATION SITE, VIRGINIA BEACH, VIRGINIA



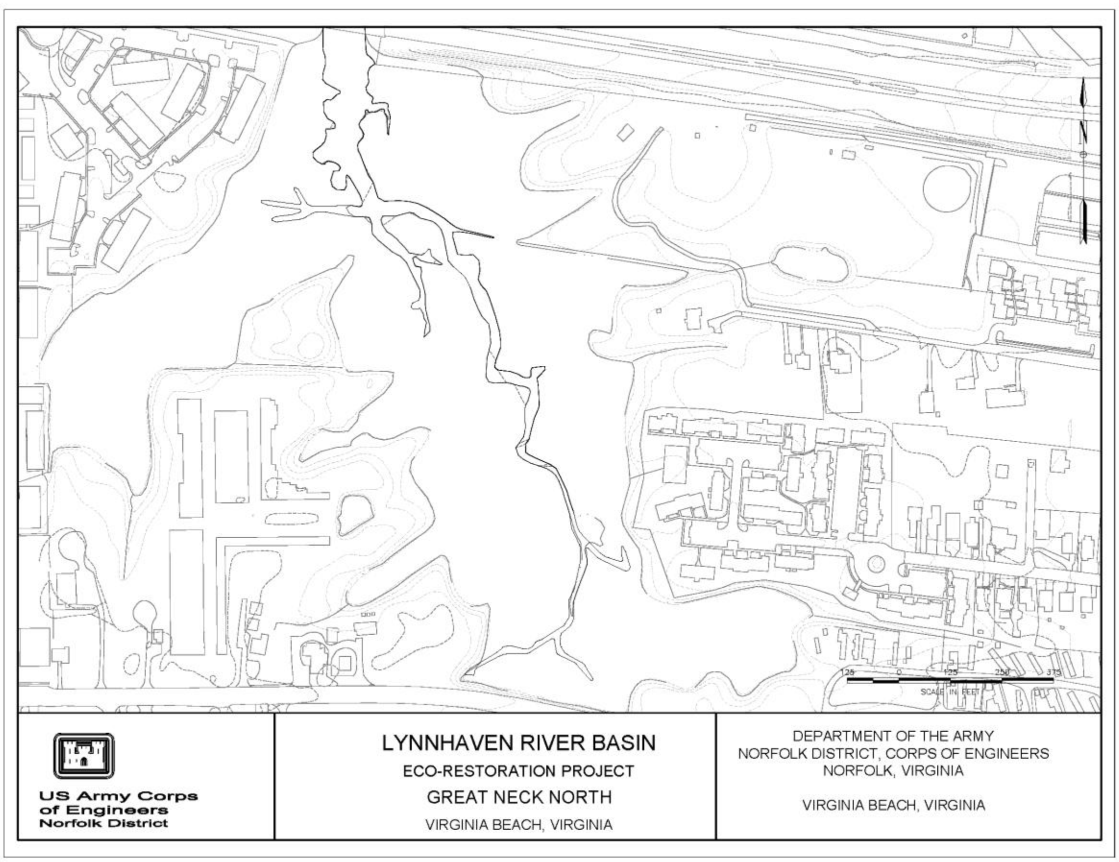
Great Neck North Site. Great Neck North (GNN) is the largest wetland site included in the Lynnhaven Restoration Project, consisting of 19.98 acres of tidal marsh (Figure 6). The GNN site is a long, narrow salt meadow running north to south. It is approximately .33 miles in length, and varies between .05 and 0.16 miles in width. The northern edge of the GNN site is defined by a bridge allowing Route 264/ Virginia Beach Expressway to cross the channel which connects the marsh to Linkhorn Bay. Tidal flushing of the site is not restricted by the bridge. The southern limit of the site is established by Virginia Beach Boulevard. A Dominion Power right-of-way defines the entire western edge of the site. The upland beyond the right-of-way is made up of a narrow, forested border, and the buildings, lawns, and paved parking lots of the two apartment complexes and the self storage business that have been constructed adjacent to the site. The eastern side of the GNN site is developed with an apartment complex, a police academy, a trailer park, and a small number of single family houses. Most of the eastern edge has a narrow buffer zone separating the marsh from the developed upland. Beyond the buffer, the upland adjacent to the site is composed of maintained lawns, structures, and impervious surfaces.

The GNN site possesses a high level of diversity, both in vegetation and habitat types. Open water habitat is provided by the central channel that runs through the site from north to south and a single secondary channel that split off the main channel. The marsh has not been extensively ditched. A few bare pannes and dead standing trees can be found throughout GNN and tidal flats are located at the northern edge of the site. Wooded island habitat can be found in the northwest corner.

A native salt marsh plant community, including *Spartina* species and marsh shrubs, is present at the site; however, the area also contains large stands of *Phragmites australis*. The northern and eastern quadrants of the GNN site are dominated by native plant species. *P. australis* fringes the main marsh and grows in large stands at drainage structures where freshwater enters the system. *P. australis* is starting to encroach on areas that are dominated by cordgrass and other native plants. The southern part of the GNN site is a mixture of native species and *P. australis*. However, larger amounts of the invasive common reed are present in this area than are found in the northern and eastern sections. The western quadrant of the site is made up almost entirely of *P. australis*, including the area west of the wooded islands that are located in the northwest corner of the site, the entire Dominion Power right-of-way, and the wetlands located to the west of the right-of-way.

Figure 16. THE GREAT NECK NORTH WETLANDS SITE, VIRGINIA BEACH, VIRGINIA

Figure 17. THE GREAT NECK NORTH WETLANDS SITE, VIRGINIA BEACH, VIRGINIA

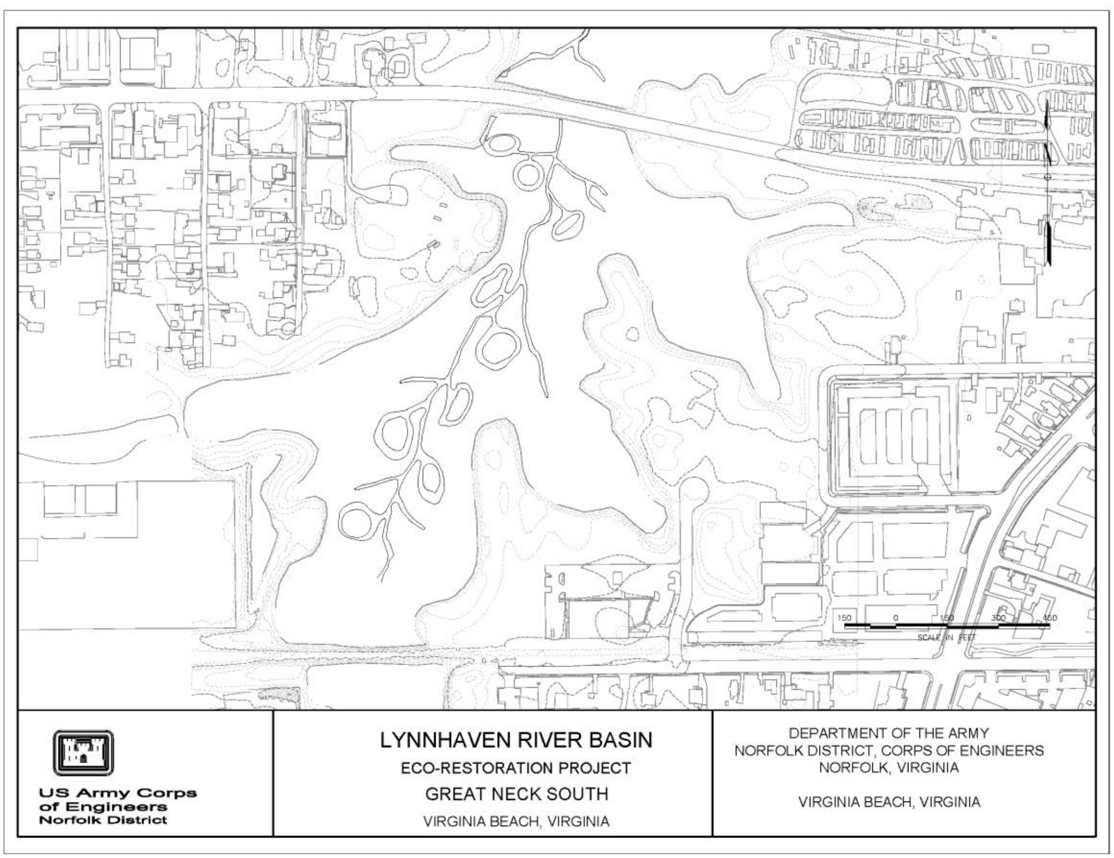


Great Neck South Site. Great Neck South (GNS) site is connected to GNN via two, small culverts that run under Virginia Beach Boulevard (Figure 7). The culverts that link the sites restrict tidal flow between the two marshes. The GNS site is a large (13.68 acres), narrow salt meadow running from north to south. The site has similar dimensions as GNN, being about 0.32 miles in length and varying between 0.05 and 0.16 miles in width. The northern edge of the site is defined by Virginia Beach Boulevard and the southern edge is marked by a railroad trestle. The Dominion Power right-of-way present at the GNN site continues along the entire western edge of the GNS site. Beyond the right-of-way, the land adjacent to the western edge contains two large commercial properties, one of which is an auto salvage yard. This area consists of large parking lots, commercial buildings, wooded uplands, and a containment pool. The eastern edge of the GNS site contains two relatively large wooded areas, one being approximately 7.5 acres in size and the other being about 5.5 acres. Three commercial properties are also located in the eastern tract, including two self storage businesses. The area consists of wooded uplands, impervious surfaces, commercial buildings, maintained lawn, and about 1.5 acres of bare earth.

The diversity in habitat type and plant species at the GNS site is low. One central channel runs the length of the marsh from north to south. The marsh is not extensively ditched, but a few small drainage channels empty into the main central stream. Wetland shrubs grow along the central channel and a few bare pannes are located in the site. However, the majority of the site is vegetated with extremely dense stands of *P. australis*.

Figure 18. THE GREAT NECK SOUTH WETLANDS SITE, VIRGINIA BEACH, VIRGINIA

Figure 19. THE GREAT NECK SOUTH WETLANDS SITE, VIRGINIA BEACH, VIRGINIA

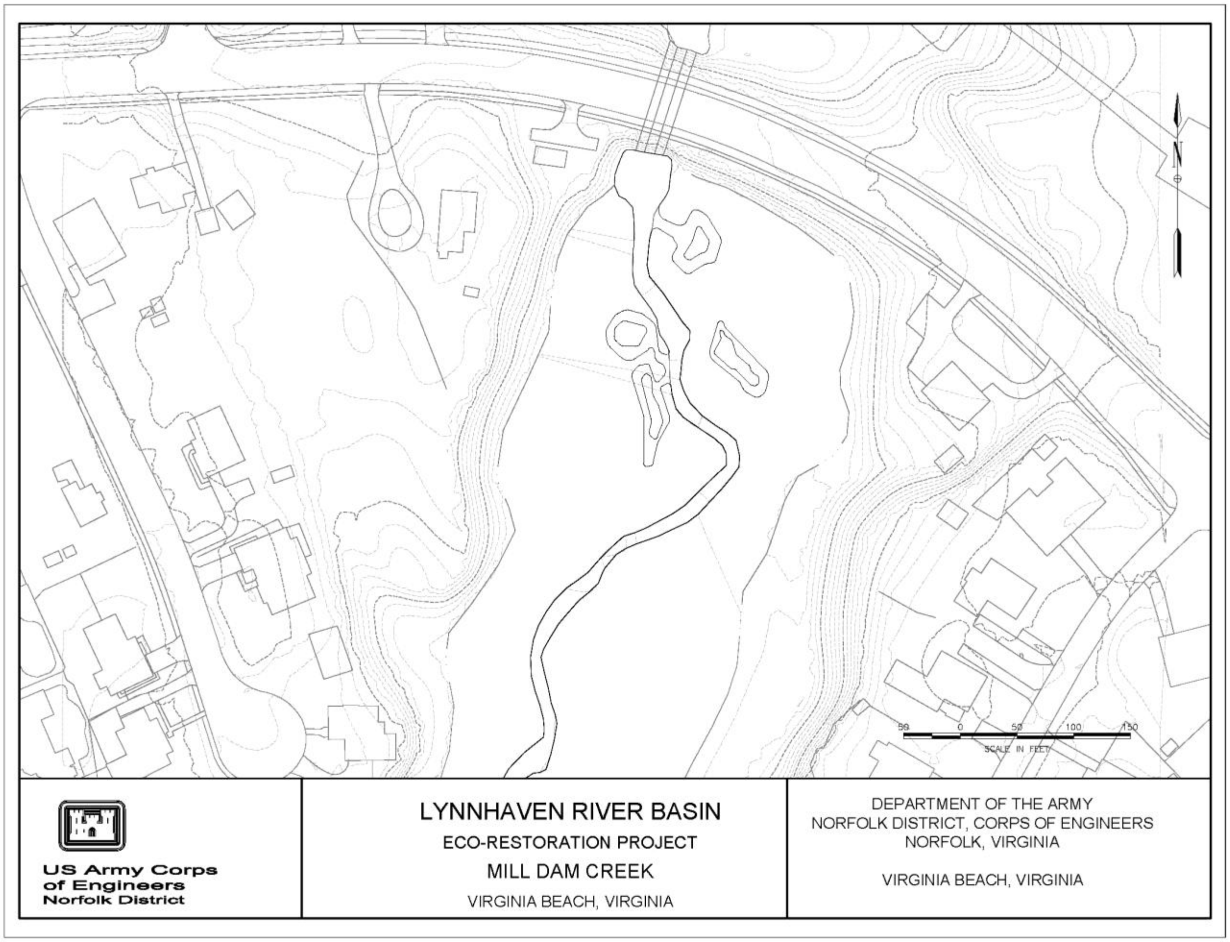


Mill Dam Creek Site. The wetland site with the smallest area is Mill Dam Creek (MDC) site, approximately 0.9 areas in size (Figure 8). The site is a long, narrow marsh running from north to south. The northern edge of the site is delineated by Mill Dam Road. The southern edge of the site consists of wooded uplands. Both the eastern and western edges of the site abut residential property. The area surrounding the site consists of wooded upland, manicured lawns, single family houses, and roadways. Culverts that run under Mill Dam Road connect the site to Mill Dam Creek, which eventually empties into Broad Bay.

Tidal flow into the MDC site is severely restricted by the culverts. One central channel runs through the site and no ditching is evident. Other than shrubs that grow along the central channel and a few dead standing trees, the marsh is composed entirely of extremely dense *P. australis* stands.

Figure 20. THE MILL DAM CREEK WETLANDS SITE, VIRGINIA BEACH, VIRGINIA

Figure 21. THE MILL DAM CREEK WETLANDS SITE, VIRGINIA BEACH, VIRGINIA



CONSTRUCTION PROCEDURES

Excavation, material hauling, and disposal of the excavated material is dependent on the contractor's means and methods and are thus unknown at this time. Reasonable options are listed for excavation, hauling of materials off-site, and the eventual disposal site for material and debris. Excavation options include:

- Digging with track-mounted hydraulic excavators.
- Scrapping with bulldozers.
- Digging by crane with dragline or clamshell bucket.
- Some combination of the above.

Hauling options include:

- Trucking material directly from the excavation site to the eventual disposal site, with road-capable vehicles that might include any combination of 10-cy dump trucks, 10-cy dump trucks pulling an 8-cy dump trailer, or 20-cy side dump trucks.

Disposal options include:

- Local landfills such as Portsmouth, SPSA (Suffolk), Holland Enterprises (Suffolk), and Bethel (Hampton).

Construction Sequence

The anticipated sequence of construction steps to be taken by the contractor is as follows:

1. Submit an Erosion Control Plan, based on contractor's means and methods at least 30 days before commencing work at the site.
2. Obtain Land Disturbing Permit from the City of Virginia Beach before commencing work.
3. Verify location and elevations of existing survey control markers. Perform construction staking survey to establish final lines and grades. Prior to start of earthwork, the Contractor shall verify all project vertical and horizontal datums.
4. The Contractor shall verify elevations of existing adjacent marshes and notify the Contracting Officer of any discrepancies in proposed planting elevations.
5. Install erosion and sediment control structures including temporary stone construction entrance, construction road stabilization, safety fence, silt fences, and tree preservation and protection.
6. Mow and spray herbicides within limits of Common Reed Zone to prevent common reed (phragmites) recontamination of exposed wetland excavation.
7. Excavate shoreline to lines and grades shown on the plans.
8. Stockpile sufficient excavated material meeting topsoil requirements to use as backfill in those final grade areas not meeting topsoil requirements and thereby requiring over-excavation and topsoil backfill.
9. Place filter-cloth and riprap to the line and grades as shown on the plans.
10. Plant new wetland vegetation as specified and shown on drawings and install goose exclusion fencing.

11. Upon work completion and when the site is stabilized to the satisfaction of the Contracting Officer, remove the temporary erosion and sediment control devices and stabilize those areas disturbed by the processes.
12. Restore any existing areas impacted by construction activities by bringing to grade and planting elevation.

Erosion Control Requirements

Erosion and sediment control design measures in accordance with provisions in the Virginia Erosion and Sediment Control Handbook (1992) are appropriate for the construction of the wetland sites and will be strictly followed. Erosion and sediment control measures include:

- Safety fence per Standard and Specification 3.01
- Construction Entrance per Standard and Specification 3.02
- Construction Road Stabilization per Standard and Specification 3.03
- Silt fence per Standard and Specification 3.05
- Permanent seeding per Standard and Specification 3.32
- Tree preservation and protection per Standard and Specification 3.38
- Dust control per Standard and Specification 3.39.

OPERATIONS AND MAINTENANCE

Operations and maintenance requirements for the wetland sites include a yearly inspection of the areas to ensure native plant growth and no encroachment of evasive plant species. Upon inspection it would be determined if additional sprig plants or the application of herbicides is necessary to restore the required wetland function. An assessment of the rock structures for displacement from wave action and/or settlement due to long term consolidation of the subgrade should also be included in the inspection. The non-Federal sponsor is responsible for all operations and maintenance features of the project.

RELOCATIONS

No relocations of infrastructure or public services, such as water service and/or electrical service, are known to be located in the areas needed for construction of the Tentatively Selected Plan. However, as with the case with all construction activities, all utility companies shall be contacted before construction is initiated.

COST ESTIMATES

Cost Estimate for Selected Plan

Introduction: The Lynnhaven River Basin is located in the city of Virginia Beach and discharges into the Chesapeake Bay. The river basin covers 64 square miles and supports recreational boating and fishing, crabbing, ecotourism, and general environmental observation. The project objective is to develop a solution that reasonably maximizes environmental restoration benefits compared to costs and is consistent with Federal and city objectives.

1. Project Description

   a. General: The proposed Lynnhaven Ecosystem Restoration Project is designed to improve habitat and biodiversity in the Lynnhaven River Basin, a tributary of the Chesapeake Bay. These restoration activities involve wetland restoration, hard reef habitat reef structures, submerged aquatic vegetation (SAV) establishment, and scallop restoration. Also see main report for background.

   b. Purpose: This feasibility study includes a plan which will improve water quality, restore and protect the environment, and provide other ecosystem benefits.

   c. Design Features: There are four main design-construction features. One is the improvement of wetland/march habitat through removal of non-native plants and restoration of restore native marsh grasses and natural drainage. The second is to restore underwater vegetation similar to what was once prevalent in this area. The third measure is to reintroduce bay scallops in the Lynnhaven River System. The fourth measure is to improve fish habitat with reef balls of various sizes at different locations throughout the river system. The design, for practical purposes, is developed only to a 30% conceptual design stage as this is a feasibility level effort. Detailed plans and specifications are not yet developed, even to a level to that has incorporated value engineering considerations.

2. Basis of Estimate

   a. Basis of Design: Lynnhaven River Basin Environmental Restoration Study, Virginia Beach, Virginia plans.

   b. Basis of quantities: The estimate development is from quotes, calculations, and unit prices. Unit prices are primarily developed with labor, equipment, and material components. Backup for these unit prices include production rates and crew output calculations shown on other sheets. The quantities are from plan takeoffs where possible. Designers provided information and quantities based on their objectives for SAV, Bay Scallops, and Reef Balls. Very little of this project can be considered typical concrete and rebar construction. Nearly all elements are unique or atypical, such as submerged aquatic vegetation (SAV) seeding, scallop seeding, and reef creation. The cost team has developed detailed estimates for the reef placement and other elements to the level of detail in the design, or what could be reasonably assumed by the estimator. Some of the minor elements (comprising less than 1% of the total cost) are priced based on historical data and assumed production rates as the project lacks specification detail at this feasibility stage.

c. Quotes: Reef Ball costs are from Reef Innovations, Inc, Sarasota, Florida; Larry Beggs (914-330-0501). Todd Barber of the Reef Foundation (941-484-7482) also provided cost information on reef balls. Sea Search of Virginia who provided the previous quote is no longer in business. The number of other regular suppliers of reef balls has decreased over the last 15 years. Marine mattresses serve as the foundation for reef balls in the softer, less stable bottom material in the Lynnhaven area. Quote information is from Jeff Fiske: Coastal & Waterway Industry Manager, Tensar International Corporation (770) 344-2123. Alan Dinges of Maccaferri, Inc; Williamsport, MD also provided information (301)-223-6910.

d. Estimate Development: The estimate employed the Mii estimating software for all work items. The project is treated as a total project in the cost estimate, with separate mobilizations included for wetland sites and reef ball installation. The wetland estimate is primarily earthwork and planting of new grasses/plants. These costs are from similar projects and the 2012 Corps of Engineers Cost Book. SAV and Bay Scallop pricing is from experienced experts in these fields.

e. Reef ball estimate: This estimate includes the material cost and the cost to deliver and place the reef balls. The project plan includes four different reef ball sizes. The bay ball is only about 3' in diameter. The goliath, super, and ultra balls are approximately 6' in diameter. The effort and time to install the large reef ball is similar for all large sizes, which vary only incrementally. Further refinement of the design will be needed to compensate for soft bottom reef placement. Stone filled marine mattresses alleviate the soft bottom conditions.

f. Reef ball placement: Five separate operations estimated by assemblies give the cost of the transportation and placement of the balls. The assumption was that a casting yard located in the Norfolk area would manufacture the reef balls. A small crane loads the balls onto a truck, which transports them to a storage area next to the water in the Lynnhaven area. A small crane unloads the truck and stockpiles the balls. After stockpiling, a small crane then loads a barge with the balls and a tug moves the barge to correct placement location. A second barge with a crane places the balls in the river. Movement of the balls requires a determination of cycle times and creation of crews in the assembly. Assumptions include the use of small 2 to 5 man crews for water based operations, shallow draft barges, and a two-barge system for transport of the balls where loading of one barge occurs at the same time as placement from the second barge. Divers provide final location help and verification for placing the balls. Water-based labor costs and workmen's compensation rates are from the Corps of Engineers Dredge Estimating Program (CEDEP) and Davis-Bacon wage rates. Wetlands Restoration labor costs are from Davis-Bacon rates. Equipment rates were from the 2011 Corps of Engineers Equipment database.

g. Site Access: Site access depends on the specific type of work. Fish habitat/reef balls, SAV's, and Bay Scallops construction will be by barge or boat. The area should be accessible throughout the year. Weekend work is not as practical because of the boat traffic in the area, especially in the summer. Earthwork and marsh planting access will be by the closest most reasonable point from land.

h. Borrow Area: There is no borrow area within the project limits of this study. Borrow material comes from offsite.

i. Mobilization: Mobilization of excavators and dozers will be by truck. Tugs will move barges, while other floating equipment may be self-propelled. Reef Ball construction will have multiple mobilizations because of the multi-year contract setup. The cost of mobilization for SAV and Scallop establishment will be small.

j. Overtime: The cost estimate includes overtime for labor for wetlands restoration and installation of the reef ball features. The remainder of the project for SAV seeding and scallop introduction did not warrant overtime production.

k. Profit has been calculated from the weighted guidelines method. The project is treated as a total project in the cost estimate, with separate mobilizations included for wetland sites and reef ball installation. The only contract that will require substantial field overhead is Base Contract 1 for wetland restoration and fish reef habitat. In this case we have included itemized FOOH for the three year duration of reef ball installation, monitoring, and adaptive management. SAV and Scallop work is mostly conducted from small craft skiff- type boats, and there are several boat ramps in the Lynnhaven to allow direct access to project sites for seeding of both project elements and monitoring.

l. Bond: Bond is now determined from the MII program.

m. TPCS (Total Project Cost Summary) The TPCS summarizes the main features of work. The features include Wetland Restoration, Reef Habitat Construction, SAV construction, and Scallop construction. These are all in CWWBS Category 06 Fish & Wildlife. As seen in the construction schedule there are three main contracts and multiple phases within each contract. Reef ball phasing allows a smaller contractor to bid on the job. Some contractors may not have enough resources to build all the reef balls in one contract in a limited time. Phasing and pilot construction of SAV's and Scallops allows monitoring and adaptive management to increase the chances for project success. The Mii estimate is broken out into separate contracts and phasing to match the schedule. The estimator transferred these work items into the TPCS. These individual work segments have separate escalation factors applied to reach the fully funded level in the TPCS. A summary of these individual work items is on the first/title TPCS page. The project cost basis is 01 October 2012. The Program Year is 2014. Work begins in FY 2017 and continues to FY 2023. See the project schedule for detailed items. The TPCS (Total Project Cost Summary) shows escalated construction costs to midpoints of construction for the various work items.

n. Other considerations: It is anticipated that the number of fish reef structures in this project will be sufficient for a supplier to develop a local production yard to supply the reef structures, which are relatively simple to construct. A local supply chain would tend to lower budget prices obtained from outside suppliers. As the concrete reef restoration industry grows and expands, it is likely the forecast prices will drop.

3. Construction Schedule: A feasibility level construction schedule was provided to the cost team that covers a six year period of construction and adaptive management. The schedule included projections from estimating for Wetlands Restoration and Reef Ball construction and from the "environmental" team for SAV and Scallop construction. Duration for reef ball activities is from the estimate. Adaptive management is a concept for ecosystem restoration that recognizes the limitations and external factors that influence successful restoration. Not trial and error, but a deliberate process that builds on successful efforts and lessons learned to move towards project restoration goals.

4. Acquisition Strategy There will be more than one contract for this work, because the individual projects are so different from each other. This is true especially for the Bay Scallop work, which can't begin until establishment of the SAV's (Submerged Aquatic Vegetation) in the Lynnhaven River. The provided acquisition strategy is to use three

contracts to accomplish the work using full and open competition. The acquisition plan and schedule help to mitigate project risk by providing open competition and option items that can be flexible and based on field monitoring results. Risk is also mitigated by ongoing actions of the local NGO that has already placed reef balls and similar shaped concrete structures in the Lynnhaven waterway, and they have been performing well. These actions should give the PDT added confidence as these installations are monitored for activity. The group concurred on a strategy that consists of three Firm Fixed Price contracts using full and open competition as follows:

a. Contract 1 (FFP- full and open competition): SOW= All phases of the Wetland Restoration/Diversification and Reef Habitat measures. Base contract will be awarded in first year identified for construction (2017) with two options for Phase 2 (2018) and Phase 3 (2019).

b. Contract 2 (FFP- full and open competition): SOW= SAV initial construction (3 phases). Base contract will be awarded in first year identified for construction (2017) with two options for Phase 2 (2018) and Phase 3 (2019).

c. Contract 3 (FFP- full and open competition): SOW= SAV large-scale construction (2 phases) and scallop reintroduction (3 phases). This contract would consist of a base plus three options. The base contract will be awarded in the fourth year identified for construction (2020) for the first phase of the SAV large scale construction. Option 1 will be awarded in 2021 and will consist of the 2nd large-scale phase of SAV construction and first phase of scallop reintroduction. Option 2 will be awarded in 2022 for the second phase of scallop reintroduction. Option 3 will be awarded in 2023 for the final large-scale scallop reintroduction.

5. Non-construction features:
   a. The basis for Planning Engineering and Design (E&D – Feature 30) costs are discussions with the project manager and established rates used on other jobs.
   b. The basis for Construction Management and Design (E&D – Feature 30) costs are discussions with the project manager, in-house construction personnel, and established rates used on other jobs.
   c. The cost for Lands & Damages (Feature 01) is from detailed reports submitted by Real Estate

6. Other Project Mark-ups

   a. Escalation: The project cost basis is 01 October 2012. The Program Year is 2014. Work begins in FY 2017 and continues to FY 2023. See the project schedule for detailed items. The TPCS (Total Project Cost Summary) shows escalated construction costs to midpoints of construction for the various work items. The TPCS uses the latest CWCCIS (Civil Works Construction Cost Index System) publication (March 2013) for cost growth calculations.

b. Contingency and Risk: From a risk standpoint, the project has limited life and safety issues. With full and open competition planned, the risk associated with limited competition and small business concerns are reduced. In addition the adaptive management process allows the team to control scope and direct efforts towards site specific actions. Adaptive management and associated monitoring is done in the option years associated with each of the three base contracts. Options can be tailored and exercised based on observed needs in the field. An abbreviated Risk Analysis has been accomplished and reflects a relatively low risk project from the contractor's perspective, with high risk for SAV and Scallops success. Turning around declining SAV coverage, reintroducing scallops where their numbers have been eliminated, and developing active reef habitat in a highly active waterway are all challenging aspects of the project; however, the adaptive management approach is designed to maximize potential for success. In this project the success of the scallops is highly dependent on the successful development of SAV beds. Risk is high for these components of the project due, almost entirely, to recognized external risks. The report is clear that there are no guarantees of total project success. The team's adaptive management plan includes several risk mitigation strategies if certain external risk are manifest; SAV fencing, signage, floating barriers, alternative siting, and re-seeding. The project contingencies are included for the items in the TPCS separately and reflective of the degree of risk   Associated risks could cause potential scope change; however, the District intent is to design/cost manage to remain within the funds made available. The District believes that scope and quantities could be adjusted, accompanied by competitive acquisition strategies, and bid schedule construct to still meet project intent.

**** TOTAL PROJECT COST SUMMARY ****

PROJECT: Lynnhaven River Basin Ecosystem Restoration
PROJECT NO: P2 121785
LOCATION: Virginia Beach, Virginia

DISTRICT: NAO-Norfolk District COE, NAD PREPARED: 7/25/2013
POC: CHIEF, COST ENGINEER Gary Szymanski

This Estimate reflects the scope and schedule in report; Lynnhaven River Feasibility Report

Civil Works Work Breakdown Structure		ESTIMATED COST				PROJECT FIRST COST (Constant Dollar Basis)				TOTAL PROJECT COST (FULLY FUNDED)				
		Estimate Prepared: 6/29/2013 Effective Price Level: 10/1/2012				Program Year (Budget EC): 2014 Effective Price Level Date: 1 OCT 13								
WBS NUMBER A	Civil Works Feature & Sub-Feature Description B	COST ($K) C	CNTG ($K) D	CNTG (%) E	TOTAL ($K) F	ESC (%) G	COST ($K) H	CNTG ($K) I	TOTAL ($K) J	Spent Thru: 1-Oct-12 ($K) K	L	COST ($K) M	CNTG ($K) N	FULL ($K) O
06	FISH & WILDLIFE FACILITIES													
	-WETLANDS RESTORATION	$822	$148	18.0%	$970	2.1%	$839	$151	$990	$0		$898	$162	$1,059
	-ESSENTIAL FISH HABITAT	$20,214	$3,598	17.8%	$23,813	2.1%	$20,630	$3,672	$24,303	$0		$22,651	$4,032	$26,683
	-SUBMERGED AQUATIC VEGETATION	$2,763	$768	27.8%	$3,531	2.1%	$2,820	$784	$3,604	$0		$3,224	$896	$4,120
	-BAY SCALLOPS	$439	$146	33.2%	$585	2.1%	$448	$149	$597	$0		$534	$177	$711
	CONSTRUCTION ESTIMATE TOTALS:	$24,238	$4,660		$28,898	2.1%	$24,737	$4,756	$29,493	$0		$27,307	$5,267	$32,574
01	LANDS AND DAMAGES	$699	$26	3.8%	$725	2.1%	$713	$27	$740	$0		$758	$28	$787
30	PLANNING, ENGINEERING & DESIGN	$2,536	$127	5.0%	$2,663	1.8%	$2,580	$129	$2,709	$0		$2,981	$149	$3,130
31	CONSTRUCTION MANAGEMENT	$1,937	$190	9.8%	$2,127	1.9%	$1,974	$193	$2,167	$0		$2,180	$214	$2,394
	PROJECT COST TOTALS:	$29,410	$5,003	17.0%	$34,413		$30,005	$5,105	**$35,110**	$0		$33,226	$5,658	$38,884

CHIEF, COST ENGINEERING
PROJECT MANAGER
CHIEF, REAL ESTATE
CHIEF, PLANNING and POLICY
CHIEF, WATER RESOURCES DIVISION
CHIEF, ENGINEERING
CHIEF, CONSTRUCTION
CHIEF, ENGINEERING and CONSTRUCTION
CHIEF, PPMD

ESTIMATED FEDERAL COST:	**65%**	**$25,275**
ESTIMATED NON-FEDERAL COST:	**35%**	**$13,609**
ESTIMATED TOTAL PROJECT COST:		**$38,884**

Lynnhaven R Ecosystem Restoration-Alt 'D" 07-24-2013

The Lynnhaven River Basin Environmental Restoration Study focuses on the Lynnhaven River Basin with an approximate area of 64 sq miles. The primary problems which this project solves are environmental restoration and protection and other water-related issues.   The scope of the study includes all existing and reasonably foreseeable future conditions that may affect the ecosystem within the Lynnhaven River Basin and its three main branches; the Eastern Branch, the Western Branch, and the Broad Bay/Linkhorn Bay complex. The proposed study will assess both potential actions and the scale of those actions needed to alter the current ecologically stable state of the river system. To shift the Lynnhaven River back to a prior, more productive ecologically stable state will require a large scale effort such as is included within the proposed study. Federal share is 65% and the non-Federal share is 35%.

Estimated by	EC-EE
Designed by	Norfolk District
Prepared by	mkh
Preparation Date	6/28/2013
Effective Date of Pricing	10/1/2012
Estimated Construction Time	Days

Designed by
Norfolk District
Estimated by
EC-EE
Prepared by
mkh

Design Document	
Document Date	7/27/2012
District	Norfolk District
Contact	
Budget Year	2014
UOM System	Original

Direct Costs

LaborCost
EQCost
MatlCost
SubBidCost
UserCost1

Timeline/Currency

Preparation Date	6/28/2013
Escalation Date	10/1/2012
Eff. Pricing Date	10/1/2012
Estimated Duration	0 Day(s)
Currency	US dollars
Exchange Rate	1.000000

Costbook CB12EB-b: MII English Cost Book 2012-b

Labor Lyn-2012: Local Labor Library - Lynnhaven, Va Beach 2012

the website for current Davis Bacon & Service Labor Rates. Fringes paid to the laborers are taxable. In a non-union job the whole fringes are taxable. In a union job, the vacation p

Labor Rates

LaborCost1
LaborCost2
LaborCost3
LaborCost4

Equipment EP11R02: MII Equipment 2011 Region 02-Local2

02 MIDEAST

Sales Tax	5.00
Working Hours per Year	1,450
Labor Adjustment Factor	1.01
Cost of Money	1.75
Cost of Money Discount	25.00
Tire Recap Cost Factor	1.50
Tire Recap Wear Factor	1.80
Tire Repair Factor	0.15
Equipment Cost Factor	1.00
Standby Depreciation Factor	0.50

Fuel

Electricity	0.096
Gas	3.620
Diesel Off-Road	3.360
Diesel On-Road	3.900

Shipping Rates

Over 0 CWT	9.67
Over 240 CWT	8.90
Over 300 CWT	8.01
Over 400 CWT	7.19
Over 500 CWT	4.67
Over 700 CWT	4.67
Over 800 CWT	7.09

Date	Author	Note
6/4/2012	mh	Adaptive Management Costs and Monitoring: Annual monitoring will be conducted for each of the measures to ensure that project objects are being fulfilled. Adaptive management (AM) costs are included in the construction costs for each of the alternatives. The AM costs for each of the measures are estimated at 10 percent of total project costs based on the following:a. Wetland sites- the annual application of herbicides to control the growth and spread of phragmites and the annual replacement of native plantings. Physical alterations may be necessary also.b. Fish reefs-up to 10 percent of construction costs, for seeding the reefs with oyster larvae.c. SAV AM-up to 10% to reseed areas that did not establish themselves.d. Scallops- up to 10 percent, in order to restock scallops in conjunction with the predation prevention measures.
7/22/2013	mh	Quote1- Reef Ball costs are from Reef Innovations, Inc, Sarasota, Florida; Larry Beggs (914-330-0501). Todd Barber of the Reef Foundation (941-484-7482) also provided cost information on reef balls. Sea Search of Virginia who provided the previous quote is no longer in business. The number of other regular suppliers of reef balls has decreased over the last 15 years.
7/22/2013	mh	Marine Mattress quotefrom: Jeff Fiske: Coastal & Waterway Industry Manager, Tensar International Corporation (770) 344-2123. Additional information is from Norfolk District coastal engineer.

Description	Quantity	UOM	ContractCost	Escalation	Contingency	SIOH	MiscOwner	ProjectCost	C/O
Project Cost Summary Report			*24,238,219.70* **24,238,220**	**0**	**0**	**0**	**0**	*24,238,219.70* **24,238,220**	
Construction Cost	**1.00**	**EA**	*24,238,219.70* **24,238,220**	**0**	**0**	**0**	**0**	*24,238,219.70* **24,238,220**	
06 Fish and Wildlife Facilities	**1.00**	**EA**	*24,238,219.70* **24,238,220**	**0**	**0**	**0**	**0**	*24,238,219.70* **24,238,220**	
0603 Wildlife Facilities & Sanctuary	**1.00**	**EA**	*24,238,219.70* **24,238,220**	**0**	**0**	**0**	**0**	*24,238,219.70* **24,238,220**	
060373 Habitat and Feeding Facilities	**1.00**	**EA**	*21,036,483.36* **24,238,220**	**0**	**0**	**0**	**0**	*21,036,483.36* **24,238,220**	
Contract 1-Wetland Restoration & Reef Habitat Constriction	**1.00**	**EA**	**21,036,483**	**0**	**0**	**0**	**0**	**21,036,483**	
Contract 2 - SAV Initial Construction	**1.00**	**EA**	*121,441.44* **121,441**	**0**	**0**	**0**	**0**	*121,441.44* **121,441**	
Contract 3 - SAV Construction & Bay Scallops	**1.00**	**EA**	*3,080,294.90* **3,080,295**	**0**	**0**	**0**	**0**	*3,080,294.90* **3,080,295**	

Description	Quantity	UOM	Contractor	DirectCost	SubCMU	CostToPrime	PrimeCMU	ContractCost	C/O
Contract Cost Summary Report				**18,729,950**	**102,683**	**18,832,632**	**5,405,587**	**24,238,220**	
				18,729,949.86		*18,832,632.49*		*24,238,219.70*	
Construction Cost	**1.00**	**EA**		**18,729,950**	**102,683**	**18,832,632**	**5,405,587**	**24,238,220**	
				18,729,949.86		*18,832,632.49*		*24,238,219.70*	
06 Fish and Wildlife Facilities	**1.00**	**EA**		**18,729,950**	**102,683**	**18,832,632**	**5,405,587**	**24,238,220**	
				18,729,949.86		*18,832,632.49*		*24,238,219.70*	
0603 Wildlife Facilities & Sanctuary	**1.00**	**EA**		**18,729,950**	**102,683**	**18,832,632**	**5,405,587**	**24,238,220**	
				18,729,949.86		*18,832,632.49*		*24,238,219.70*	
060373 Habitat and Feeding Facilities	**1.00**	**EA**		**18,729,950**	**102,683**	**18,832,632**	**5,405,587**	**24,238,220**	
				16,327,919.11		*16,430,601.74*		*21,036,483.36*	
Contract 1-Wetland Restoration & Reef Habitat Constriction	**1.00**	**EA**		**16,327,919**	**102,683**	**16,430,602**	**4,605,882**	**21,036,483**	
				593,278.65		*685,282.21*		*822,004.36*	
Wetland Restoration w/Phragmites Removal	**1.00**	**EA**		**593,279**	**92,004**	**685,282**	**136,722**	**822,004**	
				15,734,640.45		*15,745,319.53*		*20,214,479.00*	
Essential Fish Habitat (EFH)	**1.00**	**EA**		**15,734,640**	**10,679**	**15,745,320**	**4,469,159**	**20,214,479**	
				90,285.00		*90,285.00*		*121,441.44*	
Contract 2 - SAV Initial Construction	**1.00**	**EA**		**90,285**	**0**	**90,285**	**31,156**	**121,441**	
				30,095.00		*30,095.00*		*40,480.48*	
SAV Pilot Construction-Phase 1	**1.00**	**EA**		**30,095**	**0**	**30,095**	**10,385**	**40,480**	
				30,095.00		*30,095.00*		*40,480.48*	
SAV Pilot Construction-Phase 2	**1.00**	**EA**		**30,095**	**0**	**30,095**	**10,385**	**40,480**	
				30,095.00		*30,095.00*		*40,480.48*	
SAV Pilot Construction-Phase 3	**1.00**	**EA**		**30,095**	**0**	**30,095**	**10,385**	**40,480**	
				2,311,745.75		*2,311,745.75*		*3,080,294.90*	
Contract 3 - SAV Construction & Bay Scallops	**1.00**	**EA**		**2,311,746**	**0**	**2,311,746**	**768,549**	**3,080,295**	
				6,883.60		*6,883.60*		*9,172.08*	
SAV's - Submerged Aquatic Vegetation	**287.98**	**ACR**		**1,982,340**	**0**	**1,982,340**	**659,037**	**2,641,377**	
				329,405.75		*329,405.75*		*438,918.01*	
Bay Scallop	**1.00**	**EA**	**Prime3 - Scallops and SAV Construction**	**329,406**	**0**	**329,406**	**109,512**	**438,918**	

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
Project Direct Costs Report			**4,705,322**	**1,429,697**	**10,255,225**	**18,729,950**	**18,729,950**
			4,705,322.36	*1,429,696.86*	*10,255,224.89*	*18,729,949.86*	*18,729,949.86*
Construction Cost	**1.00**	**EA**	**4,705,322**	**1,429,697**	**10,255,225**	**18,729,950**	**18,729,950**
			4,705,322.36	*1,429,696.86*	*10,255,224.89*	*18,729,949.86*	*18,729,949.86*
06 Fish and Wildlife Facilities	**1.00**	**EA**	**4,705,322**	**1,429,697**	**10,255,225**	**18,729,950**	**18,729,950**
			4,705,322.36	*1,429,696.86*	*10,255,224.89*	*18,729,949.86*	*18,729,949.86*
0603 Wildlife Facilities & Sanctuary	**1.00**	**EA**	**4,705,322**	**1,429,697**	**10,255,225**	**18,729,950**	**18,729,950**
			4,705,322.36	*1,429,696.86*	*10,255,224.89*	*18,729,949.86*	*18,729,949.86*
060373 Habitat and Feeding Facilities	**1.00**	**EA**	**4,705,322**	**1,429,697**	**10,255,225**	**18,729,950**	**18,729,950**
			4,642,997.36	*1,429,696.86*	*10,255,224.89*	*16,327,919.11*	*16,327,919.11*
Contract 1-Wetland Restoration & Reef Habitat Constriction	**1.00**	**EA**	**4,642,997**	**1,429,697**	**10,255,225**	**16,327,919**	**16,327,919**
			219,865.87	*76,119.10*	*297,293.69*	*593,278.65*	*593,278.65*
Wetland Restoration w/Phragmites Removal	**1.00**	**EA**	**219,866**	**76,119**	**297,294**	**593,279**	**593,279**
			40,772.92	*12,201.88*	*53,941.04*	*106,915.84*	*106,915.84*
PA Princess Anne HS	**3.82**	**ACR**	**155,549**	**46,550**	**205,785**	**407,884**	**407,884**
			142,852.54	*46,531.79*	*182,496.10*	*371,880.43*	*371,880.43*
Construction	**1.00**	**EA**	**142,853**	**46,532**	**182,496**	**371,880**	**371,880**
			1,485.63	*5,139.78*	*0.00*	*6,625.41*	*6,625.41*
Mob	**1.00**	**EA**	**1,486**	**5,140**	**0**	**6,625**	**6,625**
			0.00	*20.20*	*0.00*	*20.20*	*20.20*
NAO L50Z4640 LOADER/BACKHOE, WHEEL, 0.80 CY (0.6 M3) FRONT END BUCKET, 9.8' (3.0 M) DEPTH OF HOE, 24" (0.61 M) DIPPER, 4X4	12.00	HR	0	242	0	242	242
			0.00	*109.52*	*0.00*	*109.52*	*109.52*
NAO T15Z6520 TRACTOR, CRAWLER (DOZER), 181-250 HP (135-186 KW), POWERSHIFT, LGP, W/UNIVERSAL BLADE	12.00	HR	0	1,314	0	1,314	1,314
			30.95	*0.00*	*0.00*	*30.95*	*30.95*
MIL B-TRKDVRHV Truck Drivers, Heavy	48.00	HR	1,486	0	0	1,486	1,486
			0.00	*33.88*	*0.00*	*33.88*	*33.88*
NAO T15Z6440 TRACTOR, CRAWLER (DOZER), 76-100 HP (57-75 KW), POWERSHIFT, W/UNIVERSAL BLADE	12.00	HR	0	407	0	407	407
			0.00	*8.91*	*0.00*	*8.91*	*8.91*
EP T45XX016 TRUCK TRAILER, LOWBOY, 50 TON, 3 AXLE (ADD TOWING TRUCK)	48.00	HR	0	428	0	428	428
			0.00	*77.86*	*0.00*	*77.86*	*77.86*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
NAO L35Z4260 LOADER, FRONT END, CRAWLER, 2.60 CY (2.0 M3) BUCKET	12.00	HR	0	934	0	934	934
			0.00	*37.80*	*0.00*	*37.80*	*37.80*
MAP T50XX028 TRUCK, HIGHWAY, 45,000 LBS GVW, 3 AXLE, 6X4 (CHASSIS ONLY-ADD OPTIONS)	48.00	HR	0	1,814	0	1,814	1,814
			2,247.97	*2,016.32*	*7,280.48*	*11,544.76*	*11,544.76*
Clearing, Demo, and Misc	**1.00**	**EA**	**2,248**	**2,016**	**7,280**	**11,545**	**11,545**
			332.53	*584.09*	*0.00*	*916.62*	*916.62*
RSM 311313100400 Selective clearing, brush, medium clearing, with dozer, ball and chain, excludes removal offsite	3.00	ACR	998	1,752	0	2,750	2,750
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
USR Herbicide -Wetlands area	3.82	ACR	370	185	4,231	4,785	4,785
USR Misc	1.00	LS	150	50	315	515	515
			2.13	*0.26*	*10.45*	*12.84*	*12.84*
RSM 015523500100 Temporary, roads, gravel fill, 8" gravel depth, excl surfacing	111.00	SY	236	29	1,160	1,425	1,425
			6.60	*0.00*	*21.00*	*27.60*	*27.60*
USR 022661120 Tubidity barrier, floating	75.00	LF	495	0	1,575	2,070	2,070
			2.05	*1.49*	*0.95*	*4.49*	*4.49*
Earthwork	**26,500.00**	**CY**	**54,291**	**39,376**	**25,200**	**118,867**	**118,867**
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
HNC 312316400020 Excavate and fill, 75 H.P. dozer, move 150', stockpile	26,500.00	BCY	52,107	35,915	0	88,022	88,022
			1.09	*1.73*	*12.60*	*15.42*	*15.42*
RSM 312323170170 Fill, from stockpile, 130 H.P., 2-1/2 C.Y., 300' haul, spread fill, with front-end loader, excludes compaction; Sand	2,000.00	LCY	2,185	3,460	25,200	30,845	30,845
			22,323.03	*0.00*	*39,477.80*	*61,800.82*	*61,800.82*
Landscaping	**3.80**	**ACR**	**84,828**	**0**	**150,016**	**234,843**	**234,843**
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Alterniflora 18" spacing, 1/2 area	42,461.20	EA	25,477	0	57,960	83,436	83,436
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Patens 18" spacing, 1/2 area	42,461.20	EA	25,477	0	57,960	83,436	83,436
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc (1/4 area)	1,912.35	EA	0	0	28,112	28,112	28,112
			7.78	*0.00*	*0.00*	*7.78*	*7.78*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only; (1/4 area)	1,912.35	EA	14,874	0	0	14,874	14,874
			5,000.00	*0.00*	*1,575.00*	*6,575.00*	*6,575.00*
USR Goose Fencing	3.80	ACR	19,000	0	5,985	24,985	24,985
			12,696.13	*18.39*	*23,288.96*	*36,003.48*	*36,003.48*
Adapt Mngmt-Wetlands	**1.00**	**EA**	**12,696**	**18**	**23,289**	**36,003**	**36,003**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
Herbicide	**0.38**	**ACR**	**37**	**18**	**421**	**476**	**476**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
USR Herbicide -Wetlalnds area	0.38	ACR	37	18	421	476	476
			18,408.80	*0.00*	*32,080.02*	*50,488.82*	*50,488.82*
Wetlands Plantings	**0.39**	**ACR**	**7,179**	**0**	**12,511**	**19,691**	**19,691**
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Alterniflora-18" spacing, 1/2 area	4,357.86	EA	2,615	0	5,948	8,563	8,563
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Patens-18" spacing, 1/2 area	4,357.86	EA	2,615	0	5,948	8,563	8,563
			5,000.00	*0.00*	*1,575.00*	*6,575.00*	*6,575.00*
USR Goose Fencing	0.39	ACR	1,950	0	614	2,564	2,564
			15,656.91	*0.00*	*29,591.10*	*45,248.01*	*45,248.01*
Shrubs	**0.35**	**ACR**	**5,480**	**0**	**10,357**	**15,837**	**15,837**
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc	704.55	EA	0	0	10,357	10,357	10,357
			7.78	*0.00*	*0.00*	*7.78*	*7.78*
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only	704.55	EA	5,480	0	0	5,480	5,480
			2,680.57	*1,160.82*	*2,422.80*	*6,264.19*	*6,264.19*
SG South Great Neck	**13.71**	**ACR**	**36,756**	**15,917**	**33,221**	**85,895**	**85,895**
			34,077.88	*15,908.95*	*28,002.61*	*77,989.44*	*77,989.44*
Construction	**1.00**	**EA**	**34,078**	**15,909**	**28,003**	**77,989**	**77,989**
			495.21	*1,713.26*	*0.00*	*2,208.47*	*2,208.47*
Mob	**1.00**	**EA**	**495**	**1,713**	**0**	**2,208**	**2,208**
			30.95	*0.00*	*0.00*	*30.95*	*30.95*
MIL B-TRKDVRHV Truck Drivers, Heavy	16.00	HR	495	0	0	495	495
			0.00	*77.86*	*0.00*	*77.86*	*77.86*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
NAO L35Z4260 LOADER, FRONT END, CRAWLER, 2.60 CY (2.0 M3) BUCKET	4.00	HR	0	311	0	311	311
			0.00	*20.20*	*0.00*	*20.20*	*20.20*
NAO L50Z4640 LOADER/BACKHOE, WHEEL, 0.80 CY (0.6 M3) FRONT END BUCKET, 9.8' (3.0 M) DEPTH OF HOE, 24" (0.61 M) DIPPER, 4X4	4.00	HR	0	81	0	81	81
			0.00	*33.88*	*0.00*	*33.88*	*33.88*
NAO T15Z6440 TRACTOR, CRAWLER (DOZER), 76-100 HP (57-75 KW), POWERSHIFT, W/UNIVERSAL BLADE	4.00	HR	0	136	0	136	136
			0.00	*109.52*	*0.00*	*109.52*	*109.52*
NAO T15Z6520 TRACTOR, CRAWLER (DOZER), 181-250 HP (135-186 KW), POWERSHIFT, LGP, W/UNIVERSAL BLADE	4.00	HR	0	438	0	438	438
			0.00	*8.91*	*0.00*	*8.91*	*8.91*
EP T45XX016 TRUCK TRAILER, LOWBOY, 50 TON, 3 AXLE (ADD TOWING TRUCK)	16.00	HR	0	143	0	143	143
			0.00	*37.80*	*0.00*	*37.80*	*37.80*
MAP T50XX028 TRUCK, HIGHWAY, 45,000 LBS GVW, 3 AXLE, 6X4 (CHASSIS ONLY-ADD OPTIONS)	16.00	HR	0	605	0	605	605
			1,048.22	*663.26*	*2,524.67*	*4,236.15*	*4,236.15*
Clearing, Demo, and Misc	**1.00**	**EA**	**1,048**	**663**	**2,525**	**4,236**	**4,236**
			332.53	*584.09*	*0.00*	*916.62*	*916.62*
RSM 311313100400 Selective clearing, brush, medium clearing, with dozer, ball and chain, excludes removal offsite	1.00	ACR	333	584	0	917	917
USR Misc	1.00	LS	150	50	315	515	515
			2.13	*0.26*	*10.45*	*12.84*	*12.84*
RSM 015523500100 Temporary, roads, gravel fill, 8" gravel depth, excl surfacing	111.00	SY	236	29	1,160	1,425	1,425
			6.60	*0.00*	*21.00*	*27.60*	*27.60*
USR 022661120 Tubidity barrier, floating	50.00	LF	330	0	1,050	1,380	1,380
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
Excavation	**9,500.00**	**CY**	**18,680**	**12,875**	**0**	**31,555**	**31,555**
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
HNC 312316400020 Excavate and fill, 75 H.P. dozer, move 150', stockpile	9,500.00	BCY	18,680	12,875	0	31,555	31,555
			16,091.40	*763.18*	*29,591.10*	*46,445.68*	*46,445.68*
Landscaping .861 AC	**0.86**	**ACR**	**13,855**	**657**	**25,478**	**39,990**	**39,990**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			9.98	*17.52*	*0.00*	*27.50*	*27.50*
RSM 329113232700 Soil preparation, structural soil mixing, rough grade & scarify subsoil to receive topsoil, clay and till, 149 kW dozer with scarifier	37.50	MSF	374	657	0	1,031	1,031
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc	1,733.19	EA	0	0	25,478	25,478	25,478
			7.78	*0.00*	*0.00*	*7.78*	*7.78*
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only	1,733.19	EA	13,481	0	0	13,481	13,481
			2,678.13	*8.23*	*5,218.77*	*7,905.13*	*7,905.13*
Adapt Mngmt-Wetlands	**1.00**	**EA**	**2,678**	**8**	**5,219**	**7,905**	**7,905**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
Herbicide	**0.17**	**ACR**	**16**	**8**	**188**	**213**	**213**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
USR Herbicide -Wetlalnds area	0.17	ACR	16	8	188	213	213
			15,656.91	*0.00*	*29,591.10*	*45,248.01*	*45,248.01*
Shrubs	**0.17**	**ACR**	**2,662**	**0**	**5,030**	**7,692**	**7,692**
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc	342.21	EA	0	0	5,030	5,030	5,030
			7.78	*0.00*	*0.00*	*7.78*	*7.78*
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only	342.21	EA	2,662	0	0	2,662	2,662
			4,536.40	*4,338.73*	*4,093.69*	*12,968.82*	*12,968.82*
MD Mill Dam Creek	**0.96**	**ACR**	**4,350**	**4,161**	**3,926**	**12,437**	**12,437**
			4,018.71	*4,159.39*	*3,271.21*	*11,449.31*	*11,449.31*
Construction	**1.00**	**EA**	**4,019**	**4,159**	**3,271**	**11,449**	**11,449**
			495.21	*1,713.26*	*0.00*	*2,208.47*	*2,208.47*
Mob	**1.00**	**EA**	**495**	**1,713**	**0**	**2,208**	**2,208**
			30.95	*0.00*	*0.00*	*30.95*	*30.95*
MIL B-TRKDVRHV Truck Drivers, Heavy	16.00	HR	495	0	0	495	495
			0.00	*77.86*	*0.00*	*77.86*	*77.86*
NAO L35Z4260 LOADER, FRONT END, CRAWLER, 2.60 CY (2.0 M3) BUCKET	4.00	HR	0	311	0	311	311
			0.00	*20.20*	*0.00*	*20.20*	*20.20*
NAO L50Z4640 LOADER/BACKHOE, WHEEL, 0.80 CY (0.6 M3) FRONT END BUCKET, 9.8' (3.0 M) DEPTH OF HOE, 24" (0.61 M) DIPPER, 4X4	4.00	HR	0	81	0	81	81

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			0.00	*33.88*	*0.00*	*33.88*	*33.88*
NAO T15Z6440 TRACTOR, CRAWLER (DOZER), 76-100 HP (57-75 KW), POWERSHIFT, W/UNIVERSAL BLADE	4.00	HR	0	136	0	136	136
			0.00	*109.52*	*0.00*	*109.52*	*109.52*
NAO T15Z6520 TRACTOR, CRAWLER (DOZER), 181-250 HP (135-186 KW), POWERSHIFT, LGP, W/UNIVERSAL BLADE	4.00	HR	0	438	0	438	438
			0.00	*8.91*	*0.00*	*8.91*	*8.91*
EP T45XX016 TRUCK TRAILER, LOWBOY, 50 TON, 3 AXLE (ADD TOWING TRUCK)	16.00	HR	0	143	0	143	143
			0.00	*37.80*	*0.00*	*37.80*	*37.80*
MAP T50XX028 TRUCK, HIGHWAY, 45,000 LBS GVW, 3 AXLE, 6X4 (CHASSIS ONLY-ADD OPTIONS)	16.00	HR	0	605	0	605	605
			762.95	*356.50*	*1,939.61*	*3,059.06*	*3,059.06*
Clearing, Demo, and Misc	**1.00**	**EA**	**763**	**356**	**1,940**	**3,059**	**3,059**
			332.53	*584.09*	*0.00*	*916.62*	*916.62*
RSM 311313100400 Selective clearing, brush, medium clearing, with dozer, ball and chain, excludes removal offsite	0.50	ACR	166	292	0	458	458
			2.13	*0.26*	*10.45*	*12.84*	*12.84*
RSM 015523500100 Temporary, roads, gravel fill, 8" gravel depth, excl surfacing	55.00	SY	117	14	575	706	706
USR Misc	1.00	LS	150	50	315	515	515
			6.60	*0.00*	*21.00*	*27.60*	*27.60*
USR 022661120 Tubidity barrier, floating	50.00	LF	330	0	1,050	1,380	1,380
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
Excavation	**600.00**	**CY**	**1,180**	**813**	**0**	**1,993**	**1,993**
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
HNC 312316400020 Excavate and fill, 75 H.P. dozer, move 150', stockpile	600.00	BCY	1,180	813	0	1,993	1,993
			2.85	*4.14*	*0.00*	*6.99*	*6.99*
Load and Haul	**300.00**	**CY**	**856**	**1,241**	**0**	**2,098**	**2,098**
			0.38	*0.60*	*0.00*	*0.98*	*0.98*
HNC 312316440325 Excavate and load, bank measure, medium material, 2-3/4 C.Y. bucket, track loader; assume 1500 cy - hauled off	300.00	BCY	113	180	0	293	293
			2.48	*3.54*	*0.00*	*6.02*	*6.02*
RSM 312323180100 Hauling, excavated or borrow material, loose cubic yards, 2 mile round trip, 2.6 loads/hour, 6 C.Y. dump truck, highway haulers, excludes loading	300.00	LCY	743	1,062	0	1,805	1,805

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			16,100.29	*778.78*	*29,591.10*	*46,470.17*	*46,470.17*
Landscaping	**0.05**	**ACR**	**725**	**35**	**1,332**	**2,091**	**2,091**
			9.98	*17.52*	*0.00*	*27.50*	*27.50*
RSM 329113232700 Soil preparation, structural soil mixing, rough grade & scarify subsoil to receive topsoil, clay and till, 149 kW dozer with scarifier	2.00	MSF	20	35	0	55	55
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc (1/4 area)	90.59	EA	0	0	1,332	1,332	1,332
			7.78	*0.00*	*0.00*	*7.78*	*7.78*
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only; (1/4 area)	90.59	EA	705	0	0	705	705
			331.70	*1.45*	*654.64*	*987.79*	*987.79*
Adapt Mngmt-Wetlands	**1.00**	**EA**	**332**	**1**	**655**	**988**	**988**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
Herbicide	**0.03**	**ACR**	**3**	**1**	**33**	**38**	**38**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
USR Herbicide -Wetlalnds area	0.03	ACR	3	1	33	38	38
			15,656.91	*0.00*	*29,591.10*	*45,248.01*	*45,248.01*
Shrubs	**0.02**	**ACR**	**329**	**0**	**621**	**950**	**950**
			0.00	*0.00*	*14.70*	*14.70*	*14.70*
USR Wetland Shrubs -1 gallon; 5' oc	42.27	EA	0	0	621	621	621
			7.78	*0.00*	*0.00*	*7.78*	*7.78*
RSM 329343100730 Planting, trees, shrubs, and ground cover, heavy or stony soil, container, 1 gallon, includes planting only	42.27	EA	329	0	0	329	329
			1,167.07	*477.22*	*2,733.38*	*4,377.67*	*4,377.67*
NG North Great Neck	**19.89**	**ACR**	**23,211**	**9,491**	**54,361**	**87,063**	**87,063**
			19,686.97	*9,477.82*	*47,967.17*	*77,131.95*	*77,131.95*
Construction	**1.00**	**EA**	**19,687**	**9,478**	**47,967**	**77,132**	**77,132**
			495.21	*1,713.26*	*0.00*	*2,208.47*	*2,208.47*
Mob	**1.00**	**EA**	**495**	**1,713**	**0**	**2,208**	**2,208**
			30.95	*0.00*	*0.00*	*30.95*	*30.95*
MIL B-TRKDVRHV Truck Drivers, Heavy	16.00	HR	495	0	0	495	495
			0.00	*77.86*	*0.00*	*77.86*	*77.86*
NAO L35Z4260 LOADER, FRONT END, CRAWLER, 2.60 CY (2.0 M3) BUCKET	4.00	HR	0	311	0	311	311

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			0.00	*20.20*	*0.00*	*20.20*	*20.20*
NAO L50Z4640 LOADER/BACKHOE, WHEEL, 0.80 CY (0.6 M3) FRONT END BUCKET, 9.8' (3.0 M) DEPTH OF HOE, 24" (0.61 M) DIPPER, 4X4	4.00	HR	0	81	0	81	81
			0.00	*33.88*	*0.00*	*33.88*	*33.88*
NAO T15Z6440 TRACTOR, CRAWLER (DOZER), 76-100 HP (57-75 KW), POWERSHIFT, W/UNIVERSAL BLADE	4.00	HR	0	136	0	136	136
			0.00	*109.52*	*0.00*	*109.52*	*109.52*
NAO T15Z6520 TRACTOR, CRAWLER (DOZER), 181-250 HP (135-186 KW), POWERSHIFT, LGP, W/UNIVERSAL BLADE	4.00	HR	0	438	0	438	438
			0.00	*8.91*	*0.00*	*8.91*	*8.91*
EP T45XX016 TRUCK TRAILER, LOWBOY, 50 TON, 3 AXLE (ADD TOWING TRUCK)	16.00	HR	0	143	0	143	143
			0.00	*37.80*	*0.00*	*37.80*	*37.80*
MAP T50XX028 TRUCK, HIGHWAY, 45,000 LBS GVW, 3 AXLE, 6X4 (CHASSIS ONLY-ADD OPTIONS)	16.00	HR	0	605	0	605	605
			1,380.76	*1,247.34*	*2,524.67*	*5,152.77*	*5,152.77*
Clearing, Demo, and Misc	**1.00**	**EA**	**1,381**	**1,247**	**2,525**	**5,153**	**5,153**
			332.53	*584.09*	*0.00*	*916.62*	*916.62*
RSM 311313100400 Selective clearing, brush, medium clearing, with dozer, ball and chain, excludes removal offsite	2.00	ACR	665	1,168	0	1,833	1,833
USR Misc	1.00	LS	150	50	315	515	515
			2.13	*0.26*	*10.45*	*12.84*	*12.84*
RSM 015523500100 Temporary, roads, gravel fill, 8" gravel depth, excl surfacing	111.00	SY	236	29	1,160	1,425	1,425
			6.60	*0.00*	*21.00*	*27.60*	*27.60*
USR 022661120 Tubidity barrier, floating	50.00	LF	330	0	1,050	1,380	1,380
			3.12	*3.18*	*13.26*	*19.56*	*19.56*
Earthwork	**1,900.00**	**CY**	**5,921**	**6,035**	**25,200**	**37,156**	**37,156**
			1.97	*1.36*	*0.00*	*3.32*	*3.32*
HNC 312316400020 Excavate and fill, 75 H.P. dozer, move 150', stockpile	1,900.00	BCY	3,736	2,575	0	6,311	6,311
			1.09	*1.73*	*12.60*	*15.42*	*15.42*
RSM 312323170170 Fill, from stockpile, 130 H.P., 2-1/2 C.Y., 300' haul, spread fill, with front-end loader, excludes compaction; Sand	2,000.00	LCY	2,185	3,460	25,200	30,845	30,845
			18,843.57	*763.66*	*32,080.02*	*51,687.25*	*51,687.25*
Landscaping	**0.63**	**ACR**	**11,890**	**482**	**20,242**	**32,615**	**32,615**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			9.98	*17.52*	*0.00*	*27.50*	*27.50*
RSM 329113232700 Soil preparation, structural soil mixing, rough grade & scarify subsoil to receive topsoil, clay and till, 149 kW dozer with scarifier	27.50	MSF	274	482	0	756	756
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Alterniflora 18" spacing, full area	14,101.59	EA	8,461	0	19,249	27,710	27,710
			5,000.00	*0.00*	*1,575.00*	*6,575.00*	*6,575.00*
USR Goose Fencing	0.63	ACR	3,155	0	994	4,149	4,149
			3,523.81	*13.07*	*6,394.24*	*9,931.12*	*9,931.12*
Adapt Mngmt-Wetlands	**1.00**	**EA**	**3,524**	**13**	**6,394**	**9,931**	**9,931**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
Herbicide	**0.27**	**ACR**	**26**	**13**	**299**	**338**	**338**
			96.80	*48.40*	*1,107.54*	*1,252.74*	*1,252.74*
USR Herbicide -Wetlalnds area	0.27	ACR	26	13	299	338	338
			18,408.80	*0.00*	*32,080.02*	*50,488.82*	*50,488.82*
Wetlands Plantings	**0.19**	**ACR**	**3,498**	**0**	**6,095**	**9,593**	**9,593**
			0.60	*0.00*	*1.37*	*1.97*	*1.97*
USR Spartina Alterniflora-18" spacing, 1/2 area	4,246.12	EA	2,548	0	5,796	8,344	8,344
			5,000.00	*0.00*	*1,575.00*	*6,575.00*	*6,575.00*
USR Goose Fencing	0.19	ACR	950	0	299	1,249	1,249
			4,423,131.49	*1,353,577.76*	*9,957,931.20*	*15,734,640.45*	*15,734,640.45*
Essential Fish Habitat (EFH)	**1.00**	**EA**	**4,423,131**	**1,353,578**	**9,957,931**	**15,734,640**	**15,734,640**
			1,618,372.84	*476,186.50*	*3,317,797.00*	*5,412,356.34*	*5,412,356.34*
Reef Habitat Construction -Phase 1	**1.00**	**EA**	**1,618,373**	**476,187**	**3,317,797**	**5,412,356**	**5,412,356**
			52.94	*18.99*	*94.50*	*166.44*	*166.44*
EFH Bay Balls	**7,046.00**	**EA**	**373,044**	**133,832**	**665,847**	**1,172,722**	**1,172,722**
			52.03	*18.76*	*94.50*	*165.29*	*165.29*
Bay Ball EFH-1	**809.00**	**EA**	**42,088**	**15,178**	**76,451**	**133,717**	**133,717**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	809.00	EA	0	0	76,451	76,451	76,451
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	809.00	EA	2,208	1,502	0	3,709	3,709
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	809.00	EA	2,276	3,203	0	5,479	5,479
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	809.00	EA	2,208	1,502	0	3,709	3,709

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			18.46	*5.32*	*0.00*	*23.78*	*23.78*
USR BrgBy1 Load Bay Balls into Barge EFH-1	809.00	EA	14,934	4,307	0	19,242	19,242
			25.29	*5.77*	*0.00*	*31.06*	*31.06*
USR PlcBy1 Transport Bay Ball by Barge & Place- Site RH-1	809.00	EA	20,463	4,664	0	25,127	25,127
			52.36	*18.85*	*94.50*	*165.70*	*165.70*
Bay Ball EFH-2	**4,577.00**	**EA**	**239,642**	**86,255**	**432,527**	**758,424**	**758,424**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	4,577.00	EA	0	0	432,527	432,527	432,527
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	4,577.00	EA	12,489	8,496	0	20,985	20,985
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	4,577.00	EA	12,878	18,121	0	31,000	31,000
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	4,577.00	EA	12,489	8,496	0	20,985	20,985
			18.60	*5.36*	*0.00*	*23.97*	*23.97*
USR BrgBy2 Load Bay Balls into Barge EFH-2	4,577.00	EA	85,134	24,555	0	109,689	109,689
			25.49	*5.81*	*0.00*	*31.30*	*31.30*
USR PlcBy2 Transport Bay Ball by Barge & Place- Site RH-2	4,577.00	EA	116,651	26,587	0	143,238	143,238
			54.50	*19.39*	*94.50*	*168.39*	*168.39*
Bay Ball EFH-3	**643.00**	**EA**	**35,045**	**12,467**	**60,764**	**108,276**	**108,276**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	643.00	EA	0	0	60,764	60,764	60,764
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	643.00	EA	1,755	1,194	0	2,948	2,948
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	643.00	EA	1,809	2,546	0	4,355	4,355
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	643.00	EA	1,755	1,194	0	2,948	2,948
			19.51	*5.63*	*0.00*	*25.13*	*25.13*
USR BrgBy3 Load Bay Balls into Barge EFH-3	643.00	EA	12,542	3,617	0	16,159	16,159
			26.73	*6.09*	*0.00*	*32.82*	*32.82*
USR PlcBy3 Transport Bay Ball by Barge & Place- Site RH-3	643.00	EA	17,185	3,917	0	21,102	21,102
			55.33	*19.60*	*94.50*	*169.43*	*169.43*
Bay Ball EFH-4	**1,017.00**	**EA**	**56,269**	**19,931**	**96,107**	**172,306**	**172,306**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	1,017.00	EA	0	0	96,107	96,107	96,107

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	1,017.00	EA	2,775	1,888	0	4,663	4,663
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	1,017.00	EA	2,862	4,027	0	6,888	6,888
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	1,017.00	EA	2,775	1,888	0	4,663	4,663
			19.85	*5.73*	*0.00*	*25.58*	*25.58*
USR BrgBy4 Load Bay Balls into Barge EFH-4	1,017.00	EA	20,191	5,824	0	26,015	26,015
			27.20	*6.20*	*0.00*	*33.40*	*33.40*
USR PlcBy4 Transport Bay Ball by Barge & Place- Site RH-4	1,017.00	EA	27,666	6,306	0	33,971	33,971
			50.06	*18.92*	*153.26*	*222.24*	*222.24*
EFH Large Balls Normal Foundation	**5,061.00**	**EA**	**253,365**	**95,759**	**775,632**	**1,124,756**	**1,124,756**
			156.23	*61.58*	*505.04*	*722.85*	*722.85*
Goliath	**674.00**	**EA**	**105,298**	**41,504**	**340,396**	**487,198**	**487,198**
			160.11	*66.52*	*505.79*	*732.42*	*732.42*
EFH-5, 6, & 7	**390.00**	**EA**	**62,441**	**25,942**	**197,260**	**285,644**	**285,644**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob Marine equipment and Cranes	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**
			411.67	*333.33*	*0.00*	*745.00*	*745.00*
USR WtrMb Mob Marine Equipment & Cranes	16.00	HR	6,587	5,333	0	11,920	11,920
USR Misc Mob work	1.00	LS	0	0	700	700	700
			143.22	*52.84*	*504.00*	*700.06*	*700.06*
Load & Place Reef Balls	**390.00**	**EA**	**55,854**	**20,609**	**196,560**	**273,023**	**273,023**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	390.00	EA	0	0	196,560	196,560	196,560
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	390.00	EA	19,791	5,708	0	25,499	25,499
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	390.00	EA	2,661	1,810	0	4,470	4,470
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	390.00	EA	27,117	6,181	0	33,298	33,298

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	390.00	EA	2,661	1,810	0	4,470	4,470
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	390.00	EA	3,625	5,101	0	8,725	8,725
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**238.00**	**EA**	**35,586**	**12,957**	**119,952**	**168,495**	**168,495**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	238.00	EA	0	0	119,952	119,952	119,952
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	238.00	EA	1,624	1,104	0	2,728	2,728
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	238.00	EA	2,212	3,113	0	5,325	5,325
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	238.00	EA	1,624	1,104	0	2,728	2,728
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	238.00	EA	12,710	3,666	0	16,376	16,376
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	238.00	EA	17,416	3,969	0	21,385	21,385
			158.08	*56.61*	*504.00*	*718.69*	*718.69*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**23,184**	**33,060**	**33,060**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	46.00	EA	0	0	23,184	23,184	23,184
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413
			146.46	*53.67*	*451.50*	*651.62*	*651.62*
Super	**674.00**	**EA**	**98,711**	**36,170**	**304,311**	**439,193**	**439,193**
			143.22	*52.84*	*451.50*	*647.56*	*647.56*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
EFH-5, 6, & 7	**390.00**	**EA**	**55,854**	**20,609**	**176,085**	**252,548**	**252,548**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	390.00	EA	0	0	176,085	176,085	176,085
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	390.00	EA	2,661	1,810	0	4,470	4,470
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	390.00	EA	3,625	5,101	0	8,725	8,725
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	390.00	EA	2,661	1,810	0	4,470	4,470
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	390.00	EA	19,791	5,708	0	25,499	25,499
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	390.00	EA	27,117	6,181	0	33,298	33,298
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**238.00**	**EA**	**35,586**	**12,957**	**107,457**	**156,000**	**156,000**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	238.00	EA	0	0	107,457	107,457	107,457
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	238.00	EA	1,624	1,104	0	2,728	2,728
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	238.00	EA	2,212	3,113	0	5,325	5,325
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	238.00	EA	1,624	1,104	0	2,728	2,728
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	238.00	EA	12,710	3,666	0	16,376	16,376
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	238.00	EA	17,416	3,969	0	21,385	21,385
			158.08	*56.61*	*451.50*	*666.19*	*666.19*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**20,769**	**30,645**	**30,645**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	46.00	EA	0	0	20,769	20,769	20,769
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413
			146.46	*53.67*	*388.50*	*588.62*	*588.62*
Ultra	**337.00**	**EA**	**49,356**	**18,085**	**130,925**	**198,365**	**198,365**
			143.22	*52.84*	*388.50*	*584.56*	*584.56*
EFH-5, 6, & 7	**195.00**	**EA**	**27,927**	**10,305**	**75,758**	**113,989**	**113,989**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	195.00	EA	0	0	75,758	75,758	75,758
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	195.00	EA	1,330	905	0	2,235	2,235
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	195.00	EA	1,812	2,550	0	4,363	4,363
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	195.00	EA	1,330	905	0	2,235	2,235
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	195.00	EA	9,895	2,854	0	12,750	12,750
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	195.00	EA	13,559	3,090	0	16,649	16,649
			149.52	*54.44*	*388.50*	*592.46*	*592.46*
EFH-8	**119.00**	**EA**	**17,793**	**6,479**	**46,232**	**70,503**	**70,503**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	119.00	EA	0	0	46,232	46,232	46,232
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	119.00	EA	812	552	0	1,364	1,364
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	119.00	EA	1,106	1,556	0	2,662	2,662
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	119.00	EA	812	552	0	1,364	1,364
			53.41	*15.40*	*0.00*	*68.81*	*68.81*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR BrgBy8 Load Large Balls into Barge RH-8	119.00	EA	6,355	1,833	0	8,188	8,188
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	119.00	EA	8,708	1,985	0	10,693	10,693
			158.08	*56.61*	*388.50*	*603.19*	*603.19*
EFH-9	**23.00**	**EA**	**3,636**	**1,302**	**8,936**	**13,873**	**13,873**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	23.00	EA	0	0	8,936	8,936	8,936
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	23.00	EA	157	107	0	264	264
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	23.00	EA	214	301	0	515	515
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	23.00	EA	157	107	0	264	264
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	23.00	EA	1,311	378	0	1,690	1,690
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	23.00	EA	1,797	410	0	2,206	2,206
			312.54	*95.76*	*1,049.40*	*1,457.69*	*1,457.69*
EFH Large Balls Soft Foundation	**1,788.00**	**EA**	**558,814**	**171,215**	**1,876,319**	**2,606,347**	**2,606,347**
			326.27	*99.24*	*1,108.80*	*1,534.31*	*1,534.31*
Goliath	**715.00**	**EA**	**233,282**	**70,955**	**792,792**	**1,097,030**	**1,097,030**
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**715.00**	**EA**	**106,906**	**38,926**	**360,360**	**506,192**	**506,192**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	715.00	EA	0	0	360,360	360,360	360,360
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	715.00	EA	4,878	3,318	0	8,196	8,196
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	715.00	EA	6,646	9,351	0	15,997	15,997
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	715.00	EA	4,878	3,318	0	8,196	8,196
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge EFH-8	715.00	EA	38,185	11,013	0	49,198	49,198
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site EFH-8	715.00	EA	52,321	11,925	0	64,246	64,246

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**715.00**	**EA**	**126,376**	**32,030**	**432,432**	**590,838**	**590,838**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	715.00	EA	53,319	15,378	0	68,697	68,697
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	715.00	EA	73,057	16,651	0	89,709	89,709
			0.00	*0.00*	*604.80*	*604.80*	*604.80*
USR Marine Mattress 8'x8'x12"- material	715.00	EA	0	0	432,432	432,432	432,432
			326.27	*99.24*	*1,056.30*	*1,481.81*	*1,481.81*
Super	**715.00**	**EA**	**233,282**	**70,955**	**755,255**	**1,059,492**	**1,059,492**
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**715.00**	**EA**	**106,906**	**38,926**	**322,823**	**468,654**	**468,654**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	715.00	EA	0	0	322,823	322,823	322,823
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	715.00	EA	4,878	3,318	0	8,196	8,196
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	715.00	EA	6,646	9,351	0	15,997	15,997
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	715.00	EA	4,878	3,318	0	8,196	8,196
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	715.00	EA	38,185	11,013	0	49,198	49,198
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	715.00	EA	52,321	11,925	0	64,246	64,246
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**715.00**	**EA**	**126,376**	**32,030**	**432,432**	**590,838**	**590,838**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	715.00	EA	53,319	15,378	0	68,697	68,697
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	715.00	EA	73,057	16,651	0	89,709	89,709
			0.00	*0.00*	*604.80*	*604.80*	*604.80*
USR Marine Mattress 8'x8'x12"- material	715.00	EA	0	0	432,432	432,432	432,432
			257.68	*81.85*	*916.96*	*1,256.49*	*1,256.49*
Ultra	**358.00**	**EA**	**92,249**	**29,304**	**328,272**	**449,825**	**449,825**
			149.52	*54.44*	*388.50*	*592.46*	*592.46*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
EFH-8	**358.00**	**EA**	**53,528**	**19,490**	**139,083**	**212,101**	**212,101**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	358.00	EA	0	0	139,083	139,083	139,083
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	358.00	EA	2,442	1,661	0	4,104	4,104
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	358.00	EA	3,327	4,682	0	8,010	8,010
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	358.00	EA	2,442	1,661	0	4,104	4,104
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	358.00	EA	19,119	5,514	0	24,633	24,633
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	358.00	EA	26,197	5,971	0	32,168	32,168
			108.16	*27.41*	*528.46*	*664.03*	*664.03*
Marine Mattress Mats	**358.00**	**EA**	**38,721**	**9,814**	**189,189**	**237,724**	**237,724**
			45.63	*13.16*	*0.00*	*58.80*	*58.80*
USR MMMk6 Load Gabion onto Barge 6'x6'	358.00	EA	16,337	4,712	0	21,049	21,049
			62.53	*14.25*	*0.00*	*76.78*	*76.78*
USR MMPlc6 Transport & Place in Water 6'x6'	358.00	EA	22,385	5,102	0	27,487	27,487
			0.00	*0.00*	*264.60*	*264.60*	*264.60*
USR Marine Mattress 6'x6' x6"- material	715.00	EA	0	0	189,189	189,189	189,189
			433,149.94	*75,381.15*	*0.00*	*508,531.08*	*508,531.08*
EFH Adaptive Management	**1.00**	**EA**	**433,150**	**75,381**	**0**	**508,531**	**508,531**
			19,533.33	*1,613.10*	*0.00*	*21,146.44*	*21,146.44*
Clean Reef Balls	**1.00**	**EA**	**19,533**	**1,613**	**0**	**21,146**	**21,146**
			53.89	*4.45*	*0.00*	*58.33*	*58.33*
USR Clean Bay Balls	175.00	EA	9,430	779	0	10,209	10,209
			134.71	*11.12*	*0.00*	*145.84*	*145.84*
USR Clean Large Reef Balls	75.00	EA	10,103	834	0	10,938	10,938
			413,616.60	*73,768.04*	*0.00*	*487,384.65*	*487,384.65*
Relocate Reef Balls	**1.00**	**EA**	**413,617**	**73,768**	**0**	**487,385**	**487,385**
			200.50	*35.76*	*0.00*	*236.25*	*236.25*
USR RelBy Relocate Bay Ball by Barge	1,100.00	EA	220,546	39,334	0	259,880	259,880
			386.14	*68.87*	*0.00*	*455.01*	*455.01*
USR RelLg Relocate Large Balls by Barge	500.00	EA	193,071	34,434	0	227,505	227,505

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			1,618,372.84	*476,186.50*	*3,317,797.00*	*5,412,356.34*	*5,412,356.34*
Reef Habitat Construction -Phase 2	**1.00**	**EA**	**1,618,373**	**476,187**	**3,317,797**	**5,412,356**	**5,412,356**
			52.94	*18.99*	*94.50*	*166.44*	*166.44*
EFH Bay Balls	**7,046.00**	**EA**	**373,044**	**133,832**	**665,847**	**1,172,722**	**1,172,722**
			52.03	*18.76*	*94.50*	*165.29*	*165.29*
Bay Ball EFH-1	**809.00**	**EA**	**42,088**	**15,178**	**76,451**	**133,717**	**133,717**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	809.00	EA	0	0	76,451	76,451	76,451
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	809.00	EA	2,208	1,502	0	3,709	3,709
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	809.00	EA	2,276	3,203	0	5,479	5,479
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	809.00	EA	2,208	1,502	0	3,709	3,709
			18.46	*5.32*	*0.00*	*23.78*	*23.78*
USR BrgBy1 Load Bay Balls into Barge EFH-1	809.00	EA	14,934	4,307	0	19,242	19,242
			25.29	*5.77*	*0.00*	*31.06*	*31.06*
USR PlcBy1 Transport Bay Ball by Barge & Place- Site RH-1	809.00	EA	20,463	4,664	0	25,127	25,127
			52.36	*18.85*	*94.50*	*165.70*	*165.70*
Bay Ball EFH-2	**4,577.00**	**EA**	**239,642**	**86,255**	**432,527**	**758,424**	**758,424**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	4,577.00	EA	0	0	432,527	432,527	432,527
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	4,577.00	EA	12,489	8,496	0	20,985	20,985
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	4,577.00	EA	12,878	18,121	0	31,000	31,000
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	4,577.00	EA	12,489	8,496	0	20,985	20,985
			18.60	*5.36*	*0.00*	*23.97*	*23.97*
USR BrgBy2 Load Bay Balls into Barge EFH-2	4,577.00	EA	85,134	24,555	0	109,689	109,689
			25.49	*5.81*	*0.00*	*31.30*	*31.30*
USR PlcBy2 Transport Bay Ball by Barge & Place- Site RH-2	4,577.00	EA	116,651	26,587	0	143,238	143,238
			54.50	*19.39*	*94.50*	*168.39*	*168.39*
Bay Ball EFH-3	**643.00**	**EA**	**35,045**	**12,467**	**60,764**	**108,276**	**108,276**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR Bay Ball-Material	643.00	EA	0	0	60,764	60,764	60,764
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	643.00	EA	1,755	1,194	0	2,948	2,948
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	643.00	EA	1,809	2,546	0	4,355	4,355
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	643.00	EA	1,755	1,194	0	2,948	2,948
			19.51	*5.63*	*0.00*	*25.13*	*25.13*
USR BrgBy3 Load Bay Balls into Barge EFH-3	643.00	EA	12,542	3,617	0	16,159	16,159
			26.73	*6.09*	*0.00*	*32.82*	*32.82*
USR PlcBy3 Transport Bay Ball by Barge & Place- Site RH-3	643.00	EA	17,185	3,917	0	21,102	21,102
			55.33	*19.60*	*94.50*	*169.43*	*169.43*
Bay Ball EFH-4	**1,017.00**	**EA**	**56,269**	**19,931**	**96,107**	**172,306**	**172,306**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	1,017.00	EA	0	0	96,107	96,107	96,107
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	1,017.00	EA	2,775	1,888	0	4,663	4,663
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	1,017.00	EA	2,862	4,027	0	6,888	6,888
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	1,017.00	EA	2,775	1,888	0	4,663	4,663
			19.85	*5.73*	*0.00*	*25.58*	*25.58*
USR BrgBy4 Load Bay Balls into Barge EFH-4	1,017.00	EA	20,191	5,824	0	26,015	26,015
			27.20	*6.20*	*0.00*	*33.40*	*33.40*
USR PlcBy4 Transport Bay Ball by Barge & Place- Site RH-4	1,017.00	EA	27,666	6,306	0	33,971	33,971
			50.06	*18.92*	*153.26*	*222.24*	*222.24*
EFH Large Balls Normal Foundation	**5,061.00**	**EA**	**253,365**	**95,759**	**775,632**	**1,124,756**	**1,124,756**
			156.23	*61.58*	*505.04*	*722.85*	*722.85*
Goliath	**674.00**	**EA**	**105,298**	**41,504**	**340,396**	**487,198**	**487,198**
			160.11	*66.52*	*505.79*	*732.42*	*732.42*
EFH-5, 6, & 7	**390.00**	**EA**	**62,441**	**25,942**	**197,260**	**285,644**	**285,644**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob Marine equipment and Cranes	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			411.67	*333.33*	*0.00*	*745.00*	*745.00*
USR WtrMb Mob Marine Equipment & Cranes	16.00	HR	6,587	5,333	0	11,920	11,920
USR Misc Mob work	1.00	LS	0	0	700	700	700
			143.22	*52.84*	*504.00*	*700.06*	*700.06*
Load & Place Reef Balls	**390.00**	**EA**	**55,854**	**20,609**	**196,560**	**273,023**	**273,023**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	390.00	EA	0	0	196,560	196,560	196,560
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	390.00	EA	19,791	5,708	0	25,499	25,499
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	390.00	EA	2,661	1,810	0	4,470	4,470
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	390.00	EA	27,117	6,181	0	33,298	33,298
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	390.00	EA	2,661	1,810	0	4,470	4,470
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	390.00	EA	3,625	5,101	0	8,725	8,725
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**238.00**	**EA**	**35,586**	**12,957**	**119,952**	**168,495**	**168,495**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	238.00	EA	0	0	119,952	119,952	119,952
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	238.00	EA	1,624	1,104	0	2,728	2,728
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	238.00	EA	2,212	3,113	0	5,325	5,325
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	238.00	EA	1,624	1,104	0	2,728	2,728
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	238.00	EA	12,710	3,666	0	16,376	16,376
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	238.00	EA	17,416	3,969	0	21,385	21,385
			158.08	*56.61*	*504.00*	*718.69*	*718.69*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**23,184**	**33,060**	**33,060**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR Goliath Reef Ball-Material	46.00	EA	0	0	23,184	23,184	23,184
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413
			146.46	*53.67*	*451.50*	*651.62*	*651.62*
Super	**674.00**	**EA**	**98,711**	**36,170**	**304,311**	**439,193**	**439,193**
			143.22	*52.84*	*451.50*	*647.56*	*647.56*
EFH-5, 6, & 7	**390.00**	**EA**	**55,854**	**20,609**	**176,085**	**252,548**	**252,548**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	390.00	EA	0	0	176,085	176,085	176,085
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	390.00	EA	2,661	1,810	0	4,470	4,470
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	390.00	EA	3,625	5,101	0	8,725	8,725
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	390.00	EA	2,661	1,810	0	4,470	4,470
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	390.00	EA	19,791	5,708	0	25,499	25,499
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	390.00	EA	27,117	6,181	0	33,298	33,298
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**238.00**	**EA**	**35,586**	**12,957**	**107,457**	**156,000**	**156,000**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	238.00	EA	0	0	107,457	107,457	107,457
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	238.00	EA	1,624	1,104	0	2,728	2,728
			9.29	*13.08*	*0.00*	*22.37*	*22.37*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	238.00	EA	2,212	3,113	0	5,325	5,325
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	238.00	EA	1,624	1,104	0	2,728	2,728
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	238.00	EA	12,710	3,666	0	16,376	16,376
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	238.00	EA	17,416	3,969	0	21,385	21,385
			158.08	*56.61*	*451.50*	*666.19*	*666.19*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**20,769**	**30,645**	**30,645**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	46.00	EA	0	0	20,769	20,769	20,769
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413
			146.46	*53.67*	*388.50*	*588.62*	*588.62*
Ultra	**337.00**	**EA**	**49,356**	**18,085**	**130,925**	**198,365**	**198,365**
			143.22	*52.84*	*388.50*	*584.56*	*584.56*
EFH-5, 6, & 7	**195.00**	**EA**	**27,927**	**10,305**	**75,758**	**113,989**	**113,989**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	195.00	EA	0	0	75,758	75,758	75,758
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	195.00	EA	1,330	905	0	2,235	2,235
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	195.00	EA	1,812	2,550	0	4,363	4,363
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	195.00	EA	1,330	905	0	2,235	2,235
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	195.00	EA	9,895	2,854	0	12,750	12,750

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	195.00	EA	13,559	3,090	0	16,649	16,649
			149.52	*54.44*	*388.50*	*592.46*	*592.46*
EFH-8	**119.00**	**EA**	**17,793**	**6,479**	**46,232**	**70,503**	**70,503**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	119.00	EA	0	0	46,232	46,232	46,232
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	119.00	EA	812	552	0	1,364	1,364
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	119.00	EA	1,106	1,556	0	2,662	2,662
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	119.00	EA	812	552	0	1,364	1,364
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	119.00	EA	6,355	1,833	0	8,188	8,188
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	119.00	EA	8,708	1,985	0	10,693	10,693
			158.08	*56.61*	*388.50*	*603.19*	*603.19*
EFH-9	**23.00**	**EA**	**3,636**	**1,302**	**8,936**	**13,873**	**13,873**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	23.00	EA	0	0	8,936	8,936	8,936
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	23.00	EA	157	107	0	264	264
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	23.00	EA	214	301	0	515	515
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	23.00	EA	157	107	0	264	264
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	23.00	EA	1,311	378	0	1,690	1,690
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	23.00	EA	1,797	410	0	2,206	2,206
			312.54	*95.76*	*1,049.40*	*1,457.69*	*1,457.69*
EFH Large Balls Soft Foundation	**1,788.00**	**EA**	**558,814**	**171,215**	**1,876,319**	**2,606,347**	**2,606,347**
			326.27	*99.24*	*1,108.80*	*1,534.31*	*1,534.31*
Goliath	**715.00**	**EA**	**233,282**	**70,955**	**792,792**	**1,097,030**	**1,097,030**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**715.00**	**EA**	**106,906**	**38,926**	**360,360**	**506,192**	**506,192**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	715.00	EA	0	0	360,360	360,360	360,360
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	715.00	EA	4,878	3,318	0	8,196	8,196
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	715.00	EA	6,646	9,351	0	15,997	15,997
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	715.00	EA	4,878	3,318	0	8,196	8,196
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge EFH-8	715.00	EA	38,185	11,013	0	49,198	49,198
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site EFH-8	715.00	EA	52,321	11,925	0	64,246	64,246
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**715.00**	**EA**	**126,376**	**32,030**	**432,432**	**590,838**	**590,838**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	715.00	EA	53,319	15,378	0	68,697	68,697
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	715.00	EA	73,057	16,651	0	89,709	89,709
			0.00	*0.00*	*604.80*	*604.80*	*604.80*
USR Marine Mattress 8'x8'x12"- material	715.00	EA	0	0	432,432	432,432	432,432
			326.27	*99.24*	*1,056.30*	*1,481.81*	*1,481.81*
Super	**715.00**	**EA**	**233,282**	**70,955**	**755,255**	**1,059,492**	**1,059,492**
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**715.00**	**EA**	**106,906**	**38,926**	**322,823**	**468,654**	**468,654**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	715.00	EA	0	0	322,823	322,823	322,823
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	715.00	EA	4,878	3,318	0	8,196	8,196
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	715.00	EA	6,646	9,351	0	15,997	15,997
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	715.00	EA	4,878	3,318	0	8,196	8,196
			53.41	*15.40*	*0.00*	*68.81*	*68.81*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR BrgBy8 Load Large Balls into Barge RH-8	715.00	EA	38,185	11,013	0	49,198	49,198
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	715.00	EA	52,321	11,925	0	64,246	64,246
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**715.00**	**EA**	**126,376**	**32,030**	**432,432**	**590,838**	**590,838**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	715.00	EA	53,319	15,378	0	68,697	68,697
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	715.00	EA	73,057	16,651	0	89,709	89,709
			0.00	*0.00*	*604.80*	*604.80*	*604.80*
USR Marine Mattress 8'x8'x12"- material	715.00	EA	0	0	432,432	432,432	432,432
			257.68	*81.85*	*916.96*	*1,256.49*	*1,256.49*
Ultra	**358.00**	**EA**	**92,249**	**29,304**	**328,272**	**449,825**	**449,825**
			149.52	*54.44*	*388.50*	*592.46*	*592.46*
EFH-8	**358.00**	**EA**	**53,528**	**19,490**	**139,083**	**212,101**	**212,101**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	358.00	EA	0	0	139,083	139,083	139,083
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	358.00	EA	2,442	1,661	0	4,104	4,104
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	358.00	EA	3,327	4,682	0	8,010	8,010
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	358.00	EA	2,442	1,661	0	4,104	4,104
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	358.00	EA	19,119	5,514	0	24,633	24,633
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	358.00	EA	26,197	5,971	0	32,168	32,168
			108.16	*27.41*	*528.46*	*664.03*	*664.03*
Marine Mattress Mats	**358.00**	**EA**	**38,721**	**9,814**	**189,189**	**237,724**	**237,724**
			45.63	*13.16*	*0.00*	*58.80*	*58.80*
USR MMMk6 Load Gabion onto Barge 6'x6'	358.00	EA	16,337	4,712	0	21,049	21,049
			62.53	*14.25*	*0.00*	*76.78*	*76.78*
USR MMPlc6 Transport & Place in Water 6'x6'	358.00	EA	22,385	5,102	0	27,487	27,487
			0.00	*0.00*	*264.60*	*264.60*	*264.60*
USR Marine Mattress 6'x6' x6"- material	715.00	EA	0	0	189,189	189,189	189,189

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			433,149.94	*75,381.15*	*0.00*	*508,531.08*	*508,531.08*
EFH Adaptive Management	**1.00**	**EA**	**433,150**	**75,381**	**0**	**508,531**	**508,531**
			19,533.33	*1,613.10*	*0.00*	*21,146.44*	*21,146.44*
Clean Reef Balls	**1.00**	**EA**	**19,533**	**1,613**	**0**	**21,146**	**21,146**
			53.89	*4.45*	*0.00*	*58.33*	*58.33*
USR Clean Bay Balls	175.00	EA	9,430	779	0	10,209	10,209
			134.71	*11.12*	*0.00*	*145.84*	*145.84*
USR Clean Large Reef Balls	75.00	EA	10,103	834	0	10,938	10,938
			413,616.60	*73,768.04*	*0.00*	*487,384.65*	*487,384.65*
Relocate Reef Balls	**1.00**	**EA**	**413,617**	**73,768**	**0**	**487,385**	**487,385**
			200.50	*35.76*	*0.00*	*236.25*	*236.25*
USR RelBy Relocate Bay Ball by Barge	1,100.00	EA	220,546	39,334	0	259,880	259,880
			386.14	*68.87*	*0.00*	*455.01*	*455.01*
USR RelLg Relocate Large Balls by Barge	500.00	EA	193,071	34,434	0	227,505	227,505
			1,186,385.81	*401,204.76*	*3,322,337.20*	*4,909,927.77*	*4,909,927.77*
Reef Habitat Construction -Phase 3	**1.00**	**EA**	**1,186,386**	**401,205**	**3,322,337**	**4,909,928**	**4,909,928**
			52.94	*18.99*	*94.50*	*166.44*	*166.44*
EFH Bay Balls	**7,044.00**	**EA**	**372,934**	**133,792**	**665,658**	**1,172,384**	**1,172,384**
			52.03	*18.76*	*94.50*	*165.29*	*165.29*
Bay Ball EFH-1	**810.00**	**EA**	**42,140**	**15,196**	**76,545**	**133,882**	**133,882**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	810.00	EA	0	0	76,545	76,545	76,545
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	810.00	EA	2,210	1,504	0	3,714	3,714
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	810.00	EA	2,279	3,207	0	5,486	5,486
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	810.00	EA	2,210	1,504	0	3,714	3,714
			18.46	*5.32*	*0.00*	*23.78*	*23.78*
USR BrgBy1 Load Bay Balls into Barge EFH-1	810.00	EA	14,953	4,313	0	19,265	19,265
			25.29	*5.77*	*0.00*	*31.06*	*31.06*
USR PlcBy1 Transport Bay Ball by Barge & Place- Site RH-1	810.00	EA	20,488	4,670	0	25,158	25,158
			52.36	*18.85*	*94.50*	*165.70*	*165.70*
Bay Ball EFH-2	**4,576.00**	**EA**	**239,590**	**86,237**	**432,432**	**758,258**	**758,258**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	4,576.00	EA	0	0	432,432	432,432	432,432
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	4,576.00	EA	12,487	8,494	0	20,981	20,981
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	4,576.00	EA	12,875	18,117	0	30,993	30,993
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	4,576.00	EA	12,487	8,494	0	20,981	20,981
			18.60	*5.36*	*0.00*	*23.97*	*23.97*
USR BrgBy2 Load Bay Balls into Barge EFH-2	4,576.00	EA	85,116	24,549	0	109,665	109,665
			25.49	*5.81*	*0.00*	*31.30*	*31.30*
USR PlcBy2 Transport Bay Ball by Barge & Place- Site RH-2	4,576.00	EA	116,625	26,581	0	143,207	143,207
			54.50	*19.39*	*94.50*	*168.39*	*168.39*
Bay Ball EFH-3	**642.00**	**EA**	**34,991**	**12,448**	**60,669**	**108,107**	**108,107**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	642.00	EA	0	0	60,669	60,669	60,669
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	642.00	EA	1,752	1,192	0	2,944	2,944
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	642.00	EA	1,806	2,542	0	4,348	4,348
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	642.00	EA	1,752	1,192	0	2,944	2,944
			19.51	*5.63*	*0.00*	*25.13*	*25.13*
USR BrgBy3 Load Bay Balls into Barge EFH-3	642.00	EA	12,522	3,612	0	16,134	16,134
			26.73	*6.09*	*0.00*	*32.82*	*32.82*
USR PlcBy3 Transport Bay Ball by Barge & Place- Site RH-3	642.00	EA	17,158	3,911	0	21,069	21,069
			55.33	*19.60*	*94.50*	*169.43*	*169.43*
Bay Ball EFH-4	**1,016.00**	**EA**	**56,213**	**19,912**	**96,012**	**172,137**	**172,137**
			0.00	*0.00*	*94.50*	*94.50*	*94.50*
USR Bay Ball-Material	1,016.00	EA	0	0	96,012	96,012	96,012
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR StkBy Unload Bay Balls & Stockpile	1,016.00	EA	2,772	1,886	0	4,658	4,658
			2.81	*3.96*	*0.00*	*6.77*	*6.77*
USR TkBy Transport Bay Balls-Truck	1,016.00	EA	2,859	4,023	0	6,881	6,881
			2.73	*1.86*	*0.00*	*4.58*	*4.58*
USR LdBy Load Bay Balls onto Truck @ Plant	1,016.00	EA	2,772	1,886	0	4,658	4,658

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			19.85	*5.73*	*0.00*	*25.58*	*25.58*
USR BrgBy4 Load Bay Balls into Barge EFH-4	1,016.00	EA	20,171	5,818	0	25,989	25,989
			27.20	*6.20*	*0.00*	*33.40*	*33.40*
USR PlcBy4 Transport Bay Ball by Barge & Place- Site RH-4	1,016.00	EA	27,639	6,299	0	33,938	33,938
			50.24	*18.98*	*153.79*	*223.01*	*223.01*
EFH Large Balls Normal Foundation	**5,061.00**	**EA**	**254,243**	**96,081**	**778,320**	**1,128,644**	**1,128,644**
			156.20	*61.55*	*505.04*	*722.79*	*722.79*
Goliath	**676.00**	**EA**	**105,591**	**41,611**	**341,404**	**488,606**	**488,606**
			160.06	*66.48*	*505.79*	*732.34*	*732.34*
EFH-5, 6, & 7	**391.00**	**EA**	**62,584**	**25,995**	**197,764**	**286,344**	**286,344**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**
			6,586.79	*5,333.28*	*700.00*	*12,620.07*	*12,620.07*
Mob Marine equipment and Cranes	**1.00**	**EA**	**6,587**	**5,333**	**700**	**12,620**	**12,620**
			411.67	*333.33*	*0.00*	*745.00*	*745.00*
USR WtrMb Mob Marine Equipment & Cranes	16.00	HR	6,587	5,333	0	11,920	11,920
USR Misc Mob work	1.00	LS	0	0	700	700	700
			143.58	*52.98*	*505.29*	*701.86*	*701.86*
Load & Place Reef Balls	**390.00**	**EA**	**55,998**	**20,662**	**197,064**	**273,724**	**273,724**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	391.00	EA	0	0	197,064	197,064	197,064
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	391.00	EA	19,842	5,723	0	25,565	25,565
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	391.00	EA	2,667	1,814	0	4,482	4,482
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	391.00	EA	27,187	6,197	0	33,384	33,384
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	391.00	EA	2,667	1,814	0	4,482	4,482
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	391.00	EA	3,634	5,114	0	8,748	8,748
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**239.00**	**EA**	**35,735**	**13,011**	**120,456**	**169,203**	**169,203**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	239.00	EA	0	0	120,456	120,456	120,456
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	239.00	EA	1,630	1,109	0	2,740	2,740
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	239.00	EA	2,221	3,126	0	5,347	5,347
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	239.00	EA	1,630	1,109	0	2,740	2,740
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	239.00	EA	12,764	3,681	0	16,445	16,445
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	239.00	EA	17,489	3,986	0	21,475	21,475
			158.08	*56.61*	*504.00*	*718.69*	*718.69*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**23,184**	**33,060**	**33,060**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	46.00	EA	0	0	23,184	23,184	23,184
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413
			146.89	*53.82*	*452.84*	*653.55*	*653.55*
Super	**674.00**	**EA**	**99,004**	**36,278**	**305,214**	**440,496**	**440,496**
			143.22	*52.84*	*451.50*	*647.56*	*647.56*
EFH-5, 6, & 7	**391.00**	**EA**	**55,998**	**20,662**	**176,537**	**253,196**	**253,196**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	391.00	EA	0	0	176,537	176,537	176,537
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	391.00	EA	2,667	1,814	0	4,482	4,482
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	391.00	EA	3,634	5,114	0	8,748	8,748

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	391.00	EA	2,667	1,814	0	4,482	4,482
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	391.00	EA	19,842	5,723	0	25,565	25,565
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	391.00	EA	27,187	6,197	0	33,384	33,384
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**239.00**	**EA**	**35,735**	**13,011**	**107,909**	**156,655**	**156,655**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	239.00	EA	0	0	107,909	107,909	107,909
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	239.00	EA	1,630	1,109	0	2,740	2,740
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	239.00	EA	2,221	3,126	0	5,347	5,347
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	239.00	EA	1,630	1,109	0	2,740	2,740
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	239.00	EA	12,764	3,681	0	16,445	16,445
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	239.00	EA	17,489	3,986	0	21,475	21,475
			158.08	*56.61*	*451.50*	*666.19*	*666.19*
EFH-9	**46.00**	**EA**	**7,271**	**2,604**	**20,769**	**30,645**	**30,645**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	46.00	EA	0	0	20,769	20,769	20,769
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	46.00	EA	314	213	0	527	527
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	46.00	EA	428	602	0	1,029	1,029
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	46.00	EA	314	213	0	527	527
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	46.00	EA	2,623	756	0	3,379	3,379
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	46.00	EA	3,594	819	0	4,413	4,413

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			147.32	*53.98*	*390.81*	*592.11*	*592.11*
Ultra	**337.00**	**EA**	**49,648**	**18,192**	**131,702**	**199,542**	**199,542**
			143.22	*52.84*	*388.50*	*584.56*	*584.56*
EFH-5, 6, & 7	**196.00**	**EA**	**28,070**	**10,357**	**76,146**	**114,574**	**114,574**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	196.00	EA	0	0	76,146	76,146	76,146
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	196.00	EA	1,337	910	0	2,247	2,247
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	196.00	EA	1,822	2,563	0	4,385	4,385
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	196.00	EA	1,337	910	0	2,247	2,247
			50.75	*14.64*	*0.00*	*65.38*	*65.38*
USR BrgBy5 Load Large Balls into Barge RH--5, RH-6, & RH-7	196.00	EA	9,946	2,869	0	12,815	12,815
			69.53	*15.85*	*0.00*	*85.38*	*85.38*
USR PlcBy5 Transport Large Balls by Barge & Place- Site RH-5, RH-6, & RH-7	196.00	EA	13,628	3,106	0	16,734	16,734
			149.52	*54.44*	*388.50*	*592.46*	*592.46*
EFH-8	**120.00**	**EA**	**17,942**	**6,533**	**46,620**	**71,095**	**71,095**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	120.00	EA	0	0	46,620	46,620	46,620
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	120.00	EA	819	557	0	1,375	1,375
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	120.00	EA	1,115	1,569	0	2,685	2,685
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	120.00	EA	819	557	0	1,375	1,375
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	120.00	EA	6,409	1,848	0	8,257	8,257
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	120.00	EA	8,781	2,001	0	10,782	10,782
			158.08	*56.61*	*388.50*	*603.19*	*603.19*
EFH-9	**23.00**	**EA**	**3,636**	**1,302**	**8,936**	**13,873**	**13,873**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	23.00	EA	0	0	8,936	8,936	8,936

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	23.00	EA	157	107	0	264	264
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	23.00	EA	214	301	0	515	515
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	23.00	EA	157	107	0	264	264
			57.02	*16.44*	*0.00*	*73.46*	*73.46*
USR BrgBy9 Load Large Balls into Barge RH-9	23.00	EA	1,311	378	0	1,690	1,690
			78.12	*17.81*	*0.00*	*95.93*	*95.93*
USR PlcBy9 Transport Large Balls by Barge & Place- Site RH-9	23.00	EA	1,797	410	0	2,206	2,206
			312.58	*95.77*	*1,049.95*	*1,458.30*	*1,458.30*
EFH Large Balls Soft Foundation	**1,789.00**	**EA**	**559,209**	**171,332**	**1,878,360**	**2,608,900**	**2,608,900**
			326.27	*99.24*	*1,108.80*	*1,534.31*	*1,534.31*
Goliath	**716.00**	**EA**	**233,609**	**71,055**	**793,901**	**1,098,564**	**1,098,564**
			149.52	*54.44*	*504.00*	*707.96*	*707.96*
EFH-8	**716.00**	**EA**	**107,056**	**38,980**	**360,864**	**506,900**	**506,900**
			0.00	*0.00*	*504.00*	*504.00*	*504.00*
USR Goliath Reef Ball-Material	716.00	EA	0	0	360,864	360,864	360,864
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	716.00	EA	4,884	3,323	0	8,207	8,207
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	716.00	EA	6,655	9,364	0	16,019	16,019
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	716.00	EA	4,884	3,323	0	8,207	8,207
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge EFH-8	716.00	EA	38,238	11,029	0	49,267	49,267
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site EFH-8	716.00	EA	52,394	11,942	0	64,335	64,335
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**716.00**	**EA**	**126,553**	**32,075**	**433,037**	**591,665**	**591,665**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	716.00	EA	53,393	15,400	0	68,793	68,793
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	716.00	EA	73,160	16,675	0	89,834	89,834
			0.00	*0.00*	*604.80*	*604.80*	*604.80*

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
USR Marine Mattress 8'x8'x12"- material	716.00	EA	0	0	433,037	433,037	433,037
			326.27	*99.24*	*1,056.30*	*1,481.81*	*1,481.81*
Super	**716.00**	**EA**	**233,609**	**71,055**	**756,311**	**1,060,974**	**1,060,974**
			149.52	*54.44*	*451.50*	*655.46*	*655.46*
EFH-8	**716.00**	**EA**	**107,056**	**38,980**	**323,274**	**469,310**	**469,310**
			0.00	*0.00*	*451.50*	*451.50*	*451.50*
USR Super Ball-Material	716.00	EA	0	0	323,274	323,274	323,274
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	716.00	EA	4,884	3,323	0	8,207	8,207
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	716.00	EA	6,655	9,364	0	16,019	16,019
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	716.00	EA	4,884	3,323	0	8,207	8,207
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	716.00	EA	38,238	11,029	0	49,267	49,267
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	716.00	EA	52,394	11,942	0	64,335	64,335
			176.75	*44.80*	*604.80*	*826.35*	*826.35*
Marine Mattress Mats	**716.00**	**EA**	**126,553**	**32,075**	**433,037**	**591,665**	**591,665**
			74.57	*21.51*	*0.00*	*96.08*	*96.08*
USR MMMk Load Gabion onto Barge	716.00	EA	53,393	15,400	0	68,793	68,793
			102.18	*23.29*	*0.00*	*125.47*	*125.47*
USR MMPlc Transport & Place in Water	716.00	EA	73,160	16,675	0	89,834	89,834
			0.00	*0.00*	*604.80*	*604.80*	*604.80*
USR Marine Mattress 8'x8'x12"- material	716.00	EA	0	0	433,037	433,037	433,037
			257.68	*81.85*	*919.18*	*1,258.72*	*1,258.72*
Ultra	**357.00**	**EA**	**91,992**	**29,222**	**328,148**	**449,362**	**449,362**
			149.52	*54.44*	*388.50*	*592.46*	*592.46*
EFH-8	**357.00**	**EA**	**53,378**	**19,436**	**138,695**	**211,508**	**211,508**
			0.00	*0.00*	*388.50*	*388.50*	*388.50*
USR Ultra Reef Ball-Material	357.00	EA	0	0	138,695	138,695	138,695
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR LdLg Load Large Balls onto Truck @ Plant	357.00	EA	2,435	1,657	0	4,092	4,092
			9.29	*13.08*	*0.00*	*22.37*	*22.37*
USR TkLg Transport Ultra / Super / Goliath Balls-Truck	357.00	EA	3,318	4,669	0	7,987	7,987

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			6.82	*4.64*	*0.00*	*11.46*	*11.46*
USR StkLg Unload Large Balls & Stockpile	357.00	EA	2,435	1,657	0	4,092	4,092
			53.41	*15.40*	*0.00*	*68.81*	*68.81*
USR BrgBy8 Load Large Balls into Barge RH-8	357.00	EA	19,066	5,499	0	24,565	24,565
			73.18	*16.68*	*0.00*	*89.85*	*89.85*
USR PlcBy8 Transport Large Balls by Barge & Place- Site RH-8	357.00	EA	26,124	5,954	0	32,078	32,078
			108.16	*27.41*	*530.68*	*666.26*	*666.26*
Marine Mattress Mats	**357.00**	**EA**	**38,613**	**9,786**	**189,454**	**237,853**	**237,853**
			45.63	*13.16*	*0.00*	*58.80*	*58.80*
USR MMMk6 Load Gabion onto Barge 6'x6'	357.00	EA	16,291	4,699	0	20,990	20,990
			62.53	*14.25*	*0.00*	*76.78*	*76.78*
USR MMPlc6 Transport & Place in Water 6'x6'	357.00	EA	22,322	5,088	0	27,410	27,410
			0.00	*0.00*	*264.60*	*264.60*	*264.60*
USR Marine Mattress 6'x6' x6"- material	716.00	EA	0	0	189,454	189,454	189,454
			24,825.00	*0.00*	*0.00*	*90,285.00*	*90,285.00*
Contract 2 - SAV Initial Construction	**1.00**	**EA**	**24,825**	**0**	**0**	**90,285**	**90,285**
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
SAV Pilot Construction-Phase 1	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			28.73	*0.00*	*0.00*	*104.50*	*104.50*
SAV's - Submerged Aquatic Vegetation	**287.98**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			88.26	*0.00*	*0.00*	*320.98*	*320.98*
SAV1,2,3 Max Main Stem/Max Broad Bay	**93.76**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
Restore SAV's -Contract 2, Pilot Studies	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			0.00	*0.00*	*0.00*	*21,820.00*	*21,820.00*
Restore SAV	**1.00**	**EA**	**0**	**0**	**0**	**21,820**	**21,820**
USR Mobilization	1.00	LS	0	0	0	320	320
			0.00	*0.00*	*0.00*	*21,500.00*	*21,500.00*
USR SAV restoration	1.00	ACR	0	0	0	21,500	21,500
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Adaptive Management-SAV	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Initial Assessment	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
USR Initial Assessment SAV Sites	1.00	YR	8,275	0	0	8,275	8,275

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
SAV Pilot Construction-Phase 2	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			28.73	*0.00*	*0.00*	*104.50*	*104.50*
SAV's - Submerged Aquatic Vegetation	**287.98**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			88.26	*0.00*	*0.00*	*320.98*	*320.98*
SAV1,2,3 Max Main Stem/Max Broad Bay	**93.76**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
Restore SAV's -Contract 2, Pilot Studies	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			0.00	*0.00*	*0.00*	*21,820.00*	*21,820.00*
Restore SAV	**1.00**	**EA**	**0**	**0**	**0**	**21,820**	**21,820**
USR Mobilization	1.00	LS	0	0	0	320	320
			0.00	*0.00*	*0.00*	*21,500.00*	*21,500.00*
USR SAV restoration	1.00	ACR	0	0	0	21,500	21,500
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Adaptive Management-SAV	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Initial Assessment	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
USR Initial Assessment SAV Sites	1.00	YR	8,275	0	0	8,275	8,275
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
SAV Pilot Construction-Phase 3	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			28.73	*0.00*	*0.00*	*104.50*	*104.50*
SAV's - Submerged Aquatic Vegetation	**287.98**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			88.26	*0.00*	*0.00*	*320.98*	*320.98*
SAV1,2,3 Max Main Stem/Max Broad Bay	**93.76**	**ACR**	**8,275**	**0**	**0**	**30,095**	**30,095**
			8,275.00	*0.00*	*0.00*	*30,095.00*	*30,095.00*
Restore SAV's -Contract 2, Pilot Studies	**1.00**	**EA**	**8,275**	**0**	**0**	**30,095**	**30,095**
			0.00	*0.00*	*0.00*	*21,820.00*	*21,820.00*
Restore SAV	**1.00**	**EA**	**0**	**0**	**0**	**21,820**	**21,820**
USR Mobilization	1.00	LS	0	0	0	320	320
			0.00	*0.00*	*0.00*	*21,500.00*	*21,500.00*
USR SAV restoration	1.00	ACR	0	0	0	21,500	21,500
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Adaptive Management-SAV	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
Initial Assessment	**1.00**	**EA**	**8,275**	**0**	**0**	**8,275**	**8,275**
			8,275.00	*0.00*	*0.00*	*8,275.00*	*8,275.00*
USR Initial Assessment SAV Sites	1.00	YR	8,275	0	0	8,275	8,275
			37,500.00	*0.00*	*0.00*	*2,311,745.75*	*2,311,745.75*
Contract 3 - SAV Construction & Bay Scallops	**1.00**	**EA**	**37,500**	**0**	**0**	**2,311,746**	**2,311,746**
			0.00	*0.00*	*0.00*	*6,883.60*	*6,883.60*
SAV's - Submerged Aquatic Vegetation	**287.98**	**ACR**	**0**	**0**	**0**	**1,982,340**	**1,982,340**
			0.00	*0.00*	*0.00*	*21,142.70*	*21,142.70*
SAV1,2,3 Max Main Stem/Max Broad Bay	**93.76**	**ACR**	**0**	**0**	**0**	**1,982,340**	**1,982,340**
			0.00	*0.00*	*0.00*	*991,170.00*	*991,170.00*
SAV Large Scale Construction Phase 1, Contract 3	**1.00**	**EA**	**0**	**0**	**0**	**991,170**	**991,170**
			0.00	*0.00*	*0.00*	*991,170.00*	*991,170.00*
Restore SAV	**1.00**	**EA**	**0**	**0**	**0**	**991,170**	**991,170**
USR Mobilization	1.00	LS	0	0	0	15,500	15,500
			0.00	*0.00*	*0.00*	*21,500.00*	*21,500.00*
USR SAV restoration	45.38	ACR	0	0	0	975,670	975,670
			0.00	*0.00*	*0.00*	*991,170.00*	*991,170.00*
SAV Large Scale Construction Phase 2, Contract 3	**1.00**	**EA**	**0**	**0**	**0**	**991,170**	**991,170**
			0.00	*0.00*	*0.00*	*991,170.00*	*991,170.00*
Restore SAV	**1.00**	**EA**	**0**	**0**	**0**	**991,170**	**991,170**
USR Mobilization	1.00	LS	0	0	0	15,500	15,500
			0.00	*0.00*	*0.00*	*21,500.00*	*21,500.00*
USR SAV restoration	45.38	ACR	0	0	0	975,670	975,670
			37,500.00	*0.00*	*0.00*	*329,405.75*	*329,405.75*
Bay Scallop	**1.00**	**EA**	**37,500**	**0**	**0**	**329,406**	**329,406**
			0.00	*0.00*	*0.00*	*20,887.30*	*20,887.30*
Scallops Adults Collected Pilot- Phase 1, Contract 3	**1.00**	**EA**	**0**	**0**	**0**	**20,887**	**20,887**
			0.00	*0.00*	*0.00*	*0.91*	*0.91*
Adults	**23,029.00**	**EA**	**0**	**0**	**0**	**20,887**	**20,887**
			0.00	*0.00*	*0.00*	*0.83*	*0.83*
USR Adult Bay Scallops-Racks	23,029.00	EA	0	0	0	19,114	19,114
			0.00	*0.00*	*0.00*	*0.08*	*0.08*
USR Adult Bay Scallops-Set free	23,029.00	EA	0	0	0	1,773	1,773

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			18,750.00	*0.00*	*0.00*	*46,547.00*	*46,547.00*
Scallops Stock Juveniles Pilot - Phase 2, Contract 3	**1.00**	**EA**	**18,750**	**0**	**0**	**46,547**	**46,547**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
Juveniles	**0.77**	**ACR**	**0**	**0**	**0**	**27,797**	**27,797**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
USR Juvenile Bay Scallops	0.77	ACR	0	0	0	27,797	27,797
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
Adapt Manage-Scallops	**1.00**	**EA**	**18,750**	**0**	**0**	**18,750**	**18,750**
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
Initial Assessment	**1.00**	**EA**	**18,750**	**0**	**0**	**18,750**	**18,750**
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
USR Initial Assessment Scallop Sites	1.00	YR	18,750	0	0	18,750	18,750
			18,750.00	*0.00*	*0.00*	*46,547.00*	*46,547.00*
Scallops Stock Juveniles Pilot - Phase 3, Contract 3	**1.00**	**EA**	**18,750**	**0**	**0**	**46,547**	**46,547**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
Juveniles	**0.77**	**ACR**	**0**	**0**	**0**	**27,797**	**27,797**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
USR Juvenile Bay Scallops	0.77	ACR	0	0	0	27,797	27,797
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
Adapt Manage-Scallops	**1.00**	**EA**	**18,750**	**0**	**0**	**18,750**	**18,750**
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
Initial Assessment	**1.00**	**EA**	**18,750**	**0**	**0**	**18,750**	**18,750**
			18,750.00	*0.00*	*0.00*	*18,750.00*	*18,750.00*
USR Initial Assessment Scallop Sites	1.00	YR	18,750	0	0	18,750	18,750
			0.00	*0.00*	*0.00*	*215,424.45*	*215,424.45*
Scallops Stock Juv & Place Adults Large Scale - Phase 4, Contract 3	**1.00**	**EA**	**0**	**0**	**0**	**215,424**	**215,424**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
Juveniles	**0.76**	**ACR**	**0**	**0**	**0**	**27,436**	**27,436**
			0.00	*0.00*	*0.00*	*36,100.00*	*36,100.00*
USR Juvenile Bay Scallops	0.76	ACR	0	0	0	27,436	27,436
			0.00	*0.00*	*0.00*	*0.91*	*0.91*
Adults	**207,264.00**	**EA**	**0**	**0**	**0**	**187,988**	**187,988**
			0.00	*0.00*	*0.00*	*0.83*	*0.83*
USR Adult Bay Scallops-Racks	207,264.00	EA	0	0	0	172,029	172,029

Description	Quantity	UOM	DirectLabor	DirectEQ	DirectMatl	DirectCost	DirectCost
			0.00	*0.00*	*0.00*	*0.08*	*0.08*
USR Adult Bay Scallops-Set free	207,264.00	EA	0	0	0	15,959	15,959

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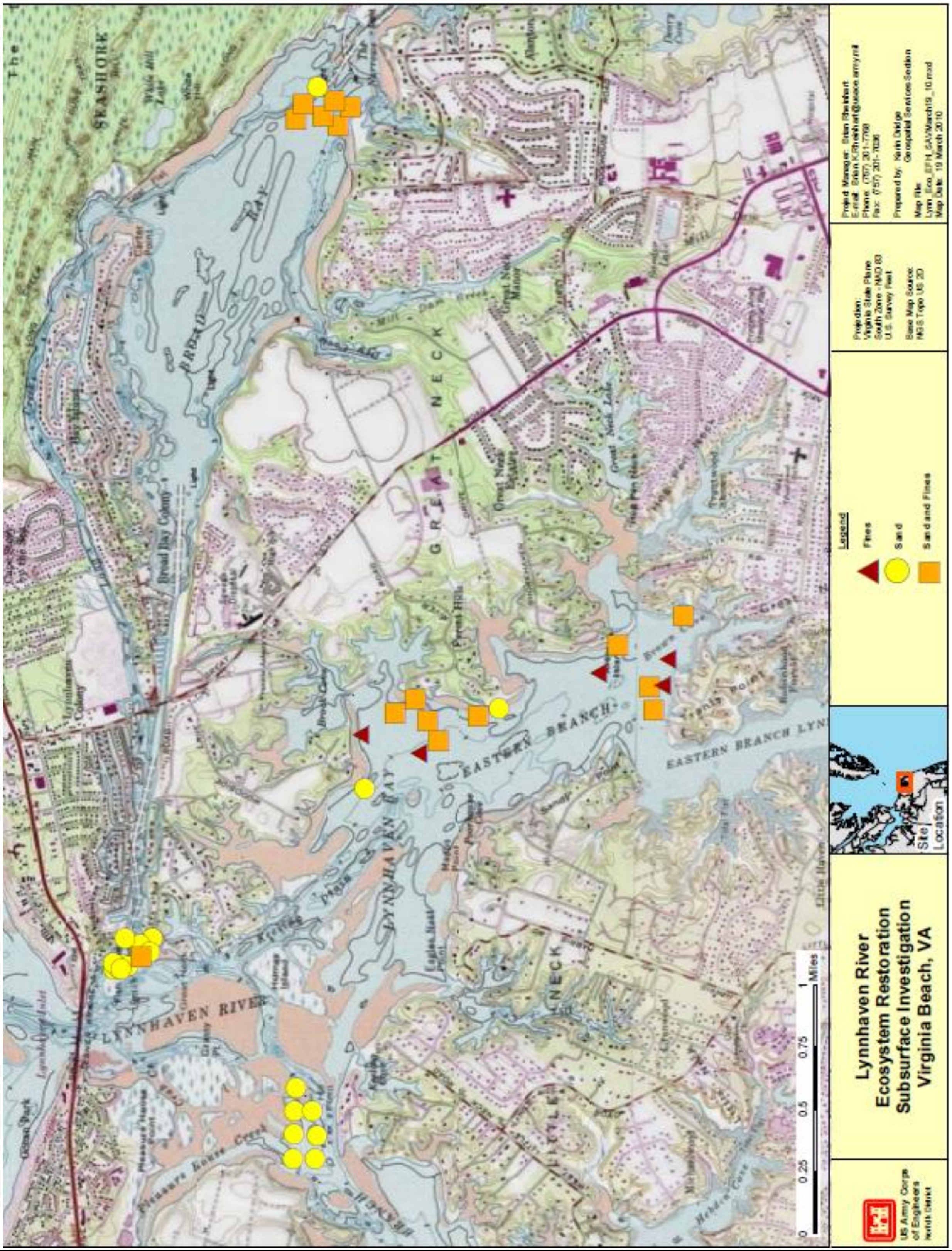
PLATE 1



Lynnhaven River
Ecosystem Restoration
Subsurface Investigation
Virginia Beach, VA
Legend
Fines
Sand
Sand and Fines
Site Location
LYNNHAVEN RIVER
EASTERN BRANCH
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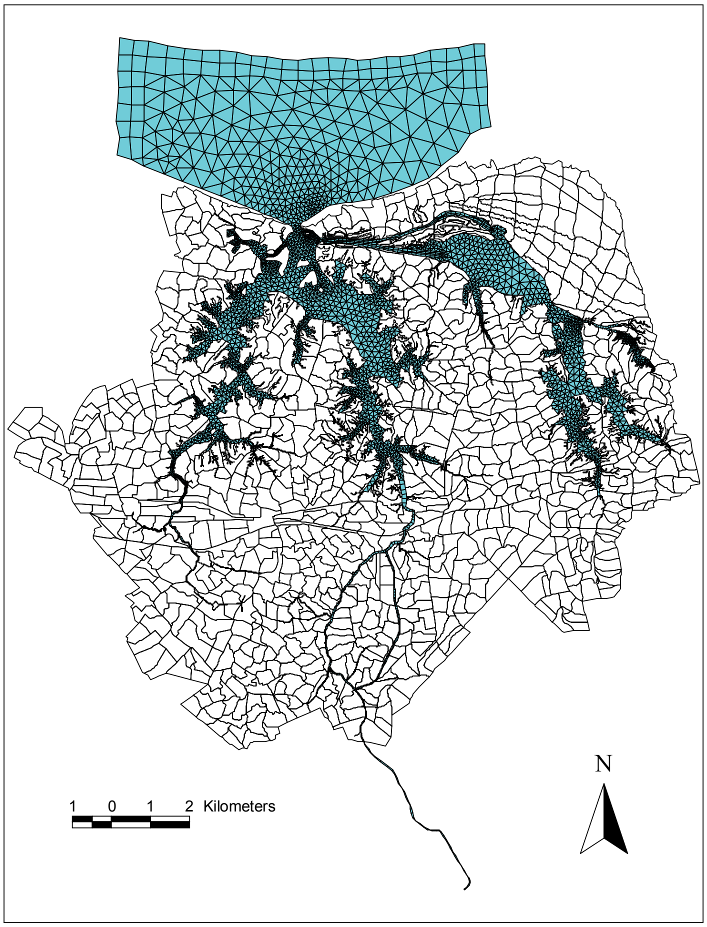
BROAD BAY
GREAT NECK
Miles

APPENDIX A

ATTACHMENT 1

DEVELOPMENT OF THE HYDRODYNAMIC AND WATER QUALITY MODELS FOR THE LYNNHAVEN RIVER SYSTEM

Development of Hydrodynamic and Water Quality Models for the Lynnhaven River System



Mac Sisson, Harry Wang, Yuepeng Li, Jian Shen, Albert Kuo,
Wenping Gong, Mark Brush, and Ken Moore

Final Report to the
U. S. Army Corps of Engineers, Fort Norfolk Office
and
The City of Virginia Beach

Special Report No. 408
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Department of Physical Sciences
Gloucester Point, Virginia 23062

November 2010

EXECUTIVE SUMMARY

"Development of Hydrodynamic and Water Quality Models for the Lynnhaven River System"

1. The Norfolk District of the US Army Corps of Engineers and the City of Virginia Beach are working together on a cost-shared basis for the feasibility study of the Lynnhaven River environmental restoration. In January 2005, these agencies contracted with the Virginia Institute of Marine Science (VIMS) for the development of hydrodynamic and water quality models for the Lynnhaven River System.

2. VIMS has performed a successful development of an integrated numerical modeling framework for the Lynnhaven River. This framework combines a high-resolution 3D hydrodynamic model (UNTRIM) that provides the required transport for a water quality model (CE-QUAL-ICM) that, in turn, provides intra-tidal predictions of 23 water quality state variables.

3. Prior to the inception of the project, all available historical Lynnhaven hydrodynamic and water quality data were amassed in a MicroSoft ACCESS database and analyzed for model calibration suitability and long-term trends. These data were collected from monitoring programs of the Virginia Department of Environmental Quality (VA-DEQ) and the Virginia Health Department, Shellfish Sanitation Division (VA-DSS), intensive surveys conducted by VIMS and Malcolm Pirnie Environmental Engineers, and tidal surveys conducted by the National Oceanic and Atmospheric Administration (NOAA).

4. A strategy of project-specific field surveys and laboratory experiments was devised based on which measurements would complement the existing historical data and be most useful to the model calibration and validation processes. These field surveys included the following:

- a hydrodynamic survey of synoptic measurements of times series of surface elevations plus currents and salinities in all Lynnhaven branches and outside the Inlet
- seasonal sediment flux measurements at the Inlet and in all branches to determine the spatial and seasonal variations of the fluxes from the water column to the sediment (and vice versa) of dissolved oxygen, ammonia, nitrate-nitrite, and phosphate
- sediment flux measurements of dissolved oxygen, ammonia, nitrate and nitrite, and phosphate in the laboratory under controlled environments
- critical shear stress measurements at multiple sites in the basin to determine the spatial and seasonal variations to the erodibility of bottom sediments
- high-frequency time series measurements of chlorophyll-a, turbidity, Colored Dissolved Organic Matter (CDOM), and dissolved oxygen (DO) to evaluate water quality conditions with high temporal resolution

5. The hydrodynamic model was calibrated using historical datasets and NOAA tide predictions. The water quality model was calibrated using the 2006 dataset collected by the VA-DEQ.

(a) Calibration of the hydrodynamic model

Calibration of the hydrodynamic model for tides was performed by comparing model results with synoptic measurements at 5 locations spanning from Long Creek to Broad Bay to Linkhorn Bay, as well as by comparing the NOAA predicted tide ranges and phases to model results at two Western Branch stations (Bayville Creek and Buchanan Creek) and one Eastern Branch location (Brown Cove). Calibration for velocity was made by comparing model predictions with high-frequency measurements made in 2003 at two locations bounding Long Creek. Calibrations for both temperature and salinity were made throughout 2006 by comparing model predictions with observations made at the 16 Lynnhaven VA-DEQ stations monitored every other month.

(b) Calibration of the water quality model

Calibration of the water quality model was performed for 2006 by comparing model predictions with measurements taken every other month at the 16 Lynnhaven DEQ stations for the parameters of dissolved oxygen (DO), chlorophyll-a (chl-a), total Kjeldahl nitrogen (TKN), total phosphorus (TP), ammonium (NH_4), nitrate-nitrite (NO_3), and ortho phosphorus (PO_4).

6. Validation of the hydrodynamic model was made by comparing the 2005 simulation results with observations collected in VIMS hydrodynamic surveys of that year. Validation of the water quality model used the two-year period 2004-2005 as the period of validation. No adjustments to the values of calibration parameters, which were set in the calibration process, were made in the validation process.

(a) Validation of the hydrodynamic model

Validation for water surface elevations was made by making a 30-day, high-frequency comparison of model predictions to observations at the Virginia Pilot's Station just inside the Inlet and a 16-day, high-frequency comparison of predictions to observations at West Neck Creek, Upper Eastern Branch. Validation of velocities was made by comparing model predictions to 30-day measurements of velocity at representative locations in each branch as well as at surface, middle, and bottom layers of a station in the channel just outside of the Inlet. Validations for both temperature and salinity were made throughout 2004-2005 by comparing model predictions with observations made at the 16 Lynnhaven VA-DEQ stations monitored every other month.

(b) Validation of the water quality model

Validation of the water quality model was performed for 2004-2005 by comparing model predictions with measurements taken every other month at the 16 Lynnhaven VA-DEQ stations for the water quality variables of dissolved oxygen (DO), chlorophyll-a (chl-a), total

Kjeldahl nitrogen (TKN), total phosphorus (TP), ammonium (NH_4), nitrate-nitrite (NO_3), and ortho phosphorus (PO_4).

7. A sediment transport model utilizing the equilibrium critical shear stress defined at the interface between layers was incorporated into the modeling framework. This model was calibrated by comparing its predictions of total suspended solids (TSS) with observations at the 16 Lynnhaven DEQ stations during 2006 and validated by comparing the 2004-2005 model results with DEQ observations for those years. Additionally, the validation compared model predictions with TSS values derived from VIMS high-frequency measurements of turbidity at 3 locations in 2005.

8. The major findings of the study included degraded water clarity due to significant concentrations of suspended sediment and localized summertime dissolved oxygen problems in headland areas. VIMS is attempting to assess the impacts that these conditions have on the restoration effort by conducting sensitivity tests of the model to reductions in the sediment and nutrient loadings associated with these conditions.

9. The entire modeling framework has been calibrated and validated and has been prepared for its application in conducting scenario runs. The models thus become a management tool for environmental assessments of the effects of variations in nutrient and sediment loadings, and other mitigation practices, in the Lynnhaven River system.

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CHAPTER I. BACKGROUND

The Lynnhaven River system, comprised of the Eastern, Western Branches, Broad Bay, and Linkhorn Bay, is a shallow-water coastal system located near the southeast corner of the Chesapeake Bay. It traverses a 64-square-mile watershed that spans most of the northern half of Virginia Beach with a land use that is 40% residential and 35% streets, commercial and office space, and military use, and it flows northerly and empties into the Chesapeake Bay about 10 miles east of Norfolk (see Figure I.1). Due to its narrow entrance and greater influence by the tide of the Bay than by river discharge, it is technically considered as a tidal inlet system. Like many Chesapeake Bay small coastal basins, the Lynnhaven River system was a highly productive ecosystem, supporting a large oyster population and various shallow water organisms. Clampitt et al. (1993) documented that 20 species of vertebrate, 39 invertebrate species, 76 plant species, and 19 types of rare natural communities of statewide significance are supported in the Lynnhaven. In the early twentieth century, Lynnhaven River was known for its abundant harvest of “oysters suitable for kings”. The Lynnhaven oyster population has since drastically diminished along with water quality degradations that include poor water clarity, recession of submerged aquatic vegetation areas, and high chlorophyll, suspended solids, and seasonally-low dissolved oxygen levels in headland regions of the branches.

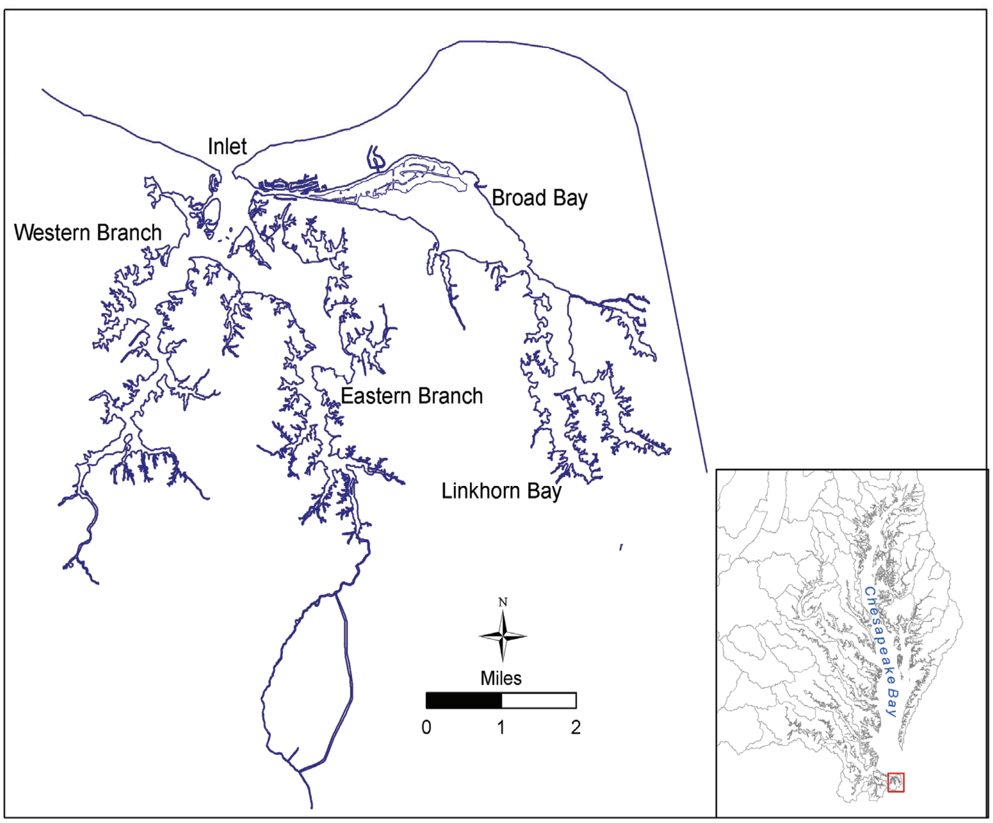


Figure I.1. Location of the Lynnhaven River in the Chesapeake Bay

In May 1998, the Lynnhaven River Environmental Restoration Study was authorized by Resolution of the Committee on Transportation and Infrastructure of the U.S. House of Representatives. Congress appropriated funding in 2002 to initiate a reconnaissance analysis in support of this authority. The ensuing reconnaissance report, issued by the U.S. Army Corps of Engineers (2002), cited a number of problems in water quality deterioration, siltation, sedimentation, and habitat management in the Lynnhaven. The report stated that "the river has become increasingly stressed as the watershed has experienced a shift from a predominantly rural to a predominantly urban/suburban land use pattern".

Over the past several decades, Lynnhaven River water quality has been degraded by increased volume and decreased quality of stormwater runoff. Non-point sources (NPS), such as storm drains, soil erosion, lawn fertilizer, street litter, estuarine sediments, animal wastes, and failing septic systems, have caused the most degradation. The reconnaissance report cites additional causes of Lynnhaven water quality degradation as including the loss of wetland buffers associated with shoreline hardening and erosion, degradation of riparian buffers near stormwater outfalls, increased siltation from land-based construction, and increased stormwater runoff due to more developments and roadways. Additional concerns regarding water quality in the Lynnhaven include water clarity and the levels of total suspended solids measured throughout the branches of the Lynnhaven as well as seasonally low dissolved oxygen and high fecal coliform levels measured in the upper Western and Eastern Branches, where the River's flushing capacity diminishes.

Whereas decreased water quality can have severe ecological impact on both benthic and pelagic populations and species diversity, there are additional ecological impacts emerging in the Lynnhaven. These impacts affect:

1) the abundance of tidal wetlands caused by construction activities such as dredging, filling, bulkheading, and channelization,
2) the oyster resources caused by high fecal coliform levels, and
3) the submerged aquatic vegetation (SAV) habitats caused by high nutrient and sediment inputs and the ensuing poor water clarity.

Another noteworthy issue regarding environmental restoration of the Lynnhaven includes siltation in the upper reaches, which has increased over the past several decades, and which can decrease the flushing capability upstream by decreasing the tidal prism. Lastly, sediments with elevated levels of heavy metals or other toxicants, which could severely impact living resources, have been noted in several Lynnhaven reports.

In an evaluation of alternative, the U.S. Army Corps of Engineers reconnaissance report determined that the alternatives would result in net environmental benefits through ecosystem restoration, and recommended that this study continue into its next phase, a cost-shared feasibility study.

The agencies in charge of the present development efforts are the Norfolk District, U.S. Army Corps of Engineers (ACE), representing the Federal Government, and the City of Virginia Beach, acting as the Local Sponsor. These agencies signed a feasibility cost-sharing agreement and embarked on determining suitable and acceptable means for designing and implementing the environmental restoration of the Lynnhaven. During discussions with personnel from VIMS and URS Corporation of Virginia Beach, it was resolved that a fully comprehensive system, including spatially high-resolution numerical modeling and watershed loading estimation, was required in order to address the issues cited in the reconnaissance report and to provide the management option of a control strategy of attaining the required endpoints for environmental restoration.

In early 2005, the ACE (Norfolk District) and the City of Virginia Beach contracted with VIMS for the development of hydrodynamic and water quality models for the Lynnhaven River System receiving waters and with URS Corporation for the development of a watershed model to provide both freshwater flows and nutrient and sediment loadings from the Lynnhaven River Basin.

CHAPTER II. INTRODUCTION

The Lynnhaven River system is an extremely shallow waterbody with average depths of only 0.62 m, 0.75 m, and 2.16 m, respectively, is the Western, Eastern, and Broad Bay/Linkhorn Bay systems (Figure II.1). It is also characterized by a narrow Inlet opening and tidal flats, small islands, and branching shorelines in its branches.
The shallow water portion of the coastal system (with water depths less than 2-3 meters) is ubiquitous along the edge of the shoreline and many coastal embayments. Its habitat supports a tremendous diversity of aquatic life, including plants, benthos, invertebrates, plankton, crabs, fish, and seabirds; in particular, it serves as the major fish spawning ground providing shelter and food sources. Therefore, the shallow water region (SWR) is a unique habitat and an integral part of the productivity of the Bay ecosystem.

The SWR is the buffer zone between aquatic and terrestrial landscapes. It has been shown that nonpoint sources of nutrient inputs, including groundwater and surface water runoff, that pass through this region contribute significantly to the overall eutrophication problem. Human activities in watersheds have caused major changes in water quality, resulting in increased loading of nutrients, organic matter, and sediment to the SWR (Fleischer, 1987; Frink, 1991; Hopkinson and Vallino, 1995). Industrial activities and agriculture generate a mixture of chemicals, including nutrients, some of which are inevitably discharged into aquatic ecosystems. As a result, the SWR, such as

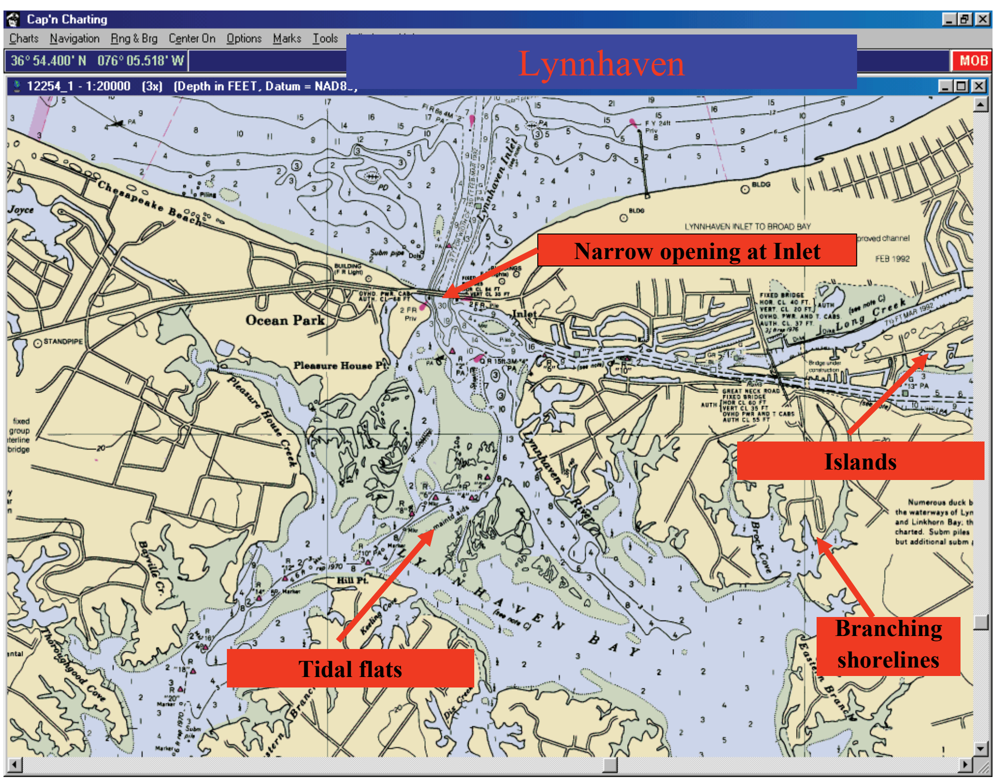


Figure II.1. Physical features of the Lynnhaven River sytem coastal lagoons and embayments, has received large inputs of nutrients from watershed due to anthropogenic activities for many years. Therefore, the SWR is a highly productive environment. Nutrient loading usually arises from sources including: fertilizer runoff, groundwater, sewage discharges, and aquaculture (Balls, 1994). Accordingly, there are increasing interests and demands for further understanding of eutrophication processes in the SWR.

The characteristics of the SWR differ from those of deepwater regions. The water table is usually at or near the surface, and it is constantly under the influence of tide, wave, and climate changes, which leads to wetting and drying of tidal flats, larger variation of salinity and nutrients change, suspension of sediment, and runoff of nutrients released from the land. The shallowness permits wind and tide-driven mixing to occur through the water column over the entire year. In deeper estuaries, stratification may be significant due to the high bottom salinity and sediment concentration. In the SWR system, however, continuous mixing causes the salinity stratification to become almost vertically homogeneous. Meanwhile, vertically well-mixed conditions also resuspend sediment material, including the nutrients required for primary productivity, to the overlying water column. Thus, the potential for the primary productivity is increased. Shallowness also enables sunlight to penetrate to the bottom of the sediments, which creates favorable conditions for the benthic primary producers. Combining these two factors, the primary productivity usually is high in this shallow water system.

The dynamics of the SWR are very rich because of the input of mechanical energy (freshwater discharge, tide, and wind), solar radiation, and nutrients (nitrogen and phosphorus). These natural resources stimulate primary production in both the water column and the benthic zone of the SWR. In contrast to a pelagic system, the benthos of the SWR may provide an important source of nutrients because of both its shallowness and the vertical turbulence caused by wind and tidal agitation. The nutrient exchange across the sediment-water interface is an important pathway for nutrient cycles in the SWR. The evaluation of the exchange oxygen and nutrients flux is indispensable to identifying the effects of SWR estuaries or embayments (Reay et al., 1995; Sanders et al., 1997; Yin and Harrison, 2000). Therefore, benthic nutrient fluxes have long been recognized as being an important component of estuarine ecosystems due to their ability to significantly influence water quality (Nixon, 1981; Blackburn and Henriksen, 1983; Boynton and Kemp, 1985; Kemp et al., 1990; Rizzo and Christian, 1996).

Furthermore, benthic microalgae (BMA) influence several key estuarine biogeochemical processes. Through photosynthesis of BMA, the upper sediment is oxygenated. An increase in the sediment oxygenation can lead to an indirect influence on sediment biogeochemistry as anoxic microbial processes are pushed deeper (Sundbäck et al., 2000). Meanwhile, BMA also uptake nutrients to sustain their autotrophic processes (Rizzo, 1990; Rizzo et al., 1992; Sundbäck et al., 2000; Anderson et al., 2003). This has important implications for regenerated nutrients as the oxic state of sediments closely controls benthic nutrient regeneration (Boynton and Kemp, 1985; Rysgaard et al., 1994; Banta et al., 1995; Chapelle, 1995). Nutrient release from the sediments increases dramatically during hypoxic and anoxic events (Sundby et al., 1992; Cowan and Boynton, 1996).

Overall, in shallow portions of estuaries, BMA photosynthesis and respiration are important components of the entire ecosystem. Several studies indicated that BMA production could account for up to 50% of the entire system primary production in shallow estuarine and coastal waters (van Raalte et al., 1976; Sullivan and Moncrieff, 1988; Sundbäck and Jönsson, 1988), and benthic respiration accounts for 25% of the organic matter respired in various environments (Nixon, 1981). Nutrient loading, resulting from human activities, can also have significant impacts on benthic photosynthesis and respiration. Nutrient enrichment has been demonstrated to increase BMA production and biomass in field experiments (van Raalte et al., 1976; Granéli and Sundbäck, 1985).

The lagoons and shallow water estuaries can be exploited for recreational purposes, and for economic activities such as oyster restoration, crab rearing, and fish farming. It is very difficult to forecast the behaviour of a shallow water ecosystem, a complex network of relationships between plants and animals within a given environment, because of its complexity. The trophic network of this ecosystem is based on primary production, nutrient loading, and the amount of solar free energy, which is converted into biomass by means of photosynthesis. Primary production varies in space and in time, and depends on three important factors: water temperature, solar energy, and nutrients such as nitrogen and phosphorus in the aquatic system.

At a qualitative level, the role of each of these three factors in the ecosystem is well understood and it is common knowledge that the primary production depends on the interaction between these factors. However, it is difficult to quantify how much each of these factors would affect the year-to-year biomass production, and the occurrence of an anoxic crisis caused by excessive primary production. An integrated modeling approach has been successfully applied in the Chesapeake Bay for investigating hypoxia and anoxia over the deep water region in the mainstem Bay and major tributaries (Cerco et al., 2002). The approach calls for a system of models including hydrodynamic, watershed, water quality, and sediment flux models to be setup and operated in the study domain. The hydrodynamic model results provide transport information for the water quality model. Meanwhile, results from the watershed model will provide the nutrient loadings from land. The rates of nutrient exchange between sediment and the overlying water column are calculated from the sediment flux model.

The concern about eutrophication in coastal areas has prompted a large number of field and modeling studies on the dynamics of these environments. A number of historical surveys for water quality data collection and modeling studies for the Lynnhaven River have been conducted by the Virginia Institute of Marine Science (VIMS), Virginia Department of Environmental Quality, Department of Shellfish and Sanitation, and Malcolm Pirnie Engineers, over the past three decades. Previous modeling efforts used a simplified tidally averaged hydrodynamic component. An initial water quality study of Buchanan Creek, a small tributary in the Western Branch of Lynnhaven, was done by Ho et al. (1977a). Later, these researchers used both slack water surveys and intensive surveys to contrast the circulation in the Lynnhaven River System with that of nearby Little Creek Harbor (Ho et al., 1977b). Malcolm Pirnie Engineers (1980), in a report to the Norfolk District Army Corps of Engineers, described the conditions of Lynnhaven at that time, citing the expected problems as the watershed was further "built-out". In response, Kuo et al. (1982) applied the inter-tidal tidal prism model to study the effects of stormwater impacts on the water quality of the Lynnhaven**.** Later, Park et al. (1995a; 1995b), in work for the Virginia Department of Environmental Quality's (DEQ's) Coastal Resources Management Program, analyzed numerous surveys from 1980 and 1994 and further refined the tidal prism model.

Early models of sediment-water nutrients fluxes were based on net heterotrophic sediments and showed fluxes as primarily net nutrient sources to the water column (DiToro and Fitzpatrick, 1993). Flux measurements were also commonly made in the dark since there was no light available at the sediment surface, and benthic metabolism was driven by the heterotrophic breakdown of particulate organic matter derived from the water column (Davies, 1975). Recently, the importance of productivity by BMA in euphotic sediments was demonstrated (Colijn and de Jonge, 1984; Rizzo and Wetzel, 1985; Sundbäck, 1986), and autotrophic benthic production was shown to have direct and indirect impacts on benthic nutrient fluxes (Andersen et al., 1984; Sundbäck and Granéli, 1988; Anderson et al., 2003; Tyler et al., 2003). These included the direct assimilation of nutrients by benthic primary producers, as well as influencing microbial metabolism through modification of sediment biogeochemistry, for example, oxygen penetration (Revsbech et al., 1980; Rueter et al., 1986; Lorenzen et al., 1998). Therefore, several mathematical models were developed that vertically integrated the effects of oxygen penetration on benthic microbial processes (Christensen et al., 1989; 1990; Blackburn, 1990).

There are many challenges to modeling efforts in shallow water regions, in general, but particularly for the Lynnhaven River for several reasons:

1) the narrow opening at the Inlet
2) extensive tidal flats just inside the Inlet
3) 150 miles of meandering shorelines throughout the Lynnhaven
4) islands within this system.

These factors primarily affect the hydrodynamic modeling efforts. A key modeling challenge for any water quality application is the determination of whether all the vital mechanisms are accounted for in the selection of state variables in the model formulation. The pioneering work done by Li (2006) has demonstrated quantitatively the important role played by BMA for the shallow-water Lynnhaven River system.

With the given basin geometry, initial condition, and loading information from the surrounding watershed as the boundary conditions, the model framework solves the mathematical equations governing the processes. The results are then calibrated and verified with the observation data. When properly tuned, the modeling framework renders a holistic view of the system functions, can assess 'what-if' scenarios, and provides tremendous predictive capability to aid management decisions and scientific research. In a similar vein, there is an excellent opportunity to make use of the integrated modeling approach to study the shallow water processes in the coastal basins. The timing is particularly appropriate, given the new shallow water monitoring technologies with high spatial and temporal coverage that are emerging (http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm). This study attempts to address these difficulties by performing an integrated modeling approach, which mimics the main features of the shallow estuary. With this model, it is possible to capture the main dynamic features of the systems at a reasonable computational cost.

In order to explore these dynamics, a BMA model has been developed and uniquely coupled to the water column model that provides an otherwise comprehensive description of physical processes and both the benthic and pelagic marine trophic systems. For the water column, the well-tested CE-QUAL-ICM model was used. The relative complexity of CE-QUAL-ICM allows consideration of the full range of potential influences that BMA may have on the marine ecosystem. More recently, a robust finite difference/finite volume model for three-dimensional flows, UnTRIM (Unstructured Tidal Residual Intertidal Mudflat), has been formulated and tested on an unstructured orthogonal grid (Casulli and Zanolli, 1998; Casulli and Walters, 2000). UnTRIM, which uses an unstructured grid to better resolve complicated coastlines in the shallow environment, was further developed using the finite volume method calculation to ensure conservation of mass for all the physical and chemical constituents. UnTRIM provides hydrodynamic information that is needed by the water quality model, such as surface water elevation, three-dimensional velocity field, vertical eddy diffusivity, and so on.

An introduction has herein been presented in Chapter II. Chapter III provides a description of the methodology utilized during the project, from the overall numerical modeling framework to the individual interactive models. Chapter IV describes field observation data, both historical data and project-specific field measurements. The calibrations of the hydrodynamic and water quality models are presented in Chapter V and their validations are presented in Chapter VI. Chapter VII describes a sensitivity analysis on benthic microalgae dynamics. Lastly, Chapter VIII provides a discussion and conclusions.

CHAPTER III. NUMERICAL MODELING METHODOLOGY

III-1. Description of Numerical Modeling Framework

Numerical modeling, in a broad sense, is a process of building a mathematical abstraction of an actual system. In the estuarine and coastal environmental context, the system consists of physical, chemical, and biological components that are interactive and feed back on one another. The VIMS numerical modeling framework, as shown in Figure III.1, involves an integrated approach that combines several different processes such as hydrodynamic, water quality, nutrient, sediment processes in order to fully address the environmental impact. Whereas the CE-QUAL-ICM water quality model is shown to be the central processing mechanism, it depends heavily upon the other models with which it interacts:

1) the UnTRIM hydrodynamic model for mass and volume transport,
2) the HSPF watershed model for freshwater discharge and nutrient loadings, and
3) the sediment model for sediment flux information.

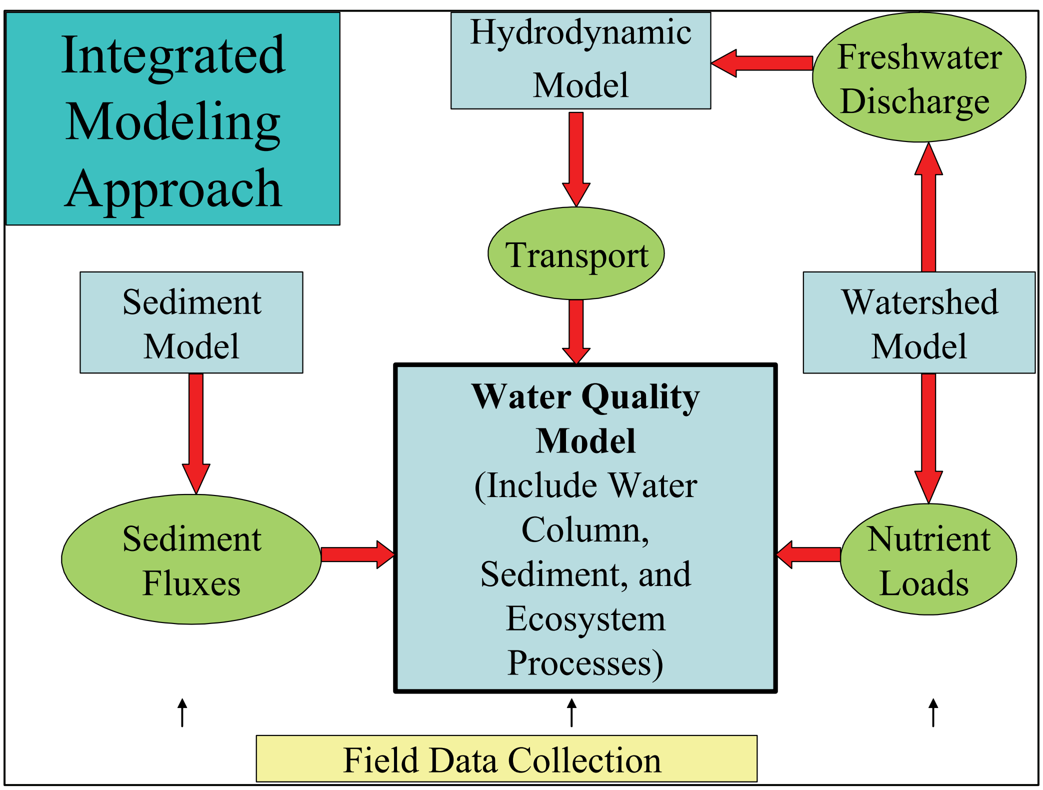


Figure III.1. The integrated modeling approach used for the VIMS water quality model

III-2. The UnTRIM hydrodynamic model

The hydrodynamic model selected for use in the numerical modeling framework is vital in that it provides the transport information required by the water quality model. The VIMS selection of UnTRIM as the hydrodynamic model for this project was based on several key features that make UnTRIM ideally suited for application to the Lynnhaven:

1) UnTRIM's use of an unstructured grid allows for a better fit of the meandering shorelines of the Lynnhaven branches
2) UnTRIM's efficient wetting-and-drying algorithm affords accurate representation of the intra-tidal areas in the system
3) UnTRIM's finite volume representation has the quality of conserving mass locally as well as globally
4) UnTRIM's independence from the Courant-Friedrich-Levy (CFL) stability criterion allows for the use of a comparatively long timestep for calculations (several minutes) despite maintaining high spatial resolutions on the order of 10 meters

III-2-1. Description of UnTRIM

The hydrodynamic model UnTRIM (Unstructured Tidal, Residual, and Intertidal Mudflat) was developed by Professor Vincenzo Casulli (Trento University, Italy). UnTRIM is a semi-implicit finite difference (-volume) model based on the three-dimensional shallow water equations as well as on the three-dimensional transport equation for salt, heat, dissolved matter and suspended sediments. UnTRIM is governed by the equations of motion, the equation of continuity, and the transport equation.

UnTRIM is able to work on unstructured orthogonal grids (UOG). The modeling domain is covered by a grid consisting of a set of non-overlapping convex polygons, usually either triangles or quadrilaterals. The grid is said to be an *unstructured orthogonal grid* if within each polygon a point (hereafter called a center) can be identified in such a way that the segment joining the center of two adjacent polygons and the side shared by the two polygons, have a non-empty intersection and are orthogonal to each other (Casulli and Zanolli, 1998).

UnTRIM has been widely used (Li, 2002; Li et al., 2004; Wang et al., 2004; Luckenbach et al., 2005; Sisson et al., 2005; Shen et al., 2006). The governing equations of UnTRIM are solved using a semi-implicit, finite difference/finite volume numerical scheme based on the three-dimensional shallow water equations as well as on the three-dimensional transport equation. Quantities computed by the model include three-dimensional velocities, surface elevation, vertical viscosity and diffusivity, salinity, and temperature. Li (2006) performed numerous rigorous tests comparing the inlet dynamics predicted from UnTRIM with the classic analytical solutions of Keulegan (1967), King (1974), and DiLorenzo (1988) using ideal cases.

The numerical algorithms of UnTRIM (Casulli and Zanolli, 1998; Casulli, 1999; Casulli and Walters, 2000; Casulli and Zanolli, 2002) are relatively straightforward, and yet general and robust. The detailed model description can be found in the above references. Compared with an unstructured finite element model, UnTRIM has a number of interesting properties, such as global and local mass conservation, high-order numerical accuracy, and unconditional stability.

An unstructured orthogonal grid differs from the orthogonal grid, such as that used by other models like the Hydrodynamic Eutrophication Model in 3 Dimensions (HEM-3D) or the Princeton Ocean Model (POM). The orthogonal grid used by HEM-3D and POM consist of only four-sided structured polygons, but UnTRIM can use both three- or four-sided polygons. As with other models, the horizontal computational domain must be covered with a set of non-overlapping convex three- or four-sided polygons. Each side of the polygon is either a boundary line or a side of an adjacent polygon.

The highest numerical accuracy is obtained when a uniform grid, composed of equilateral triangles or uniform quadrilaterals (i.e., rectangles), is used. In these cases, the normal velocity on each face of each polygon is located at the center point of the face and the centers of two adjacent polygons are equally spaced from the common face. Consequently, the discretization error is small. An unstructured, nonuniform grid can be used with a somewhat larger discretization error (Casulli and Zanolli, 1998). The error would be amplified as the simulation time is long enough, which is common in water quality simulation. However, this error can be minimized when the polygon size and shape variations through the flow domain are properly arranged. So, in order to take full advantage of the new flexibilities of the unstructured grid, the grid size and shape should change gradually.

In the UnTRIM numerical scheme, the local volume conservation is assured by the finite volume formulation. At the same time, a finite volume method is used to discretize the free-surface two-dimensional equation at each polygon. In this fashion, local and global volume conservation is guaranteed. The transport equations are solved by using the sub-cycle upwind scheme, or using a higher resolution scheme -- flux limiter method (Casulli and Zanolli, 2005). Therefore, when the transport equations are calculated, mass is also conserved locally and globally because a finite volume form is used.

The Eulerian–Lagrangian method (ELM), also known as the semi-Lagrangian method (SL), is applied in the UnTRIM numerical scheme to solve the momentum equations. It allows one to achieve a very accurate discretization of the nonlinear advection terms (Staniforth and Temperton, 1991). The advection term is solved by the Lagrangian method, which can be computed independently at each time step by the method of characteristics applied to a fixed grid domain. ELM is especially efficient when applied to unstructured Cartesian grids (Casulli and Walters, 2000; Casulli and Zanolli, 2002; Cheng et al., 1993). When momentum equations are solved, ELM combines the advantages of the Eulerian method and the Lagrangian method, by merging the simplicity of a fixed Eulerian grid with the computational power of the Lagrangian method. The advantage of ELM is that the sharp front of velocity or concentration is easier to trace since the system matrix becomes symmetric and diagonal (Casulli and Zanolli, 2002). Secondly, a large time step can be used, since the Courant number is not constrained by the small grid size (Casulli and Cattani, 1994; Casulli, 1999; Casulli and Walters, 2000; Casulli and Zanolli, 2002; Cheng and Casulli, 1996).

In applications to domains using the unstructured grid, there are two keys steps: approximation of the Lagrangian paths (characteristic streamlines) and interpolation at the departure point of the Lagrangian trajectory. The determination of the approximation of the characteristic streamline is solved using an integration method (Euler method) with a small time step shorter than the global time step. The method used by UnTRIM is called "Substepping" for the approximation of the backward trajectory (Casulli and Cattani, 1994; Casulli, 1999). In order to calculate the departure point, the bilinear interpolation is used by UnTRIM, which is sufficiently accurate.

The minimum grid size for a UnTRIM application can be as small as a few meters. However, due to its unconditional stability, UnTRIM can still use a very large timestep on the order of 10 minutes. Casulli and Cattani (1994) noted that the stability analysis of the semi-implicit finite difference method has been carried out in the case of barotropic and hydrostatic flow on a uniform rectangular grid. They assumed that the governing differential equations are linear, with constant coefficients, and are defined over an infinite horizontal domain. The analysis shows that the method is stable. Computational results of several test cases have indicated that no additional stability restrictions are required when a non-uniform unstructured mesh is used and when the hydrostatic assumption is removed. Thus, the stability of the present algorithm is independent of the celerity, wind stress, vertical viscosity, and bottom friction. It does depend on the discretization of the advection and horizontal viscosity terms. When an Eulerian-Lagrangian method is used for the explicit terms, a mild limitation on the time step depends on the horizontal viscosity coefficient and on the smallest polygon size. A further mild limitation on the time step is imposed in baroclinic flows because the baroclinic pressure term in the momentum equation has been discretized explicitly. This limitation is related to the internal wave speed that is typically smaller than the surface wave speed. This method becomes unconditionally stable for barotropic flows when the horizontal viscosity terms are neglected.

III-2-2. Formulation of UnTRIM governing equations

The UnTRIM model was developed by Casulli (1999). Detailed descriptions of the numerical algorithms of the model can by found in Casulli and Zanolli (1998), Casulli (1999), and Casulli and Walters (2000). In Cartesian coordinates, the governing continuity and momentum equations for three-dimensional flows solved by the model are:

$$\frac{\partial \mathbf{u}}{\partial x}+\frac{\partial \mathbf{v}}{\partial y}+\frac{\partial \mathbf{w}}{\partial z}=0 \qquad \text{(III-1)}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\eta} \mathbf{u} dz + \frac{\partial}{\partial y}\int_{-h}^{\eta} \mathbf{v} dz = 0 \qquad \text{(III-2)}$$

$$\frac{D\mathbf{u}}{Dt} - fv = -\frac{\partial p_a}{\partial x} - g\frac{\partial \eta}{\partial x} - g\frac{\partial}{\partial x}\int_{z}^{\eta} \frac{\rho - \rho_0}{\rho_0} d\xi - \frac{\partial q}{\partial x} + \frac{\partial}{\partial z}(\nu_v \frac{\partial \mathbf{u}}{\partial z}) + \nu_h\left(\frac{\partial^2 \mathbf{u}}{\partial x^2} + \frac{\partial^2 \mathbf{u}}{\partial y^2}\right) \qquad \text{(III-3)}$$

$$\frac{D\mathbf{v}}{Dt} + fu = -\frac{\partial p_a}{\partial y} - g\frac{\partial \eta}{\partial y} - g\frac{\partial}{\partial y}\int_{z}^{\eta} \frac{\rho - \rho_0}{\rho_0} d\xi - \frac{\partial q}{\partial y} + \frac{\partial}{\partial z}(\nu_v \frac{\partial \mathbf{v}}{\partial z}) + \nu_h\left(\frac{\partial^2 \mathbf{v}}{\partial x^2} + \frac{\partial^2 \mathbf{v}}{\partial y^2}\right) \qquad \text{(III-4)}$$

The transport equation for salt, temperature, and conservative solutes, C, and an equation of state showing that the water density is a function of salinity and temperature are:

$$\frac{\partial C}{\partial t} + \frac{\partial(\mathbf{u}C)}{\partial x} + \frac{\partial(\mathbf{v}C)}{\partial y} + \frac{\partial(\mathbf{w}C)}{\partial z} = \frac{\partial}{\partial z}(K_v \frac{\partial C}{\partial z}) + \frac{\partial}{\partial x}\left(Kh\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kh\frac{\partial C}{\partial y}\right) \qquad \text{(III-5)}$$

$$\rho = \rho_0 [1 + \alpha s + \beta(T - T_0)^2] \qquad \text{(III-6)}$$

where (u, v, w) are (x, y, z) velocity components, η is the free-surface elevation measured from a reference datum, v_v and v_h are vertical and horizontal eddy viscosities, $\frac{D}{Dt}$ is the substantial derivative, ρ and ρ_0 are density and a reference density, p_a is atmospheric pressures, q is non-hydrostatic pressure component, f is the Coriolis parameter, C represents salinity, temperature, or other conservative solutes, K_v and K_h are the vertical and horizontal eddy diffusivities, s is salinity in practical salinity units (psu), T and T_0 are temperature and a reference temperature in ^{0}C, respectively, and constants $\alpha = 7.8 \times 10^{-4}$ and $\beta = 7 \times 10^{-6}$.

The surface wind stress components are computed using the quadratic relationships and the surface boundary conditions are:

$$\nu_v \frac{\partial u}{\partial z} = \tau_{sx} = C_a \rho_a \mid \mathbf{u}_a \mid \mathbf{u}_a \qquad \text{(III-7)}$$

$$\nu_v \frac{\partial v}{\partial z} = \tau_{sy} = C_a \rho_a \mid \mathbf{u}_a \mid \mathbf{v}_a \qquad \text{(III-8)}$$

where $|\mathbf{u}_a| = (\mathbf{u}_a^2 + \mathbf{v}_a^2)^{1/2}$, u_a and v_a are the horizontal components of wind velocity near the ocean surface, ρ_a is the air density, and C_a is the drag coefficient based on the following equation:

$$C_a = (0.75 + \mathbf{0}.067\,|\mathbf{u}_a|) \times 10^{-3} \qquad \text{(III-9)}$$

The bottom stress is represented by the Manning's friction relationship:

$$\nu_v \frac{\partial \mathbf{u}}{\partial z} = \tau_{bx} = \rho \frac{gn^2}{(\Delta z)^{1/3}} (\mathbf{u}^2 + \mathbf{v}^2)^{1/2} \mathbf{u} \qquad \text{(III-10)}$$

$$\nu_v \frac{\partial \mathbf{v}}{\partial z} = \tau_{by} = \rho \frac{gn^2}{(\Delta z)^{1/3}} (\mathbf{u}^2 + \mathbf{v}^2)^{1/2} \mathbf{v} \qquad \text{(III-11)}$$

where n is the Manning parameter, *u* and *v* are bottom layer horizontal velocities, Δz is the bottom layer thickness, and ρ is the water density.

The model is a general three-dimensional model capable of simulating both 2-dimensional (vertical averaged) and 3-dimensional hydrodynamics and transport processes. The model uses a combined finite difference and finite volume scheme. Also, it uses an orthogonal, unstructured grid with mixed triangular and quadrilateral grid cells, which allows better fitting boundaries and local grid refinements to meet the needs of resolving spatial resolution in numerical modeling tasks. Figure III.2 shows an example of an orthogonal grid. The domain is covered by a set of non-overlapping convex polygons. Each side of a polygon is either a boundary line or a side of an adjacent polygon. The z-coordinate is used in the vertical. To relax the CFL condition, the Eulerian-Lagrangian transport scheme is used for treating the convective terms. A semi-implicit finite-difference method of solution was implemented in the model (Casulli, 1999). The terms that affect the numerical stability are treated implicitly, and the remaining terms are treated explicitly, which has proven to be computationally efficient (Cheng and Casulli, 2002). With the use of a Eulerian-Lagrangian transport scheme, the model is not restricted by the CFL condition. Therefore, very fine model grids can be used to represent the model domain without reducing computational efficiency.

III-3. The CE-QUAL-ICM Water Quality Model

The CE-QUAL-ICM water quality model was initially developed as one component of a model package employed to study eutrophication processes in Chesapeake Bay (US Army ERDC, 2000). ICM stands for "integrated compartment model," which is analogous to the finite volume numerical method. The model computes and reports concentrations, mass transport, kinetics transformations, and mass balances. This eutrophication model computes 22 state variables including multiple forms of algae, carbon, nitrogen, phosphorus, silica, and dissolved oxygen. One significant feature of ICM is a diagenetic sediment sub-model, which interactively predicts sediment-water oxygen and nutrient fluxes. Alternatively, these fluxes may be specified based on observations.

CE-QUAL-ICM has been applied to many sites, including Chesapeake Bay, Inland Bays of Delaware, New York Bight, Newark Bay, New York - New Jersey Harbors and

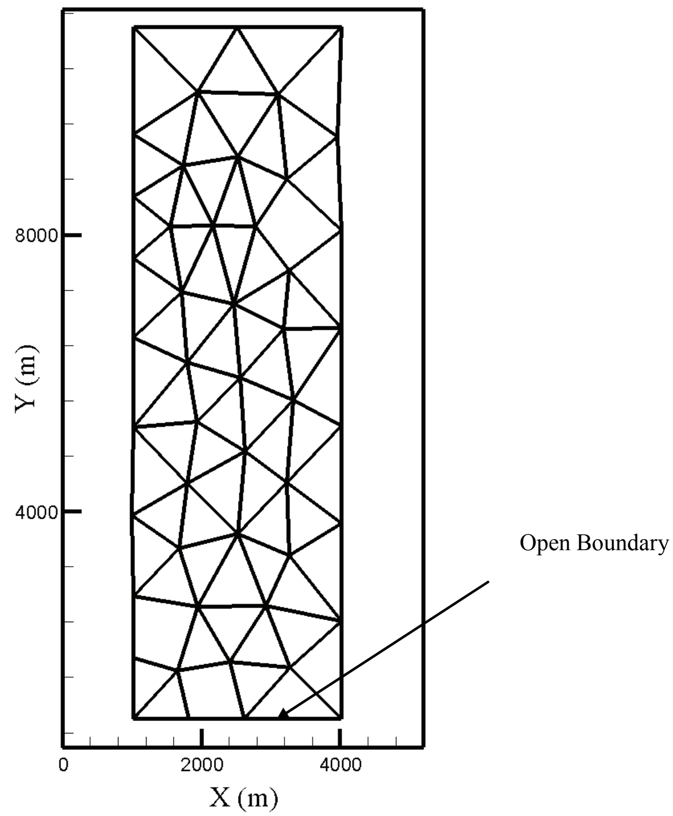


Figure III.2. An example of an orthogonal grid.

Estuaries, Lower Green Bay, Los Angeles - Long Beach Harbors, Cache River wetlands, San Juan Bay and Estuaries, Florida Bay, and Lower St. Johns River.

The foundation of CE-QUAL-ICM is the solution to the three-dimensional mass-conservation equation for a control volume based on the finite volume approach. Transport within the CE-QUAL-ICM (Cerco and Cole, 1995) is based on the integrated compartment method (or box model methodology). The present version of CE-QUAL-ICM transport is a loose extension of the original WASP code (Ambrose et al., 1986). The notion of utilizing the box model concept was retained in order to allow the coupling, via map files, of ICM with various hydrodynamic models. ICM represents "integrated compartment model," which is the finite volume numerical method. The model computes constituent concentrations resulting from transport and transformations in well-mixed cells that can be arranged in arbitrary triangular and quadrilateral configurations. Thus, the model employs an unstructured grid system, which is compatible with UnTRIM.

III-3-1. Linkage between UnTRIM and CE-QUAL-ICM

The foundation of CE-QUAL-ICM is the solution to the three-dimensional mass-conservation equation for a control volume based on the finite volume approach. For each volume and for each state variable, the governing equation that CE-QUAL-ICM solves is:

$$\frac{\delta V_j C_j}{\delta t} = \sum_{k=1}^{n} Q_k C_k + \sum_{k=1}^{n} A_k D_k \frac{\delta C}{\delta x_k} + \sum_{k=1}^{n} S_j \qquad \text{(III-12)}$$

where:
V_j = volume of j^{th} control volume (m^3)
C_j = concentration in j^{th} control volume (mg m^{-3})
t, x = temporal and spatial coordinates
n = number of flow faces attached to j^{th} control volume
Q_k = volumetric flow across flow face k of j^{th} control volume (m^3 sec^{-1})
C_k = concentration in flow across flow face k (mg m^{-3})
A_k = area of flow face k (m^2)
D_k = diffusion coefficient at flow face k (m^2 sec^{-1})
S_j = external loads and kinetic sources and sinks in j^{th} control volume (mg sec^{-1})

The above conservation-of-mass equation is solved in two steps. In the first step, an intermediate value is computed. The intermediate value includes the effects of change in cell volume, longitudinal and lateral transport, and external loading. This horizontal transport is solved using the UPWIND algorithm or the third-order-accurate non-uniform grid QUICKEST algorithm. In the second step, the effects of vertical transport and kinetic transformation are computed. The second-order implicit Crank-Nicolson scheme is used in the vertical direction. The linkage between UnTRIM and CE-QUAL-ICM focuses on the horizontal transport. The details of the horizontal transport methodology and the modifications required for a non-uniform and non-structured grid are presented below.

The original horizontal advection operator in CE-QUAL-ICM was designed to work with structured grid hydrodynamic models such as CH3D (Chapman and Cole, 1992). For a structured grid, grid information is described by rows and columns of cells combined with cell dimensions. The box lengths are directly calculated according to the relationship of rows and columns using a structured grid, and then are used to compute the UPWIND or QUICKEST transport multipliers. Due to prior successful applications of the UPWIND and QUICKEST transport algorithms in CE-QUAL-ICM (Dortch et al., 1991; Chapman and Cole, 1992), a similar approach was adopted for the non-structured version of CE-QUAL-ICM. The vertical transport computation utilizes the same solution, both for structured and unstructured grids.

An essential task of this study was the development of linkage software to provide geometric and hydrodynamic information transferring from UnTRIM output to the CE-QUAL-ICM code and to test the success of the linkage. The software development consisted of three basic parts:

a. Unstructured grid information used by the hydrodynamic model was transferred into CE-QUAL-ICM, including the number of polygons, faces, and the relationship between polygons and faces. The linkage software was developed to map the unstructured grid configuration and geometry information into several files that could be interpreted by the CE-QUAL-ICM code.

b. Hydrodynamic simulation results required for output and transferred into CE-QUAL-ICM. A postprocessor code of UnTRIM was developed to output the 3-dimensional surface area of each polygon and volume of each polygon only at the beginning of the simulation. The 3-dimensional velocity field, surface water elevation information at each face and the center point of each polygon, and vertical diffusivity were output at each time step.
c. CE-QUAL-ICM was modified to accept the UnTRIM linkage information, especially in the input program and transport calculation.

The mapping of grid information between UnTRIM and CE-QUAL-ICM, and the transfer of information between these two models, are described in more detail in Li (2006).

III-3-2. Dissolved oxygen process

(1) Effects of algae in water column on dissolved oxygen

Algae produce oxygen during photosynthesis and consume oxygen through respiration. The quantity produced during photosynthesis depends on the form of nitrogen taken up. Since oxygen is released in the reduction of nitrate (NO_3), more oxygen is produced, per unit of carbon fixed, when NO_3 is the algal nitrogen source than when ammonia NH_4 is the source. When NH_4 is the nitrogen source, one mole of oxygen is produced per mole carbon dioxide fixed. When NO_3 is the nitrogen source, 1.3 moles oxygen are produced per mole carbon dioxide fixed. The equation that describes the effect of algae photosynthesis on DO in the model is:

$$\frac{\delta DO}{\delta t} = \sum_x \left(\left(1.3 - 0.3\,PN_x\right) P_x \right) \mathrm{AOCR} \cdot \mathrm{B_x} \qquad \text{(III-13)}$$

where:

PN_x = algal group x preference for ammonium

P_x = production rate of algal group x (day^{-1})

AOCR = DO-to-carbon ratio in respiration (2.67 g O_2 per g C)

B_x = algal biomass (g C m^{-3})

As employed here, basal metabolism is the sum of all internal processes that decrease algal biomass. A portion of the metabolism is respiration and may be viewed as a reversal of production. In respiration, carbon and nutrients are returned to the environment accompanied by the consumption of DO. Respiration cannot proceed in the absence of DO. Basal metabolism cannot decrease in proportion to oxygen availability. Formulation of this process is described as:

$$\frac{\delta DO}{\delta t} = \sum_{x} \left(-\frac{DO}{KHR_x + DO} BM_x \right) AOCR \cdot B_x \qquad \text{(III-14)}$$

where:

KHR_x = half-saturation constant of DO for algal DOC exudation (g O_2 m^{-3})
BM_x = basal metabolism rates for algal group x (day^{-1})

(2) Effects of nitrification on dissolved oxygen

Nitrification is a process mediated by specialized groups of autotrophic bacteria that obtain energy through the oxidation of ammonia to nitrite and oxidation of nitrite to nitrate. A simplified expression for complete nitrification is:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^{2+} \qquad \text{(III-15)}$$

The equation indicates that two moles of oxygen are required to nitrify one mole of ammonia into nitrate. The simplified equation is not strictly true, however. Cell synthesis by nitrifying bacteria is accomplished by the fixation of carbon dioxide so that less than two moles of oxygen are consumed per mole ammonium utilized (Wezernak and Gannon, 1968). In this study, nitrification is modeled as a function of available ammonium, dissolved oxygen, and temperature:

$$NT = \frac{DO}{KHONT + DO} \frac{NH_4}{KHNNT + NH_4} f(T) \cdot NTM \qquad \text{(III-16)}$$

where:

NT = nitrification rate (gm N m^{-3} day^{-1})
NTM = maximum nitrification rate at optimal temperature (gm N m^{-3} day^{-1})
KHONT = half-saturation constant of DO required for nitrification (gm DO m^{-3})
KHNNT = half-saturation constant of NH_4 required for nitrification (gm N m^{-3})

Therefore, the effect of nitrification on DO is described as follows:

$$\frac{\delta DO}{\delta t} = -AONT \cdot NT \qquad \text{(III-17)}$$

where:

AONT = mass DO consumed per mass ammonia nitrified (4.33 gm DO gm^{-1} N)

(3) Effects of surface reaeration on dissolved oxygen

Reaeration occurs only in the model surface cells. The effect of reaeration is:

$$\frac{\delta DO}{\delta t} = \frac{K_R}{\Delta z_s}(DO_S - DO) \qquad \text{(III-18)}$$

where:

K_R = reaeration coefficient (m day^{-1})
Δz_s = model layer thickness (m)
DO_S = dissolved oxygen saturation concentration (gm DO m^{-3})

Saturation dissolved oxygen concentration DO_S is computed (Genet et al., 1974):

$$DO_S = 14.5532 - 0.38217 \cdot T + 0.0054258 \cdot T^2 - \frac{S}{1.80655}\left(0.1665 - 5.866 \cdot 10^{-3} \cdot T + 9.796 \cdot 10^{-5} \cdot T^2\right) \qquad \text{(III-19)}$$

where:

S = salinity (ppt)

(4) Effects of Chemical Oxygen Demand on dissolved oxygen

In the present model, chemical oxygen demand represents the reduced materials that can be oxidized through inorganic means. The kinetic equation showing the effect of chemical oxygen demand is:

$$\frac{\delta DO}{\delta t} = -\frac{DO}{KHO_{COD} + DO} K_{COD} \cdot COD \qquad \text{(III-20)}$$

where:

COD = chemical oxygen demand concentrations (g O_2-equivalents m^{-3})
KHO_{COD} = half-saturation constant of DO for oxidation of COD (g O_2 m^{-3})
K_{COD} = oxidation rate of COD (day^{-1})

$$K_{COD} = K_{CD} \cdot \exp\left(KT_{COD}[T - TR_{COD}]\right) \qquad \text{(III-21)}$$

where:

K_{CD} = oxidation rate of COD at reference temperature TR_{COD} (day^{-1})

KT_{COD} = effect of temperature on oxidation of COD (°C^{-1})
T = water temperature (°C)
TR_{COD} = reference temperature for oxidation of COD (°C).

Overall, the internal sources and sinks of dissolved oxygen include algal photosynthesis and respiration, atmospheric reaeration (surface cells only), heterotrophic respiration, nitrification, and oxidation of COD. The complete kinetic equation showing sediment oxygen demand (bottom cells only) is:

$$\frac{\delta DO}{\delta t} = \sum_x \left((1.3 - 0.3 \cdot PN_x) P_x \ - \ \frac{DO}{KHR_x + DO} BM_x \right) AOCR \cdot B_x$$
$$+ \ \lambda_1 \frac{K_R}{\Delta z_S} \left(DO_S \ - \ DO \right) - \ \frac{DO}{KHO_{DOC} + DO} AOCR \cdot K_{DOC} \cdot DOC \qquad \text{(III-22)}$$
$$- \ AONT \cdot NIT \ - \ \frac{DO}{KHO_{COD} \ + \ DO} K_{COD} \cdot COD \ + \ \lambda_2 \frac{SOD}{\Delta z}$$

III-3-3. Model Phytoplankton Kinetics

There are three functional groups for algae: cyanobacteria, diatoms, and green algae. This grouping is based upon the distinctive characteristics of each class and upon the significant roles these characteristics play in the ecosystem. Cyanobacteria are characterized by their bloom-forming characteristics in freshwater. They are characterized as having small settling velocity and are subject to low predation pressure. Diatoms are large phytoplankton that usually produces the spring bloom in the saline water. Settling velocity of diatoms is relatively large, so the diatoms settling into sediment may be a significant source of carbon for sediment oxygen demand. Diatoms are also distinguished by their requirement of silica as a nutrient. The green algae represent the mixture that characterizes blooming in saline waters during summer and autumn, and are subject to relatively high grazing pressure.

Equations governing the three algal groups are similar. Differences among groups are expressed through the magnitudes of parameters in the equations. Generic equations are presented below, except when group-specific relationships are required. Algal sources and sinks in the conservation equation include production, metabolism, predation, and settling. In the following equations, a subscript, **x**, is used to denote three algal groups: **c** for cyanobacteria, **d** for diatoms, and **g** for green algae. The internal sources and sinks included are growth (production), basal metabolism (respiration and exudation), predation, and settling. The kinetic equations for algae are:

$$\frac{\delta B_x}{\delta t} = \left(P_x \ - \ BM_x \ - \ PR_x \right) B_x \ - \ WS_x \frac{\delta B_x}{\delta z} \qquad \text{(III-23)}$$

where:

B_x = algal biomass, expressed as carbon (g C m^{-3})
P_x = growth (production) rates of algae (day^{-1})
BM_x = basal metabolism rates of algae (day^{-1})
PR_x = predation rates of algae (day^{-1})
WS_x = algal settling velocity (m day^{-1})
z = vertical coordinate

(1) Growth (Production)

Algal growth rate depends on nutrient availability, ambient light, and temperature. The effects of these processes are considered to be multiplicative as follows:

$$P_x = PM_x \cdot f(N) \cdot f(I) \cdot f(T) \qquad \text{(III-24)}$$

where:

PM_x = maximum production rate under optimal conditions (day^{-1})
f(N) = effect of sub-optimal nutrient
f(I) = effect of light intensity
f(T) = effect of temperature

(2) Effect of nutrient on growth

Liebig's "law of the minimum" (Odum, 1971) is used, so that nutrient limitation is determined by the single most limiting nutrient:

$$f(N) = \text{minimum}\left\{\frac{NH_4 + NO_3}{KHN_x + NH_4 + NO_3}, \frac{PO_{4d}}{KHP_x + PO_{4d}}, \frac{SAd}{KHS_d + SAd}\right\} \qquad \text{(III-25)}$$

where:

NH_4, NO_3 = ammonium and nitrate nitrogen concentrations, respectively (g N m^{-3})
PO_4d = dissolved phosphate concentration (g P m^{-3})
SAd = dissolved silica concentration (g Si m^{-3})
KHN_x = half-saturation constant for algal nitrogen uptake (g N m^{-3})
KHP_x = half-saturation constant for algal phosphorus uptake (g P m^{-3})
KHS_d = half-saturation constant for silica uptake by diatoms (g Si m^{-3})

(3) Effects of light on growth

The influence of light on phytoplankton production is represented by a chlorophyll-specific production equation (Jassby and Platt, 1976):

$$P^B = P^B m \frac{I}{\sqrt{I^2 + IK^2}} \quad \text{(III-26)}$$

where:

P^B = photosynthetic rate (g C g^{-1} Chl d^{-1})
$P^B m$ = maximum photosynthetic rate (g C g^{-1} Chl d^{-1})
I = irradiance (E m^{-2} d^{-1})

Parameter Ik is defined as the irradiance at which the initial slope of the production vs. irradiance relationship intersects the value of $P^B m$:

$$IK = \frac{P^B m}{\alpha} \quad \text{(III-27)}$$

where:

α = initial slope of production vs. irradiance relationship (g C g^{-1} Chl (E $m^{-2})^{-1}$)

Chlorophyll-specific production rate is readily converted to carbon-specific growth rate, through division by the carbon-to-chlorophyll ratio:

$$G = \frac{P^B}{CChl} \quad \text{(III-28)}$$

where:

CChl = carbon-to-chlorophyll ratio (g C g^{-1} chlorophyll-a)

(4) Effect of temperature on growth

The effect of temperature on algal production is represented by a function similar to a Gaussian probability curve:

$$\begin{aligned} f(T) &= \exp\left(-KTG1_x\,[T - TM_x]^2\right) \quad \text{when } T \le TM_x \\ &= \exp\left(-KTG2_x\,[TM_x - T]^2\right) \quad \text{when } T > TM_x \end{aligned} \quad \text{(III-29)}$$

where:

TM_x = optimal temperature for algal growth (°C)
$KTG1_x$ = effect of temperature below TM_x on algal growth (°C^{-2})
$KTG2_x$ = effect of temperature above TM_x on algal growth (°C^{-2})

(5) Constructing the photosynthesis vs. irradiance curve

A production versus irradiance relationship is constructed for each model cell at each time step. First, the maximum photosynthetic rate under ambient temperature and nutrient concentrations is determined:

$$P^{B}m(N,T) = P^{B}m * f(T) * f(N) \qquad \text{(III-30)}$$

where:

$P^{B}m(N,T)$ = maximum photosynthetic rate under ambient temperature and nutrient concentrations (g C g^{-1} Chl d^{-1})

The single most limiting nutrient is employed in determining the nutrient limitation. Next, parameter Ik is derived from Equation III-27. Finally, the production vs. irradiance relationship is constructed using $P^{B}m$ (N,T) and Ik.

(6) Water surface irradiance

Irradiance at the water surface is evaluated at each model time step. Instantaneous irradiance is computed by fitting a sine function to daily total irradiance:

$$I_o = \frac{I_T}{FD}\frac{\pi}{2}\sin\left(\pi\frac{DSSR}{FD}\right) \qquad \text{(III-31)}$$

where:

I_o = irradiance at water surface (E m^{-2} d^{-1})

IT = daily total irradiance (E m-1)
FD = fractional daylength (0 < FD < 1)
DSSR = time since sunrise (d)

I_o is evaluated only during the interval:

$$\frac{1-FD}{2} \le DSM \le \frac{1+FD}{2} \qquad \text{(III-32)}$$

where:

DSM = time since midnight (d)

Outside the specified interval, I_o is set to zero.

Irradiance declines exponentially with depth below the surface. The diffuse attenuation coefficient, K_e, is computed as a function of background extinction and concentrations of chlorophyll-a and total suspended solids.

(7) The light attenuation model

The water quality model requires daily solar radiation intensity and fractional day length, in order to simulate the algal growth. The light attenuation model also requires input of the light attenuation coefficient. It is assumed that the light extinction coefficient consists of three parts: background extinction, the light extinction due to suspended solids, and light extinction due to algae:

$$\mathrm{Ke} = \mathrm{a}_1 + \mathrm{a}_2 * TSS + \mathrm{a}_3 * CHL \qquad \text{(III-33)}$$

where:

a_1 = background attenuation (m^{-1})
a_2 = attenuation by inorganic suspended solids ($m^2\ g^{-1}$)
a_3 = attenuation by organic suspended solids ($m^2\ g^{-1}$ CHL)
TSS = total suspended solids concentration ($g\ m^{-3}$)
CHL = chlorophyll-a concentration (mg CHL m^{-3})

The "background" attenuation term included attenuation from both water and dissolved organic matter. Individual parameters were determined from Park et al. (1995b). The value for a_1 used in the model is 0.735 m^{-1}, a_2 is 0.018 $m^2\ g^{-1}$, and a_3 is 0.06 $m^2\ mg^{-1}$ CHL.

(8) Basal metabolism

Basal metabolism is commonly considered to be an exponentially increasing function of temperature:

$$\mathrm{BM}_x = \mathrm{BMR}_x * \exp\left(\mathrm{KTB}_x\,[\mathrm{T} - \mathrm{TR}_x]\right) \qquad \text{(III-34)}$$

where:

BMR_x = metabolic rate at reference temperature TR_x (day^{-1})
KTB_x = effect of temperature on metabolism ($C^{\circ -1}$)
TR_x = reference temperature for metabolism (C°)

(9) Predation

The predation formulation is identical to basal metabolism. The difference in predation and basal metabolism lies in the distribution of the end products of these processes.

$$PR_x = BPR_x \exp(KTB_x (T - TR_x)) \quad \text{(III-35)}$$

where:

BPR_x = predation rate at TR_x (day $^{-1}$)
KTB_x = effect of temperature on predation ($C^{\circ -1}$)
TR_x = reference temperature for predation (C°)

(10) Settling velocity

The algal settling rate employed in the model represents the total effect of all physiological and behavioral processes that result in the downward transport of phytoplankton. The settling rate employed, from 0.1 m d^{-1} to 0.2 m d^{-1}, was used in the model to optimize the agreement between predicted and observed algae.

(11) Effect of algae on phosphorus

Model phosphorus state variables include total phosphate (dissolved, sorbed, and algal), dissolved organic phosphorus, labile particulate organic phosphorus, and refractory particulate organic phosphorus. The amount of phosphorus incorporated in algal biomass is quantified through a stoichiometric ratio. Thus, total phosphorus in the model is expressed:

$$TotP = PO_4d + PO_4p + \sum_x Apc*Bx + DOP + LPOP + RPOP \quad \text{(III-36)}$$

where:

TotP = total phosphorus (g P m^{-3})
PO_4d = dissolved phosphate (g P m^{-3})
PO_4p = particulate inorganic phosphate (g P m^{-3})
Apc = algal phosphorus-to-carbon ratio (g P g^{-1} C)
DOP = dissolved organic phosphorus (g P m^{-3})
LPOP = labile particulate organic phosphorus (g P m^{-3})
RPOP = refractory particulate organic phosphorus (g P m^{-3})

Algae take up dissolved phosphate during production and release dissolved phosphate and organic phosphorus through respiration. The fate of phosphorus released by respiration is determined by empirical distribution coefficients. The fate of algal phosphorus incorporated by zooplankton and lost through zooplankton mortality is determined by a second set of distribution parameters.

(12) Effect of algae on nitrogen

Model nitrogen state variables include ammonium, nitrate + nitrite, dissolved organic nitrogen, labile particulate organic nitrogen, and refractory particulate organic nitrogen. The amount of nitrogen incorporated in algal biomass is quantified through a stoichiometric ratio. Thus, total nitrogen in the model is expressed:

$$TotN = NH_4 + NO_3 + \sum_x Anc*Bx + DON + LPON + RPON \qquad \text{(III-37)}$$

where:

TotN = total nitrogen (g N m^{-3})
NH_4 = ammonium (g N m^{-3})
NO_3 = nitrate + nitrite (g N m^{-3})
Anc = algal nitrogen-to-carbon ratio (g N g^{-1} C)
DON = dissolved organic nitrogen (g N m^{-3})
LPON = labile particulate organic nitrogen (g N m^{-3})
RPON = refractory particulate organic nitrogen (g N m^{-3})

Algae take up ammonium and nitrate + nitrite during production and release ammonium and organic nitrogen through respiration. Nitrate + nitrite is internally reduced to ammonium before synthesis into biomass occurs (Parsons et al., 1984). Trace concentrations of ammonium inhibit nitrate reduction so that, in the presence of multiple nitrogenous nutrients, ammonium is utilized first. The "preference" of algae for ammonium is expressed by an empirical function (Thomann and Fitzpatrick, 1982):

$$\begin{aligned} PN &= NH_4 * \frac{NO_x}{(KHn + NH_4)*(KHn + NO_x)} \\ &+ NH_4 * \frac{KHn}{(NH_4 + NO_x)*(KHn + NO_x)} \end{aligned} \qquad \text{(III-38)}$$

where:

PN = algal preference for ammonium uptake ($0 < Pn < 1$)
KHn = half saturation concentration for algal nitrogen uptake (g N m^{-3})

When nitrate + nitrite is absent, the preference for ammonium is unity. When ammonium is absent, the preference is zero.

(13) Effect of algae on silica

The model incorporates two siliceous state variables: dissolved silica and particulate biogenic silica. The amount of silica incorporated in algal biomass is quantified through a stoichiometric ratio. Thus, total silica in the model is expressed:

$$TotSi = Dsil + Asc * Bx + PBS \qquad \text{(III-39)}$$

where:

TotSi = total silica (g Si m^{-3})
Dsil = dissolved silica (g Si m^{-3})
Asc = algal silica-to-carbon ratio (g Si g^{-1} C)
PBS = particulate biogenic silica (g Si m^{-3})

As with the other nutrients, the fate of algal silica released by metabolism and predation is represented by distribution coefficients.

III-3-4. Benthic sediment process

Additionally, a benthic sediment process model developed by DiToro and Fitzpatrick (1993) was incorporated and coupled with CE-QUAL-ICM for the present model application. The model state variables, and resulting fluxes, include dissolved oxygen, ammonium, nitrate-nitrite, and phosphate and the parameters used in this sediment flux model are listed in the Table V.10 of Chapter V.

The sediments in this model are represented by two layers: the upper aerobic layer (Layer 1) and the lower anoxic layer (Layer 2). The sediment process model is coupled with the water column eutrophication model through depositional and sediment fluxes. First, the sediment model is driven by net settling of particulate organic matter from the overlying water column to the sediments (depositional flux). Then, the mineralization of particulate organic matter in the lower anoxic sediment layer produces soluble intermediates, which are quantified as diagenesis fluxes. The intermediates react in the upper oxic and lower anoxic layers, and portions are returned to the overlying water column as sediment fluxes. Computation of sediment fluxes requires mass-balance equations for ammonium, nitrate, phosphate, sulfide/methane, and available silica. Mass-balance equations are solved for these variables for both the upper and lower layers. Complete model documentation of the sediment flux model can be found in DiToro and Fitzpatrick (1993).

It should be noted that, due to the critical nature of impacts to Lynnhaven water clarity from total suspended solids (TSS), a decision was made to add to the project scope of work the development of a sediment transport model capable of fully simulating the processes of erosion, deposition, and sediment resuspension. This sediment transport model is described in the next section.

III-4. Description of the sediment transport model

The model utilized in this study is principally based on that of Sanford (2008). As the mud percentage of the bottom sediments in the Lynnhaven basin is larger than 10% in most parts of the Basin and the bottom sediments are mainly composed of silty clay, the formulae of cohesive sediment erosion and deposition were adopted, which are described in the following. The spatial distribution of the sand percentage, and the percentage of silt and clay in the bottom sediment was obtained by grain size analysis of the sediment samples in the basin (Figure III.3). It can be seen that in the inlet and the main channels of the Western and Eastern Branches, sand takes up most part of the sediment. Sand also dominates in the shallow area along the shoreline, mostly induced by shoreline erosion. For most of the area in the basin, sand percentage is less than 90%.

In this study, only silt and clay were simulated. To account for the sediment consolidation, the method of Sanford (2008) for adjusting the bottom critical shear stress was adopted. It assumes that there exists a vertical profile of the equilibrium critical shear stress through the sediment bed, and the actual critical shear stress adapts to the equilibrium one in a first-order time evolution manner.

$$\frac{\partial \tau_c}{\partial t} = r_c(\tau_{ceq} - \tau_c)H(\tau_{ceq} - \tau_c) + r_s(\tau_{ceq} - \tau_c)H(\tau_c - \tau_{ceq}) \qquad \text{(III-40)}$$

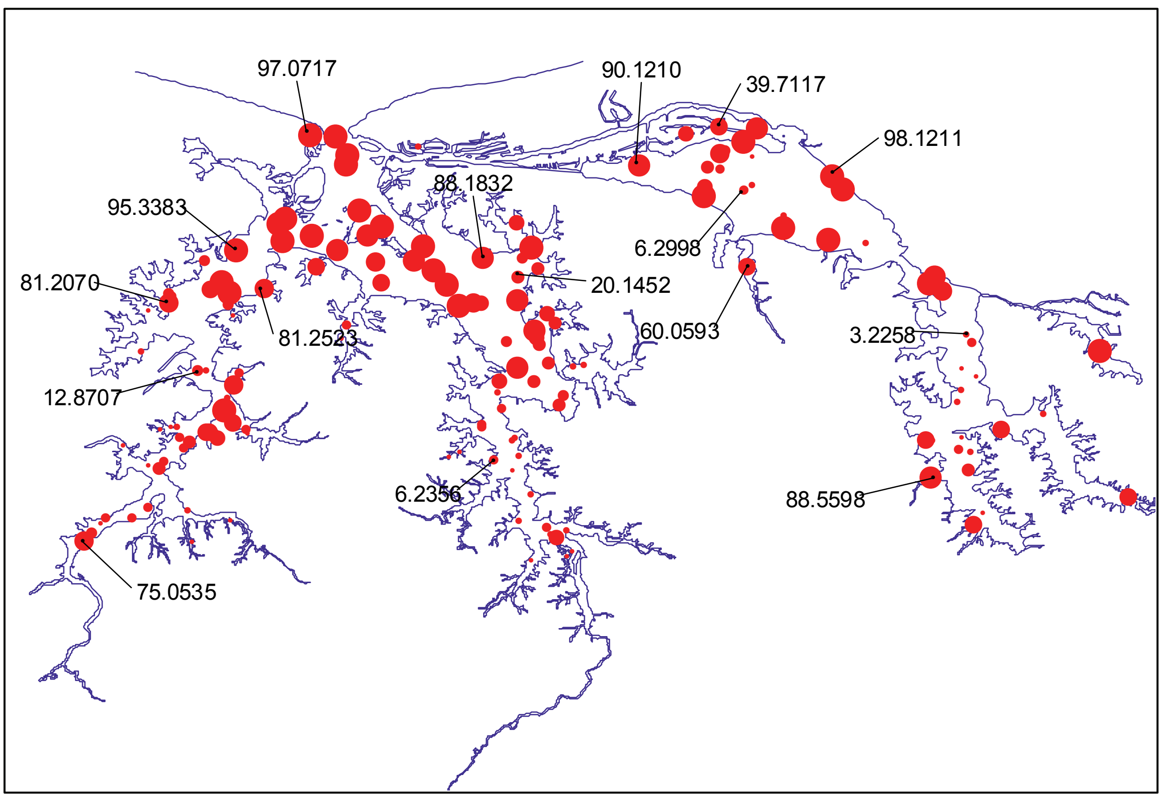


Figure III.3. Sand percentage of the bottom sediment of the Lynnhaven River.

Where τ_c is the instantaneous critical shear stress, τ_{ceq} is the equilibrium critical shear stress, H is the Heaviside step function, defined such that $H = 1$ when its argument is ≥ 0 and $H = 0$ otherwise. In Eq. (III-40), r_c is the first-order consolidation rate and r_s is the first-order swelling rate, which is much smaller than r_c. In this study r_c was set as $\frac{1}{3}$ per day and $r_s = 0.01 r_c$, following Sanford (2008).

The erosion rate is

$$E = M\left(\frac{\tau_b(t)}{\tau_c} - 1\right) \qquad if(\tau_b > \tau_c)$$

$$E = 0 \qquad if(\tau_b \le \tau_c) \qquad \text{(III-41)}$$

Where τ_b is the bottom stress, M is an erosion rate parameter, which can be obtained from the observation data, like that in Baltimore Harbor, Maryland, USA (Lin et al., 2003). In this study it was adjusted until the model results agreed with measurements and, thus, the calibrated value of M is 0.0004 g/m^2/s.

In this study, the equilibrium critical shear stress profile was set equal to the critical stress profile obtained by bottom sediment erodibility tests in Lynnhaven basin by Sanford and Suttles.

$$\tau_{ceq} = 0.7006 m^{1.5309} \qquad \text{(III-42)}$$

Where τ_{ceq} is the equilibrium critical shear stress defined at the interface between layers, m is the accumulated sediment mass (kg) within the layers above the interface. The equilibrium critical shear stress at the water-sediment interface was specified spatially varying. The spatial distribution of the water-sediment interface equilibrium critical shear stress was obtained by executing the hydrodynamic model for approximately one month to cover the spring-neap tidal variability, and averaging the modeled bottom stress for every cell. The result of equilibrium critical shear stress distribution at the water-sediment interface is shown in Figure III.4. It can be seen that the shear stress has good correlation with the sand percentage of the bottom sediment, the higher sand percentage, the larger of the shear stress. This is consistent with the findings of Molinaroli et al. (2007) that the sediment sorting was mostly controlled by the tidal hydrodynamics in the Lagoon of Venice, Italy. They obtained a good relationship between the sand percentage of the bottom sediment and the mean tidal velocity.

The equilibrium critical shear stress of water-sediment interface was assigned to the corresponding cells. From Figures III.3 and III.4, the equilibrium critical shear stress of the water-sediment interface for the areas with sand percentages less than 70% was mostly close to 0.03 Pa, which is consistent with the measurement data of Sanford and Suttles. Under the water-sediment interface, a total of 25 bed layers were defined. At each layer of the first 20 layers a sediment mass of 0.5 kg/m^2 was specified, whereas for the last 5 layers sediment masses were given as 5.0, 25, 50, 75 and 100 kg/m^2, respectively. The equilibrium critical shear stress for each layer was specified as the larger of water-sediment interface one and that derived from Eq. (III-42).

At each time step, the bed layers were adjusted by adding or removing layers to account for the deposition or erosion in the bed based on Sanford (2008). With newly deposited sediment at first layer of the bottom, the critical shear stress at the water-sediment interface was decreased as demonstrated by Lin et al. (2003). When the sediment was eroded from the layer, the critical shear stress was increased as illustrated from Eq. (III-41). After the above adjustment, the critical shear stresses were relaxed to the equilibrium ones based on Eq. (III-40).

The deposition rate of cohesive sediment was calculated as

$$D = \begin{cases} w_s C_b \dfrac{\tau_{dc} - \tau_b}{\tau_{dc}} & \text{for } \tau_{dc} > \tau_b \\ 0 & \tau_{dc} \le \tau_b \end{cases} \qquad \text{(III-43)}$$

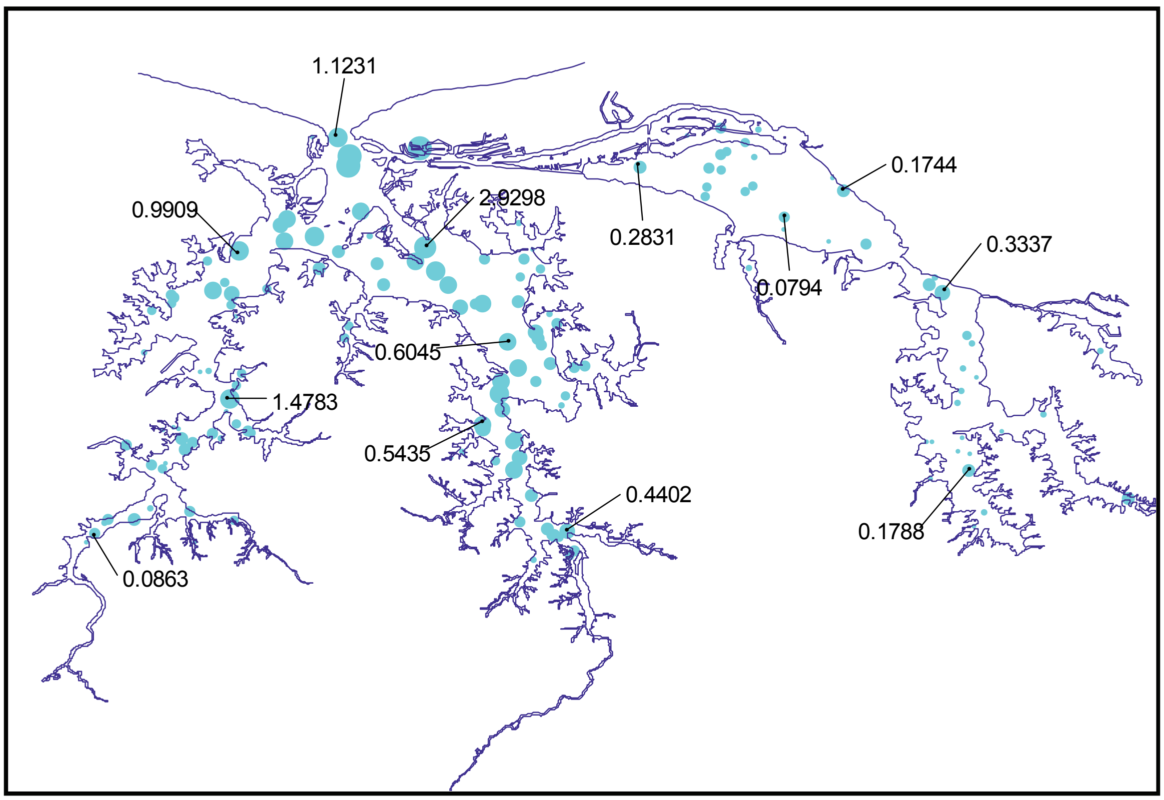


Figure III.4. Average bottom shear stress obtained by one month of hydrodynamic simulation.

Where τ_{dc} is the critical shear stress for deposition, which was set as 0.03 *Pa* in this study. The existence of a critical shear stress for deposition is debatable, a value of 0.035 *Pa* has been utilized in Lin and Kuo's (2003) study, and a continuous settling concept was adopted by Sanford (2008).

To account for the flocculation, the cohesive sediment's settling velocity dependence on concentration was utilized, which was obtained by Kwon (2005) through measurement in the York River as follows:

$$w_s = 3.5 * 10^{-5} C^{0.375} \qquad \text{(III-44)}$$

where w_s is in units of m/s and C is in units of g m^{-3}.

The calibration of the Lynnhaven River sediment transport model is presented in Section V-3 and its validation is presented in Section VI-3.

III-5. Description of the watershed model for the Lynnhaven River Basin

As VIMS has developed the hydrodynamic and water quality models for the Lynnhaven River receiving waters, URS Corporation of Virginia Beach has developed a watershed model for the Lynnhaven River Basin. The watershed model used by URS is HSPF (Hydrological Simulation Program – FORTRAN), version 12 (URS Technical Memorandum, Hydrologic Concepts and Parameter Development, 2006).

The goal of the watershed modeling effort is to provide the freshwater discharge and nutrient and sediment loadings from the watershed at high spatial and temporal resolutions. The Lynnhaven River Basin, consisting of 7 sub-basins, has been delineated into 1,079 catchments, ranging in size from approximately 40 acres, as shown in Figure III.5.

The landuse in the Lynnhaven Basin is 40% residential and 35% composed of streets, commercial and office space, and military use. In its watershed model development, URS selected a total of 23 land uses within the Lynnhaven River basin into which zoning codes could then be grouped. URS then assigned to each landuse a directly connected impervious percentage, as shown in Table III.1. Landuse was employed to develop effective impervious area percentages for the nearly 57,000 land parcels within the Lynnhaven Basin.

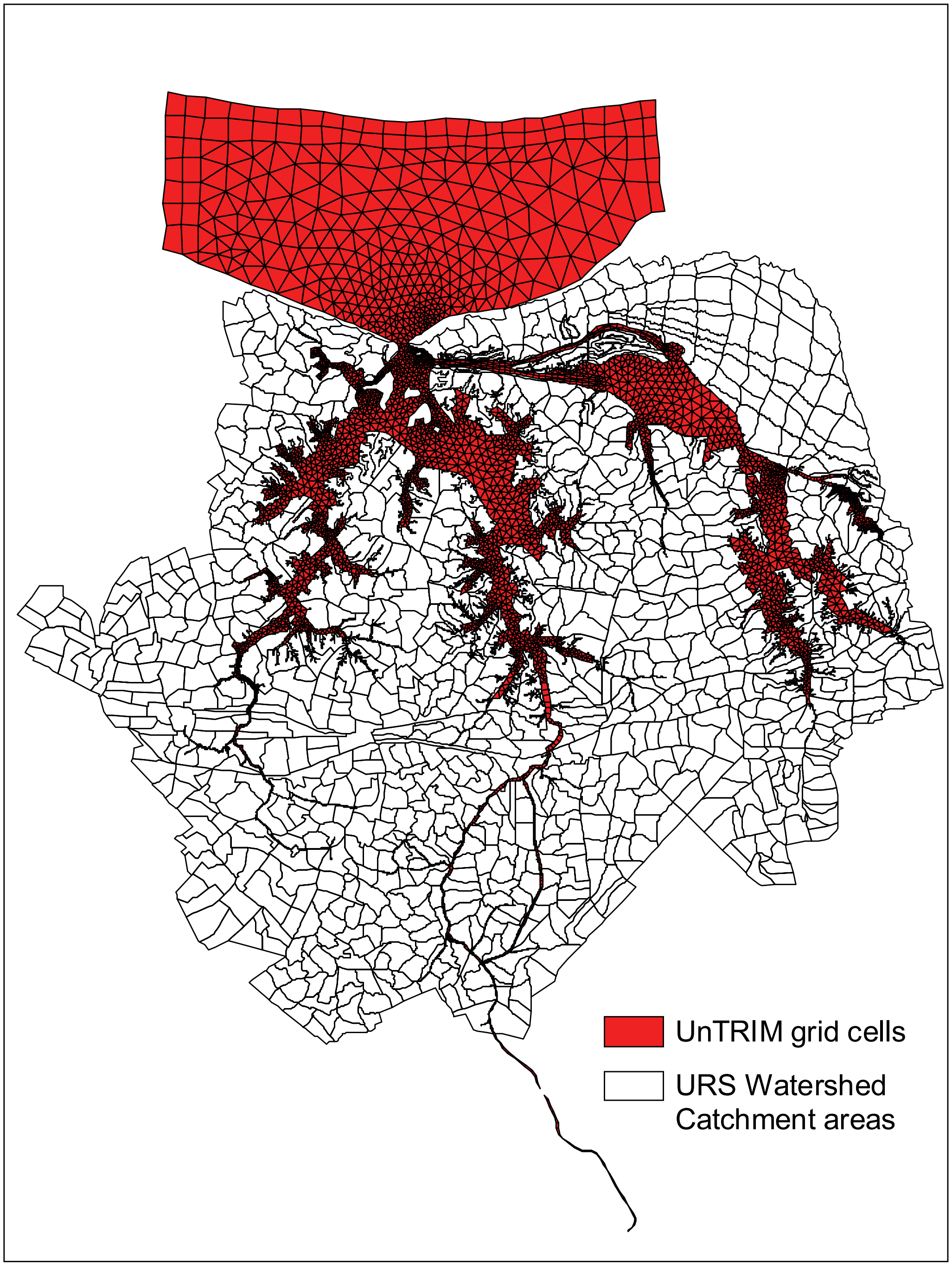


Figure III.5. The 1079 catchment areas delineated by the URS watershed model superimposed on the UnTRIM model grid.

For each of these catchments, the URS model simulates the following 9 constituents:

- biochemical oxygen demand (BOD)
- total dissolved solids (TDS)
- chemical oxygen demand (COD)
- nitrate – nitrite (NO_3)
- total Kjeldahl nitrogen (TKN)
- ammonia (NH3)
- total phosphorus (TP)
- dissolved phosphorus (DP)
- total suspended sediments (TSS)

The URS model was calibrated for by comparing its predictions to monitoring data collected at 5 sites within and/or nearby the Lynnhaven basin (URS, 2007). The calibrated model was then used to provide multi-year datasets of its outputs of hourly nutrient loadings and freshwater discharge to the VIMS models.

Table III.1. Impervious percentages of Lynnhaven Basin Landuse Categories.

Landuse No.	Landuse	Landuse Description	Impervious Percentage
1	AG	Agricultural	15%
2	SFL	Single Family Low Density	16%
3	SFM	Single Family Medium Density	21%
4	SFH	Single Family High Density	24%
5	MFM	Multi-Family Medium Density	37 %
6	MFH	Multi-Family High Density	62%
7	PD	Planned Development	29%
8	O	Office	71%
9	NB	Neighborhood Business	39%
10	B	Business	73%
11	I	Industrial	45%
12	RT	Resort Tourist	71%
13	PK	Park	5%
14	GC	Golf Course	5%
15	OS	Open Space	0.5%
16	OF	Other facilities	8%
17	SC	School	47%
18	ST	Street	60%
19	CM	Cemetary	5%
20	CH	Church	47%
21	WT	Wetland	100%
22	BMP	Best Management Practice	100%
23	WAT	Water	100%

CHAPTER IV. HISTORICAL DATA AND FIELD OBSERVATION PROGRAM

IV-1. Historical Data

Historical monitoring and survey data collection in the Lynnhaven River have taken place since the late 1950s. Prior to the inception of this project, VIMS made a conscious effort to gather all available hydrodynamic and water quality data recorded from the Lynnhaven River system into a central database. The intended range of parameters included in the database span those needed for the calibration and validation of the hydrodynamic and water quality models. Specifically, these include hydrodynamic parameter data (tides, velocities, salinities, and temperatures) and water quality parameter data (dissolved oxygen, chlorophyll, nutrient concentrations, and sediment-related measurements). Historical data for the Lynnhaven originated from 3 state agencies (Virginia Department of Environmental Quality [VA-DEQ], Virginia Department of Shellfish Sanitation [VA-DSS], and Virginia Institute of Marine Science [VIMS]), 1 federal agency (National Oceanic and Atmospheric Administration [NOAA]), and 1 environmental consulting company (Malcolm Pirnie Engineers). Whereas VIMS, NOAA, and Malcolm Pirnie conducted surveys of the Lynnhaven, most water quality parameter measurements have been provided by the ongoing monitoring programs of VA-DEQ (every other month, 1984 to present) and VA-DSS (monthly, 1986 to present). These data are summarized in Table IV.1.

Table IV.1. Lynnhaven monitoring and survey data collected, by parameter and agency.

Sections	Parameter	Number of Observations by Agency				Total Observations
		DEQ	DSS	VIMS	M. PIRNIE	
IIA	Tides					5953
IIB	Velocity					
IIC	Salinity	2924	2269	511	200	5904
IID	Temperature	2648	1275	475	200	4598
IIIA	Dissolved Oxygen	5208	-	527	400	6135
IIIB	Chlorophyll a	149	-	511	200	860
IIIC	BOD5	2133	-	135	200	2468
IIID	Total Organic Carbon	1863	-	-	-	1863
IIIE	TKN	1954	-	459	200	2613
IIIF	Ammonia	2351	-	-	-	2351
IIIG	Nitrite	2645	-	-	-	2645
IIIH	Nitrate	2224	-	-	-	2224
IIII	Total Phosphorus	1682	-	459	200	2341
IIIJ	Ortho Phosphorus	1158	-	-	-	1158
IIIK	Dissolved Silica	315	-	36	-	351
IIIL	TSS	2072	-	16	200	2288
IIIM	Volatile Susp. Solids	2076	-	-	-	2076
IIIN	Volatile Solids	1771	-	-	-	1771
IIIO	Turbidity	1061	-	-	-	1061
IIIP	Secchi depths	-	1142	459	200	1801
IIIQ	Fecal Coliform	1010	17,725	459	200	19,394
TOTAL		35,097	22,411	4047	2200	69,855

Spatial plots of long-term averages of hydrodynamic and water quality parameters can often reveal important characteristics of a waterbody such as the Lynnhaven. It can be seen from the long-term averages for salinity at DEQ stations, shown in Figure IV.1, that much larger salinity gradients exist in the Western and Eastern Branches than in the Broad Bay / Linkhorn Bay Branch. This is because the freshwater inputs from the former branches are larger than that of the later. Spatial plots of water quality parameters can be used to highlight the spatial gradient of the water quality parameters as well as identify the regions of concerns, such as the DEQ stations at Thalia Creek and London Bridge, as shown in Figure IV.2. One of the major characteristics revealed was that the concentration of all water quality variables were higher at the upstream of each branch and decreased moving downstream toward the Inlet.

The availability of long-term monitoring data additionally allows for time series analysis and, in the case of long-term trend, a simple linear trend analysis was performed for all parameters. Examples of this include the long-term decrease of dissolved oxygen at the Thalia Creek Station shown in Figure IV.3a and the decrease of total organic carbon at the Broad Bay Station BBY002.88 shown in Figure IV.3b. Table IV.2 enumerates the long-term trends of all water quality parameters measured at each Lynnhaven DEQ station as either increasing (I) or decreasing (D).

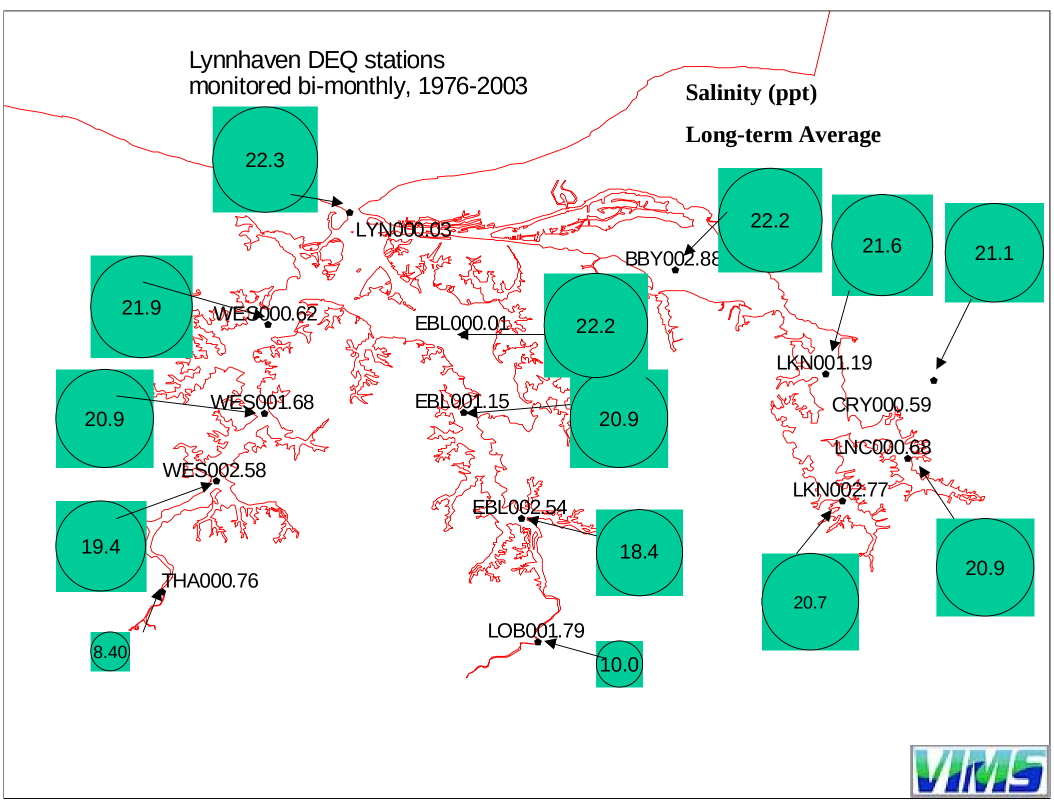


Figure IV.1. Long-term average salinity based on Lynnhaven DEQ observations.

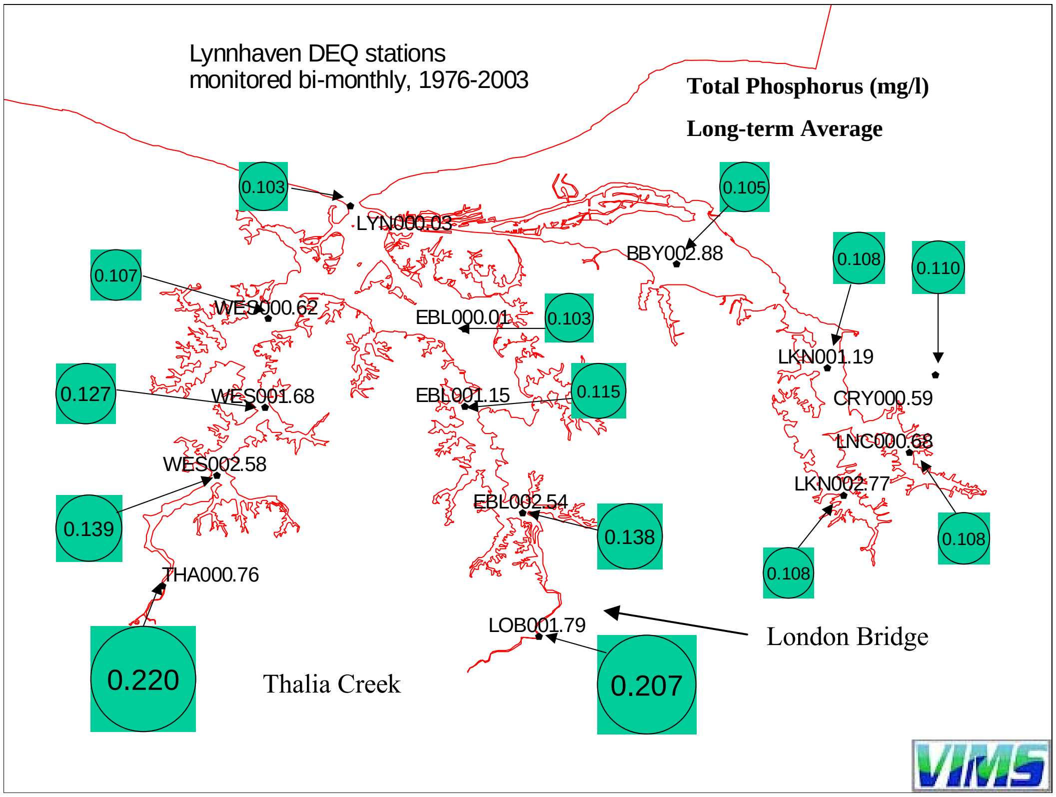


Figure IV.2. Long-term average total phosphorus based on Lynnhaven DEQ observations.

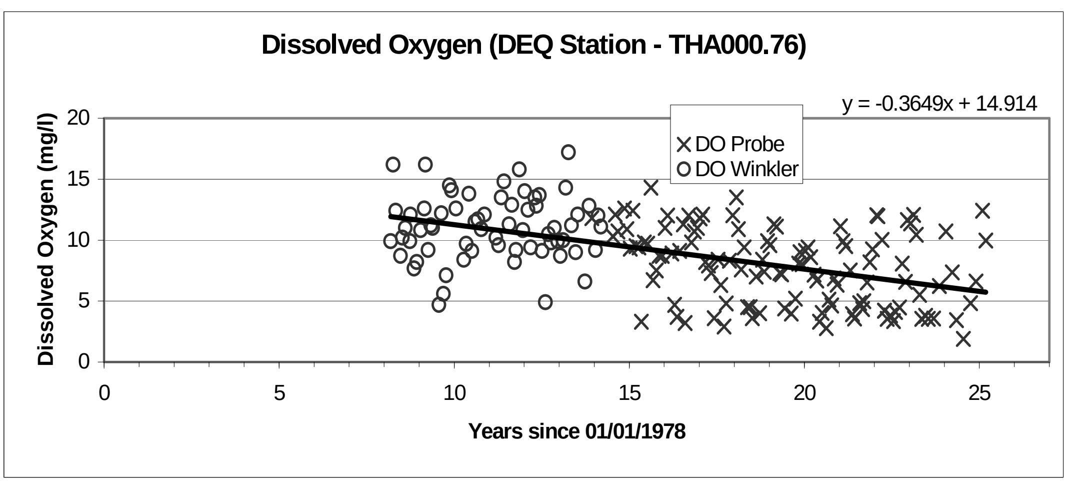


Figure IV.3a. Long-term trend of observed dissolved oxygen at DEQ Station THA000.76.

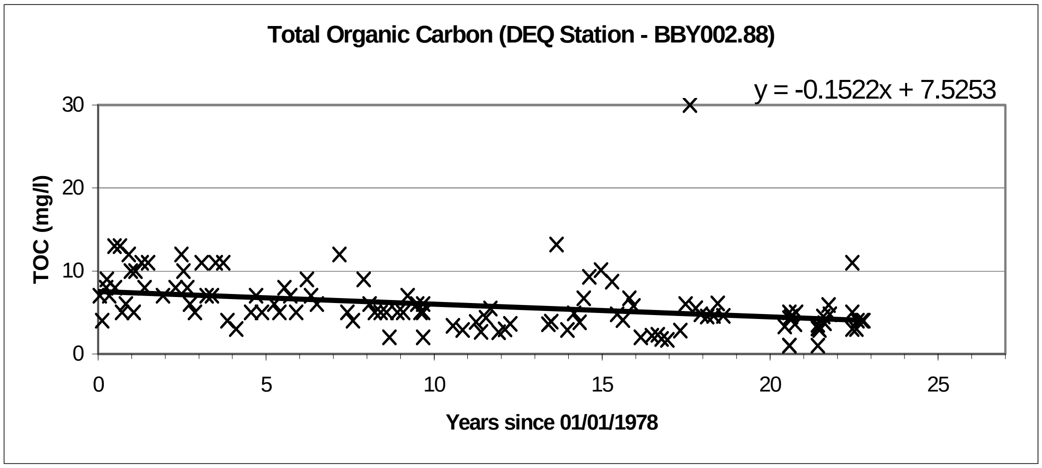


Figure IV.3b. Long-term trend of observed TOC at DEQ Station BBY002.88.

Table IV.2. Lynnhaven DEQ monitoring long-term trends.

DEQ Station	THA000.76	WES002.58	WES001.68	WES000.62	LYN000.03	EBL000.01	EBL001.15	EBL002.54	LOB001.79	BBY002.88	LNK001.19	LNK002.77	LNC000.68	CRY000.59
Parameter														
Salinity	I	I	I	I	I	I	I	I	I	I	I	I	I	I
Temperature	D	I	I	I	I	I	I	I	D	I	I	I	I	I
Dissolved Oxygen	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Chlorophyll a														
BOD5	D	D	I	I	D	I	D	D	D	D	I	I	D	D
TOC	D	D	D	D	D	D	D	D	D	D	D	D	D	D
TKN	I	I	I	I	I	I	I	I	I	I	I	I	I	I
Ammonia	Regression not reported - interference from detection limit change													
Nitrite	Regression not reported - interference from detection limit change													
Nitrate	Regression not reported - interference from detection limit change													
Total Phosphorus	Regression not reported - interference from detection limit change													
Ortho Phosphorus	D	D	D	I	I	I	I	I	D	D	D	D	D	D
Dissolved Silica	D	D	D	D	D	D	D	D	D	D	D	D	D	D
TSS	D	D	D	D	D	D	D	D	D	D	D	D	D	D
VSS	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Volatile Solids	I	D	D	D	D	D	D	D	I	D	D	D	D	D
Turbidity	D	D	I	D	I	D	D	D	I	I	I	I	D	D

“I” denotes a long-term increasing trend and “D” denotes a long-term decreasing trend

IV-2. Project-specific field measurements

For the data to be useful for the hydrodynamic and water quality modeling, project-specific measurements are required. There are five field data collections were designed and conducted during the course of the project. They are described in the following sections: (1) the hydrodynamic survey in Section IV-2-1, (2) seasonal sediment flux measurements in Section IV-2-2, (3) sediment critical shear stress measurements in Section IV-2-3, (4) High spatial resolution dataflow surveys in Section IV-2-4, and (5) high-frequency time series measurements in Section IV-2-5.

IV-2-1. VIMS hydrodynamic survey

A unique VIMS hydrodynamic survey was conducted from November 1, 2005 to December 1, 2005. The purpose of the survey was to obtain a synoptic dataset of tide and representative currents for validation of the hydrodynamic model. In order that the data can be analyzed using harmonic analysis, the survey was designed to be at the least on the order of 30 days (at least 697 hours).

There are multiple measurements that were conducted depending on the site characteristics. Instruments were deployed as follows: 1) a tide gauge recording water surface elevations at 6-minute intervals at the Virginia Pilot's Station, 2) an Acoustic Doppler Current Profiler (ADCP) outside the Inlet recording current magnitude and direction at 20-minute intervals at each of ten 0.3-m intervals in the vertical, and 3) S4 current meters located at mid-depths in each of the three Lynnhaven Branches recording velocity speed and direction, temperature, and salinity at 30-minute intervals.

The instrument locations are shown in Figure IV.4. Tide measured at the Virginia Pilot's Station (Inlet mouth) showed a 1-hour phase lag from that at the nearby Chesapeake Bay Bridge Tunnel (CBBT) primary station, as well as a drop in amplitude to 36 cm from 38 cm at CBBT (Figure IV.5). The ADCP profiler was used because the channel has a greater depth and potentially different velocities from surface to bottom. The ADP velocity measured results outside the Inlet, as shown in Figure IV.6, and indeed showed a 2-layer circulation with a slight residual in the ebb (north) direction at the surface and in the flood (south) direction at the bottom.

Within the branches, the single S4 current meters were deployed due to their shallow depth. The time series plots show maximum currents on the order of 30 cm/sec, 40 cm/sec, and 80 cm/sec, respectively, for the Western, Eastern, and Broad Bay Branches (Figures IV.7 - IV.9). The larger velocity measured in Broad Bay was because the location of deployment was near Long Creek, where the cross section is much narrower. Otherwise, the range of velocity was typical for the coastal bays in the Chesapeake Bay. Additionally, the impacts of both a heavy rainstorm on salinity (Figures IV.7 and IV.9) and a noteworthy cold front on water temperature (Figures IV.10 and IV.11) are readily observable in this shallow water system.

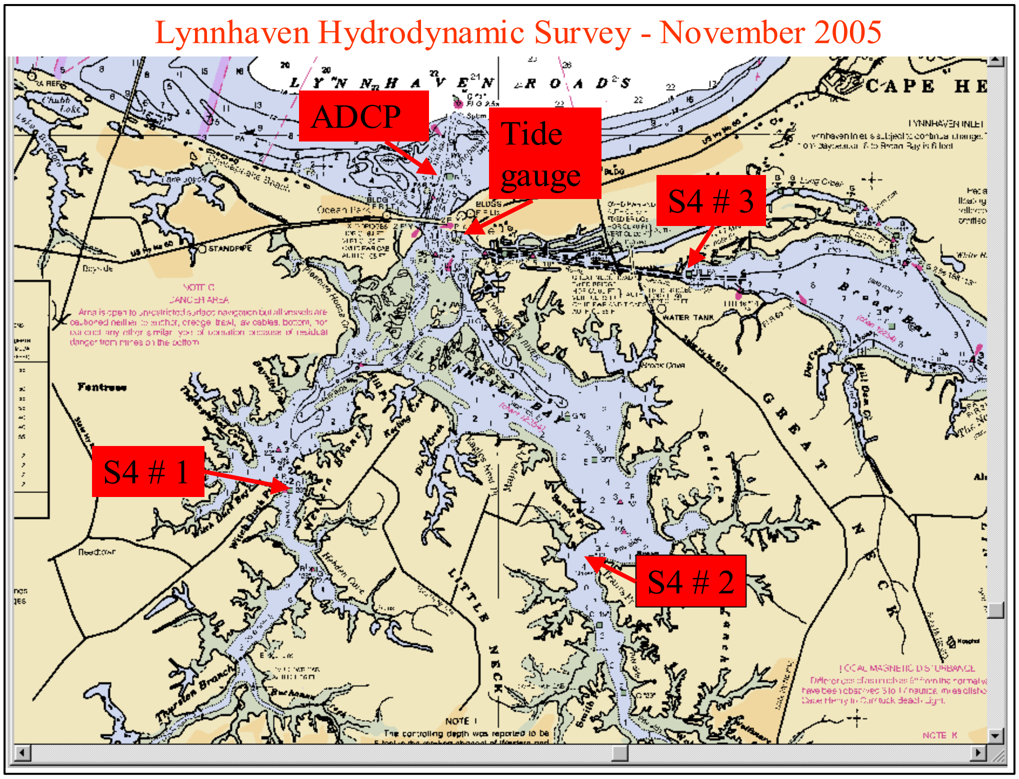


Figure IV.4. Instrument Locations for VIMS Hydrodynamic Survey.

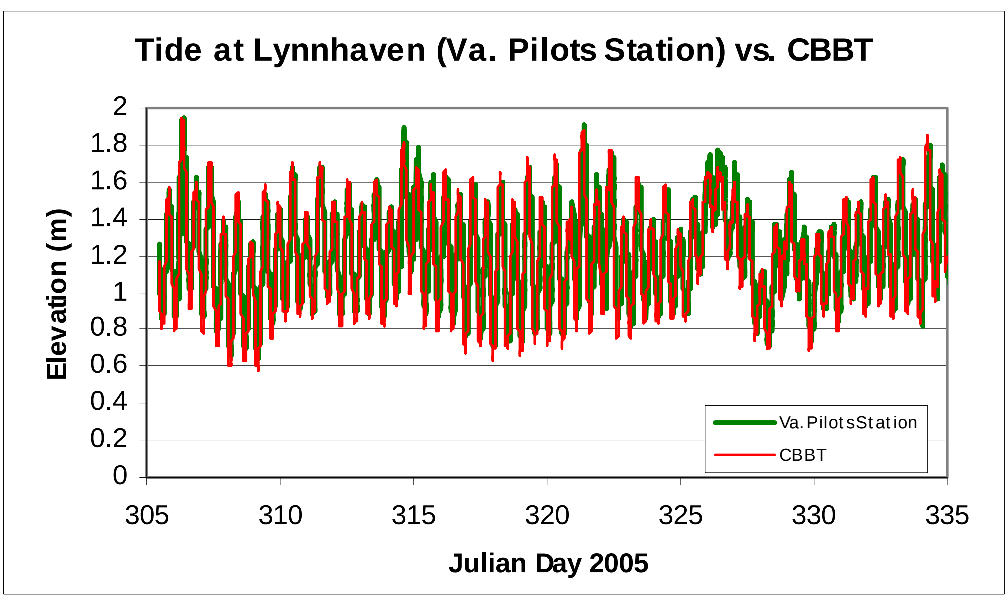


Figure IV.5. Tide at Inlet versus CBBT tide.

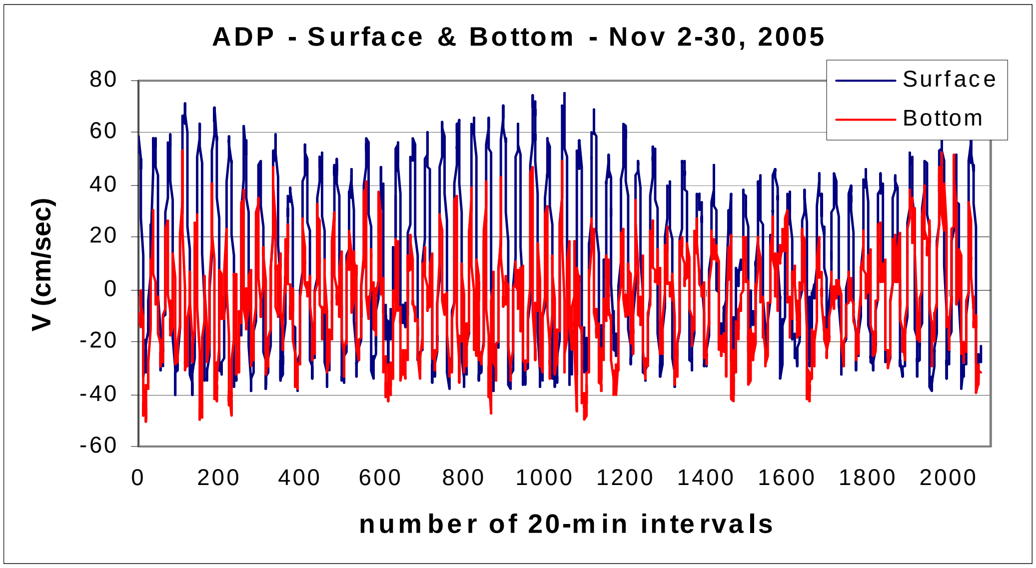


Figure IV.6. ADP velocity outside Inlet.

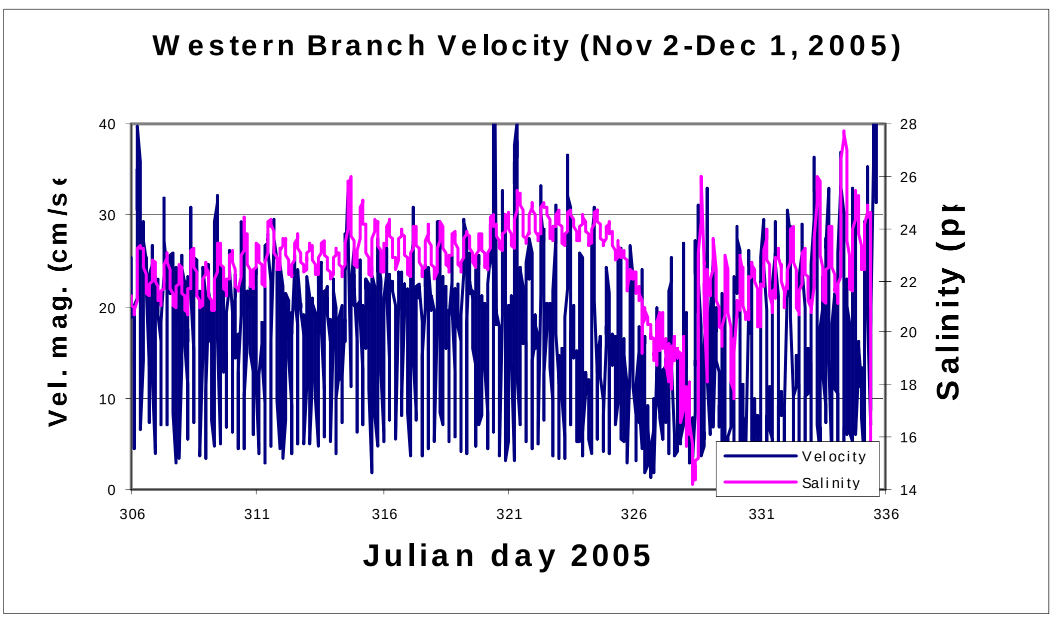


Figure IV.7. Western Branch velocity and salinity.

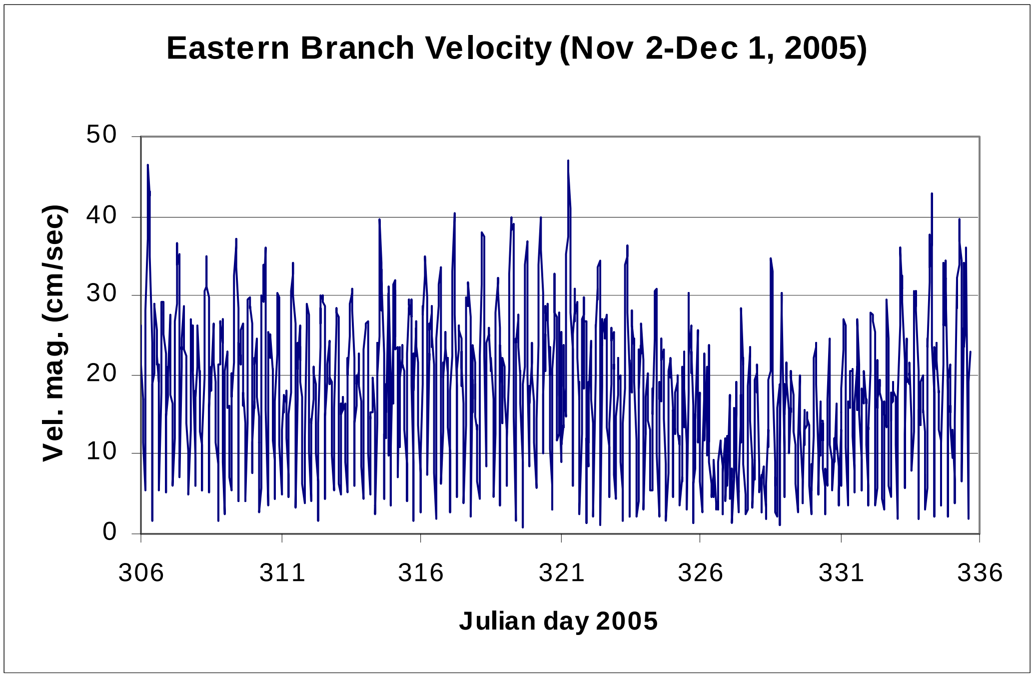


Figure IV.8. Eastern Branch velocity.

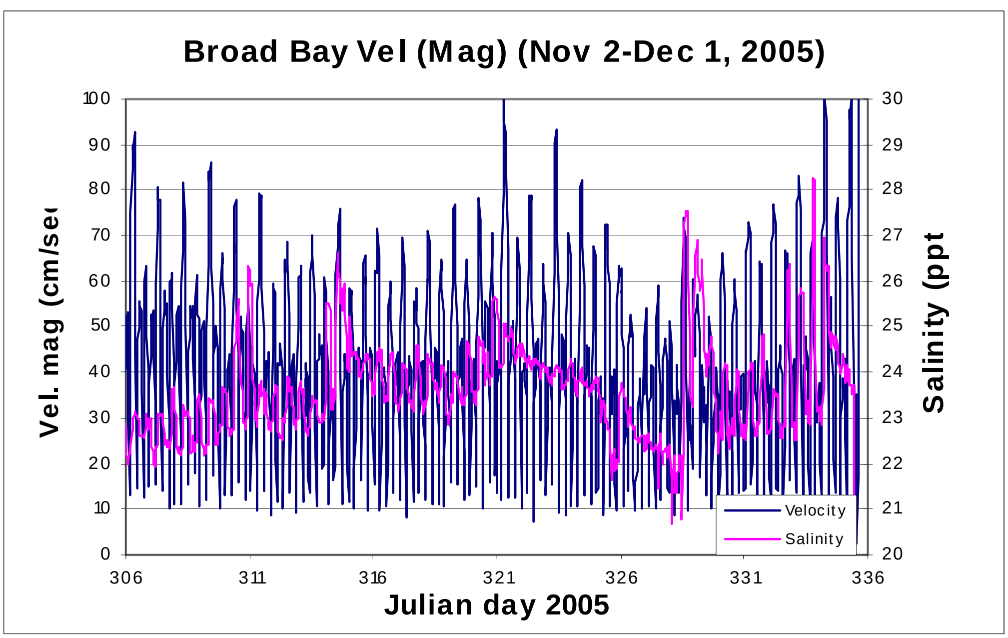


Figure IV.9. Broad Bay velocity and salinity.

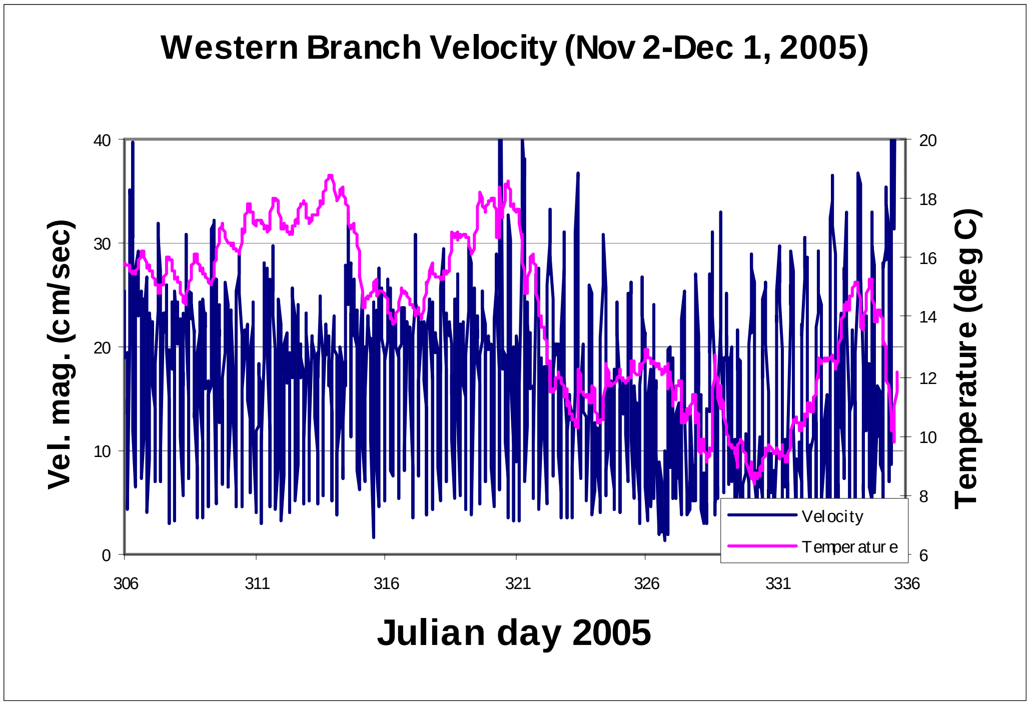


Figure IV.10. Western Branch velocity and temperature.

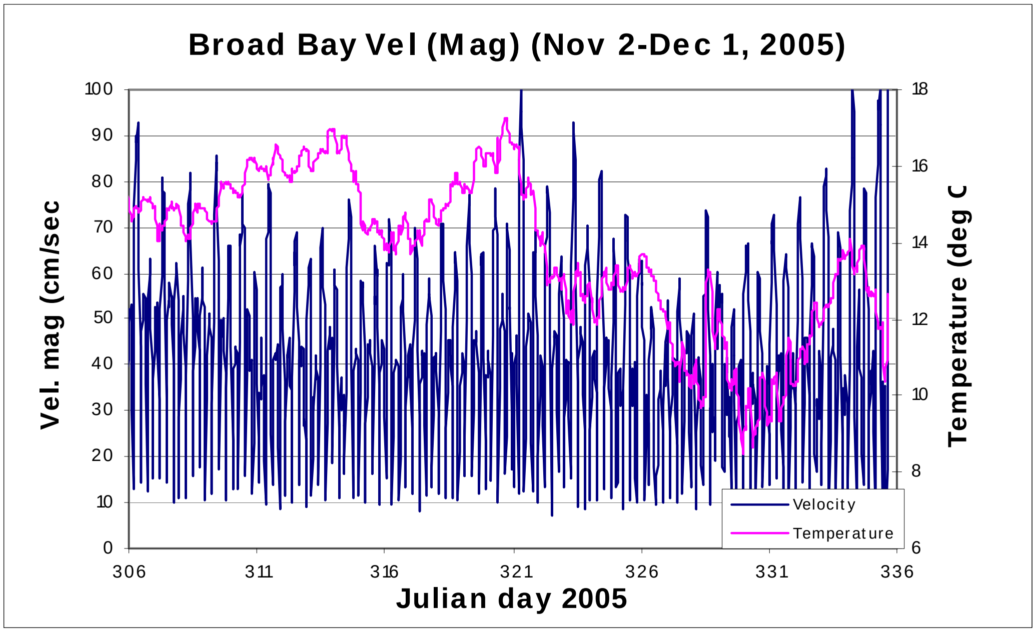


Figure IV.11. Broad Bay velocity and temperature.

IV-2-2. Seasonal sediment flux measurements

Due to the shallowness of the Lynnhaven River, the sediment and water column interact. Fluxes of dissolved oxygen and inorganic nutrients between sediments and the overlying water column were measured seasonally in four selected regions of the Lynnhaven River system: Western Branch, Eastern Branch, the Inlet, and Broad Bay (Figure IV.12). Sites were selected in nearshore, shallow regions of the Lynnhaven so samples would contain actively photosynthesizing benthic microalgae (BMA), which can dominate carbon production in shallow systems, in addition to the microbial community that dominates respiration at all depths. The averaged water depth at the collection sites was about 0.4 meter at mean low water with a tidal range of 1.0 meter. Within each embayment, four sediment cores were taken during each survey. A preliminary site selection and characterization study was conducted in March 2005, with flux studies occurring in April 2005 (14°C), July 2005 (26°C), November 2005 (15°C), and May 2006 (22°C).

In the field, four sediment cores (clear acrylic, 20-cm sediment depth, 20-cm overlying water, 13.3 cm diameter) were collected from each embayment with minimal disturbance. For each core, a second small core was collected for measurement of sediment bulk density, organic content, and BMA biomass measured as chlorophyll-*a* in the top 1 and 3 cm of sediment. Ambient water was collected at each site for use during core incubations.

All cores were placed in a temperature and light-controlled environmental chamber at VIMS, submerged (without lids) in large mesocosms with site-specific water (Figure IV.13), and gently bubbled with air overnight to allow cores to acclimate to the experimental chamber. Two "water blank" cores per site were filled with water only to serve as controls to correct for processes occurring in the water overlying each sediment core. Temperature in the chamber was set to the average field temperature to ensure comparability.

The following morning, cores were capped with clear lids fit with magnetic stir-bars to gently circulate the water within the cores, controlled by a central motor in each mesocosm (Figure IV.13). Each lid was equipped with two ports, one for sampling and a second to allow replacement water to flow in from a reservoir with site-specific water. Care was taken to exclude bubbles while capping the cores.

Cores were incubated following the general procedure of Anderson et al. (2003), beginning in the dark for 3-4 hours to measure fluxes associated with sediment respiration. Samples were collected hourly for determination of concentrations of dissolved oxygen (DO), ammonium (NH_4^+), nitrate + nitrite (NO_x^-), and phosphate (PO_4^{3-}). Following the last sampling, the lights in the environmental chamber were turned on to approximately saturating levels of irradiance for BMA (417-673 $\mu E\ m^{-2}\ s^{-1}$ at the

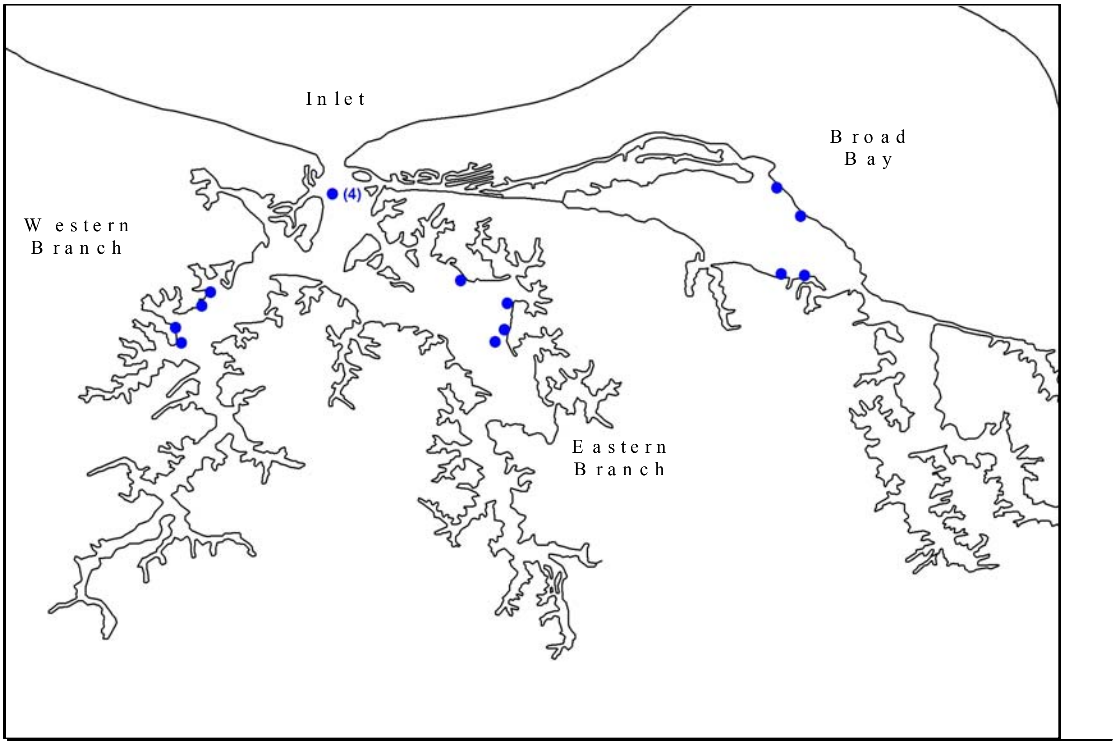


Figure IV.12. Location of core collection sites for sediment flux in the Lynnhaven River. Four cores were collected in close proximity inside the Inlet.

water surface; 165-360 µE m^{-2} s^{-1} at the sediment surface). Cores were allowed to acclimate for 30 minutes after which DO and nutrients were again sampled hourly for 3-4 hours to measure fluxes associated with BMA photosynthesis.

DO and nutrients in each reservoir of replacement water were measured at the beginning, midpoint, and end of each experiment to allow for dilution correction of the water within each core.

Dissolved oxygen and temperature were measured with an Orion galvanic DO sensor. Samples for nutrients were filtered through 0.45 µm filters (Gelman Supor) and frozen (-15°C) until later analysis on a Lachat autoanalyzer. Samples for sediment chlorophyll-*a* and pheophytin concentrations were frozen until extraction with 100% acetone following the methods of Pinckney and Zingmark (1994) as modified by Pinckney and Lee (2008). Concentrations were analyzed on a Shimadzu UV-1601 spectrophotometer and calculated using the equations of Lorenzen (1967). Sediment organic content was determined as the percent weight loss following combustion at 500°C for 5 hours.

Flux rates in the light and dark were computed as the time rate of change (i.e., slope) of concentration, corrected for dilution by reservoir water. To determine fluxes attributable to the sediments only, the average slope from the two water blanks at each site was subtracted from the slope of each sediment core.

Results

BMA biomass as measured by sediment chlorophyll-a concentration was higher at the Broad Bay and Inlet sites than at the Eastern and Western Branch sites (Figure IV.14), but there were no consistent seasonal trends in biomass. Approximately half of the measured BMA biomass occurred in the upper 1 cm of sediment.

Typical time courses of DO during the incubations are shown in Figure IV.15. Linear slopes were fit to the results for DO and each nutrient species and used to compute the mean net fluxes shown in Figures IV.16 through IV.22 after correcting sediment cores for the water blanks.

Net fluxes of DO were into the sediments in the dark and out of the sediments in the light, confirming the dominance of microbial respiration at night and BMA photosynthesis during the day (Figure IV.16). With the exception of the Western Branch, daytime DO production exceeded nighttime DO consumption, in many cases by a large amount, suggesting these nearshore sites were net autotrophic due to BMA primary production which likely contributes a significant fraction of total carbon fixation in the Lynnhaven.

Dark DO fluxes at each site were directly related to water temperature, with warmer temperatures leading to higher rates of respiration (Figure IV.17). Dark fluxes were not related to sediment chlorophyll, nor were chlorophyll-normalized rates related to temperature, confirming that the majority of sediment respiration was due to the bacterial community. Dark fluxes were also independent of sediment organic content, which ranged from 0.3 to 4.3% at these sites.

Taken as a whole, DO fluxes in the light were generally related to BMA biomass measured as chlorophyll-a content (Figure IV.17). Rates were not correlated to organic content or water temperature, nor were chlorophyll-normalized rates correlated to temperature. BAM photosynthetic rates were high at most sites regardless of season (Figure IV.16).

Fluxes of NH_4^+ were highest in the warmer months, and generally out of the sediments in the dark and into the sediments or near zero in the light (Figure IV.18). NH_4^+ is the product of organic matter degradation by bacteria in the sediments, which was responsible for the dark release.

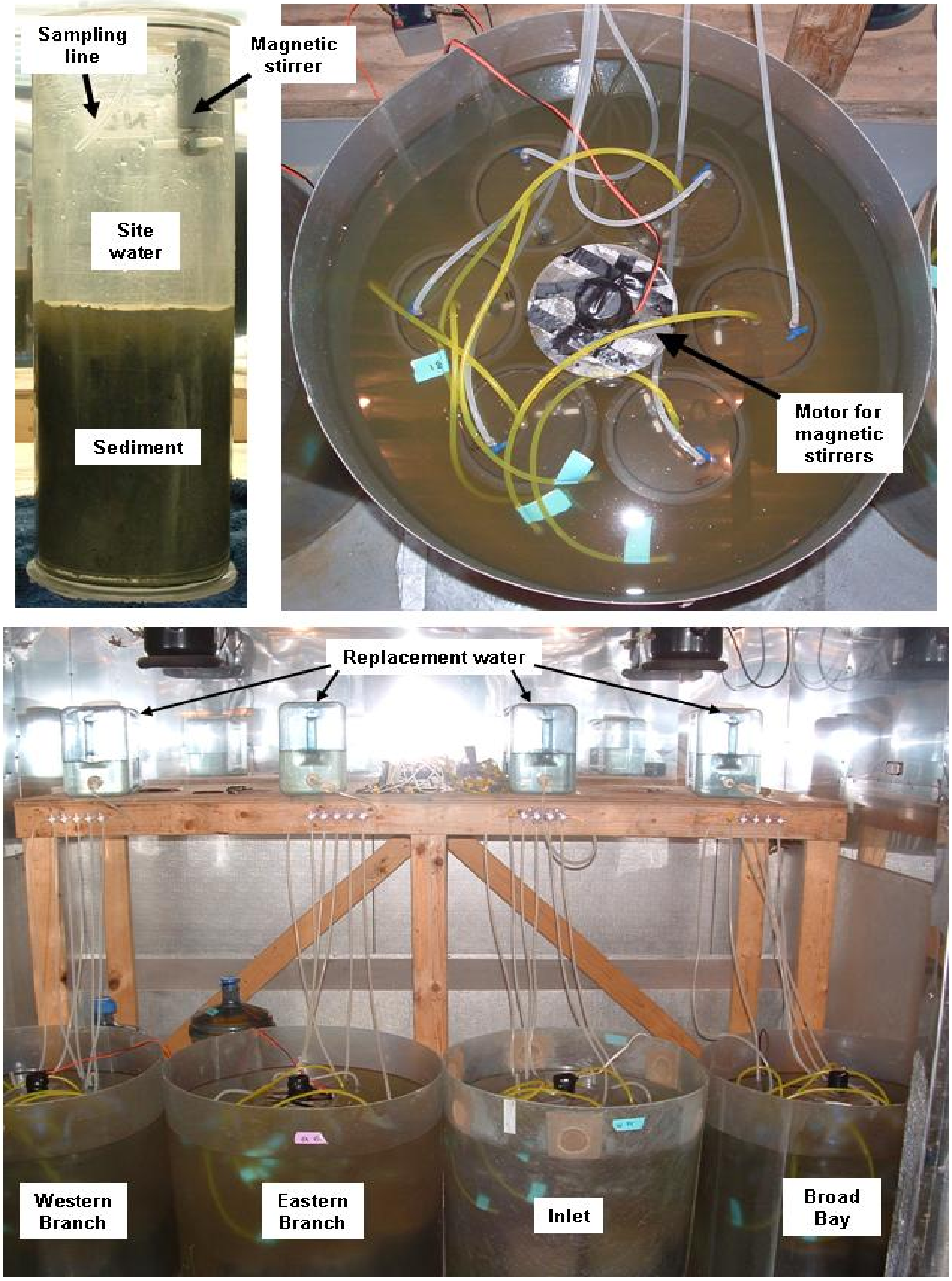


Figure IV.13. Experimental design for sediment flux experiments. Four mesocosms were filled with site water, four sediment cores with overlying water, and two cores with water only to serve as controls. Core water was mixed with a central magnetic stirrer, and hourly samples withdrawn from each core were replaced by site water held in reservoirs ("replacement water").

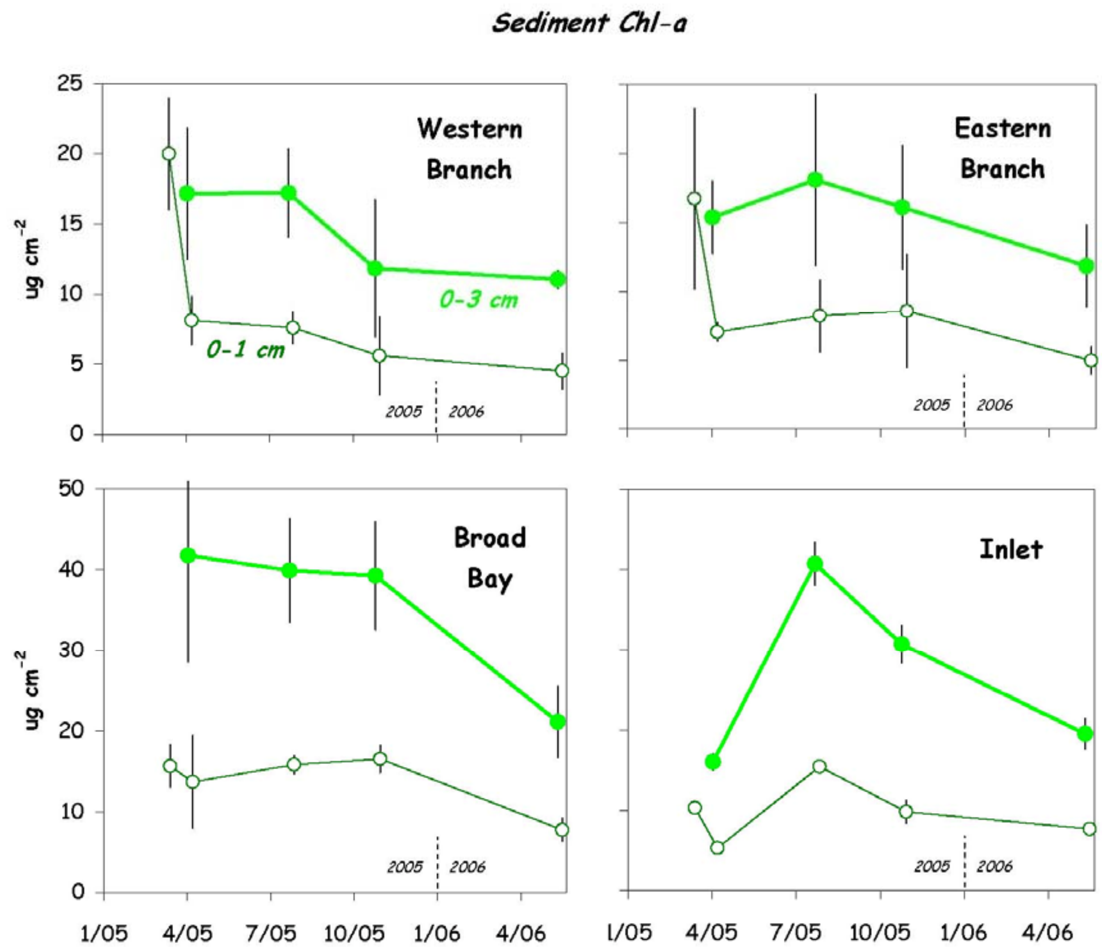


Figure IV.14. Chlorophyll-*a* concentrations measured in the top 1 and 3 cm of sediment at each site. Error bars denote 1 standard deviation.

Uptake by BMA in the light to support photosynthetic production was enough to greatly reduce, eliminate, or completely reverse this release (Figure IV.18). Fluxes of NO_x^- were much lower than for NH_4^+ and mostly centered around zero (Figure IV.19; note different scales between Figures IV.18 and IV.19). The net uptake of NO_x^- at the Eastern Branch and Inlet sites in November 2005 was likely due to denitification. Fluxes of PO_4^{3-}, also a by-product of organic matter degradation by bacteria, were often small and highly variable with no consistent trends (Figure IV.20).

Since NH_4^+ and PO_4^{3-} remineralization and subsequent release from sediments is the result of bacterial decomposition of organic matter, rates in the dark (in the absence of BMA production) should generally be correlated to dark DO consumption (i.e., respiration), although BMA have been shown to take up nutrients in the dark to support

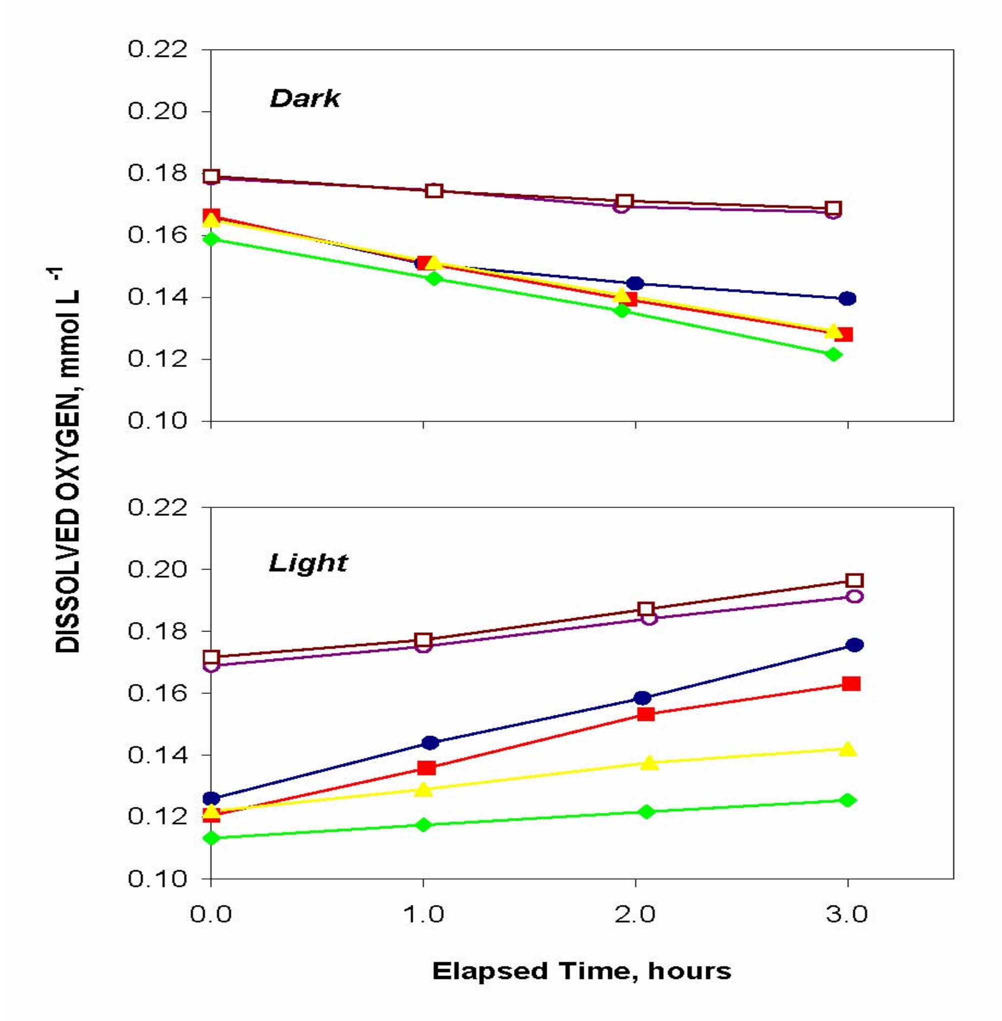


Figure IV.15. Typical time course for DO incubated in the dark and light. Filled symbols depict the sediment cores; open symbols depict the water blanks.

subsequent daytime production. While the relationships contained scatter, dark nutrient releases were generally correlated to dark DO consumption and therefore water temperature (Figure IV.21). Scatter was likely the result of dark BMA uptake and coupled nitrification-denitification. To assess the potential for the former, the rates of nutrient uptake measured in the light were compared to computed BMA demand for nutrients based on DO production rates (Figure IV.16) and molar conversions for nitrogen (9:9:1 O_2:C:N, F. Parker unpublished data) and phosphorus (106:106:1 O_2:C:P, Redfield ratios). With one exception, computed BMA nutrient demand was always greater than measured uptake in the light, suggesting a large amount of BMA demand is satisfied by uptake at night (Figure IV.22).

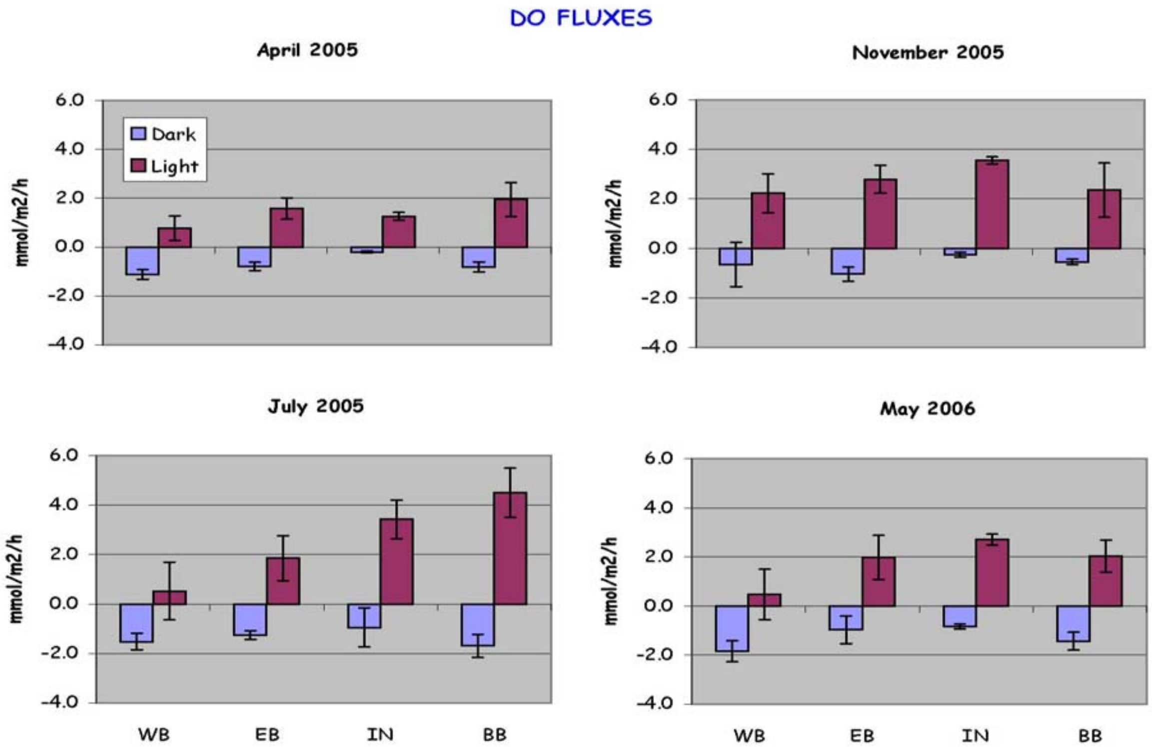


Figure IV.16. Net sediment-water fluxes of dissolved oxygen by site and date. Positive values reflect a release to the water; negative values indicate uptake by the sediments. Error bas denote 1 standard deviation.

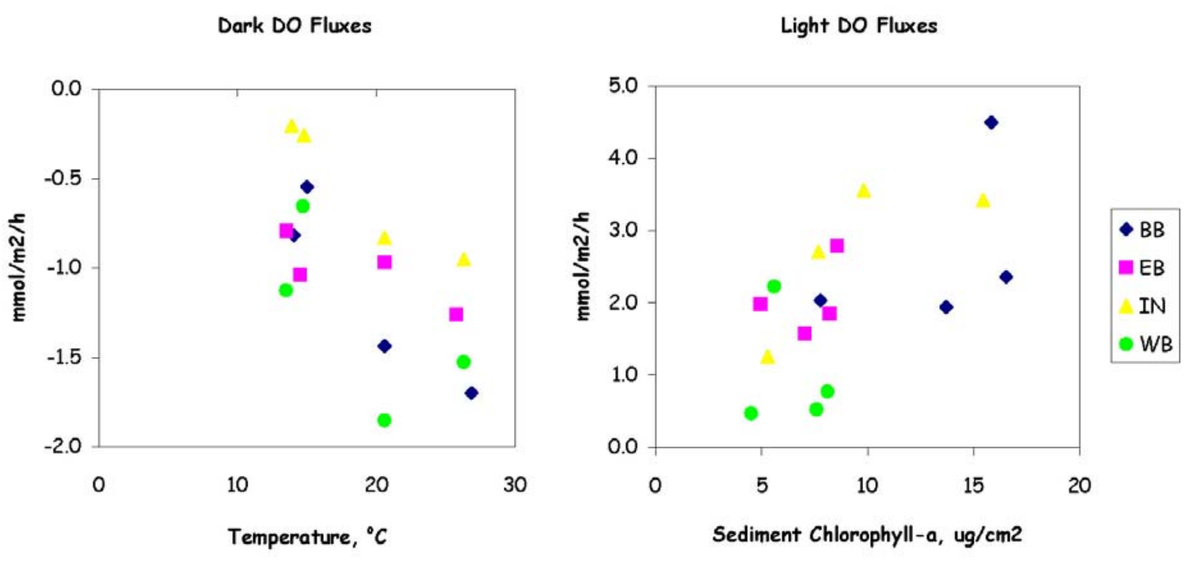


Figure IV.17. Relationship of net sediment-water DO fluxes to water temperature in the dark (left) and sediment chlorophyll in the light (right).

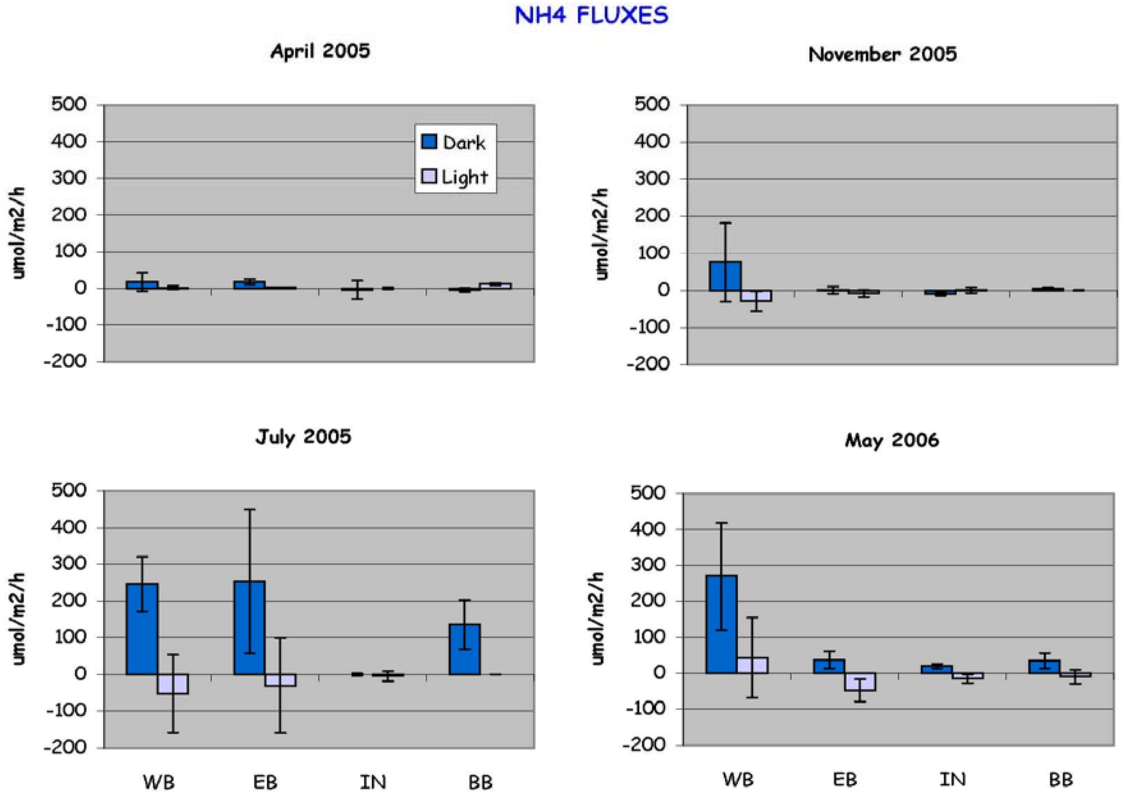


Figure IV.18. As for Figure IV.16, but for fluxes of NH_4^+.

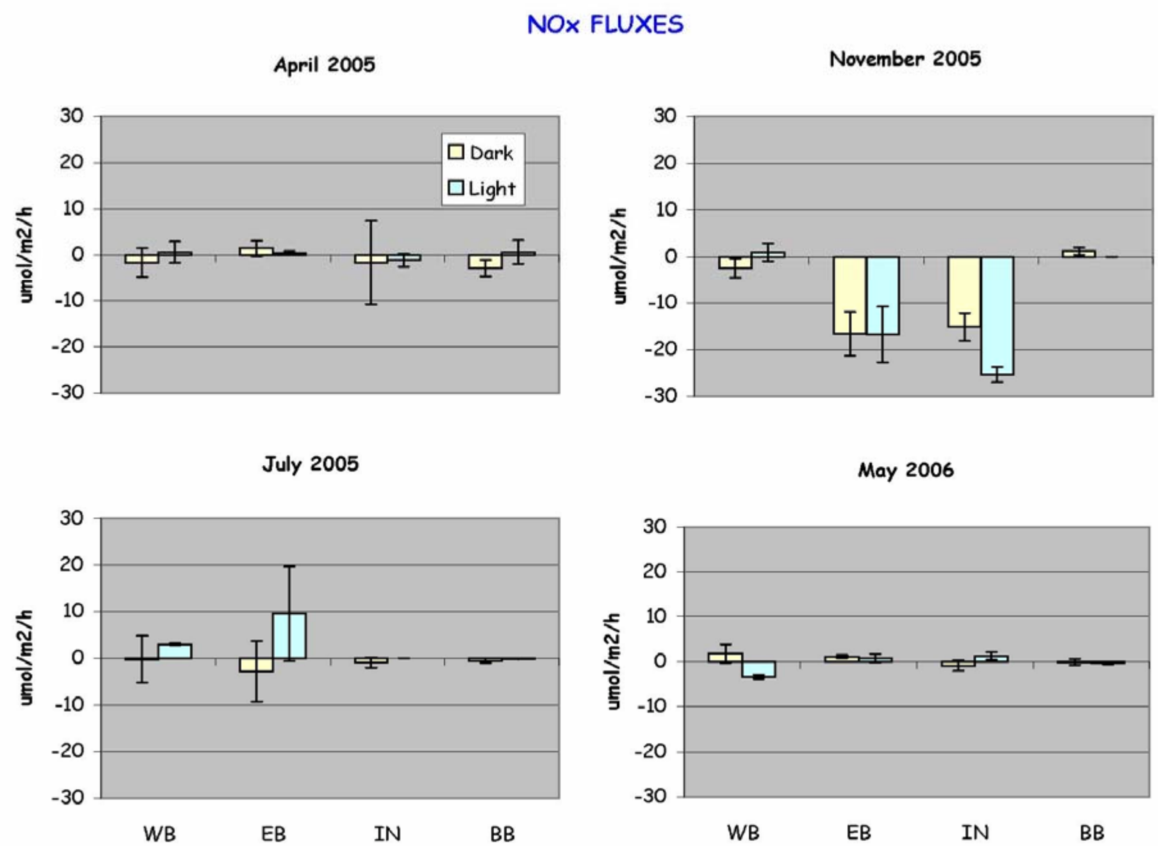


Figure IV.19. As for Figure IV.16, but for fluxes of NO_x^- (NO_2^- + NO_3^-).

Our results confirm the importance of BMA in the Lynnhaven River, as reported for other shallow nearshore systems (e.g., Anderson et al., 2003). While sediment-water fluxes for deeper estuaries are typified by uptake of DO and release of nutrients due to respiration and subsequent remineralization, BMA have the potential to completely reverse these heterotrophic fluxes during the day due to photosynthetic biomass production. The BMA-associated biomass and sediment flux rates determined in this study should serve as useful calibration data for eutrophication and water quality modeling efforts in the Lynnhaven.

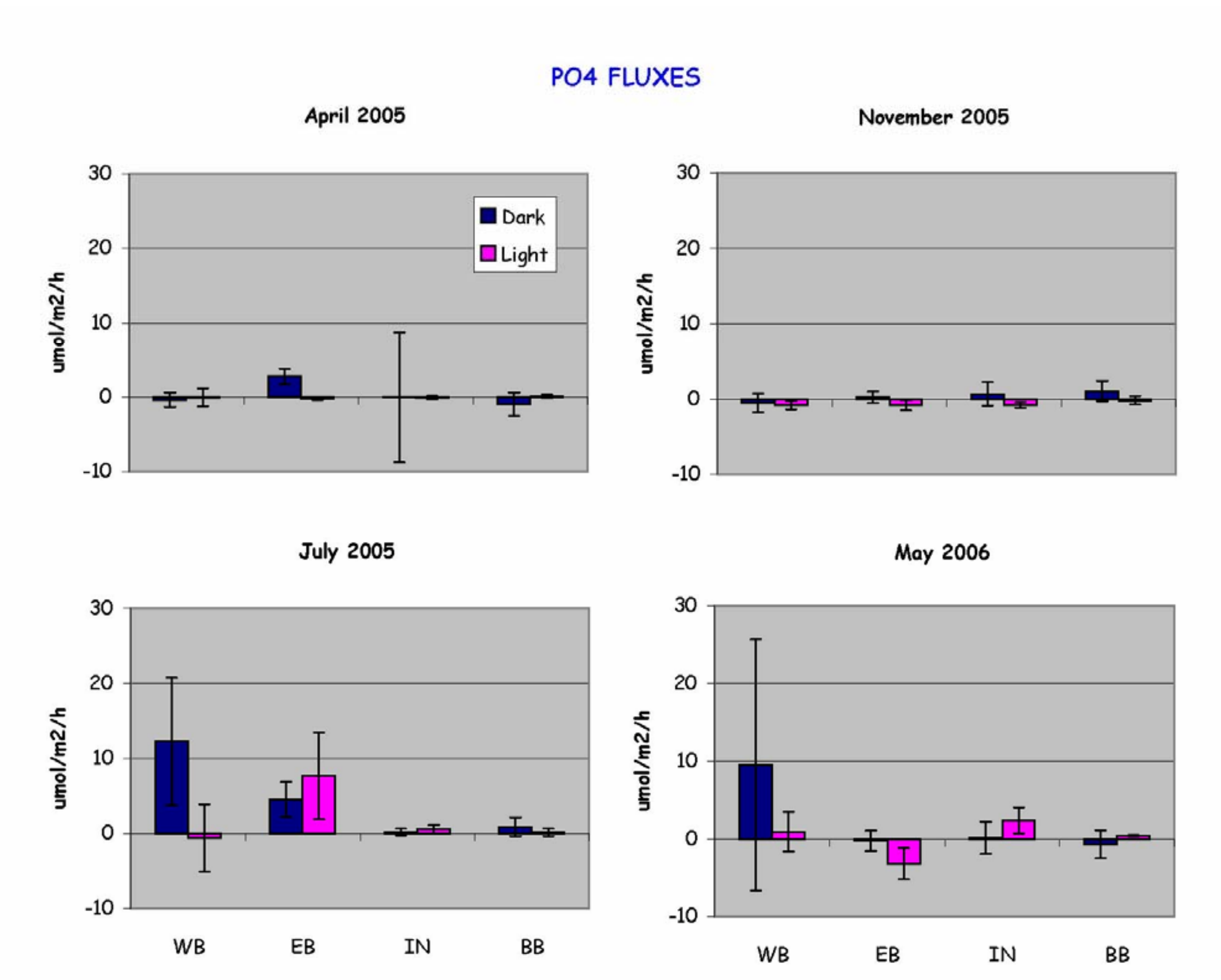


Figure IV.20. As for Figure IV.16, but for fluxes of PO_4^{3-}.

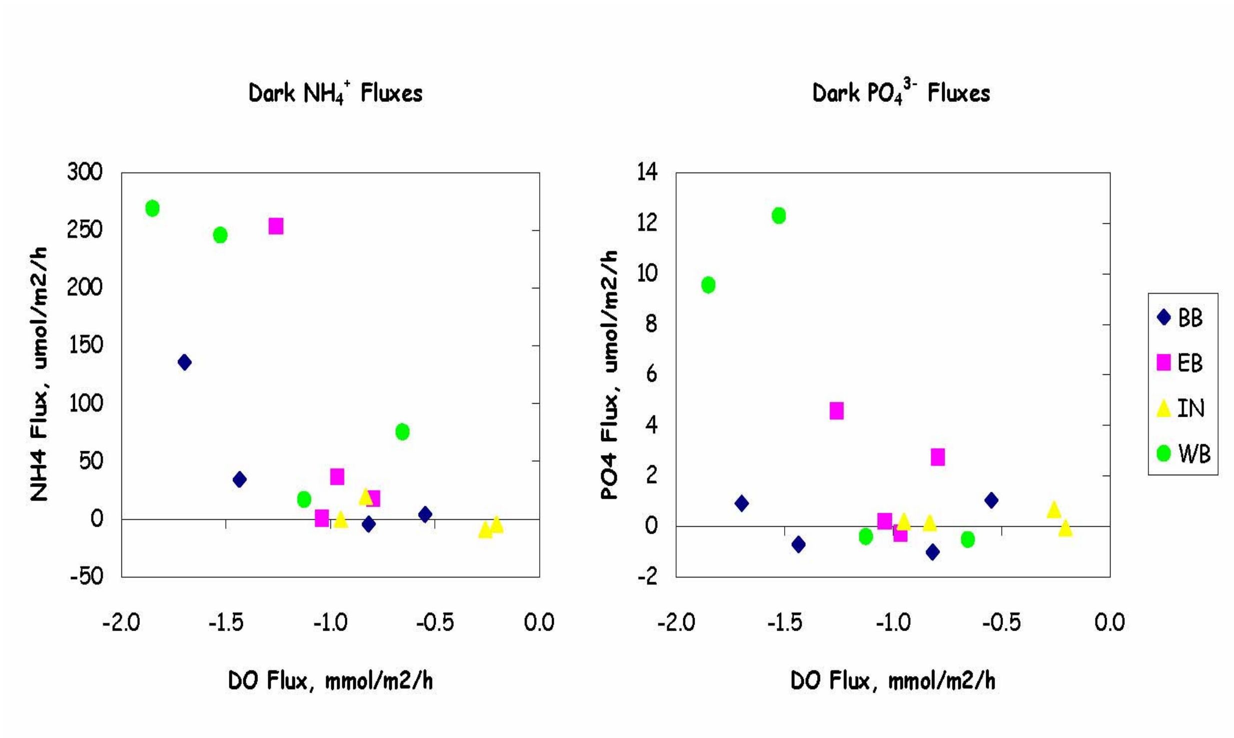


Figure IV.21. Relationship of net sediment-water nutrient and oxygen fluxes in the dark.

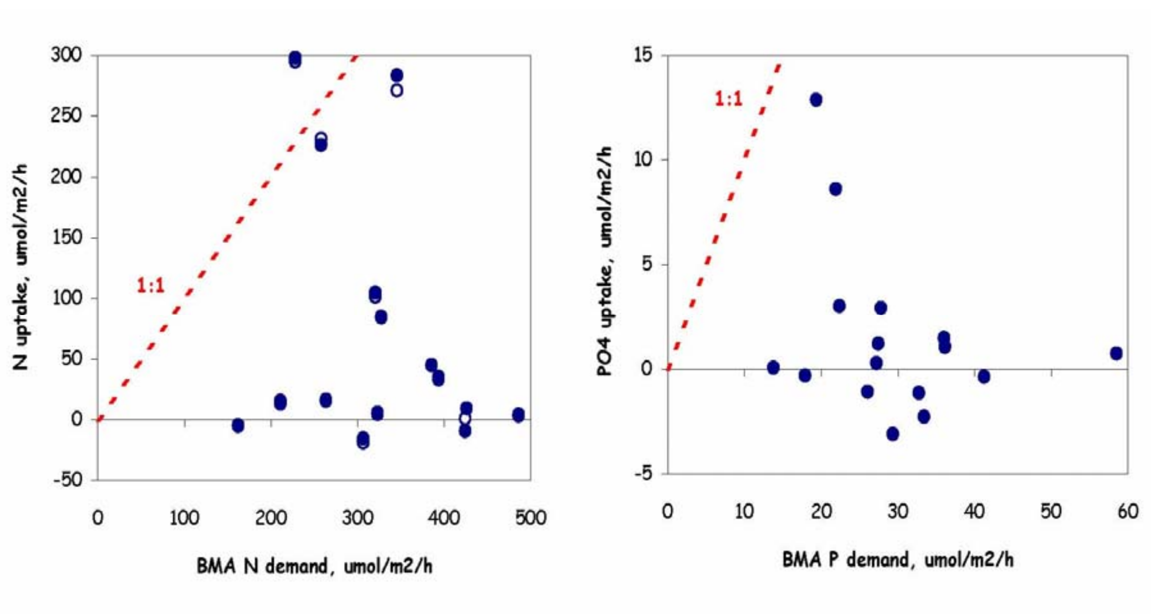


Figure IV.22. Relationship of computed BMA nutrient demand in the light vs. computed uptake in the light. Filled symbols in the plot on the left are for NH_4^+ only; open circles behind the points are for $NH_4^+ + NO_x^-$.

IV-2-3. Sediment critical shear stress measurements

The calculation of sediment concentration in the CE-QUAL-ICM model has a critical dependence on the determination of critical shear stress, which varies spatially and seasonally in the Lynnhaven River. For this reason, a series of surveys were conducted to measure critical shear stress in each branch in different seasons.

An initial bottom sediment mapping survey of the Lynnhaven River Basin was carried out by VIMS to characterize spatial distributions of sediment grain size, water content, etc. Based on the results of this survey, four sites were selected to represent the different environments of the bay and to characterize spatial variability. These sites are located near the Inlet entrance, in the Lower Western and Eastern Branches, and in Broad Bay. These sites were visited 3 times between autumn 2003 and autumn 2004 to conduct erosion experiments. At least two of the erosion testing sites remained fixed as index sites for characterizing seasonal variability. The other two erosion testing sites were moved to increase spatial coverage, depending on the results of the sediment mapping survey.

The sediment was characterized at 19 locations, as shown in Figure IV.23. The results of this sediment characterization survey are shown in Figure IV.24. It is readily seen that the upstream silt and clay fractions give way to the sand fraction moving toward the Inlet in any of the 3 branches.

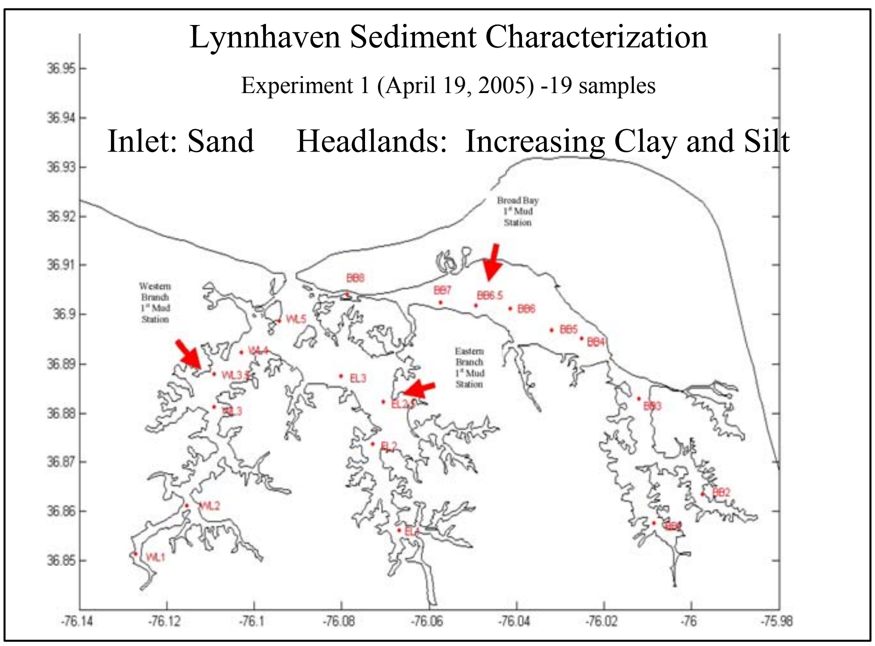
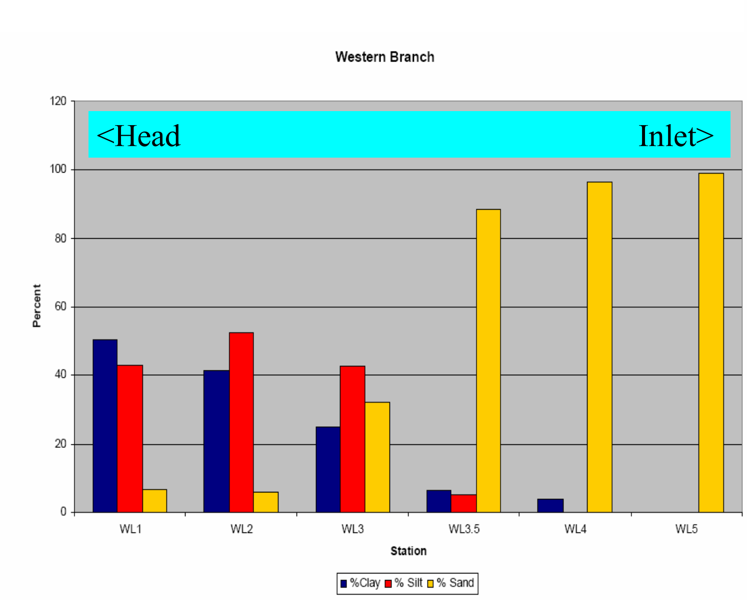
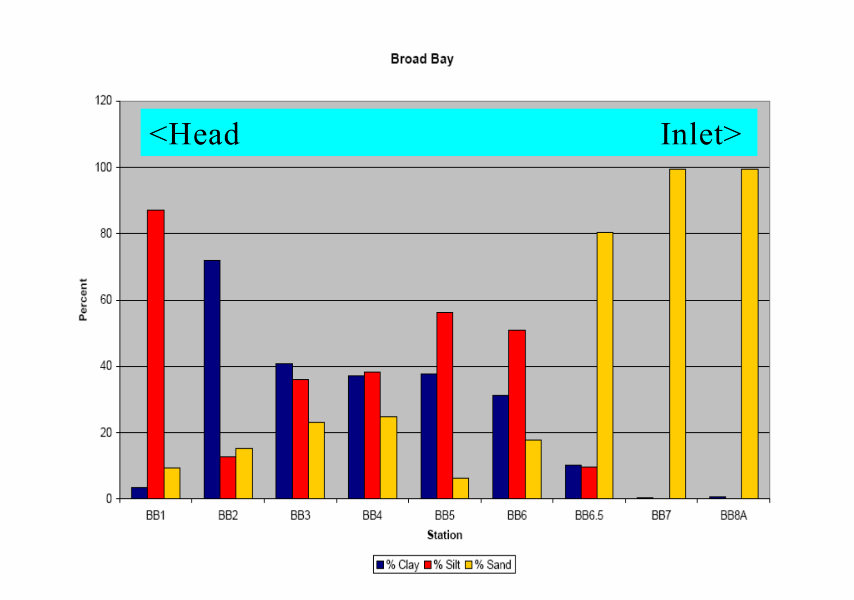


Figure IV.23. Locations for 19 samples characterized for grain size prior to critical shear stress surveys.





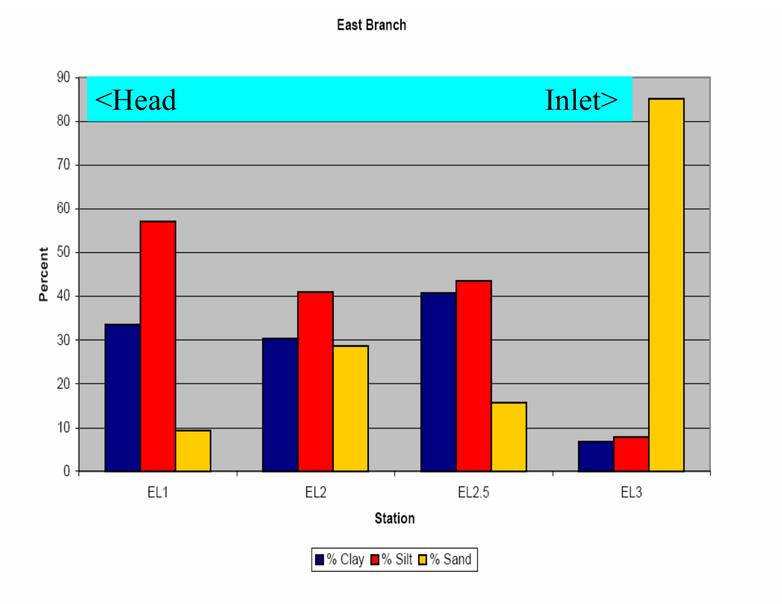


Figure IV.24. Percentage distributions of sand, silt, and clay for 19 sediment samples.

Erosion tests were carried out using an existing erosion testing system, called a microcosm system, operational at Horn Point Laboratory. This Microcosm system consists of 2 10-cm Gust Microcosms (Gust and Mueller, 1997), a Campbell Datalogger connected to a laptop computer, a Fluid Metering Inc. (FMI) positive displacement pump, 2 turbidimeters, and 2 Maxon precision motors. The Microcosms use a spinning disk with central suction to generate a controllable, nearly uniform shear stress (Gust and Mueller, 1997). The Campbell Datalogger controls the pump and motor and collects and stores data.

During erosion experiments, a sequence of increasing levels of shear stress is applied to the undisturbed cores. The effluent from each Microcosm is passed through a turbidimeter and time series of turbidity are measured. The effluent is collected, filtered and weighed to determine the actual mass eroded during each step, which is used to calibrate the turbidimeter. HPL and VIMS shared the filtering responsibilities, and VIMS carried out all filter analyses. Erosion rate is subsequently calculated as the product of pumping rate and suspended sediment concentration.

There were a total of 3 critical shear stress surveys conducted in May 2005, February 2006, and August 2006. It is important to measure at different times of the season because the sediment erodibility could be affected by the activity due to bio-turbation. The locations of the erodibility core sites for all 3 surveys are shown in Figure IV.25.

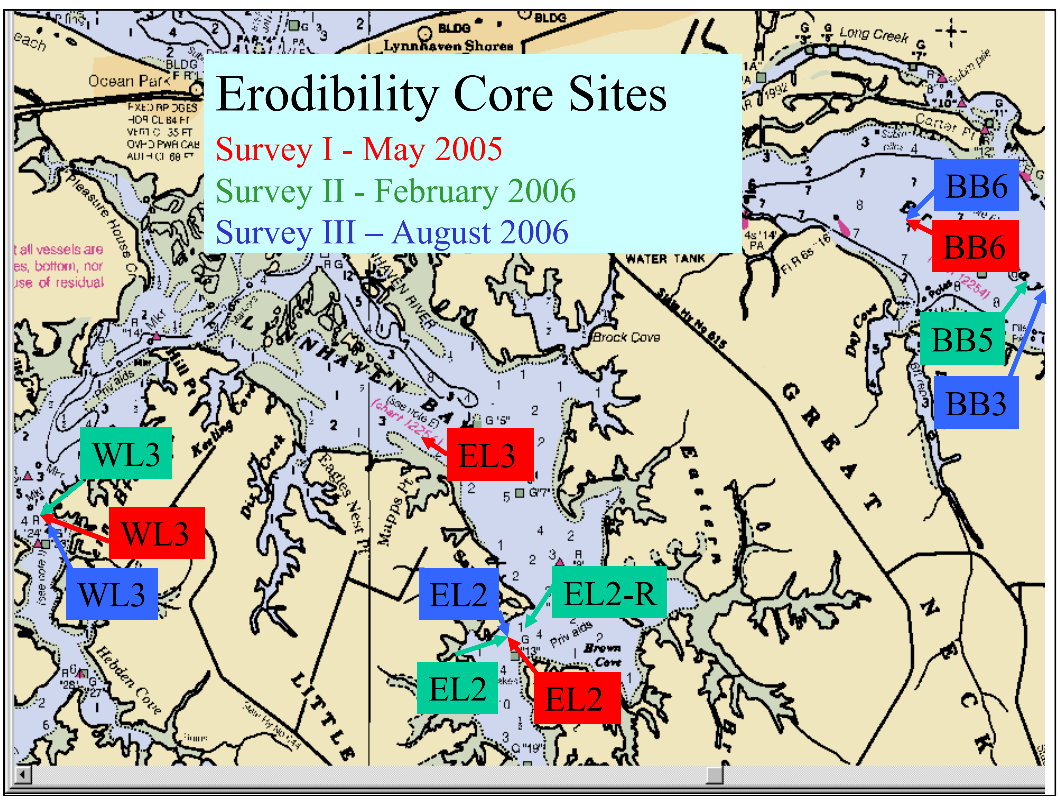


Figure IV.25. Locations of erodibility core sites for all 3 critical shear stress surveys.

Critical stress profiles for all twenty-four cores that were processed from the three field erosion studies are shown in Figure IV.26. X-axis is critical shear stress in Pascals, and Y-axis is eroded mass in kilograms per square meter. The plots of the cores are color-coded so that all cores from May 2005 are green, those from February 2006 are blue, and those from August 2006 are red.

The erosion data were analyzed using the erosion formulation of Sanford and Maa (2001). This erosion formulation uses a linear erosion rate expression with depth-varying critical stress to describe both unlimited and limited erosion, with erosion behavior depending on the rate of increase in critical stress relative to the rate of change of bottom shear stress. Results from this formulation are then incorporated into the sediment transport model to represent the real *in situ* sediment erosion rate.

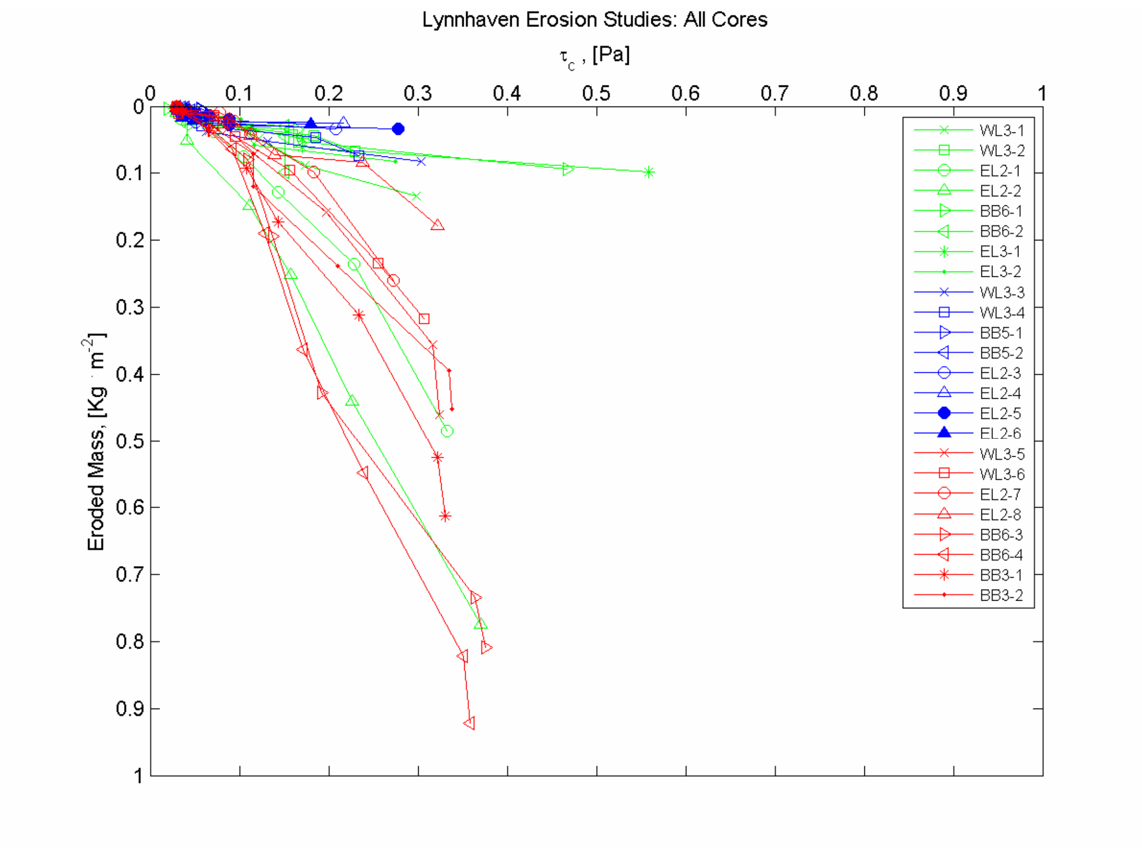


Figure IV.26. Critical stress profiles for all twenty-four cores that were run from the three field erosion studies. X-axis is critical shear stress in Pascals, and Y-axis is eroded mass in kilograms per square meter.

IV-2-4. VIMS dataflow surveys

The development of new water quality standards for turbidity, chlorophyll, and dissolved oxygen, has placed new requirements on accurate measurements of the temporal and spatial variability of water quality constituents. Detailed ecosystem modeling also requires high density spatial measurement for model calibration and validation. Until recently our capacity to measure, monitor, and evaluate water quality constituents in detail over ecologically relevant regions and time scales was limited. However, there has been recent application in Virginia of a new state-of-the-art DATAFLOW Surface Water Quality Mapping System (www.VECOS.org) for high-speed, high-resolution mapping of surface water quality from small vessels capable of sampling shoal, littoral areas. Such a mapping system has been demonstrated to have practical application in the determination of attainment of water quality criteria constituents in shallow water designated use areas. Here we have implemented these new technologies to provide information over small spatial scales to assist in the monitoring of and modeling of light attenuation, chlorophyll concentrations, surface dissolved oxygen, and other water quality conditions in the Lynnhaven River system.

DATAFLOW Mapping System

DATAFLOW is a compact, self-contained surface water quality mapping system, suitable for use in a small boat operating at speeds of up to 25 KT. The system collects water through a pipe ("ram") deployed on the transom of the vessel, pumps it through an array of water quality sensors, and then discharges the water overboard. The entire system from intake ram tube to the return hose is shielded from light to negate any effect high-intensity surface light might have on phytoplankton in the flow-through water that is being sampled. A blackened sample chamber is also used to minimize any effect of light on measurements by the fluorescence probe.

The DATAFLOW mapping system collects a sample once every 2-4 seconds. The resulting distance between samples is therefore a function of vessel speed. An average speed of 25 knots results in one observation collected every 40-60 m.

The DATAFLOW system has a YSI (Yellow Springs Instruments, Inc.) 6600 sonde equipped with a flow-through chamber. The sensors include a Clark-type 6562 DO probe, a 6561 pH probe, a 6560 conductivity/temperature probe, a 6026 turbidity probe, and a 6025 chlorophyll probe. The sonde transmits data collected from the sensors directly to a 600 MHz embedded computer board contained in a waterproof Pelican case using a data acquisition system created with LabVIEW software (National Instruments Corporation, Austin, TX). Custom software written in the LabVIEW environment provides for data acquisition, display, control, and storage. Real-time graphs and indicators provide feedback to the operator in the field, ensuring quality data is being collected. All calibrations and maintenance on the YSI 6600 sondes are completed in accordance with the YSI, Inc. operating manual methods (YSI 6-series Environmental Monitoring Systems Manual; YSI, Inc. Yellow Springs, OH). Table IV.3 provides the precision, accuracy and minimum detection limits of the sensors.

Table IV.3. Precision and accuracy of YSI Data (model 6600)

PARAMETER	UNITS	PRECISION	ACCURACY	MDL
DO	% Saturation	0.1%	± 2%	0 %
DO	mg/L	0.01mg/L	0.2mg/L	0 mg/L
Salinity	ppt	0.01ppt	0.1ppt	0 ppt
Temperature	ºC	0.01ºC	±0.15ºC	-5ºC
pH	unit	0.01units	±0.2units	0 units
Turbidity	NTU	0.1NTU	2 NTU	0 NTU
Chlorophyll	µg/L Chl	0.1µg/L Chl	-	0 µg/L Chl

The DATAFLOW system was equipped with a Garmin GPSMAP 168 Sounder. This unit served several functions including chart plotting, position information, and depth. The unit was WAAS (Wide Area Augmentation System) enabled and provided a position accuracy of better than three meters 95 percent of the time. The NEMA 0183 data sentence containing all pertinent position and depth information was output to the SBC data acquisition system.

The DATAFLOW system utilized a SBC data acquisition system for data collection and storage. The system was based on 600 MHz single, embedded board computer designed to run on a Windows Intel platform. All data, including latitude and longitude, was collected simultaneously in one file, removing any errors associated with merging separate files into one.

Calibration Sampling

A total of eight calibration stations were sampled along the cruise tracks each month. Stations were selected to maximize the range of values that are seen along a track (e.g., when moving up a tributary with a salinity gradient, samples were taken to get a high, medium, and low salinity value). Extra sampling supplies were available to sample more stations under special conditions such as in areas of large blooms. At each station the boat was stopped and water samples were collected from the effluent tubing of the DATAFLOW System (sampling water depth of approximately 0.25 - 0.5 m) for total suspended solids (TSS), volatile suspended (VSS), chlorophyll-a, chlorophyll-b, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), total phosphorus (TP), particulate inorganic phosphorus (PIP), and dissolved oxygen (DO) for processing with the Winkler method. At these stations secchi depth and a vertical profile of photosynthetically available radiation (PAR) were also measured. Samples for TSS, VSS, DIN, DIP, and chlorophyll were collected in darkened bottles, which were rinsed three times with ambient water before filling. Samples for DIN, DIP, chlorophyll and pheophytin were immediately filtered into sterile Whirl-Pak™ bags upon collection. These were then packed on ice and returned to the laboratory where they were stored at -20ºC. Samples were then delivered to the VIMS Analytical Service Center, Gloucester Point, VA for further processing. Additionally, at each verification station light attenuation was measured from in situ light profiles using EPA-approved LI-COR (LI-COR Biosciences, Lincoln, NEB) underwater quantum sensors.

Quality Assurance and Quality Control

The quality assurance procedures followed in this project were documented in "Work/Quality Assurance Project Plan for Spatially Intensive Water Quality Monitoring (For the Period: April 1, 2004 through June 30, 2004)". This plan was submitted and approved by EPA Chesapeake Bay Program and the Virginia Department of Environmental Quality, Richmond, Virginia.

All field data were recorded on specially prepared field data sheets. The initials of the person recording the data were recorded on each data sheet. The raw data sheets were reviewed for possible missing data values due to sample collection problems prior to data entry. These sheets were filed in the VIMS laboratory. A cruise logbook was also kept.

Results

Dataflow mapping cruises were undertaken approximately monthly from March 2005 through November 2005 and again March 2006 through November 2006. The archived data and visualized tracks of surface temperature, salinity, dissolved oxygen, turbidity, chlorophyll and pH are available at the website www.VECOS.org. Figure IV.27 shows the typical cruise tracks with the range of turbidities recorded during the May 24, 2005 cruise, and the reaches of the of the cruise tracks that are presented as examples in subsequent figures.

Regressions of calibration station sample measurements with simultaneous DATAFLOW measurements were used to develop Lynnhaven-specific calibration of the in vivo measurements. Figure IV.28 shows the regression of the DATAFLOW turbidity measurements to downwelling light attenuation (K_d) profiles for all calibration stations during 2006. Light attenuation was then used to calculate light at depth using the standard Lambert-Beer relationship,

$$I_z = I_o \exp [(-K_d) (Z)] \qquad \text{(IV-1)}$$

where I_z is light at depth Z, I_0 is light at surface, and K_d is the light attenuation coefficient.

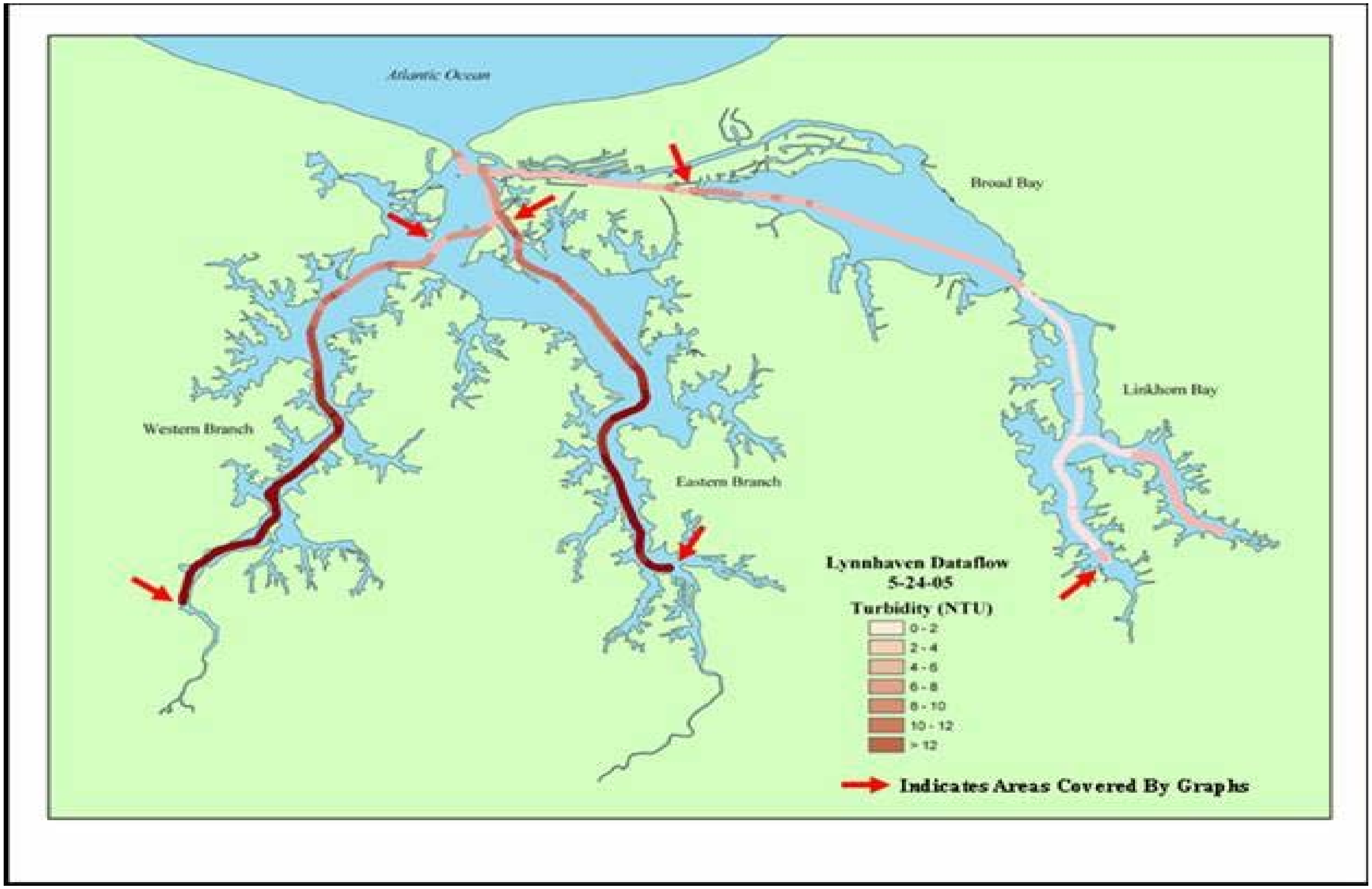


Figure IV.27. Lynnhaven River system DATAFLOW cruise tracks showing turbidity levels during the 5-24-05 cruise. Arrows indicate the reaches that are presented in subsequent graphs in this chapter.

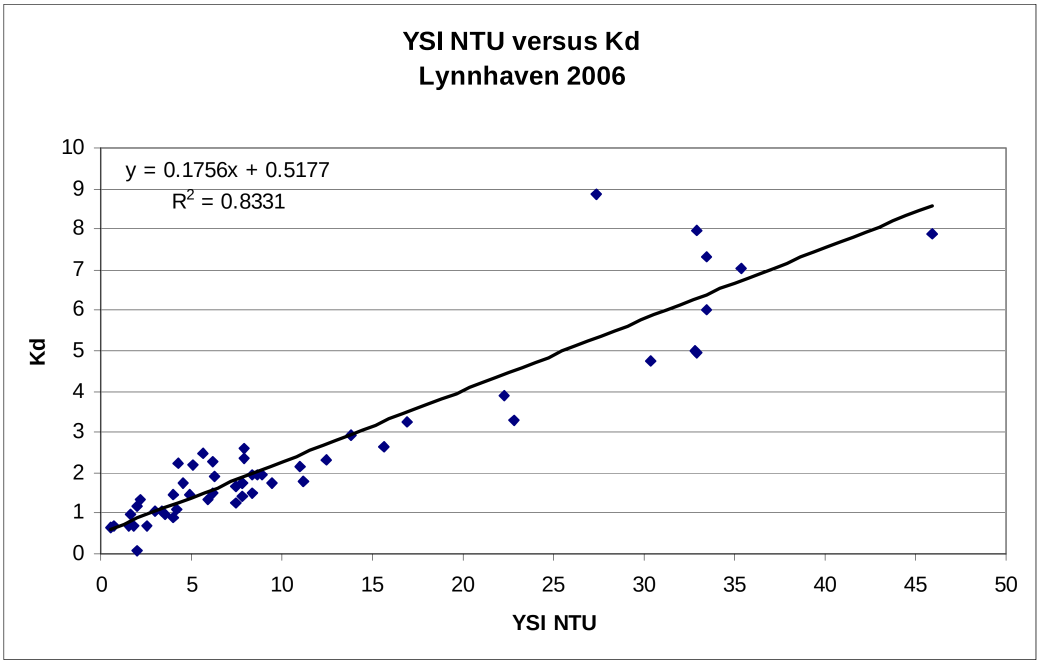
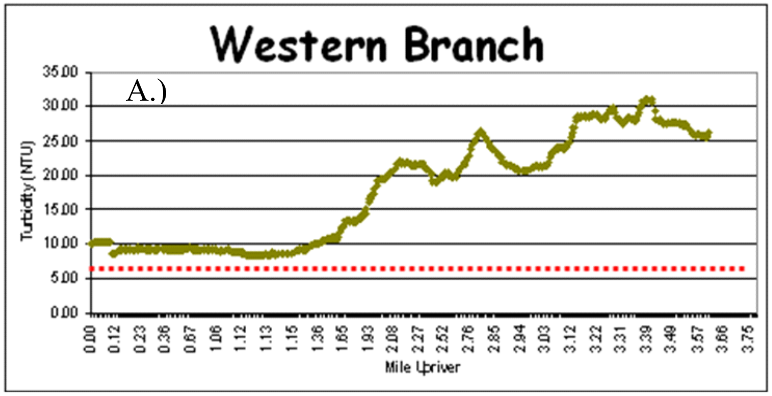


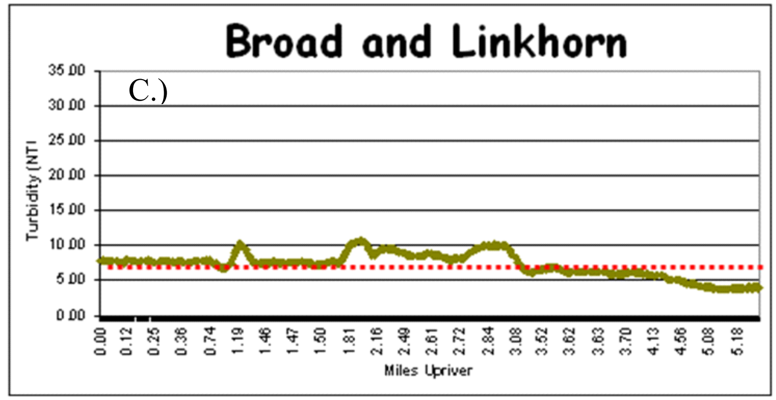
Figure IV.28. 2006 verification station YSI NTU (turbidity) vs. light attenuation (Kd)

Figures IV.29A, B, and C show representative concentration-distance plots of turbidities (NTU) for the individual branches of the Lynnhaven system. Using the 2006 Lynnhaven system NTU to light attenuation relationship (Figure IV.28) the turbidity (~6 NTU) that is equal to 22% of surface irradiance at 1m bottom depth is provided for a reference. Typically, 22% of surface irradiance is used as a standard by EPA and the Commonwealth of Virginia to define sufficient light available for SAV sustained growth.

All three systems had comparable turbidities near the inlet of the Lynnhaven. Turbidities in the Eastern and Western Branches increased precipitously with distance upstream during July (Figures IV.29A and IV.29B) and during most other months (data not shown). Levels in Broad and Linkhorn Bays were much lower than the other two branches (Figure IV.29C). Turbidities in parts of Linkhorn Bay were lower compared to Broad Bay.

Figure IV.30 shows the spatially averaged turbidity for each of the three individual branches of the Lynnhaven system for the eight cruises in 2006. Averaged turbidities were seasonally highest in September of 2006 and highest in the Eastern Branch. Averaged turbidities in Broad and Linkhorn Bays were lower during all months than the Eastern and Western Branches.





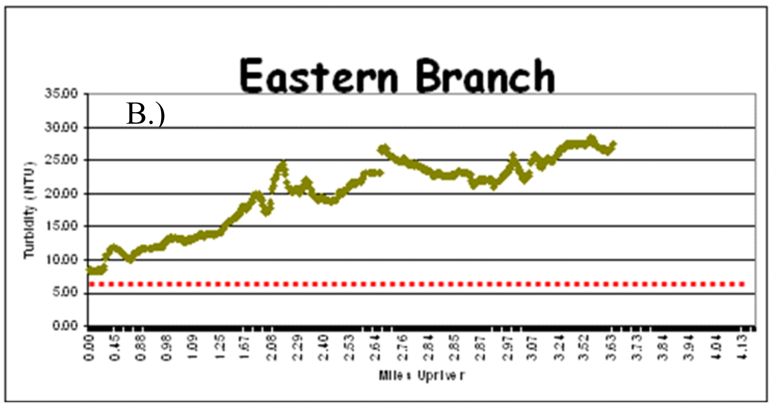


Figure IV.29. Concentration-distance plots of turbidity along the A.) Western Branch, B.) Eastern Branch, and C.) Broad and Linkhorn Bays during July 2006. Dotted red lines indicate turbidity levels where light at 1m depth is equal to 22% of surface irradiance (SAV light criteria).

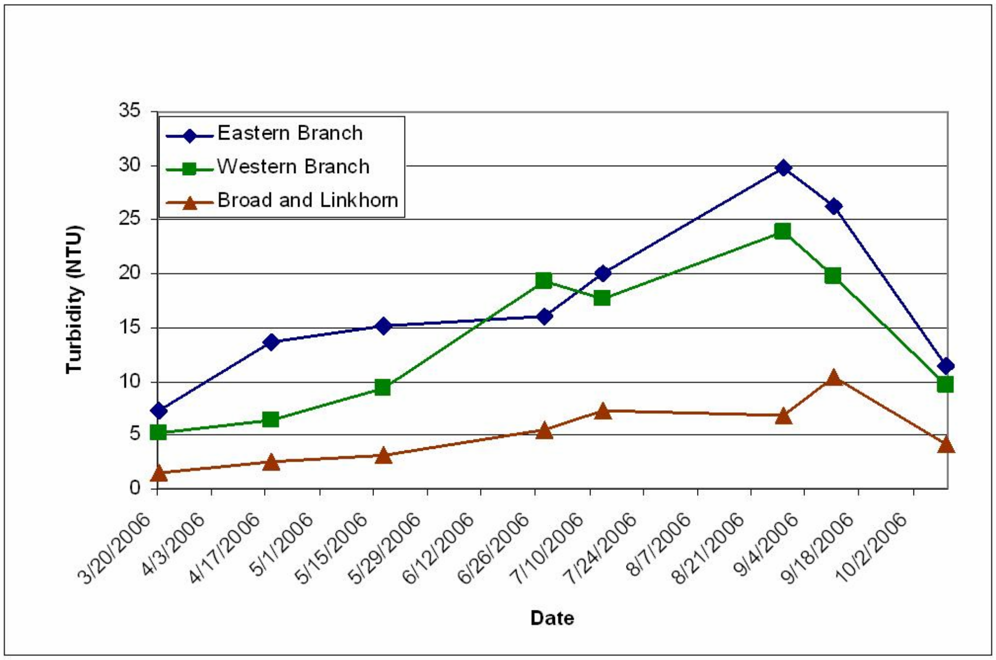


Figure IV.30. Spatially averaged turbidities (NTU) for the individual branch cruise track reaches for each monthly DATAFLOW cruise in 2006.

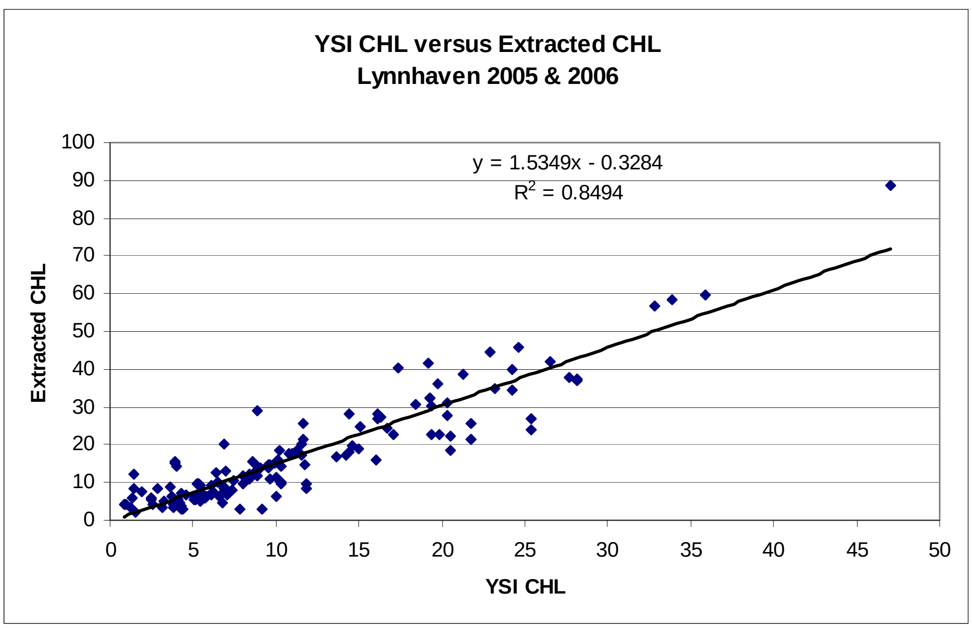


Figure IV.31. 2005-2006 verification station YSI chlorophyll vs. extracted chlorophyll.

All in vivo DATAFLOW chlorophyll data have been converted to extracted chlorophyll values using the 2005 and 2006 Lynnhaven system YSI chlorophyll to extracted chlorophyll relationship developed from the calibration station data (Figure IV.31).

Figures IV.32A, B, and C show representative concentration-distance plots of chlorophyll for the individual branches of the Lynnhaven system for July 2006. All three branches have low comparable chlorophyll levels in the vicinity of the inlet. In July 2006 these levels were comparable to the summertime chlorophyll standards set by the Virginia DEQ for the James River (red line). Rapid increases in chlorophyll were observed with distance upstream for the Eastern and Western Branches. There was some increases in Broad and Linkhorn Bays but during July concentrations only reached approximately 15 μg/l.

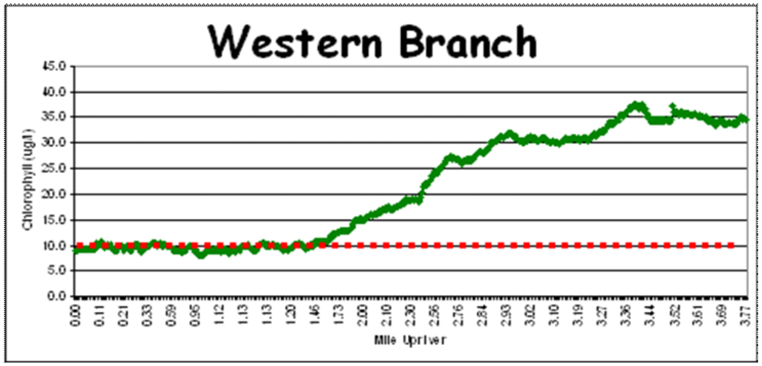
Figure IV.33 shows the spatially averaged chlorophyll concentrations for each of the three individual branches of the Lynnhaven system for the eight cruises in 2006. These data indicate that the average chlorophyll concentrations in all branches of the system exceeded the water quality standards from approximately April through September. The Eastern Branch has the highest levels followed by the Western Branch and the Broad and Linkhorn Bays

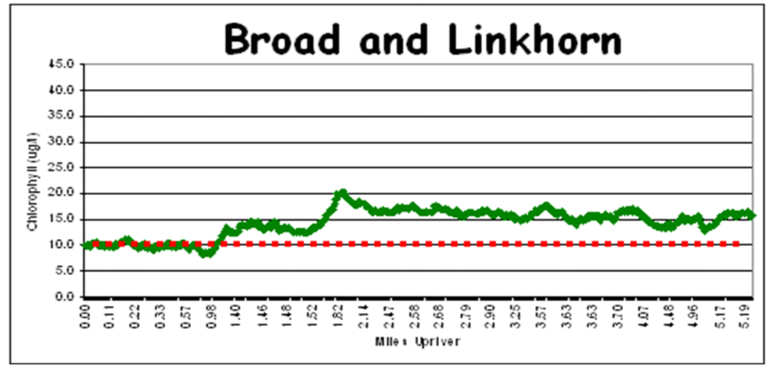
Figures IV.34A, B, and C show representative concentration-distance plots of dissolved oxygen for the individual branches of the Lynnhaven system for July 2006. All three branches recorded high, daytime, dissolved oxygen levels that varied little from the inlet region to the upper regions of the branches. In July 2006 these levels met the summertime dissolved oxygen standards set by the Virginia DEQ for the James River (red line) of 4.3 mg/l.

Figure IV.35 shows the spatially averaged surface dissolved oxygen concentrations for each of the three individual branches of the Lynnhaven system for the eight cruises in 2006. These data indicate that the average dissolved oxygen concentrations in all branches of the system met the standards throughout the year.

Summary

Water quality measurements using spatially intensive water quality mapping (DATAFLOW) for the Lynnhaven system demonstrated that Broad and Linkhorn Bays had distinctly better water quality that the Western and Eastern Branches. Water quality was generally best in all regions in the vicinity of Lynnhaven Inlet and rapidly deteriorated with distance upriver in both the Western and Eastern Branches. Turbidity levels in both the Western and Eastern Branches generally exceeded that required for SAV growth to 1m while levels appeared sufficient for SAV growth in both Broad and





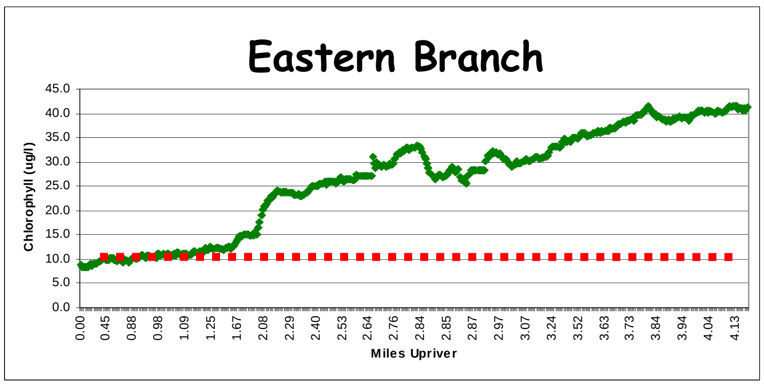


Figure IV.32. Concentration-distance plots of chlorophyll along the A.) Western Branch, B.) Eastern Branch, and C.) Broad and Linkhorn Bays during July 2006. Dotted red lines indicate DEQ summer chlorophyll standards for the James River of 10 µg/l.

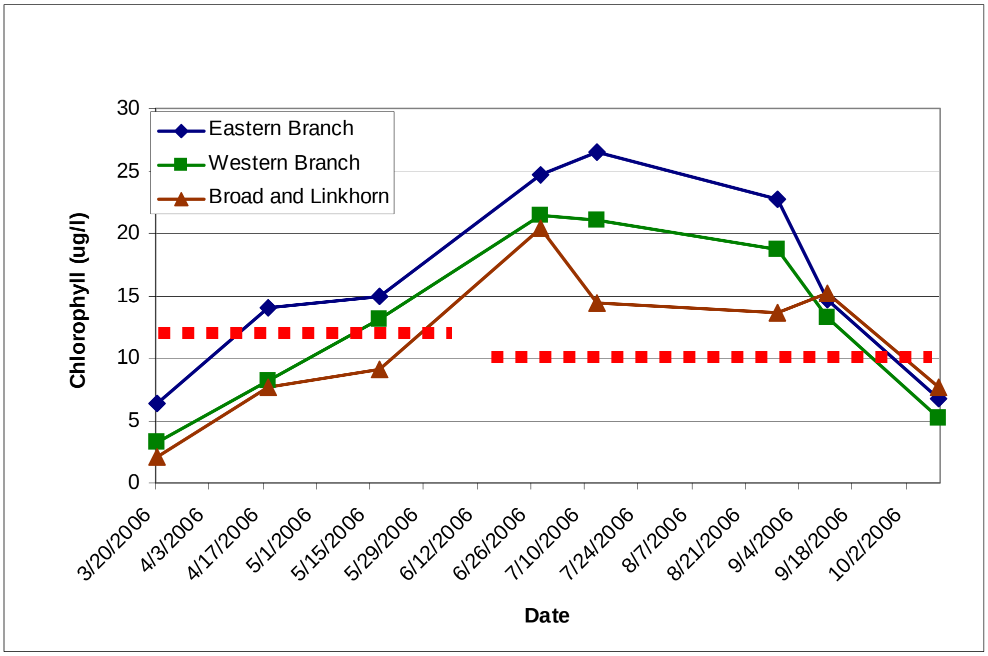
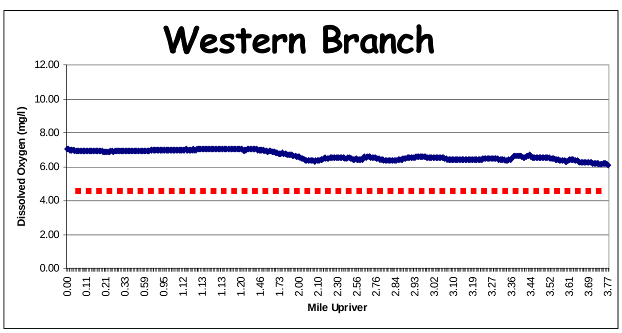
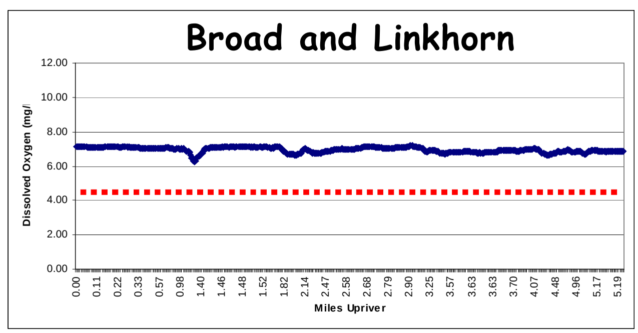


Figure IV.33. Spatially averaged chlorophyll concentrations for the individual branch DATAFLOW cruise track reaches for each monthly cruise in 2006. Red lines indicate the Va. DEQ chlorophyll standards of 12 µg/l for March 1 - May 31 and 10µ for July 1 – September 30.





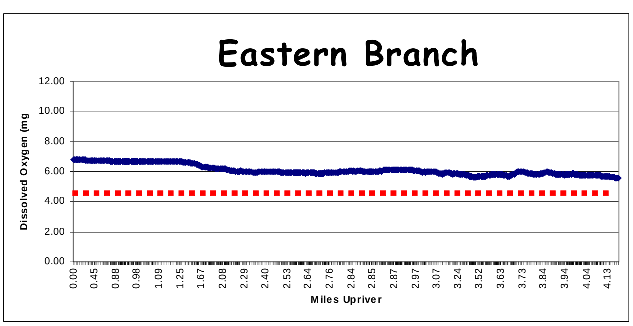


Figure IV.34. Concentration-distance plots of dissolved oxygen along the A.) Western Branch, B.) Eastern Branch, and C.) Broad and Linkhorn Bays during July 2006. Dotted red lines indicate DEQ surface dissolved oxygen standards for the James River of 4.3 mg/l.

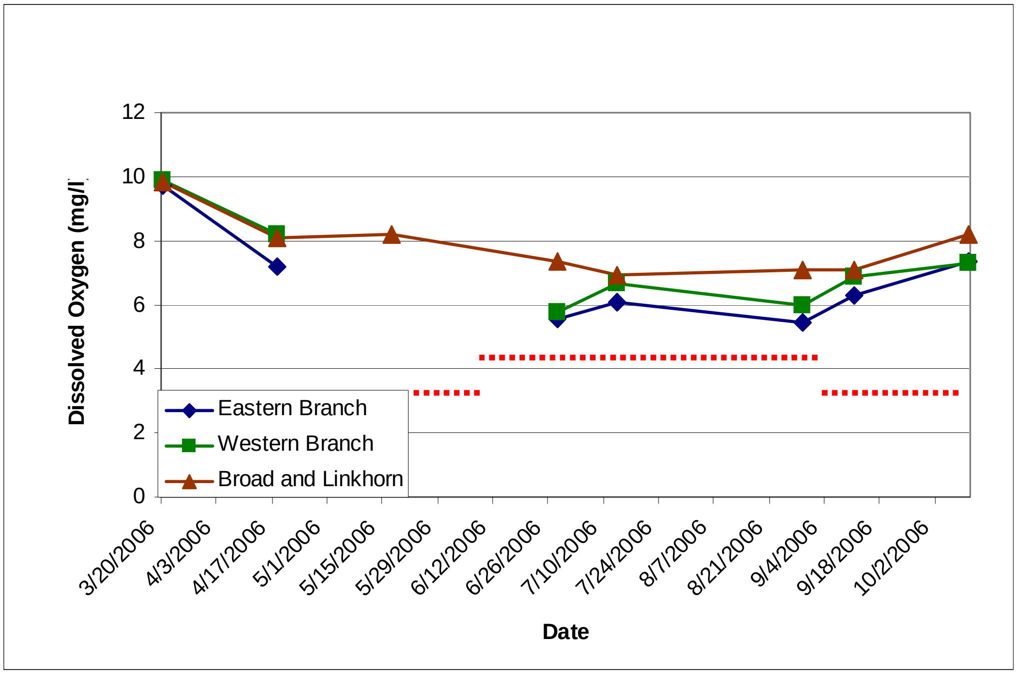


Figure IV.35. Spatially averaged surface dissolved oxygen concentrations for the individual branch DATAFLOW cruise track reaches for each monthly cruise in 2006. Red lines indicate the Va. DEQ dissolved oxygen of 12 µg/l for March 1 - May 31 and 10 µg/l for July 1 – September 30.

Linkhorn Bays. These measurements agreed with the current distributions of SAV that are currently only found in Broad and Linkhorn Bays.

Chlorophyll levels were above the numeric standards in most areas except for the region near Lynnhaven Inlet from April through September. Highest concentrations occurred during July and in the upper reaches of the Western and Eastern Branches where concentrations approached 40 µg/l during July 2006. Daytime surface dissolved oxygen concentrations were generally good and met the standards throughout the system. Nightime concentrations were not measured, but concentrations could be expected to drop significantly in the upper reaches of the Western and Eastern Branches due to the high phytoplankton biomass and other factors.

IV-2-5. VIMS high-frequency time series measurements

High frequency water quality measurements were obtained for use in model calibration, assessing water quality, and understanding the Lynnhaven ecosystem from 2005 to 2008 with a network of *in situ* sensors (Figure IV.36). Self-cleaning, internally-logging WET Labs ECO fluorometers (www.wetlabs.com/products/eflcombo/fl.htm) were deployed approximately 0.5 m below the surface (MLLW) to measure phytoplankton biomass as chlorophyll-a (chl-a), turbidity expressed in nephelometric turbidity units (NTU), and water temperature. Since seagrass has traditionally been found in Broad Bay (web.vims.edu/bio/sav) and is highly dependent on adequate light penetration, an additional WET Labs fluorometer capable of measuring the concentration of chromophoric dissolved organic matter (CDOM) was also deployed in Broad Bay to enable measurement of all three parameters that affect light penetration (chl-a, NTU, CDOM) in that embayment. A self-cleaning, internally-logging Hydrolab DS-5X instrument (www.hydrolab.com/products/hydrolabds5x.asp) was deployed approximately 0.5 m above the bottom to measure temperature, salinity, and dissolved oxygen (DO) using optical sensor technology. This instrument was deployed in the Eastern Branch in 2005 and the Western Branch in 2006.

Monitoring began in 2005 with a single fluorometer and DS-5X in the Eastern Branch (moved from the lower to upper branch part way through the summer), and both types of WET Labs fluorometers in Broad Bay (Figure IV.36, Tables IV.4 and IV.5). In 2006 new equipment acquisitions allowed us to expand into the upper and lower Eastern and Western Branches. The DS-5X was moved to the upper Western Branch to assess a second location for low DO. To assess the potential for local phytoplankton bloom formation within the Lynnhaven as opposed to advection of blooms from the lower Chesapeake Bay, a final WET Labs fluorometer was deployed at the NOAA tide station on the Chesapeake Bay Bridge-Tunnel (CBBT) fishing pier.

All sensors recorded data at 30-minute intervals and were serviced as frequently as possible (approximately every two weeks). At each servicing, water samples were collected for determination of chlorophyll-a, total suspended solids (TSS – 2006 only), and CDOM concentrations for sensor calibration, and independent measurements of DO and salinity were made with a freshly calibrated Hydrolab to provide data for sensor confirmation. Chlorophyll samples were filtered onto 0.7 µm GF/F filters and frozen until extraction with a 45/45/9.9/0.1% acetone/DMSO/distilled water/diethylamine solution for 24 hours (Shoaf and Lium, 1976) followed by analysis on a model 10-AU Turner Designs fluorometer. TSS samples were filtered onto pre-weighed 0.7 µm GF/F filters and dried to constant weight at 50°C. CDOM samples were filtered through a 0.2 µm membrane filter and frozen until analysis of absorption on a Shimadzu UV-1601 scanning spectrophotometer (Gallegos and Neale, 2002; Gallegos et al., 2005).

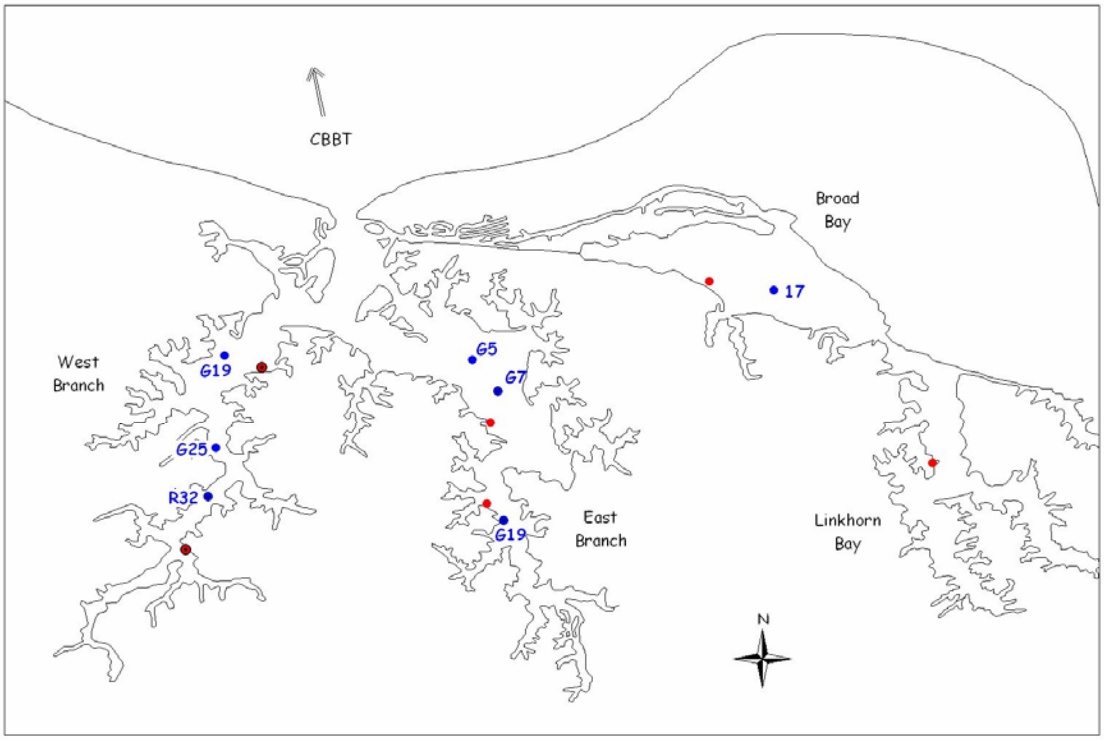


Figure IV.36. Locations of time series sensors. Blue stations are navigational markers used in 2005-06. Sites with dotted circles denote the location of the bottom oxygen sensors. Red stations are docks used in 2007-08. Sites with dotted circles denote the location of the surface oxygen sensors. Green stations are the sites of auxiliary chlorophyll samples collected by Lynnhaven River Now.

Absorption at 440 nm (m^{-1}) was taken as the index of CDOM concentration. Chlorophyll and NTU data from nearby Dataflow calibration stations and long-term Virginia Department of Environmental Quality monitoring stations were also used to develop sensor calibration curves. A sample calibration curve is shown in Figure IV.37. In 2005, Lynnhaven River Now personnel collected shore-based chlorophyll samples (analyzed at VIMS) at two sites (Fig. 1) for comparison of nearshore concentrations to those measured at the mid-channel *in situ* sensors. All sensor data were quality controlled via visual inspection and through use of the independent DO and salinity data to remove obviously corrupted data due to sensor fouling and malfunction.

One of the key parameters in shallow aquatic systems is the vertical attenuation coefficient of irradiance, k_D, which controls the amount of light available to support both water column and benthic primary production according to Beer's Law:

$$I_z = I_o e^{-k_D z} \quad \text{(IV-2)}$$

Table IV.4. Sensor deployment locations (navigational markers), dates (excluding gaps), and parameters[1].

	Location	Dates	Parameters
2005			
E. Branch	G7	5/5-8/12	Chl, NTU, T (surface)
		7/7-7/27	T, S, DO (bottom)
	G19	8/17-11/15	Chl, NTU, T (surface)
		7/14-10/22	T, S, DO (bottom)
Broad Bay	17	5/31-9/1	Chl, NTU, T, CDOM (surface)
2006			
Lower W. Branch	G19	4/14-11/8	Chl, NTU, T (surface)
Upper W. Branch	R32[2]	2/16-11/9	Chl, NTU, T (surface)
	R32	5/17-9/22	T, S, DO (bottom)
Lower E. Branch	G7[3]	4/14-11/9	Chl, NTU, T (surface)
Upper E. Branch	G19	4/14-9/20	Chl, NTU (surface)
Broad Bay	17	2/16-8/24	Chl, NTU, T (surface)
		3/9-8/11	CDOM (surface)
CBBT[4]	-	2/16-7/6	Chl, NTU (surface)
2007-08[5]			
Lower W. Branch	see Fig 1	5/17/07-3/26/08	Chl, NTU (surface)
		6/20/07-7/3/08	T, S, DO (surface)
Upper W. Branch	see Fig 1	5/17/07-7/1/08	Chl, NTU (surface)
		9/13/07-6/19/08	T, S, DO (surface)
Lower E. Branch	see Fig 1	5/17/07-7/1/08	Chl, NTU (surface)
Upper E. Branch	see Fig 1	5/17/07-6/5/08	Chl, NTU (surface)
Broad Bay	see Fig 1	5/17/07-7/1/08	Chl, NTU (surface)
Linkhorn Bay	see Fig 1	5/17/07-7/1/08	Chl, NTU (surface)

[1] Parameter abbreviations are as follows: Water temperature (T), Salinity (S), Dissolved oxygen (DO), Chlorophyll-*a* (Chl), Turbidity (NTU), Chromophoric dissolved organic matter (CDOM).
[2] Sensor moved from marker G25 to R32 on 2/23/06 to get farther up the branch.
[3] Sensor moved to marker G5 on 6/29/06 when G7 was hit by a vessel.
[4] NOAA tide station on the Chesapeake Bay Bridge-Tunnel.
[5] Several gaps in the record exist but were excluded due to limited space.

Table IV.5. Coordinates of sensor locations.

	Location	Latitude	Longitude
2005-06			
Lower W. Branch	G19	36°53'17.69"N	76° 6'29.66"W
Upper W. Branch	R32	36°52'9.23"N	76° 6'37.71"W
	G25	36°52'32.64"N	76° 6'33.96"W
Lower E. Branch	G7	36°53'0.43"N	76° 4'16.93"W
	G5	36°53'15.61"N	76° 4'29.49"W
Upper E. Branch	G19	36°51'57.59"N	76° 4'14.19"W
Broad Bay	17	36°53'49.53"N	76° 2'3.07"W
CBBT	-	36°58'0.68"N	76° 6'49.17"W
2007-08			
Lower W. Branch	dock	36°53'12.11"N	76° 6'11.66"W
Upper W. Branch	dock	36°51'43.33"N	76° 6'48.74"W
Lower E. Branch	dock	36°52'45.18"N	76° 4'20.64"W
Upper E. Branch	dock	36°52'5.46"N	76° 4'22.50"W
Broad Bay	dock	36°53'53.55"N	76° 2'34.10"W
Linkhorn Bay	dock	36°52'25.44"N	76° 0'45.68"W

in which I_o and I_z are incident irradiance at the surface and irradiance at depth z, respectively. k_D is controlled by the concentrations of chlorophyll-a, turbidity (as NTU or TSS), and CDOM in the water column. To develop a simple empirical model for predicting k_D as a function of these water quality parameters, data for chlorophyll, NTU, TSS, and k_D measured by the DATAFLOW group at their calibration stations were combined with CDOM concentrations measured as described above at the same stations (water provided by the DATAFLOW group after each cruise) to develop a multiple linear regression. This regression for k_D was then combined with the *in situ* sensor time series data from Broad Bay to compute the amount of light reaching the bottom as this is a key index for survival of submerged aquatic vegetation (SAV) such as eelgrass (*Zostera marina*) which has historically been present in Broad Bay.

Finally, enough funds were saved throughout the project to make possible an extra sensor deployment over an annual cycle in 2007-08 (Tables IV.4-IV.5), combined with measurements of water column primary production and respiration to complement the sediment flux data of Brush and Anderson, make possible a total metabolic budget of the

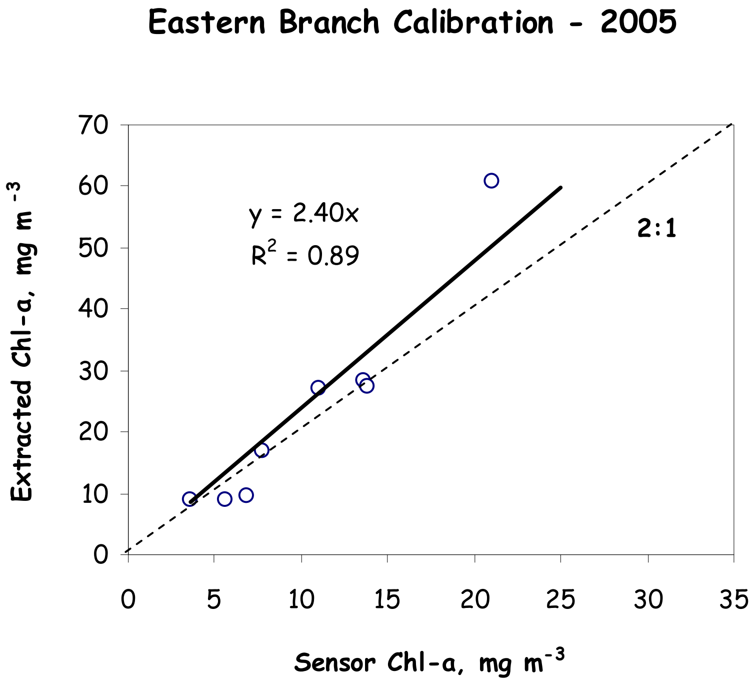


Figure IV.37. Sample calibration plot relating sensor output to measured water quality, in this case chlorophyll-a.

system, and provide critical rate process data for model calibration. WET Labs sensors were deployed on private docks throughout the Lynnhaven (Figure IV.36) and serviced approximately monthly from spring through fall and bimonthly in the winter. During each servicing trip, calibration samples were collected for measurement of chlorophyll and dissolved inorganic nutrients (0.45 µm Supor filters), temperature, salinity, and k_D were measured (using Hydrolab MS5, YSI 6600V2, and Li-Cor LI-1400 and LI-192SA instrumentation), and water samples were returned to VIMS for incubation at field temperatures in 60 mL bottles in a temperature-controlled light gradient box for determination of photosynthesis-irradiance (P-I) curves. Photosynthesis and respiration were measured as the rate of change in dissolved oxygen as measured with Hach HQ40d optical DO sensors. On three trips, sediment cores were collected at each site and incubated in the dark and at saturating irradiance to obtain data from the same annual cycle for comparison to the earlier sediment flux data of Brush and Anderson. Hydrolab and/or YSI sensors were deployed 0.5 m below the surface on selected trips to collect DO data every 30 minutes for computation of metabolism using the free water method for comparison to the incubation results. This annual cycle was recently completed and data are still being analyzed.

Results

Time series data displayed high frequency variations due to tidal and diel cycles, as well as longer-term, event scale and phytoplankton bloom dynamics on the order of 1-2 weeks (Figure IV.38). Shore-based samples had similar concentrations and patterns as the mid-channel, *in situ* sensors, suggesting the latter were reflective of the entire embayment within which they were located (Figure IV.39).

Chlorophyll-a from 2006 showed the expected increasing trend in phytoplankton biomass from the lower to the upper estuary, with highest values in the upper Western Branch (Figure IV.40). Lowest chlorophyll concentrations occurred in Broad Bay. Chlorophyll at all locations was higher than in the lower Chesapeake Bay as measured at the CBBT. A small February bloom at the CBBT also occurred inside the Lynnhaven. The spring phytoplankton bloom in the lower bay typically occurs in April. While none was detected at the CBBT, a late April bloom was detected throughout the Lynnhaven, as were frequent blooms throughout the season. These blooms were higher than at the CBBT, and often occurred at multiple stations. The data suggest that conditions within the Lynnhaven are favorable to bloom formation, and counter an alternative hypothesis that blooms are the result of advection of high chlorophyll water from the lower Chesapeake into the system.

Bottom water hypoxia occurred in both years in the upper branches of the Lynnhaven (Figure IV.41). Values were fairly constant around 5 mg L^{-1} on average in the Eastern Branch, with lower values being limited to the early morning hours as part of the diel cycle. In contrast, large swings in DO appeared to occur in the Western Branch. However, the sensor at this site was repeatedly and heavily fouled throughout the sampling season and appeared to be located within a thick bottom layer of detritus and macroalgae which likely resulted in the low DO. The repeated, rapid declines in DO following each servicing of the sensor and erratic changes in salinity (sensor also fouled) support this conclusion. However, the long term hypoxia from late July through early August appears to have been a real phenomenon, although it is impossible to determine if this was a lower water column event or restricted to the bottom detrital layer at this site.

Phytoplankton blooms in the Lynnhaven as measured by chlorophyll-a concentration often coincided at multiple sites around the system (Figure IV.42). In many cases chlorophyll and turbidity showed similar dynamics suggesting they were driven by the same forces (e.g. rain or wind events), while in other cases they were inversely related to one another, suggesting limitation of photosynthesis by high turbidity. Rain events should lead to runoff which would deliver sediments (thereby increasing turbidity) and nutrients which could stimulate phytoplankton blooms, while wind events would mix bottom sediments and potentially benthic microalgal chlorophyll into the water column. Blooms in 2005 often followed rain events, although the pattern in 2006 was less clear, and it is likely that internal remineralization of nutrients is also a major driver of bloom dynamics in this system.

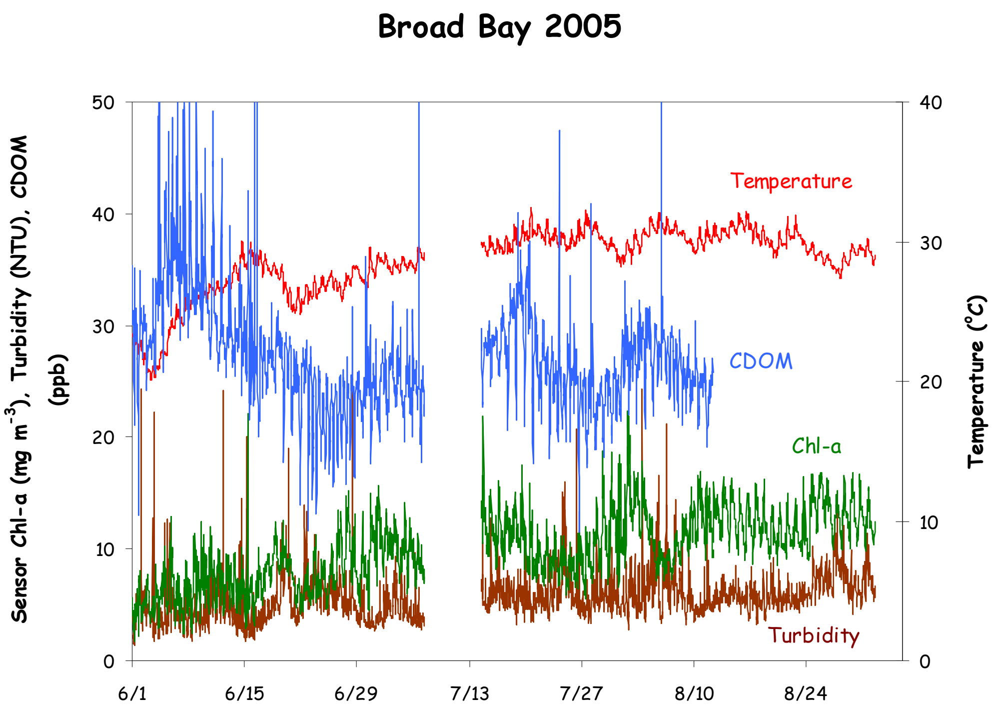


Figure IV.38. Time series measurements from 2005 in Broad Bay.

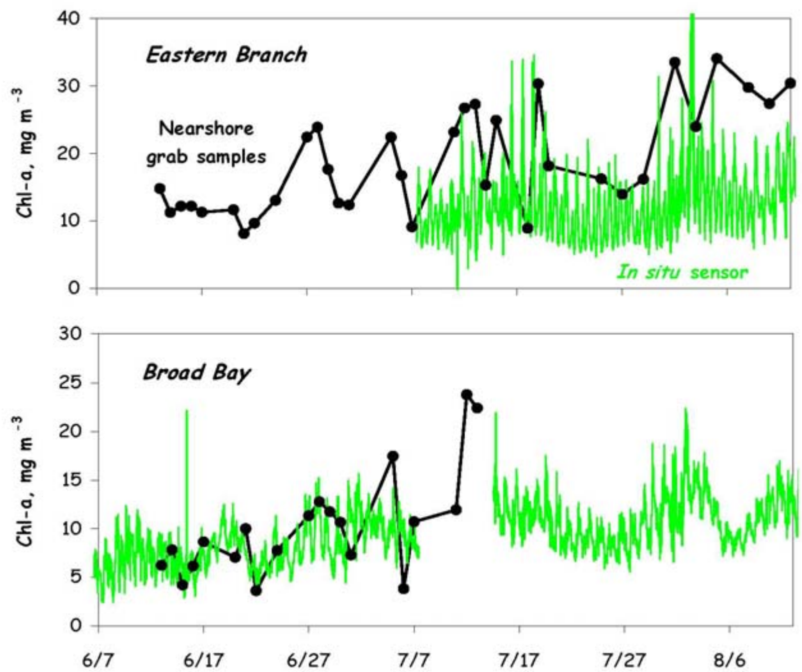


Figure IV.39. Time series of chlorophyll-a collected at shore-based sites by Lynnhaven River Now in 2005 compared to *in situ* fluorometer time series deployed mid-channel at navigational markers.

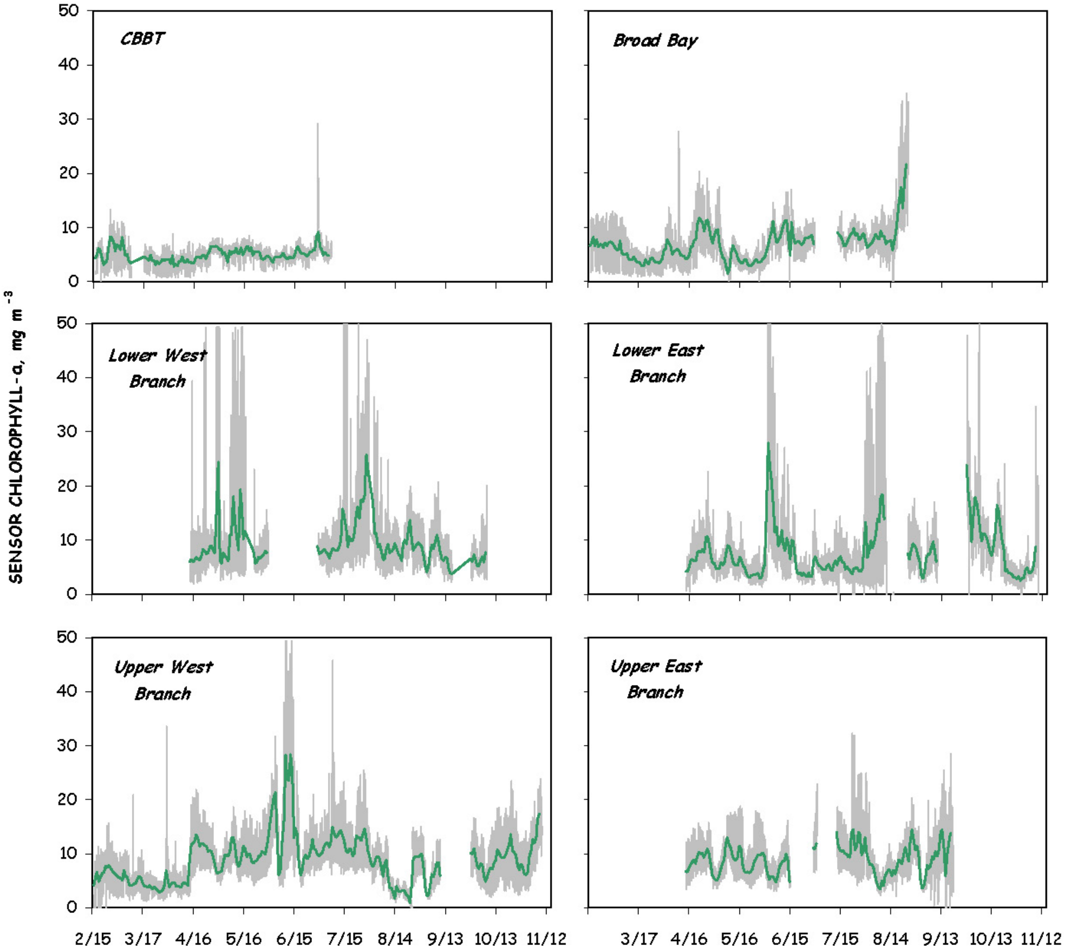


Figure IV.40. Time series measurements of surface chlorophyll-a in 2006. Green lines represent daily averages from the 30-minute data (grey lines).

Dynamics of chlorophyll and DO were linked, presumably through photosynthetic oxygen production, even though DO was measured on the bottom. DO concentrations also appeared closely related to incident irradiance, more so than chlorophyll-a, suggesting the importance of benthic microalgal production and sediment respiration in this system. CDOM and salinity also appeared closely coupled to recent rain events in 2005.

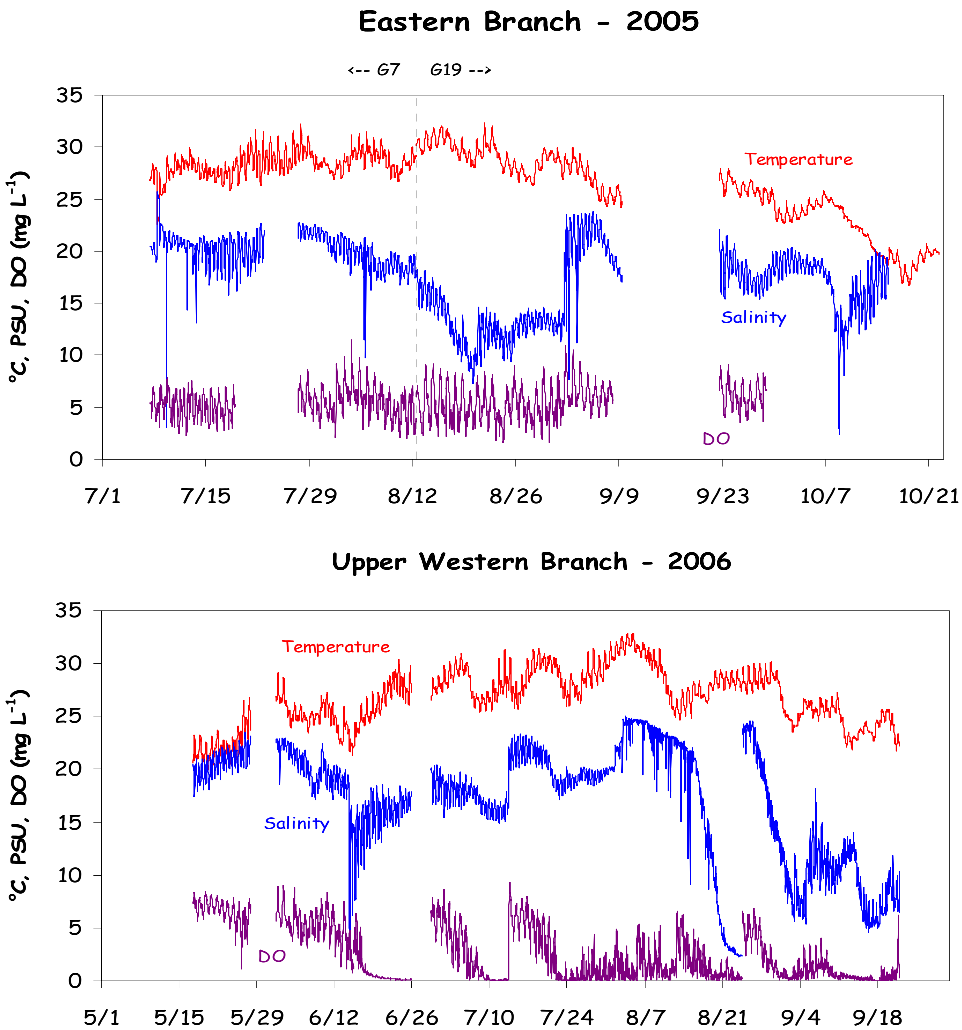
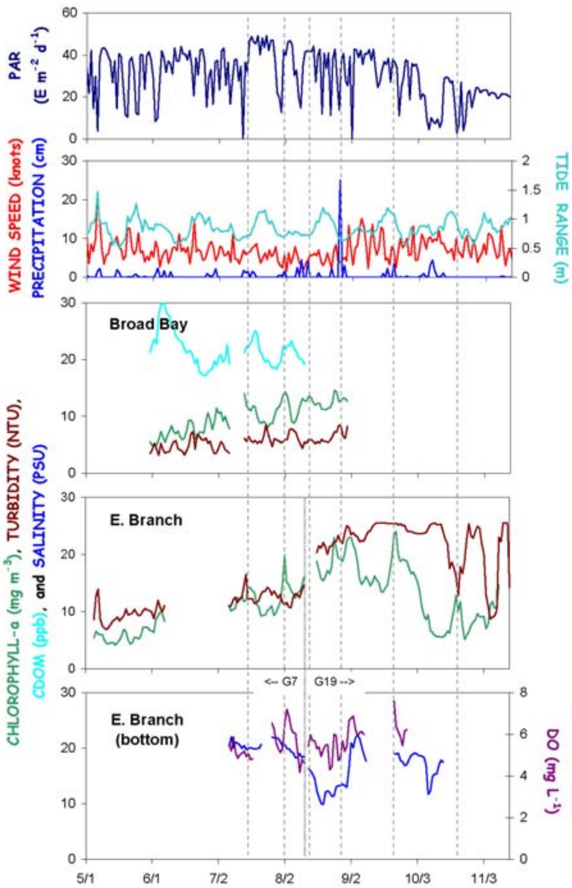


Figure IV.41. Time series measurements of bottom water quality.

Attenuation of light in the Lynnhaven was correlated to both chlorophyll and turbidity, with the latter having the stronger correlation (Figure IV.43a-b). Attenuation did not appear to have a strong correlation with CDOM in this system (Figure IV.43c). Three different multiple regression models for predicting k_D were fit to the data (Table IV.6). The first two used all three attenuating substances, one using NTU for turbidity and the other using TSS, while the third used only chlorophyll and NTU. Model fit was better when turbidity was expressed in NTU units, and inclusion of CDOM did not improve model fit. The resulting regressions reproduced measured k_D well (Figure IV.43d).

2005



2006

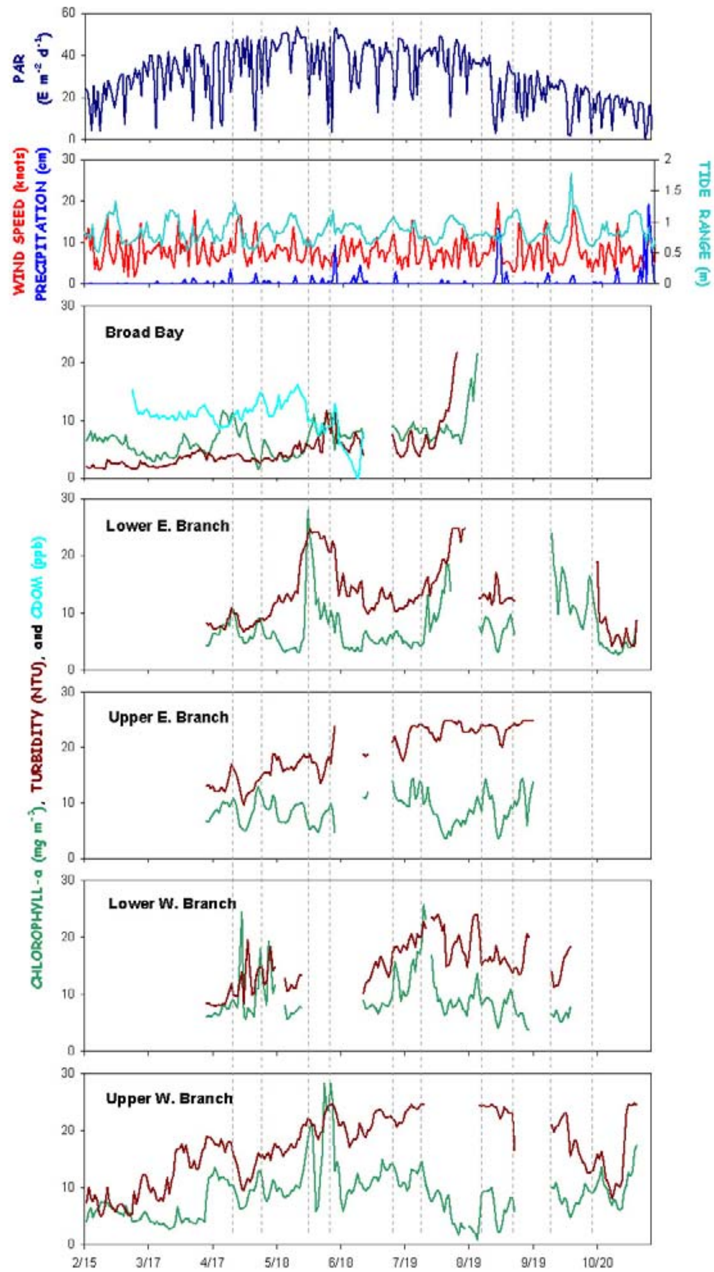


Figure IV.42. Daily average values from the 2005-06 time series sensors plotted with daily irradiance from the Chesapeake Bay Virginia National Estuarine Research Reserve site on the York River (photosynthetically active radiation, PAR), average daily wind speed and total daily precipitation at the Norfolk International Airport (obtained from the NOAA National Climatic Data Center), and daily tide range at the NOAA CBBT tide station. Vertical lines connect approximately co-occurring chlorophyll blooms. Most turbidity sensors were not factory calibrated to read higher than 25 NTU.

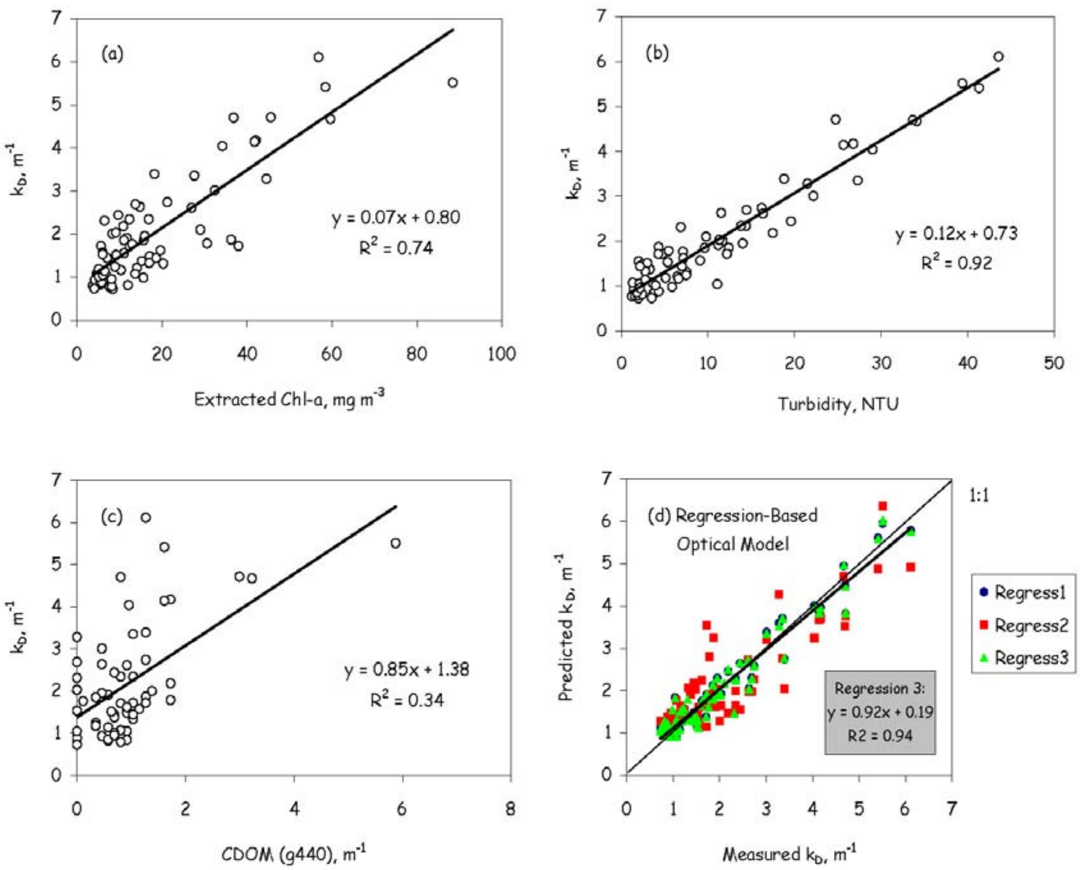


Figure IV.43. Relationship between measured attenuation coefficient for light (k_D) and (a) chlorophyll-a, (b) turbidity, and (c) CDOM, and (d) confirmation of a multiple regression-based model for predicting k_D as a function of these parameters. See Table IV.6 for a definition of the three regressions that were tested.

Table IV.6. Multiple linear regression models for predicting light attenuation as a function of water quality parameters.

Model	Equation	r^2
Regress1	y = 0.71 + 0.022*Chl + 0.089*NTU - 0.032*CDOM	0.94
Regress2	y = 0.98 + 0.075*Chl - 0.0013*TSS - 0.18*CDOM	0.76
Regress3	y = 0.71 + 0.02*Chl + 0.09*NTU	0.94

The resulting regression for k_D (Regress3 in Table IV.6) was combined with the 2005 and 2006 times series data from Broad Bay to estimate the average k_D in the system (1.57 m^{-1}). Using Beer's Law, this value translates into a depth at which 20% of surface irradiance remains of 1.02 m. The 20% light level is generally the minimum light requirement for SAV survival in the polyhaline Chesapeake (Dennison et al., 1993; Kemp et al., 2004). Using the bathymetry from Wang et al.'s hydrodynamic-water quality model, only a thin area of bottom around the shoreline of Broad Bay receives enough light to support SAV, in marked agreement with the observed long-term SAV distribution as reported by VIMS (Figure IV.44). The shoreline along the northeast quadrant of Broad Bay which appears to have enough light but no SAV historically has in fact supported ephemeral *Ruppia maritima* beds, although sediments are likely too sandy for eelgrass.

While results from the 2007-08 time series and metabolic measurements are still being analyzed, a typical P-I curve is shown in Figure IV.45. Water column production increased rapidly from negative values in the dark (i.e., net respiration) and saturated at high light levels. Data will be used to develop a metabolic budget for the entire Lynnhaven system, assess its net metabolic balance, and assess water column vs. sediment dominance of metabolism.

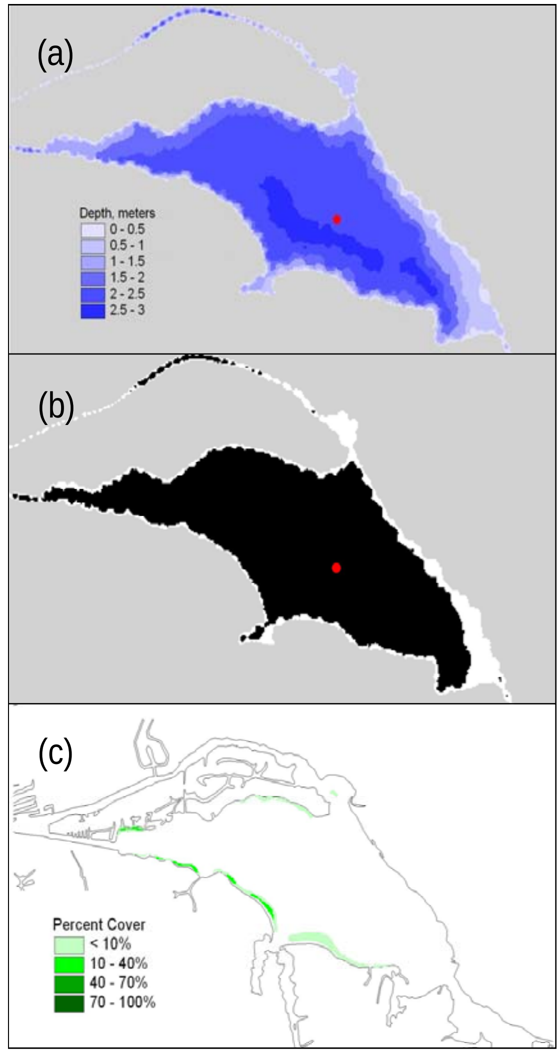


Figure IV.44. Calculation of potential SAV habitat in Broad Bay from (a) bathymetry and *in situ* time series sensors (red point). (b) Area of Broad Bay receiving greater than 20% of incident irradiance on average (white). (c) Long term average SAV cover in Broad Bay, 1992-2003, based on VIMS SAV monitoring program data.

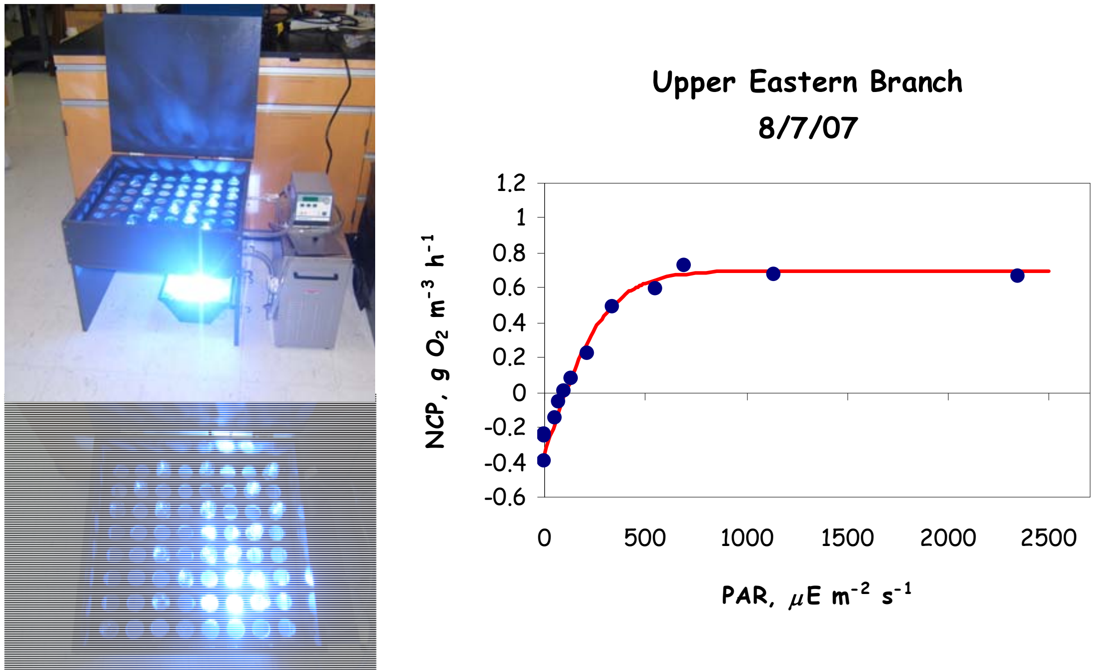


Figure IV.45. Experimental setup (light gradient box) for P-I measurements in 2007-08 and a typical result (blue circles) with a statistically-fit regression (red line). Photosynthesis is expressed as net community production (NCP). Irradiance is expressed as photosynthetically active radiation (PAR).

CHAPTER V. MODEL CALIBRATION

The hydrodynamic and water quality models applied to the Lynnhaven River system were developed using the framework outlined in Chapter III. The calibration is a process by which the performance parameters are constrained by comparing with the field measured observations. For example, the bottom friction parameters were adjusted during the calibration process. A calibration assures that the model will produce results that meet or exceed some defined criteria with a specified degree of confidence. The hydrodynamic model was calibrated with observed surface elevations and velocities using historical data and VIMS hydrodynamic survey data collected in November 2005. The water quality model was calibrated using the 2006 DEQ data and validated over the years 2004 and 2005, during which period both the freshwater discharge and the non-point source loading data were provided by the HSPF watershed model developed for the Lynnhaven by URS Corporation.

V-1 Calibration of the Hydrodynamic Model

The model calibration for the Lynnhaven River used NOAA historical tide data of the late 1970s, NOAA tide prediction data at locations in both the Eastern and Western branches, and short-term velocity measurements taken in the Broad Bay branch in 2003, providing an early view of the model's ability to reproduce the system's hydrodynamics. However, VIMS later decided to conduct a systematic, high-frequency hydrodynamic survey, measuring water elevations inside the inlet synoptically with representative currents and salinities in each branch as well as outside of the Inlet (see Section IV-2-A for a full description of the VIMS Lynnhaven hydrodynamic survey). With these data in hand, validation then consisted of a real-time simulation of the prototype condition for the period November 1 to November 30, 2005. The validation of the hydrodynamic model is described in Chapter VI.

V-1-1 Boundary conditions

For the application of the UnTRIM hydrodynamic model to the Lynnhaven, it was necessary to specify both downstream and upstream boundary conditions. The downstream boundary conditions consisted of specifications of time series of surface elevation and salinity along the row of grid cells at the northern extent of the model grid outside of the Inlet, as shown in Figure V.1. These data were measured at the NOAA facility at the nearby Chesapeake Bay Bridge Tunnel (CBBT), and the surface elevation boundary specification was adjusted for phase by comparing the CBBT record with that from the Kiptopeke primary NOAA station on the Eastern Shore.

Of the 3 Lynnhaven branches, only the Eastern Branch extends beyond the terminus of the watershed region discussed earlier in Section III-5. Therefore, specification of the upstream boundary condition of surface elevation was based on time series of surface elevations recorded at Creeds, VA (i.e., connecting to the southeastern end of the Eastern Branch).

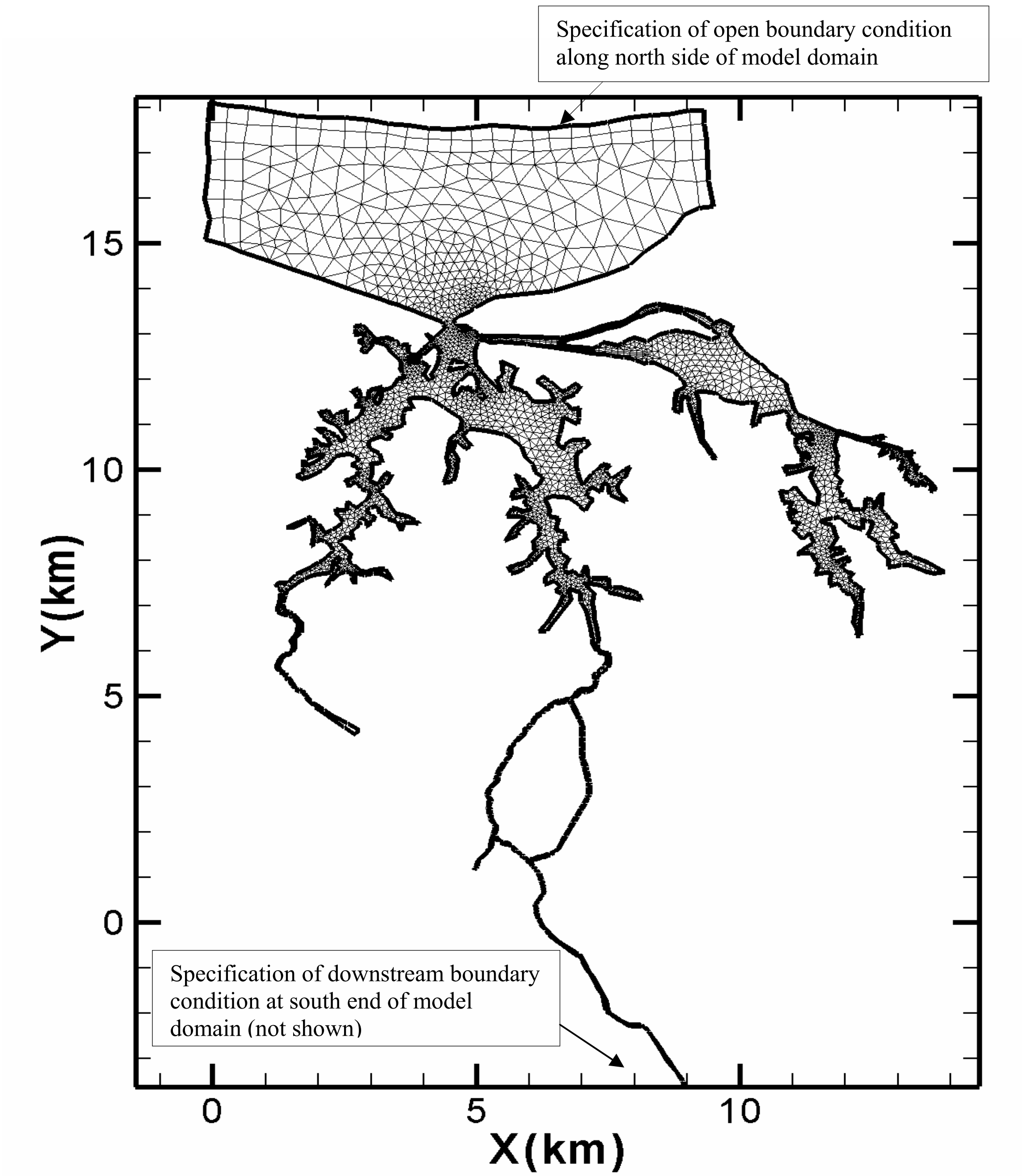


Figure V.1. Locations of boundary condition specifications for Lynnhaven River models

However, the period of measurement of surface elevation at Creeds, VA (2006) differed from the period required for calibration. In the upstream areas of the Eastern Branch, the flow direction is controlled by wind direction as well as tide. For that reason, VIMS performed a correlation between time series of the 2006 CBBT high-frequency wind and the 2006 Creeds, VA surface elevations. The results of this correlation are shown in Figure V.2. Using a relationship based on this correlation, it was then possible to generate a water surface time series specification for the upstream boundary condition of the model at Creeds, VA. An example of the estimated upstream boundary condition is shown in Figure V.3.

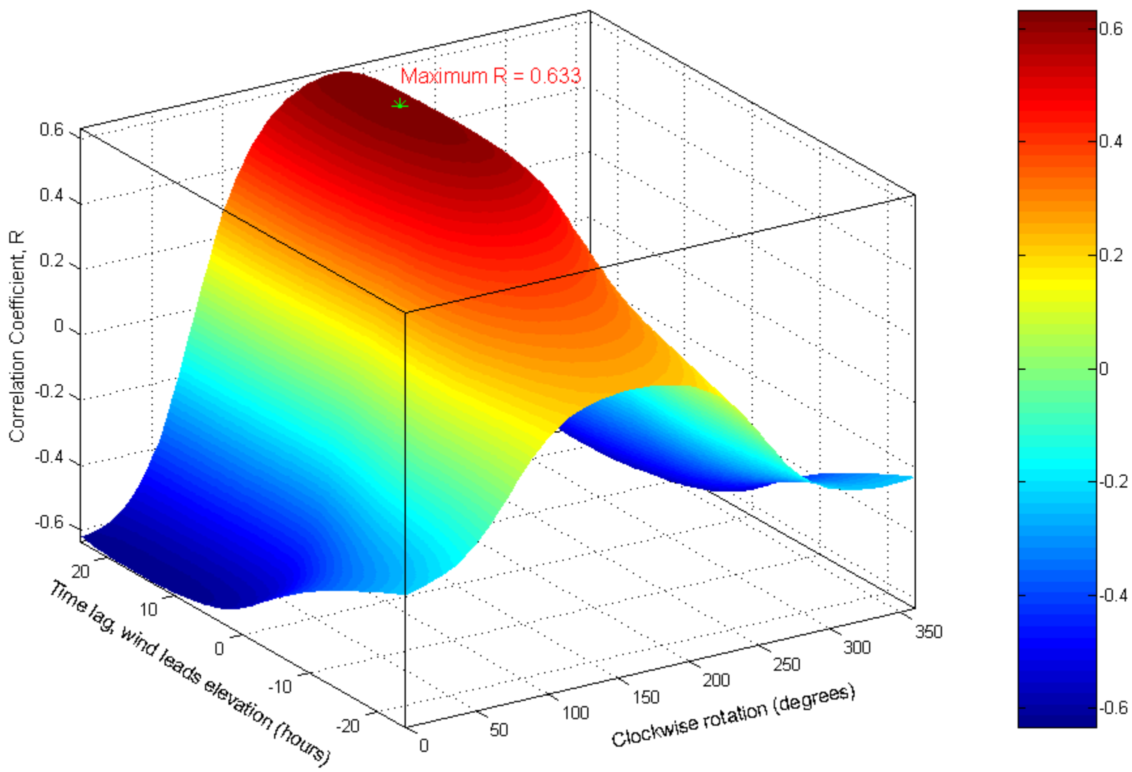


Figure V.2. Correlation of CBBT wind speed with Creeds, VA surface elevation.

V-1-2 External loading

There are no USGS gauges recording freshwater inflow to any of the Lynnhaven branches. For this reason, the VIMS hydrodynamic model was entirely dependent upon the URS watershed model for its freshwater discharge inputs. As discussed in Section III-5, the URS model included hourly freshwater discharge values at each catchment site along with its non-point source loadings.

V-1-3 Calibration for tidal elevation

The astronomical tide accounts for about 80 % of the energy of water surface fluctuations in the Lynnhaven River system. Therefore an accurate reproduction of the tidal wave propagation in the Lynnhaven River is of the utmost importance. Furthermore, once the model is calibrated with respect to astronomical tide, a minimum of additional adjustment is required for calibrations of surface elevation and current velocity.

Preliminary testing of the UnTRIM capability to simulate the propagation of tide was performed prior to the inception of the project, and a thorough search for historical tide data in the Lynnhaven led to a set of 6 stations spanning from outside the Inlet through

Broad Bay and lastly Linkhorn Bay. The locations of these stations are shown in Figure V.4. Measurements at these 6 stations occurred in the late 1970s, but they were synoptic! Tidal propagation in an estuary is controlled by river geometry and frictional dissipation of energy. With river geometry and average tidal range at the open boundary given, we used the distribution of tidal range as a function of distance along the Broad Bay/Linkhorn Bay to calibrate against the roughness height, the model parameter for bottom friction. Figure V.5 shows the comparison of both amplitudes and phase lags of modeled and measured values of the primary tidal constituent (i.e., M_2) at Stations T2 through T6.

The top panel of Figure V.5 shows that dampening of the M_2 tidal amplitude from approximately 0.35 m at the Inlet to approximately 0.18 m at the head of Linkhorn Bay. It can be seen in Figure V.5 that the modeled vs. measured comparison of amplitude is within 2 cm at all 6 stations.

The lower panel of Figure V.5 shows a tidal phase lag of approximately 2.5 hours moving from the Inlet to the head of Linkhorn Bay. The modeled vs. measured phase difference is within a few minutes at all 6 stations.

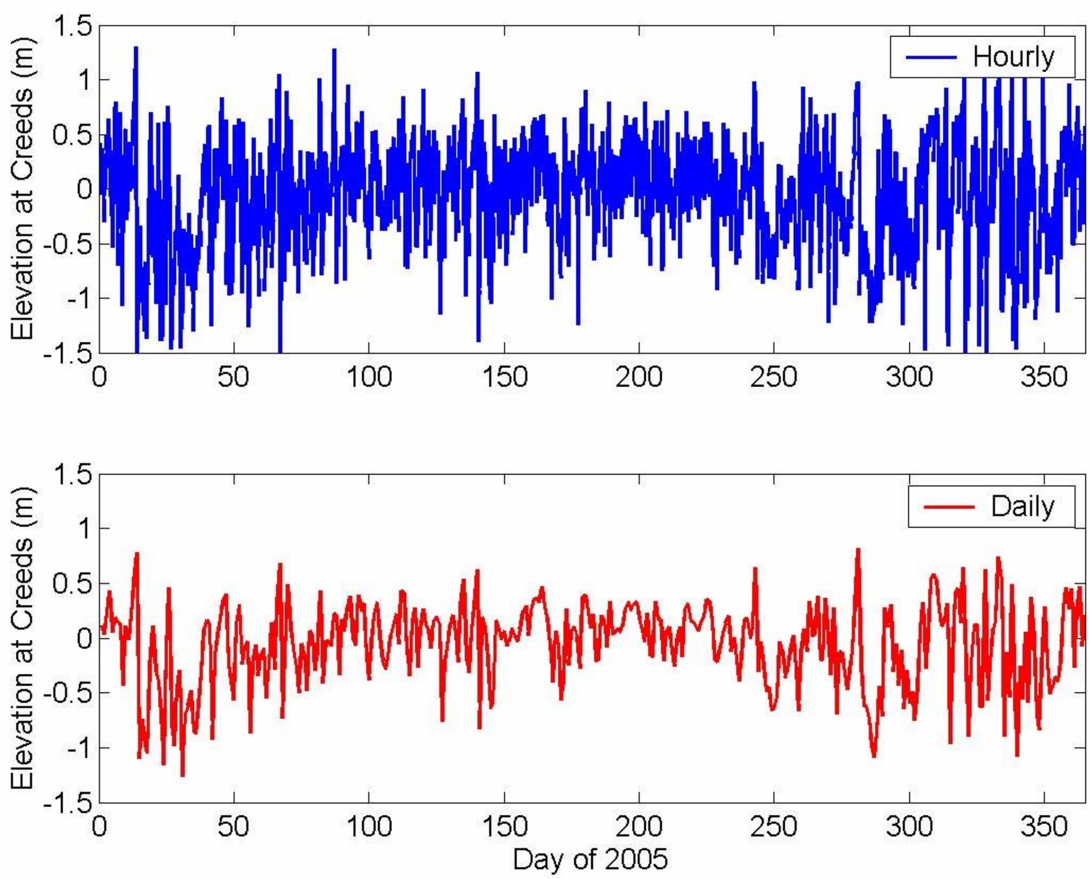


Figure V.3. Constructed series of 2005 surface elevations used for upstream boundary.

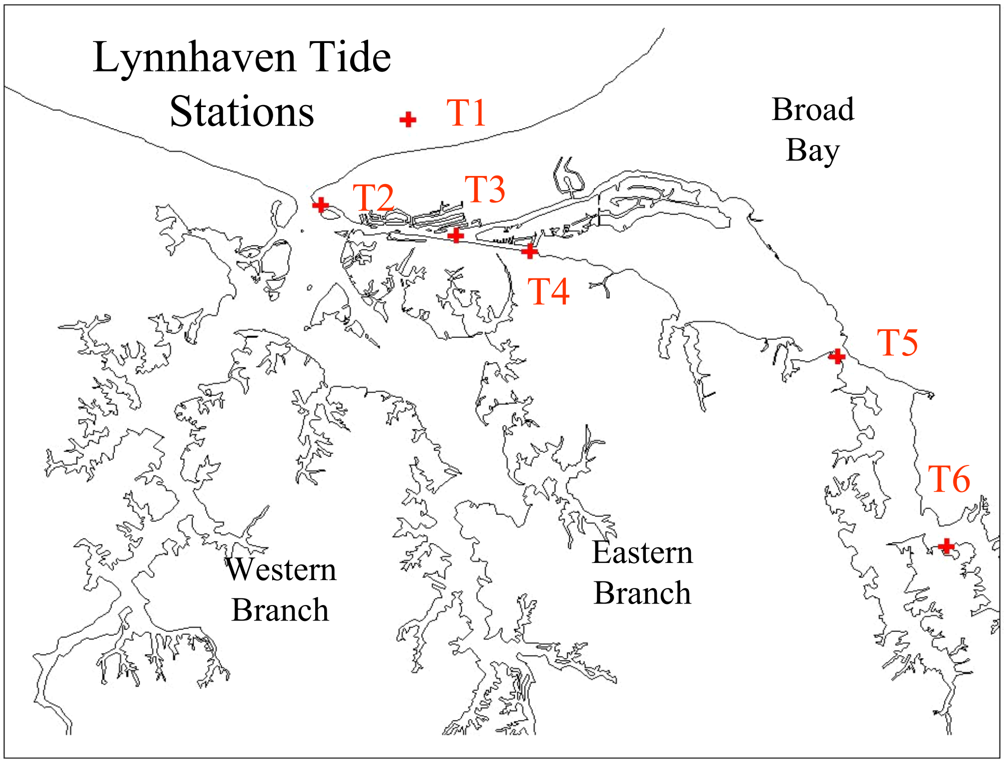


Figure V.4. Locations of NOAA tide stations monitored in the Lynnhaven in the late 1970s.

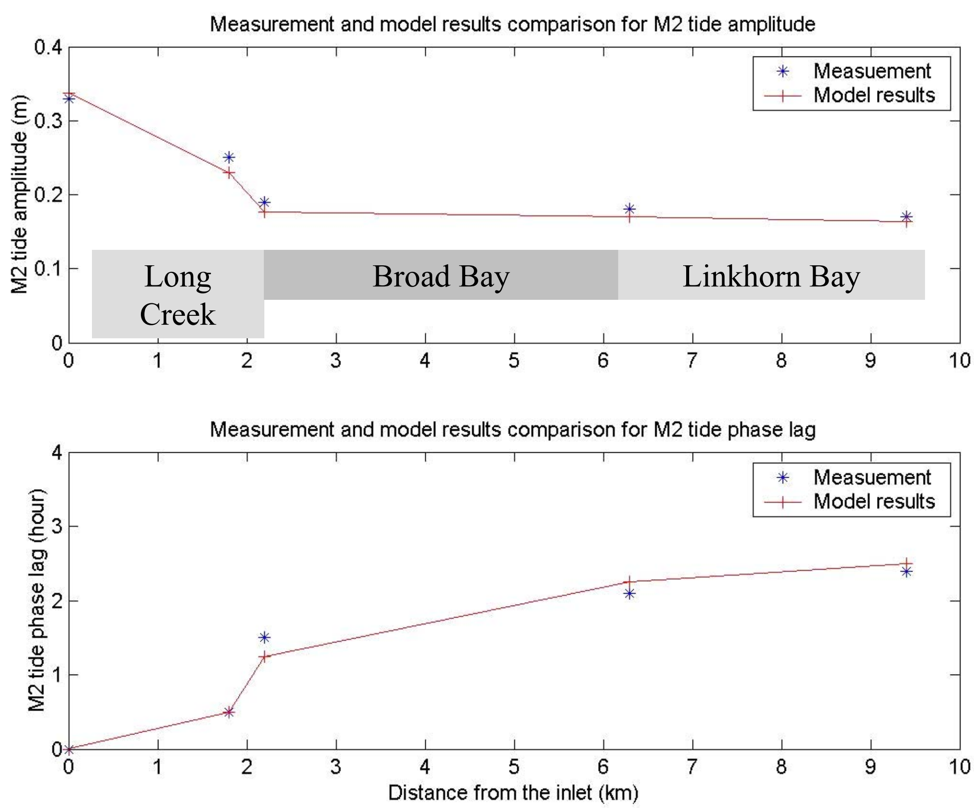


Figure V.5. Comparison of modeled and measured M_2 amplitudes and phases in the Broad Bay/Linkhorn Bay Branch of the Lynnhaven.

Early efforts to calibrate the tides in the Broad Bay/Linkhorn Bay Branch using the CBBT 6-minute tides as an open boundary resulted in good comparisons between prediction of the UnTRIM model and the 1977 NOAA observed tides. Real-time comparisons at Stations T2 through T6 are shown in Figure V.6 below.

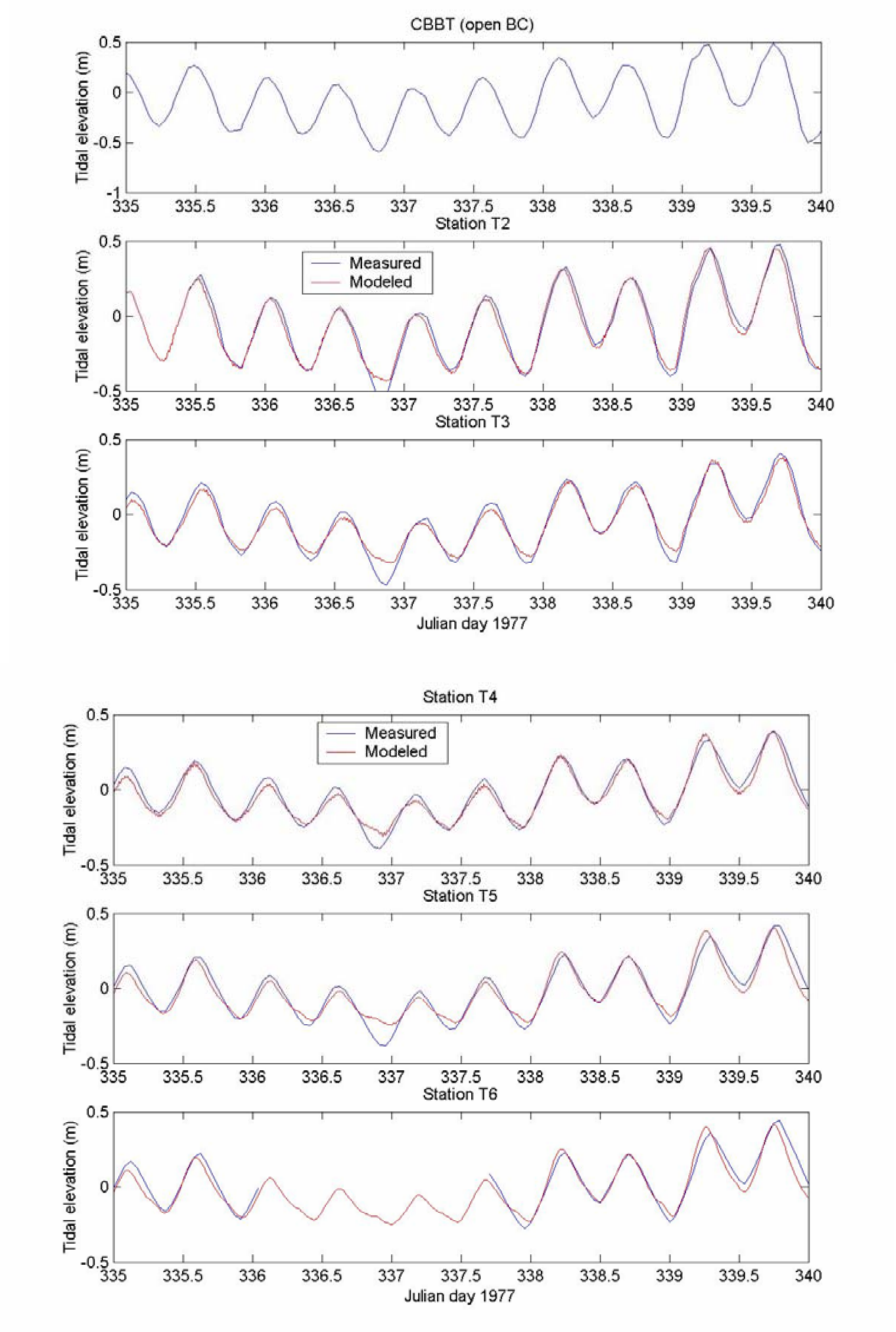


Figure V.6. Real-time comparisons of UnTRIM predictions and NOAA water surface observations.

Table V.1. UnTRIM Modeled Tide Predictions versus Tide Table Predictions in Lynnhaven River Eastern and Western Branches.

Station		Tide Range (m)	High tide phase (minutes later than Inlet)	Low tide phase (minutes later than Inlet)
Bayville Creek (Western Br.)	Tide Tables	0.518	59	97
	Model Results	0.518	60	99
Buchanan Creek (Western Br.)	Tide Tables	0.579	69	105
	Model Results	0.578	63	115
Brown Cove (Eastern Br.)	Tide Tables	0.518	55	97
	Model Results	0.554	45	78

Whereas no historical data could be found in either the Western or Eastern Branches, the published NOAA Tide Tables did provide predictions at 2 locations in the Western Branch (Bayville Creek and Buchanan Creek) and 1 location in the Eastern Branch (Brown Cove) for both tidal range and phase lag from the Inlet. These predictions were compared with results from the model when driven by average tidal range with no discharge or wind specifications, and are shown in Table V.1.

V-1-4 Calibration for velocity

In conjunction with early attempts to calibrate the model for tide, 2 locations were measured for velocity in October, 2003. ADCP instruments were deployed at 2 locations bounding the Long Creek portion of Broad Bay, as shown in Figure V.7 below.

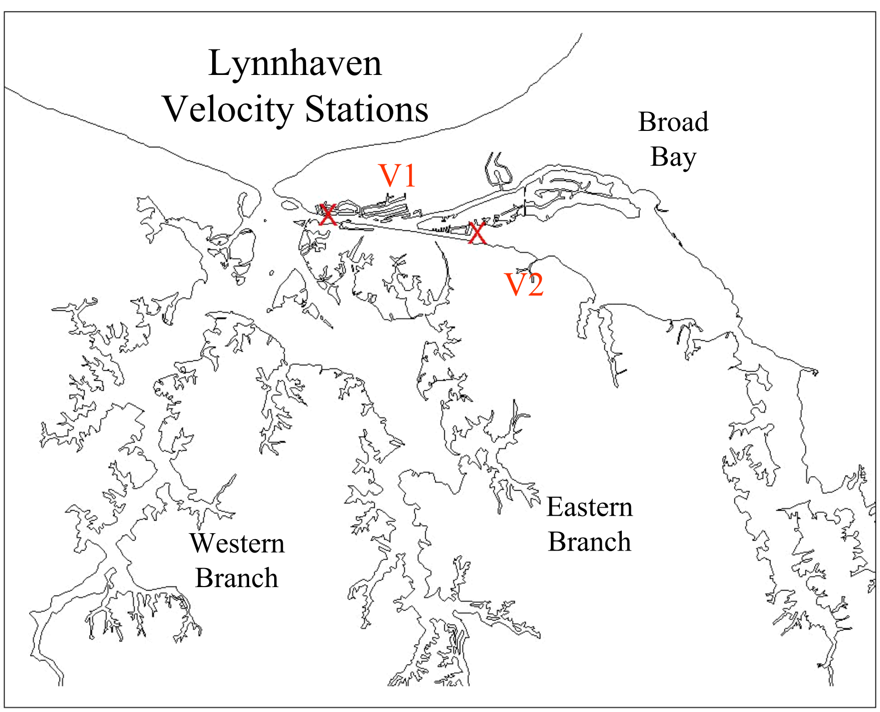


Figure V.7. Locations of Lynnhaven Velocity ADCP Stations, October 2003.

These ADCP measurements were high-frequency (measurements every 60 seconds). Whereas the deployments were of short duration (less than 2 days), they were sufficient in length to confirm the predictive capability of the UnTRIM model for velocity. The comparisons of measured and modeled velocities are shown in Figures V.8 and V.9, respectively, for Stations V1 and V2.

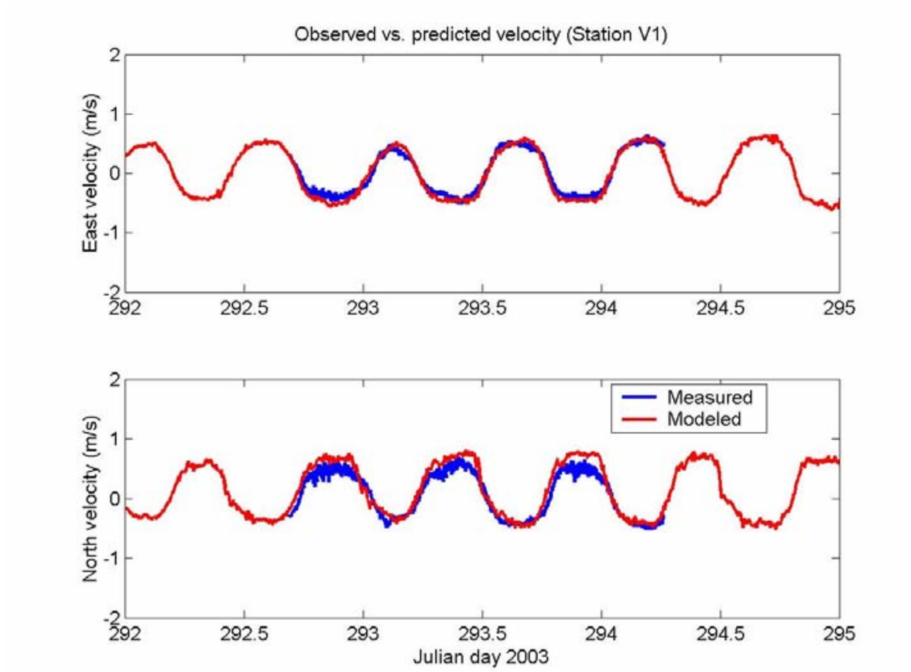


Figure V.8. East-west and north-south components of measured versus modeled velocity at Station V1 of Long Creek, Lynnhaven.

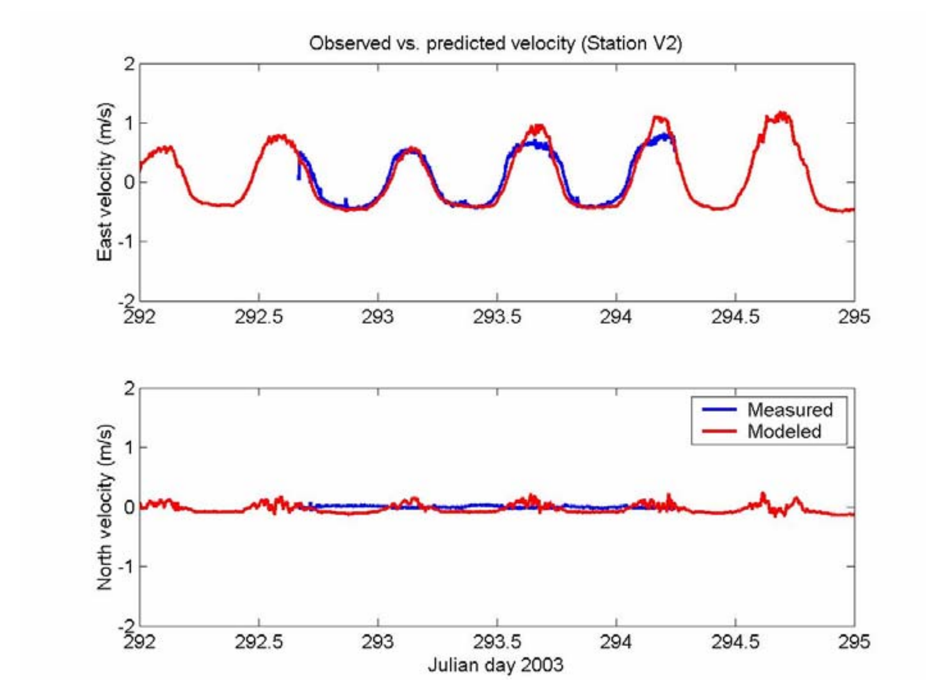


Figure V.9. East-west and north-south components of measured versus modeled velocity at Station V2 of Long Creek, Lynnhaven.

V-1-5 Calibration for salinity

In an estuary, freshwater originating from inland river sources encounters the salt water coming from the ocean to produce the longitudinal salinity gradient. The baroclinic pressure gradient generated from the fresh water at the upstream of the estuary and the salt water at the downstream then serves as the major driving force for the gravitational circulation, in which the freshwater flows seaward while the salt water flows landward. When freshwater overlays salt water, the vertical profile of salinity exhibits stratification as a result of the density difference from surface to bottom. The turbulent mixing induced by forces such as tide, wind, surface waves, internal waves and internal current shear, on the other hand, tends to homogenize property gradients in the water column both in the vertical and the horizontal direction. This turbulent activity thus counter-acts the stratification produced by the buoyancy forces.

In order to calibrate salinity predicted by the UnTRIM hydrodynamic model, comparisons between measurements and model predictions were made at all 16 VA-DEQ stations monitored every other month in the Lynnhaven River throughout calendar year 2006. The locations of these stations are shown below in Figure V.10.

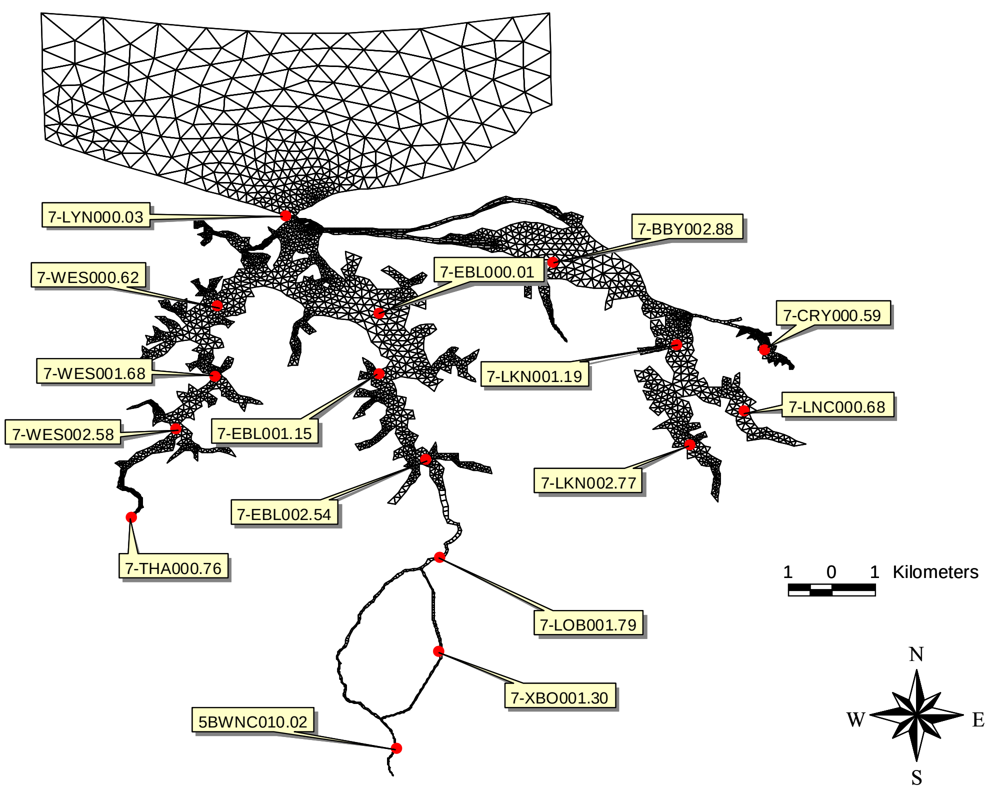


Figure V.10. Locations of Lynnhaven DEQ stations used to compare measured and modeled salinity, temperature, and water quality parameters.

Each estuary has its own shoreline, topography, hydrology, freshwater inputs, and turbulent mixing pattern; the salinity distributions are thus different from one another. By carefully examining the salinity pattern, the characteristics of the estuary can be revealed and classified. Salinity is also an excellent natural tracer due to its conservative property. All in all, salinity is an important parameter for estuarine hydrodynamics and thus is selected to assess the performance of the estuarine hydrodynamic model. In this study, salinity time series and spatial distributions are presented from prototype measurement and compared with the model simulation results.

Measured salinity data also included those made by the VIMS dataflow surveys during this period (please note that the dataflow coverage did not extend to all 16 stations). The modeled vs. measured salinities for 2006 are shown in Figures V.11 through V.13 for comparison at DEQ stations in the Western, Eastern, and Broad Bay /Linkhorn Bay Branches, respectively. It is noted that the model predictions shown in Figures V.11 through V.13 are represented by a gray band bounded by the minimum and maximum daily predictions of salinity at each specified Lynnhaven DEQ station.

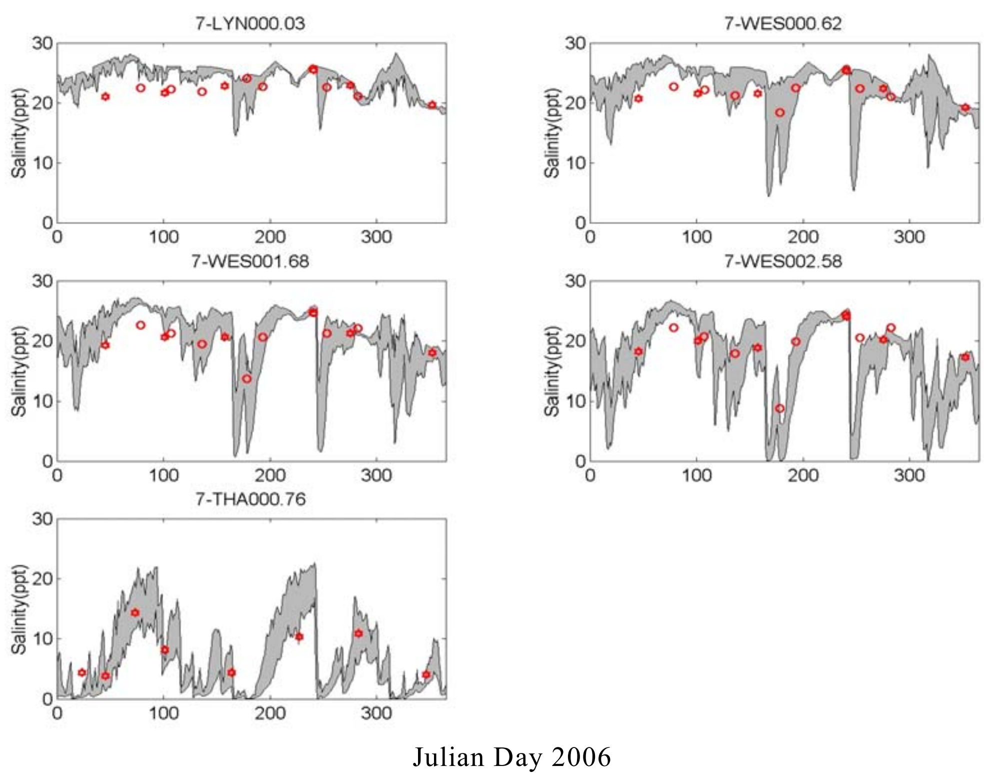


Figure V.11. UnTRIM modeled versus measured salinities at Western Branch DEQ stations for 2006. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

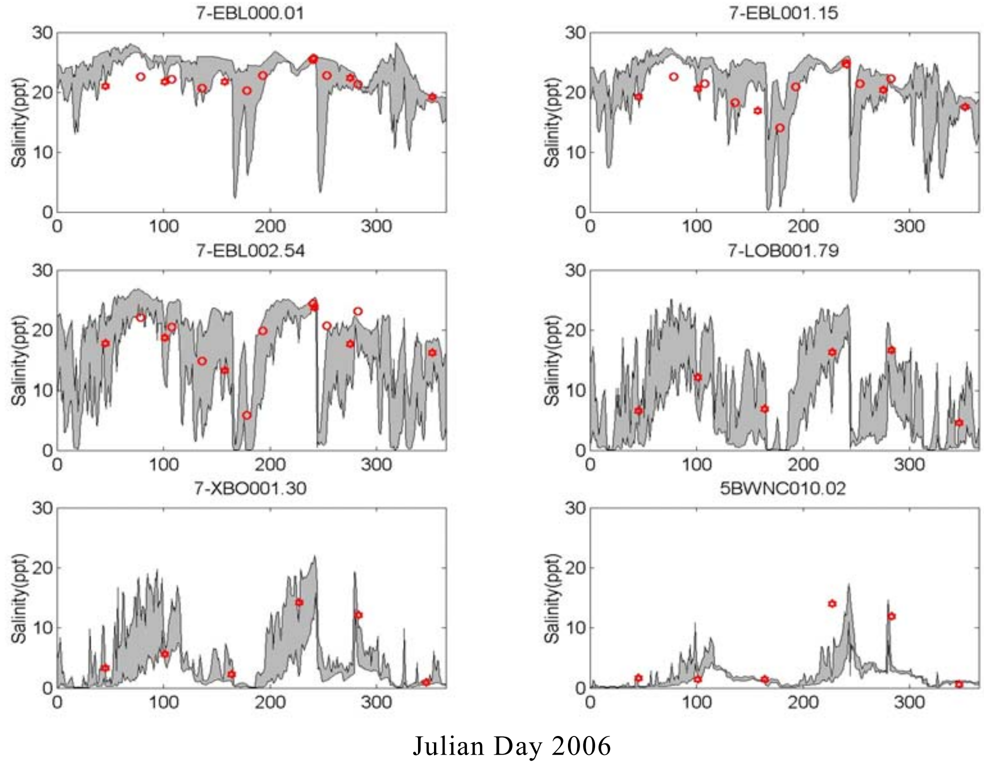


Figure V.12. UnTRIM modeled versus measured salinities at Eastern Branch DEQ stations for 2006. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

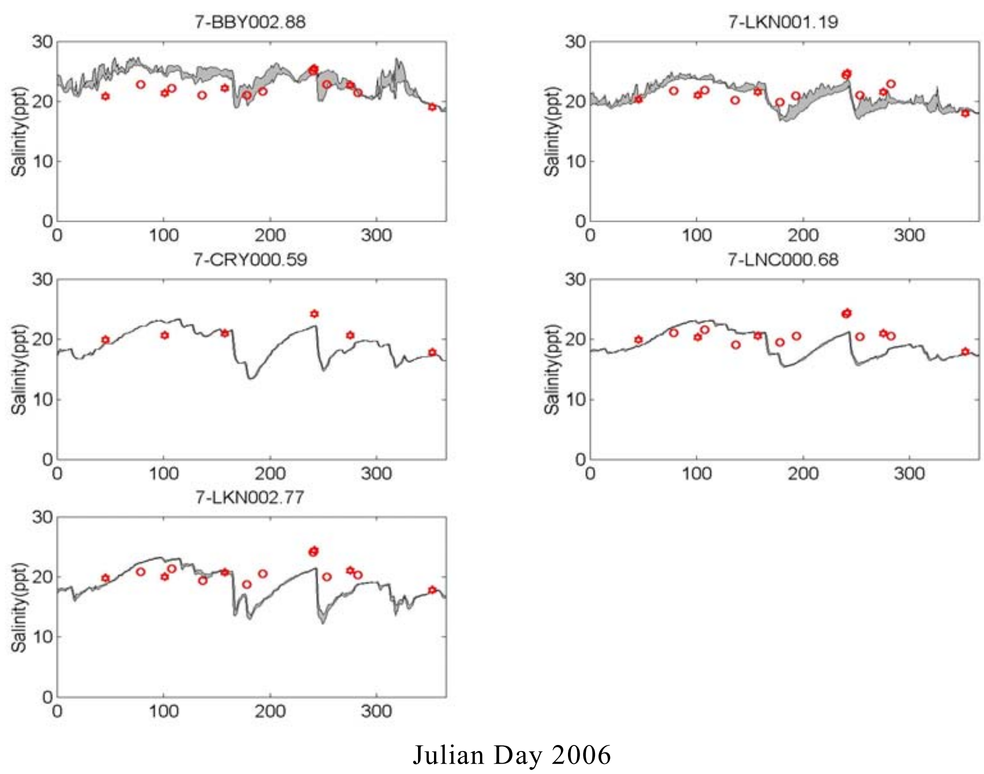


Figure V.13. UnTRIM modeled versus measured salinities at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

V-1-6 Calibration for temperature

The modeled vs. measured water temperatures for 2006 are shown in Figures V.14 through V.16 for comparison at DEQ stations in the Western, Eastern, and Broad Bay /Linkhorn Bay Branches, respectively.

Modeling of water temperatures is an essential part of the overall water quality modeling effort due to the critical role that temperature plays in the kinetics for all other state variables. As can be seen in Figures V.14 through V.16, water temperatures in the Lynnhaven show a wide seasonal variation from about 5 degrees Celsius in the winter to approximately 25 degrees Celsius in the summer.

Figures V.14 through V.16 show excellent agreement between predicted and observed water temperatures throughout the domain, with some small discrepancies at the most headland stations (e.g., 7-THA000.76 at the head of the Western Branch and 7-LKN002.77 in the upper Linkhorn Bay).

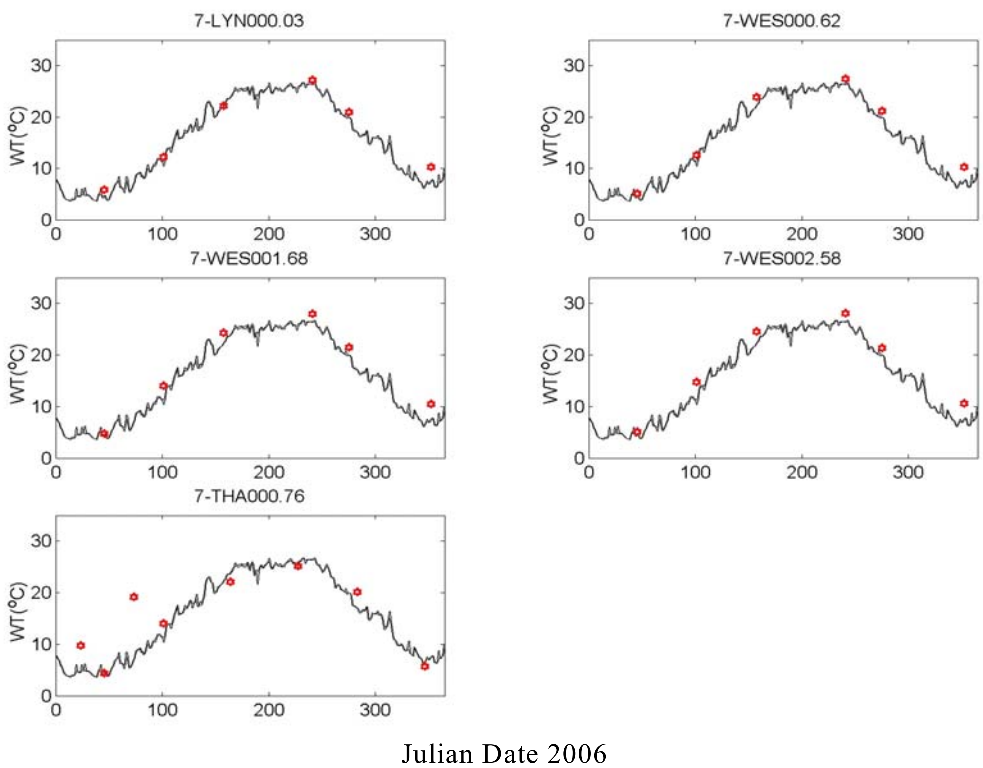


Figure V.14. UnTRIM modeled versus measured temperatures at Western Branch DEQ stations for 2006.

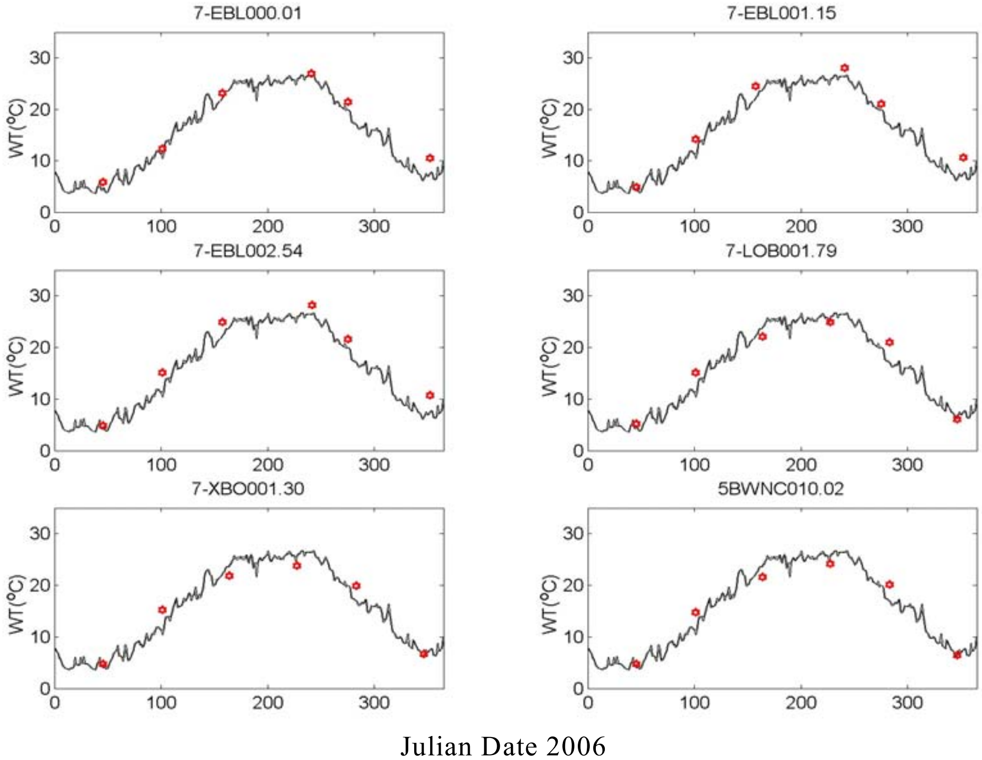


Figure V.15. UnTRIM modeled versus measured temperatures at Eastern Branch DEQ stations for 2006.

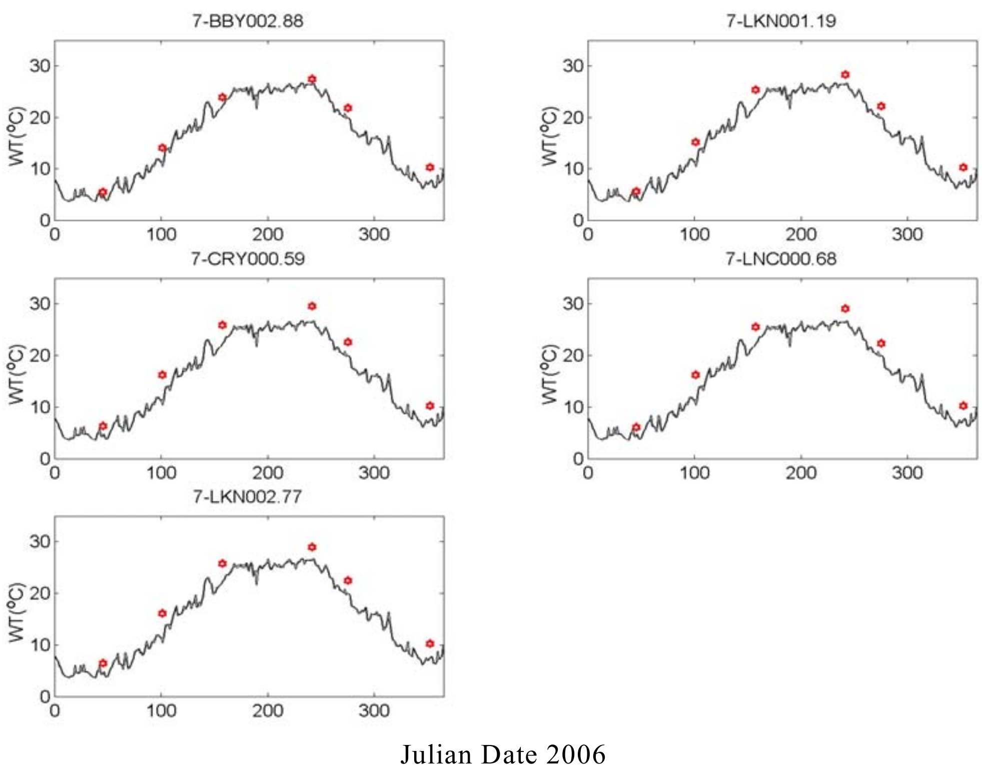


Figure V.16. UnTRIM modeled versus measured temperatures at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

V-2 Calibration of Water Quality Model

The overall objective of the model calibration is to tune the water quality model to the observed data utilizing a set of model coefficients and parameters that are consistent with field measurements and are within the general ranges of values accepted by the modeling community as reported in the literature.

The main steps involved in the calibration of the water quality model are: the appropriate boundary condition has to be chosen, the verified external nutrient loads have to be included, the correct initial condition has to be specified, and the suitable parameter values have to be estimated.

V-2-1 Boundary condition

As was done for the salinity calibration, the water quality monitoring data from Stations CB8.1 and CB8.1E of the Chesapeake Bay Program (CBP) were used for the water quality open boundary condition (Figure V.17). The monthly water quality parameters at both the surface and bottom are available from 1984 to present. Table V.11 shows the parameters measured.

The data from CBP Stations 8.1 and 8.1E are available semi-monthly during the period from spring to fall and monthly during the winter at both the surface and bottom. The middle layers were specified from the linear interpolation between the layers which were measured. The daily values were interpolated between the measured period either semi-monthly or monthly. The present water quality model is configured such that the freshwater discharge and nutrient loadings input are specified as lateral input. The open boundary condition for the hydrodynamic model was forced by the averaged measured tide of the NOAA tidal station at the Chesapeake Bay Bridge Tunnel.

V-2-2 External loading

There is no point source input into the Lynnhaven River. The nonpoint nutrient loadings from the watershed discharged to the Lynnhaven River were obtained from the watershed model developed by URS Corporation of Virginia Beach (see Chapter III, Section III-5). Nonpoint source loads enter the water quality model through specification of the loading at model grid cells adjacent to the land. The procedure involves mapping of the hydrodynamic model grid with watershed catchment areas adjacent to the receiving waters. These nonpoint source inputs are specified at the surface of the model cell at the location of discharge. The external nutrient loads also include the atmospheric loads that are generated by the watershed model and are specified at each surface cell of the model. The time increment for loading input from the watershed model is hourly.

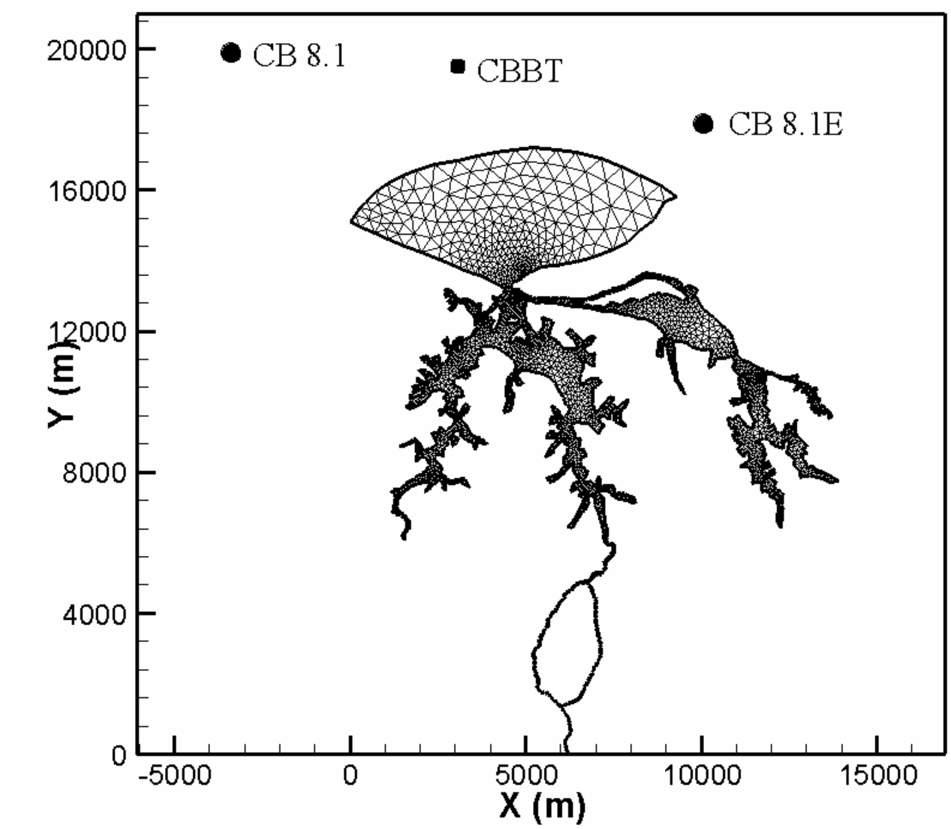


Figure V.17. Locations of CBP Stations CB8.1 and CB8.1E to the northeast and northwest of Lynnhaven River model domain (from Li (2006)).

V-2-3 Initial condition

For an initial simulation, an initial condition was specified as the long-term averaged data measured by DEQ, interpolated spatially. Within the Lynnhaven, the initial condition for each cell was specified through linear interpolation between two adjacent DEQ stations. Since only surface water data are available, the same value was specified for each layer vertically for those cells. Outside of the Lynnhaven, the initial condition was specified based on the linear interpolation between DEQ Station 7-LYN000.03 and CBP Station CB8.1. Upon attaining dynamic equilibrium, the values of all computed model cell output from prior model results were used to specify a suitable initial condition.

V-2-4 Estimation of parameters

Most of the parameters in the CE-QUAL-ICM water quality model were adopted from the default parameters for the Chesapeake Bay (Cerco and Cole, 1994). The parameters used in the water column of this study are listed in Tables V.4 to V.9. The modification of parameters depended on the comparison with measured data or unique features of the Lynnhaven. The remaining parameters used in the sediment flux are listed in Table V.10.

Table V.2. Model state variables in the eutrophication water quality model

Parameter	symbol
Temperature	T
Salinity	S
Total Suspended Solids	TSS
Cyanobacteria	B_c
Diatoms	B_d
Green Algae	B_g
Refractory Particulate Organic Carbon	RPOC
Labile Particulate Organic Carbon	LPOC
Dissolved Organic Carbon	DOC
Refractory Particulate Organic Nitrogen	RPON
Labile Particulate Organic Nitrogen	LPON
Dissolved Organic Nitrogen	DON
Ammonium Nitrogen	NH_4
Nitrate+nitrite Nitrogen	NO_3
Refractory Particulate Organic Phosphorus	RPOP
Labile Particulate Organic Phosphorus	LPOP
Dissolved Organic Phosphorus	DOP
Total Phosphate	PO_4t
Particulate Biogenic Silica	SU
Available Silica	SA
Chemical Oxygen Demand	COD
Dissolved Oxygen	DO

Table V.3. Model state variables and fluxes in the benthic sediment flux model

Parameters
particulate organic carbon in Layer 2 (G_1, G_2 and G_3 classes)
particulate organic nitrogen in Layer 2 (G_1, G_2 and G_3 classes)
particulate organic phosphorus in Layer 2 (G_1, G_2 and G_3 classes)
particulate biogenic silica in Layer 2
sulfide (salt water) or methane (fresh water) in Layers 1 and 2
ammonium nitrogen in Layers 1 and 2
nitrate nitrogen in Layers 1 and 2
phosphate phosphorus in Layers 1 and 2
available silica in Layers 1 and 2
ammonium nitrogen flux
nitrate nitrogen flux
phosphate flux
silica flux
sediment oxygen demand
release of chemical oxygen demand
sediment temperature
benthic microalgae

Table V.4. Parameters related to algae in the water column

parameter	description	value	units
PM_c	maximum growth rate of algae group 1	250	g C g^{-1} Chl d^{-1}
PM_d	maximum growth rate of algae group 2	300	g C g^{-1} Chl d^{-1}
PM_g	maximum growth rate of algae group 3	300	g C g^{-1} Chl d^{-1}
KHN_x	half-saturation constant of N uptake by algae	0.01	g N m^{-3}
KHP_x	half-saturation constant of P uptake by algae	0.001	g P m^{-3}
KHS	half-saturation constant of Si uptake by diatoms	0.05	g Si m^{-3}
KHRx	half-saturation constant of DO for algal excretion of DOC	0.5	g O_2 m^{-3}
α_c	initial slope of production vs. irradiance relationship for algal group 1	8	g C g^{-1} Chl $(E\ m^{-2})^{-1}$
α_d	initial slope of production vs. irradiance relationship for algal group 2	8	g C g^{-1} Chl $(E\ m^{-2})^{-1}$
α_g	initial slope of production vs. irradiance relationship for algal group 3	8	g C g^{-1} Chl $(E\ m^{-2})^{-1}$
a_1	background light attenuation coefficient	0.735	m^{-1}
a_2	light attenuation coefficient due to total suspended solid	0.018	m^2 per g TSS
a_3	light attenuation coefficient due to algae	0.06	m^2 per mg CHL
$CCHL_x$	C-to-CHL ratio in algae	60.0	g C per g CHL
TM_c	optimum T for algal group 1 growth	29.0	°C
TM_d	optimum T for algal group 2 growth	16.0	°C
TM_g	optimum T for algal group 3 growth	25.0	°C
$KTG1_c$	effect of T below optimum T on algal Group 1 growth	0.006	$°C^{-2}$
$KTG2_c$	effect of T above optimum T on algal Group 1 growth	0.006	$°C^{-2}$
$KTG1_d$	effect of T below optimum T on algal Group 2 growth	0.004	$°C^{-2}$
$KTG2_d$	effect of T above optimum T on algal Group 2 growth	0.006	$°C^{-2}$
$KTG1_g$	effect of T below optimum T on algal Group 3 growth	0.012	$°C^{-2}$
$KTG2_g$	effect of T above optimum T on algal Group 3 growth	0.007	$°C^{-2}$
BMR_c	basal metabolism rate of algae group 1 at reference T	0.02	day^{-1}
BMR_d	basal metabolism rate of algae group 2 at reference T	0.04	day^{-1}
BMR_g	basal metabolism rate of algae group 3 at reference T	0.02	day^{-1}
PRR_c	predation rate of algae group 1 at reference T	0.02	day^{-1}
PRR_d	predation rate of algae group 2 at reference T	0.15	day^{-1}
PRR_g	predation rate of algae group 3 at reference T	0.25	day^{-1}
KTB_x	effect of T on basal metabolism of algae	0.069	$°C^{-1}$
TR_x	reference T for basal metabolism of algae	20.0	°C
WS_c	settling velocity for algal group 1 0.1	m day^{-1}	

Table V.4 (cont'd)

WS_d	settling velocity for algal group 2	0.2	m day^{-1}
WS_g	settling velocity for algal group 3	0.1	m day^{-1}

Table V.5. Parameters related to organic carbon in the water column

Parameters	description	value	units
FCRP	fraction of predated algal C produced as RPOC	0.20	none
FCLP	fraction of predated algal C produced as LPOC	0.65	none
FCDP	fraction of predated algal C produced as DOC	0.15	none
FCD_x	fraction of metabolized C by algae produced as DOC	0.0	none
KHR_x	half-saturation constant of DO for algal excretion of DOC	0.5	g O_2 m^{-3}
KHO_{DOC}	half-saturation constant of DO for oxic respiration of DOC	0.5	g O_2 m^{-3}
K_{RC}	minimum respiration rate of RPOC	0.005	day^{-1}
K_{LC}	minimum respiration rate of LPOC	0.075	day^{-1}
K_{DC}	minimum respiration rate of DOC	0.020	day^{-1}
K_{Rcalg}	constant relating respiration of RPOC to algal biomass	0.0	day^{-1} per g C m^{-3}
K_{Lcalg}	constant relating respiration of LPOC to algal biomass	0.0	day^{-1} per g C m^{-3}
K_{Dcalg}	constant relating respiration of DOC to algal biomass	0.0	day^{-1} per g C m^{-3}
KT_{HDR}	effect of T on hydrolysis/ mineralization of POM/DOM	0.069	$°C^{-1}$
KT_{MNL}	effect of T on hydrolysis/ mineralization of POM/DOM	0.069	$°C^{-1}$
TR_{HDR}	reference T for hydrolysis of POM	20.0	°C
TR_{MNL}	reference T for mineralization of DOM	20.0	°C
$KHNDN_N$	half-saturation constant of NO_{23} for denitrification	0.1	g N m^{-3}
AANOX	ratio of denitrification to oxic DOC respiration rate	0.5	none

Table V.6. Parameters related to nitrogen in the water column

Parameters	description	value	units
FNRP	fraction of predated algal N produced as RPON	0.15	none
FNLP	fraction of predated algal N produced as LPON	0.25	none
FNDP	fraction of predated algal N produced as DON	0.20	none
FNIP	fraction of predated algal N produced as NH_4	0.40	none
FNR	fraction of metabolized algal N produced as RPON	0.05	none
FNL	fraction of metabolized algal N produced as LPON	0.20	none
FND	fraction of metabolized algal N produced as DON	0.20	none
FNI	fraction of metabolized algal N produced as NH_4	0.55	none
ANC_{min}	minimum N-to-C ratio in algae	0.135	g N per g C
ANC_{max}	maximum N-to-C ratio in algae	0.20	g N per g C
ANDC	mass of NO_{23}-N consumed per mass DOC oxidized	0.933	g N per g C
K_{RN}	minimum hydrolysis/mineralization rate of RPON	0.005	day^{-1}
K_{LN}	minimum hydrolysis/mineralization rate of LPON	0.075	day^{-1}
K_{DN}	minimum hydrolysis/mineralization rate of DON	0.015	day^{-1}
K_{Rnalg}	constant relating hydrolysis/mineralization of RPON to algal biomass	0.0	day^{-1} per g N m^{-3}
K_{Lnalg}	constant relating hydrolysis/mineralization of LPON to algal biomass	0.0	day^{-1} per g N m^{-3}
K_{Dnalg}	constant relating hydrolysis/mineralization of DON to algal biomass	0.0	day^{-1} per g N m^{-3}
$KHDO_{NIT}$	half-saturation constant of DO for nitrification	1.0	g O_2 m^{-3}
KHN_{NIT}	half-saturation constant of NH_4 for nitrification	1.0	g N m^{-3}
NT_M	maximum nitrification at optimum T	0.007	day^{-1}
KT_{NT1}	effect of T below optimum T on nitrification rate	0.0045	$°C^{-2}$
KT_{NT1}	effect of T above optimum T on nitrification rate	0.0045	$°C^{-2}$
TM_{NT}	optimum T for nitrification rate	27.0	°C

Table V.7. Parameters related to phosphorus in the water column

Parameter	description	value	units
FPRP	fraction of predated algal P produced as RPOP	0.03	none
FPLP	fraction of predated algal P produced as LPOP	0.07	none
FPDP	fraction of predated algal P produced as DOP	0.40	none
FPIP	fraction of predated algal P produced as DIP	0.50	none
FPR_x	fraction of metabolized P by algae produced as RPOP	0.0	none
FPL_x	fraction of metabolized P by algae produced as LPOP	0.0	none
FPD_x	fraction of metabolized P by algae produced DOP	0.25	none
FPI_x	fraction of metabolized P by algae produced DOP	0.75	none
APCMIN	minimum P-to-C ratio in algae	0.0125	g P per g C
APCMAX	maximum P-to-C ratio in algae	0.0175	g P per g C
PO4DMAX	maximum PO4d beyond which APC = APCMAX	0.01	g P m^{-3}
K_{RP}	minimum hydrolysis/mineralization rate of RPOP	0.005	day^{-1}
K_{LP}	minimum hydrolysis/mineralization rate of LPOP	0.075	day^{-1}
K_{DP}	minimum hydrolysis/mineralization rate of DOP	0.1	day^{-1}
K_{Rpalg}	constant relating hydrolysis/ mineralization of RPOP to algal biomass	0.0	day^{-1} per g P m^{-3}
K_{Lpalg}	constant relating hydrolysis/ mineralization of LPOP to algal biomass	0.0	day^{-1} per g P m^{-3}
K_{Dpalg}	constant relating hydrolysis/ mineralization of DOP to algal biomass	0.0	day^{-1} per g P m^{-3}

Table V.8. Parameters related to silica in the water column

Parameter	description	value	units
FSA	fraction of predated diatom Si as SA	0.0	none
ASC_d	Si-to-C ratio in diatoms	0.5	g Si per g C
K_{SU}	dissolution rate of SU at reference T	0.025	day^{-1}
KT_{SUA}	effect of T on dissolution of SU	0.092	$°C^{-1}$
TR_{SUA}	reference T for dissolution of SU	20.0	°C

Table V.9. Parameters related to chemical oxygen demand and dissolved oxygen in the water column

Parameters	description	value	units
KHO_{COD}	half-saturation constant of DO for oxidation of COD	1.5	g O_2 m^{-3}
K_{CD}	oxidation rate of COD at reference temperature	20.0	day^{-1}
KT_{COD}	effect of T on oxidation of COD	0.041	$°C^{-1}$
TR_{COD}	reference T for oxidation of COD	20.0	°C
K_{RDO}	reaeration coefficient	2.4	m day^{-1}
AOCR	mass DO consumed per mass C respired by algae	2.67	g O_2 per g C
AONT	mass DO consumed per mass NH_4-N nitrified	4.33	g O_2 per g N

Table V.10. Parameters used in the sediment flux model

parameter	description	value	units
HSEDALL	depth of sediment	10	cm
DIFFT	heat diffusion coefficient between water column and sediment	0.0018	cm^2 sec^{-1}
SALTSW	salinity for dividing fresh and saltwater for SOD kinetics (sulfide in saltwater or methane in freshwater) and for PO_4 sorption coefficients	1.0	ppt
SALTND	salinity for dividing fresh or saltwater for nitrification/denitrification rates (larger values for freshwater)	1.0	ppt
FRPPH1(1)	fraction of POP in algal group No. 1 routed into G_1 class	0.65	none
FRPPH1(2)	fraction of POP in algal group No. 1 routed into G_2 class	0.255	none
FRPPH1(3)	fraction of POP in algal group No. 1 routed into G_3 class	0.095	none
FRPPH2(1)	fraction of POP in algal group No. 2 routed into G_1 class	0.65	none
FRPPH2(2)	fraction of POP in algal group No. 2 routed into G_2 class	0.255	none
FRPPH2(3)	fraction of POP in algal group No. 2 routed into G_3 class	0.095	none
FRPPH3(1)	fraction of POP in algal group No. 3 routed into G_1 class	0.65	none

Table V.10 (cont'd)

FRPPH3(2)	fraction of POP in algal group No. 3 routed into G_2 class	0.255	none
FRPPH3(3)	fraction of POP in algal group No. 3 routed into G_3 class	0.095	none
FRNPH1(1)	fraction of PON in algal group No. 1 routed into G_1 class	0.65	none
FRNPH1(2)	fraction of PON in algal group No. 1 routed into G_2 class	0.28	none
FRNPH1(3)	fraction of PON in algal group No. 1 routed into G_3 class	0.07	none
FRNPH2(1)	fraction of PON in algal group No. 2 routed into G_1 class	0.65	none
FRNPH2(2)	fraction of PON in algal group No. 2 routed into G_2 class	0.28	none
FRNPH2(3)	fraction of PON in algal group No. 2 routed into G_3 class	0.07	none
FRNPH3(1)	fraction of PON in algal group No. 3 routed into G_1 class	0.65	none
FRNPH3(2)	fraction of PON in algal group No. 3 routed into G_2 class	0.28	none
FRNPH3(3)	fraction of PON in algal group No. 3 routed into G_3 class	0.07	none
FRCPH1(1)	fraction of POC in algal group No. 1 routed into G_1 class	0.65	none
FRCPH1(2)	fraction of POC in algal group No. 1 routed into G_2 class	0.255	none
FRCPH1(3)	fraction of POC in algal group No. 1 routed into G_3 class	0.095	none
FRCPH2(1)	fraction of POC in algal group No. 2 routed into G_1 class	0.65	none
FRCPH2(2)	fraction of POC in algal group No. 2 routed into G_2 class	0.255	none
FRCPH2(3)	fraction of POC in algal group No. 2 routed into G_3 class	0.095	none
FRCPH3(1)	fraction of POC in algal group No. 3 routed into G_1 class	0.65	none
FRCPH3(2)	fraction of POC in algal group No. 3 routed into G_2 class	0.255	none
FRCPH3(3)	fraction of POC in algal group No. 3 routed into G_3 class	0.095	none
KPDIAG(1)	reaction (decay) rates for G_1 class POP at 20°C	0.035	day^{-1}
KPDIAG(2)	reaction (decay) rates for G_2 class POP at 20°C	0.0018	day^{-1}
KPDIAG(3)	reaction (decay) rates for G_3 class POP at 20°C	0.0	day^{-1}
DPTHTA(1)	constant for T adjustment for G_1 class POP decay	1.10	none
DPTHTA(2)	constant for T adjustment for G_2		

Table V.10 (cont'd)

	class POP decay	1.15	none
KNDIAG(1)	reaction (decay) rates for G_1 class PON at 20°C	0.035	day^{-1}
KNDIAG(2)	reaction (decay) rates for G_2 class PON at 20°C	0.0018	day^{-1}
KNDIAG(3)	reaction (decay) rates for G_3 class PON at 20°C	0.0	day^{-1}
DNTHTA(1)	constant for T adjustment for G_1 class PON decay	1.10	none
DNTHTA(2)	constant for T adjustment for G_2 class PON decay	1.15	none
KCDIAG(1)	reaction (decay) rates for G_1 class POC at 20°C	0.035	(day^{-1})
KCDIAG(2)	reaction (decay) rates for G_2 class POC at 20°C	0.0018	(day^{-1})
KCDIAG(3)	reaction (decay) rates for G_3 class POC at 20°C	0.0	(day^{-1})
DCTHTA(1)	constant for T adjustment for G_1 class POC decay	1.10	none
DCTHTA(2)	constant for T adjustment for G_2 class POC decay	1.15	none
KSI	1^{st}-order reaction (dissolution) rate of PSi at 20°C	0.5	day^{-1}
THTASI	constant for T adjustment for PSi dissolution	1.1	none
M1	solid concentrations in Layer 1	0.5	$kg\ l^{-1}$
M2	solid concentrations in Layer 2	0.5	$kg\ l^{-1}$
THTADP	constant for T adjustment for diffusion coefficient for particle mixing	1.117	none
THTADD	constant for T adjustment for diffusion coefficient for dissolved phase	1.08	none
KAPPNH4F	optimum reaction velocity for nitrification in Layer 1 for freshwater	0.20	$m\ day^{-1}$
KAPPNH4S	optimum reaction velocity for nitrification in Layer 1 for saltwater	0.14	$m\ day^{-1}$
THTANH4	constant for T adjustment for nitrification	1.08	none
KMNH4	half-saturation constant of NH_4 for nitrification	1500.0	$mg\ N\ m^{-3}$
KMNH4O2	half-saturation constant of DO for nitrification	1.0	$g\ O_2\ m^{-3}$
PIENH4	partition coefficient for NH_4 in both layers	1.0	per $kg\ l^{-1}$
KAPPNO3F	reaction velocity for denitrification in Layer 1 at 20°C for freshwater	0.3	$m\ day^{-1}$
KAPPNO3S	reaction velocity for denitrification		

Table V.10 (cont'd)

	in Layer 1 at 20°C for saltwater	0.125	m day^{-1}
K2NO3	reaction velocity for denitrification in Layer 2 at 20°C	0.25	m day^{-1}
THTANO3	constant for T adjustment for denitrification	1.08	none
KAPPD1	reaction velocity for dissolved H_2S oxidation in Layer 1 at 20°C	0.2	m day^{-1}
KAPPP1	reaction velocity for particulate H_2S oxidation in Layer 1 at 20°C	0.4	m day^{-1}
PIE1S	partition coefficient for H_2S in Layer 1	100.0	per kg l^{-1}
PIE2S	partition coefficient for H_2S in Layer 2	100.0	per kg l^{-1}
THTAPD1	constant for T adjustment for both dissolved & particulate H_2S oxidation	1.08	none
KMHSO2	constant to normalize H_2S oxidation rate for oxygen	4.0	g O_2 m^{-3}
CSISAT	saturation concentration of Si in the pore water	40000.0	mg Si m^{-3}
DPIE1SI	incremental partition coefficient for Si in Layer 1	10.0	per kg l^{-1}
PIE2SI 2	partition coefficient for Si in Layer 2	100.0	per kg l^{-1}
O2CRITSI	critical DO concentration for Layer 1 incremental Si sorption	1.0	g O_2 m^{-3}
KMPSI	half-saturation constant of PSi for Si dissolution	5×10^7	mg Si m^{-3}
JSIDETR	detrital flux of PSi to account for PSi settling to the sediment that is not associated with algal flux of PSi	100.0	mg Si m^{-2} day^{-1}
DPIE1PO4F*	incremental partition coefficient for PO_4 in Layer 1 for freshwater	3000.0	per kg l^{-1}
DPIE1PO4S*	incremental partition coefficient for PO_4 in Layer 1 for saltwater	300.0	per kg l^{-1}
PIE2PO4*	partition coefficient for PO_4 in Layer 2	100.0	per kg l^{-1}
O2CRIT	critical DO concentration for Layer 1 incremental PO_4 sorption	2.0	g O_2 m^{-3}
KMO2DP	half-saturation constant of DO for particle mixing	4.0	g O_2 m^{-3}
TEMPBEN	temperature at which benthic stress accumulation is reset to zero	10.0	°C
KBENSTR	1^{st}-order decay rate for benthic stress	0.03	day^{-1}
KLBNTH	ratio of bio-irrigation to bioturbation	0.0	none
DPMIN	minimum diffusion coefficient for particle mixing	3×10^{-6}	m^2 day^{-1}
KAPPCH4	reaction velocity for dissolved CH_4 oxidation in Layer 1 at 20°C	0.2	m day^{-1}

Table V.10 (con't)

THTACH4	constant for T adjustment for dissolved CH_4 oxidation	1.08	none
VSED	net burial (sedimentation) rate	0.25	cm yr^{-1}
VPMIX	diffusion coefficient for particle mixing	1.2×10^{-4}	m^2 day^{-1}
VDMIX	diffusion coefficient in pore water	0.001	m^2 day^{-1}
WSCNET	net settling velocity for algal group 1	0.1	m day^{-1}
WSDNET	net settling velocity for algal group 2	0.3	m day^{-1}
WSGNET	net settling velocity for algal group 3	0.1	m day^{-1}

Table V.11. Water quality parameters in CBP monitoring data

Parameters	**symbol**	**units**
temperature	T	degrees C
salinity	S	ppt
dissolved oxygen	DO	mg/l
chlorophyll-a	CHL	μg/l
total suspended solids	TSS	mg/l
secchi depth		m
particulate carbon	PC	mg/l
dissolved organic carbon	DOC	mg/l
particulate nitrogen	PN	mg/l
total dissolved nitrogen	TDN	mg/l
ammonium nitrogen	NH_4	mg/l
nitrate+nitrite nitrogen	NO_3	mg/l
particulate phosphorus	PP	mg/l
total dissolved phosphorus	TDP	mg/l
dissolved phosphate	PO_4d	mg/l
particulate inorganic phosphorus	PIP	mg/l
particulate biogenic silica	SU	mg/l
dissolved silica	SA	mg/l

V-2-5 Model Calibration Results

Calibration of the water quality model is shown by the comparison of time series plots of selected water quality parameters with DEQ observations at all 16 DEQ stations spanning the Lynnhaven River. The locations of the stations are shown in Figure V.18. To facilitate the comparison, stations of each Lynnhaven River branch are clustered in the figures comparing observed versus predicted values of each parameter for stations of that branch.

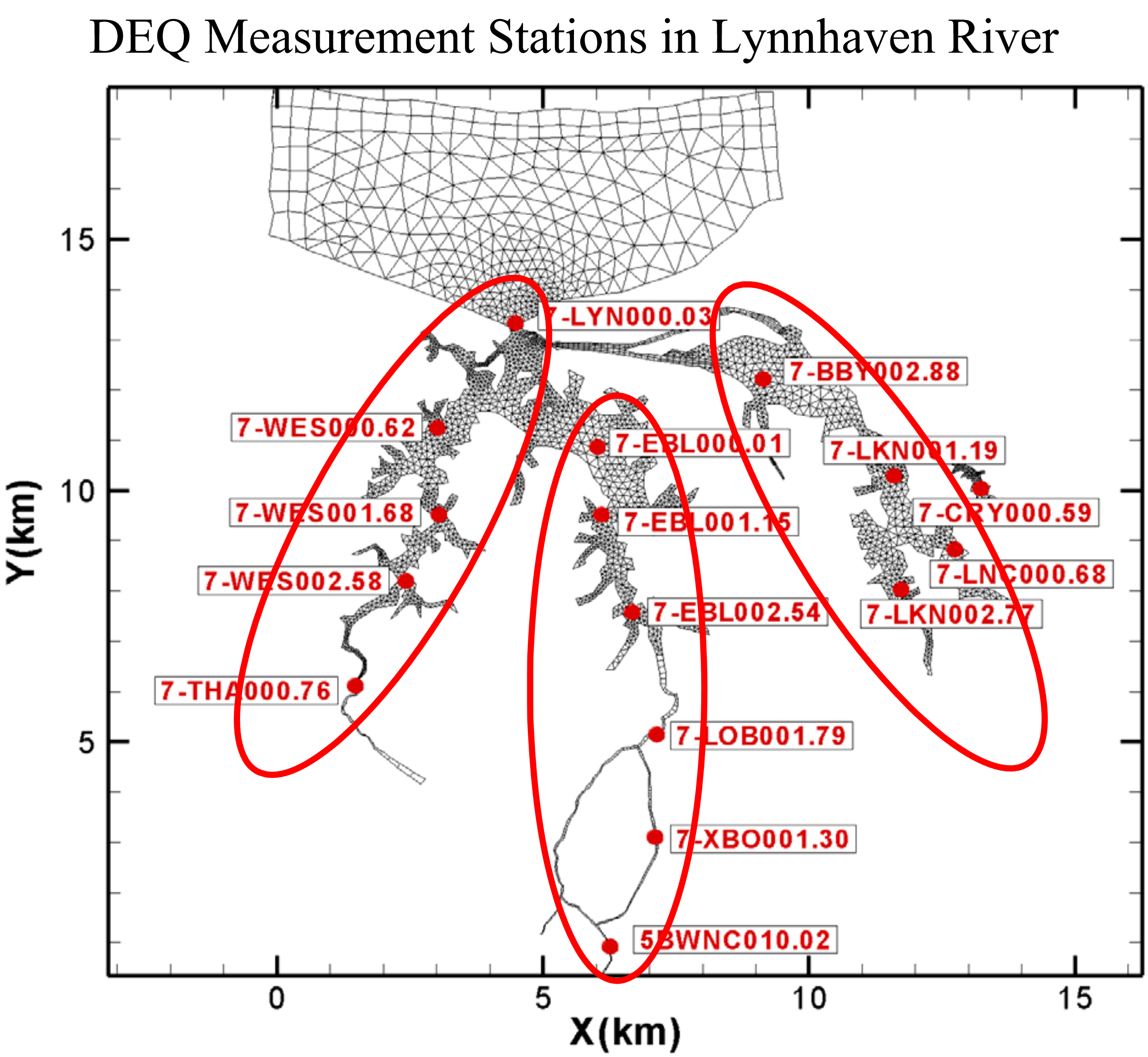


Figure V.18. Grouping of Lynnhaven DEQ stations by branch, as used in displaying CE-QUAL-ICM water quality model calibration results.

For the calibration, comparisons at each station were made for the full calendar year 2006. These comparisons included the primary parameters of dissolved oxygen, chlorophyll-a, total Kjeldahl nitrogen (TKN), ammonium, nitrate-nitrite, total phosphorus, and ortho phosphorus. For validation of the model, these same comparisons were also made for the full calendar years 2004 and 2005 and are presented in Chapter VI.

The quantification of the model's overall ability to reproduce the observed data at these stations, as measured by statistical analysis, is presented later in this section. For the analysis on each water quality state variable, the differences of predicted and observed values for all 16 Lynnhaven DEQ stations were included.

A. Western Branch DEQ stations calibration results

Water quality model calibration results for Western Branch DEQ stations for 2006 are shown in Figures V.19 through V.25. In all figures comparing modeled and measured water quality parameters, the model predictions are represented as a gray band bounded by daily minimum and maximum predictions.

Results for dissolved oxygen are shown in Figure V.19. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen reasonably well, with some discrepancy at the upstream Thalia Creek station, the only Western Branch DEQ station where DO values fall below 5 mg/l. Figure V.20 presents the predicted versus observed comparisons for chlorophyll-a, catching the trend for the downstream stations, but showing slight under-predictions. Figure V.21 shows that the model captures TKN values well for all Western Branch DEQ stations. The predictions of ammonium and nitrate-nitrite shown in Figures V.22 and V.23, respectively, have some large diurnal fluctuations, but observed values primarily fall within these ranges. Figures V.24 and V.25 show that both total phosphorus and ortho phosphorus measurements are captured reasonably well at all stations. An inspection of Figures V.19 through V.25 shows the gradual decrease of dissolved oxygen and increases of both chlorophyll-a and nutrients in moving from the Inlet upstream to Thalia Creek.

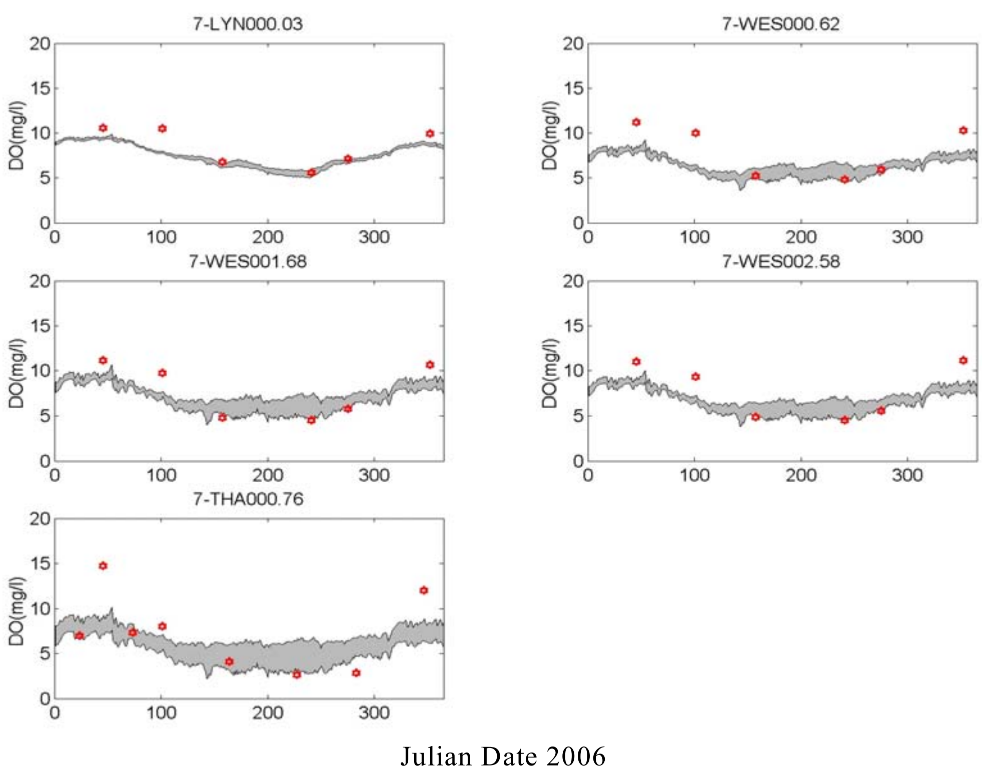


Figure V.19. Predicted vs. observed DO at Western Branch DEQ stations for 2006.

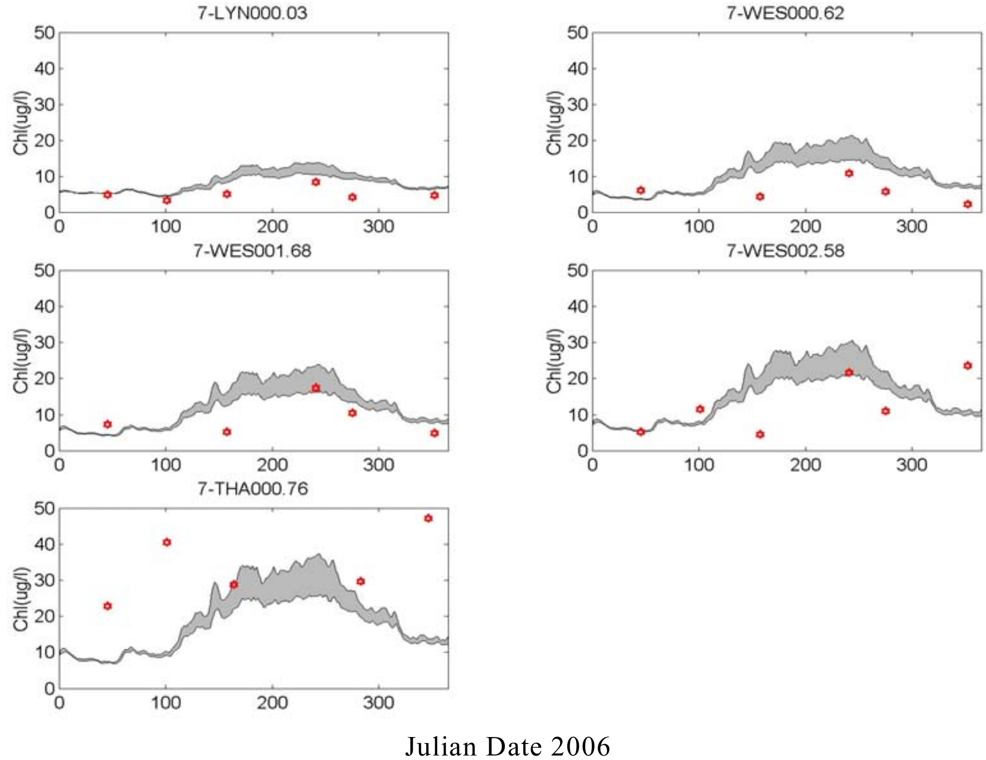


Figure V.20. Predicted vs. observed chlorophyll-a at Western Branch DEQ stations for 2006.

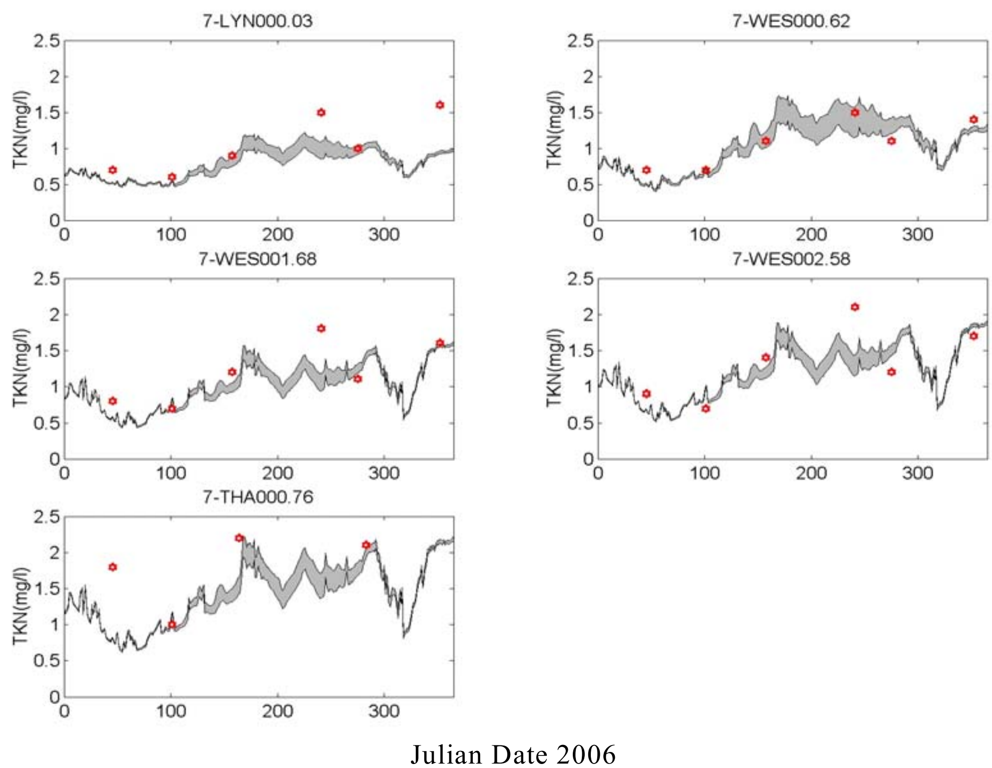


Figure V.21. Predicted vs. observed TKN at Western Branch DEQ stations for 2006.

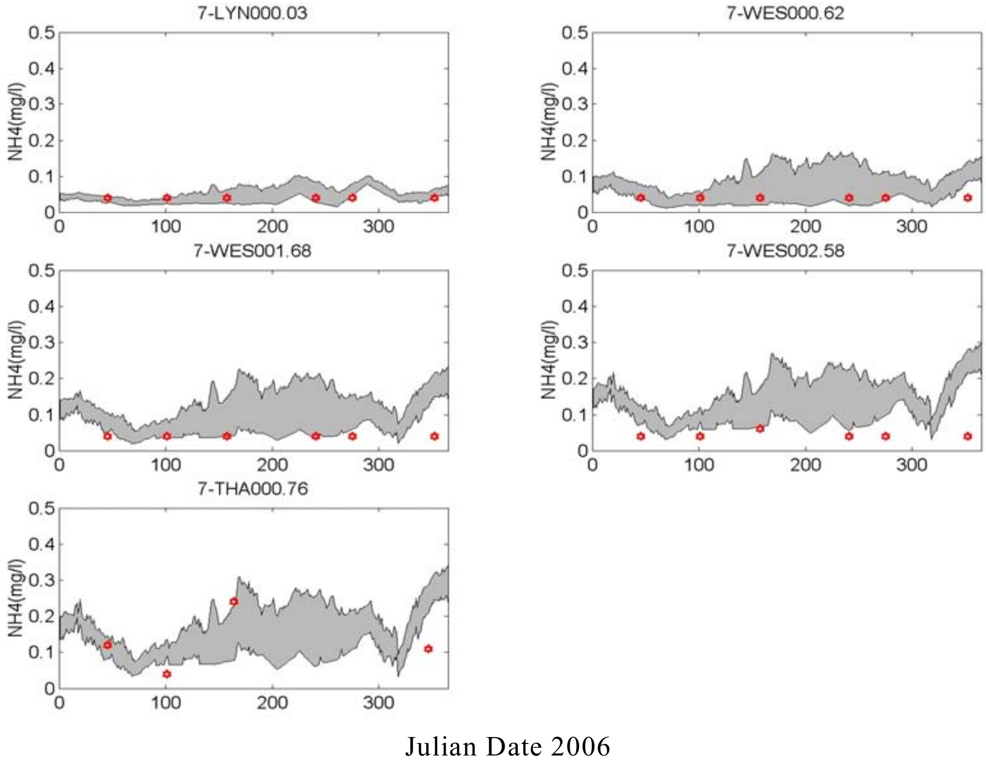


Figure V.22. Predicted vs. observed ammonium at Western Branch DEQ stations for 2006.

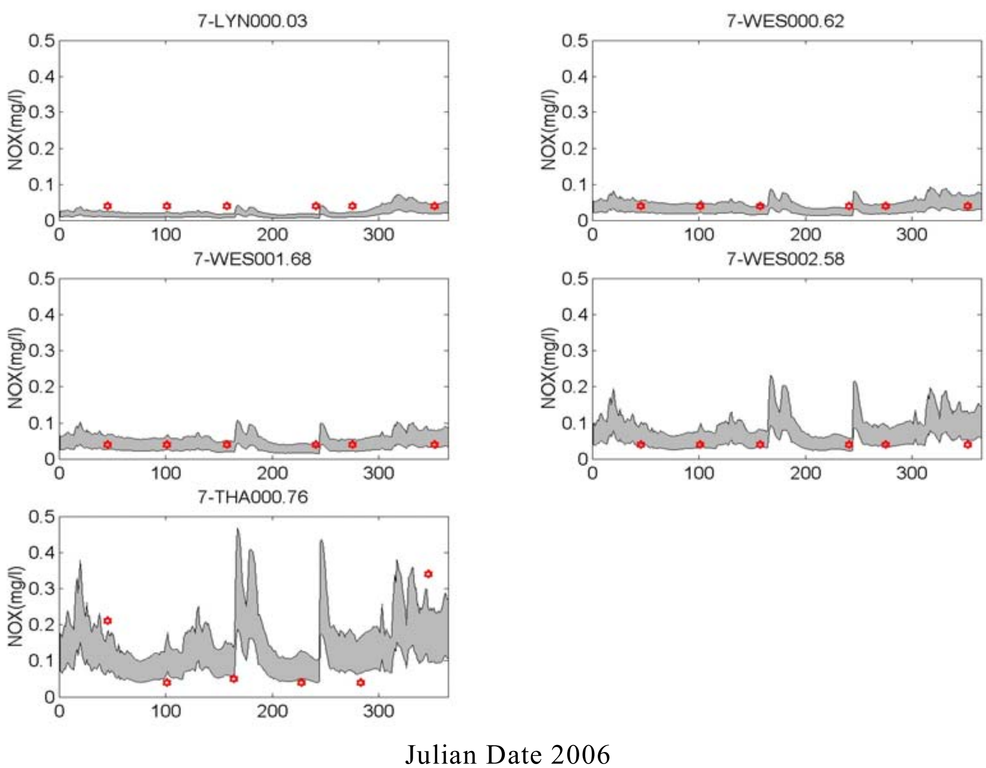


Figure V.23. Predicted vs. observed nitrate-nitrite at Western Branch DEQ stations for 2006.

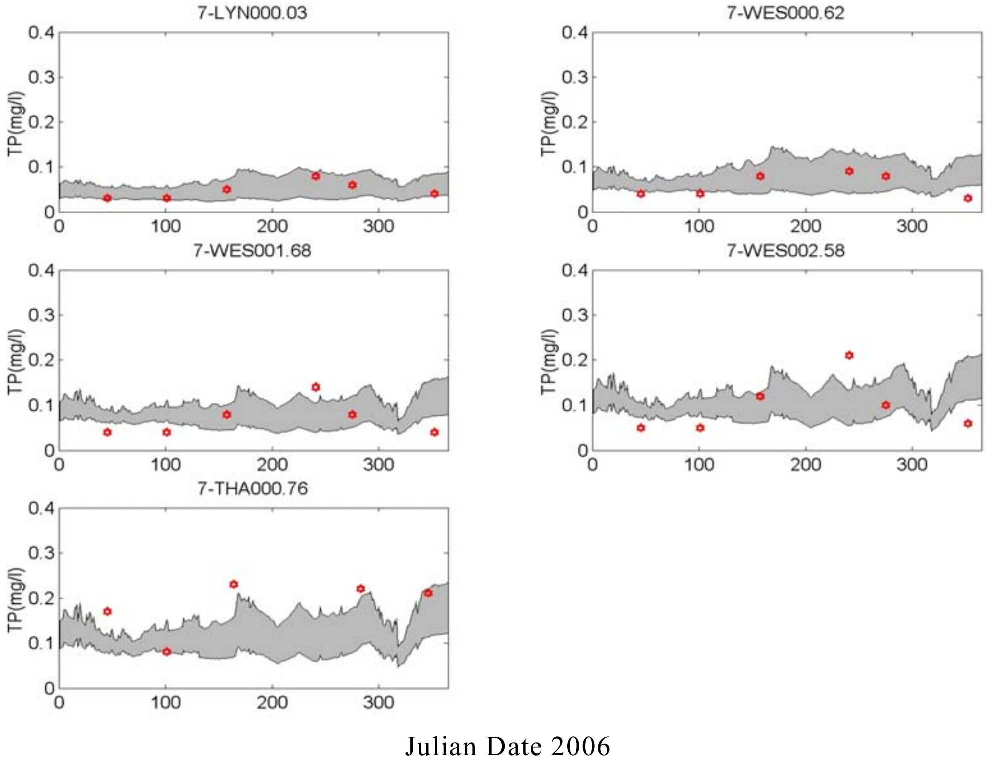


Figure V.24. Predicted vs. observed total phosphorus at Western Branch DEQ stations for 2006.

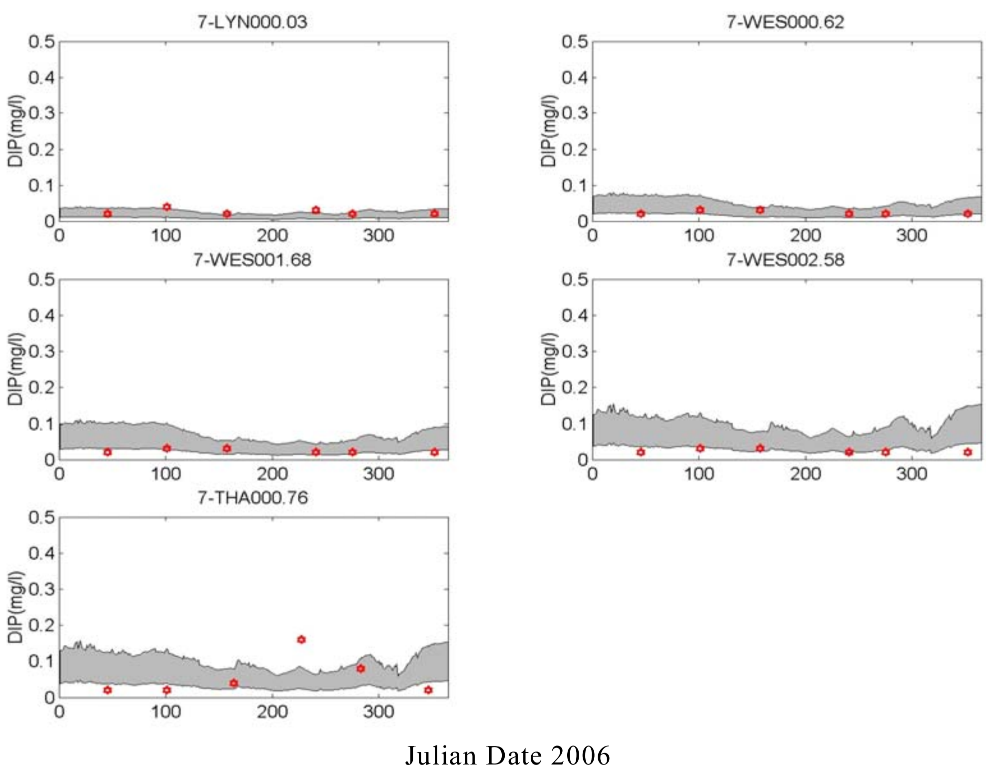


Figure V.25. Predicted vs. observed ortho phosphorus at Western Branch DEQ stations for 2006.

B. Eastern Branch DEQ stations calibration results

The calibration process was continued from the DEQ stations located in the Western Branch to the 6 DEQ stations located in the Eastern Branch. Initially, it was uncertain whether the model calibration coefficients and parameters would be the same in the Eastern Branch as in the Western Branch due to different characteristics. For example, the Eastern Branch is much longer than the Western Branch and includes a canal that was dredged and deepened to the headwater. Since nonpoint sources are the only source of pollutants, the increase in freshwater runoff to the Eastern Branch will have an accompanying increase in pollutant loads that will affect general property of algae growth rates, respiration rates, cell nutrient composition, and sediment characteristics.

At a meeting in June 2005 between representatives of the City of Virginia Beach, the Army Corps, URS, and VIMS, representatives from the City of Virginia Beach expressed a concern that the VIMS modeling domain did not extend to the West Neck Creek region. This region is at the head of the Eastern Branch and is known as the West Neck Creek - London Bridge Creek System, including the Canal No. 2. It was noted that many water quality issues were associated with conditions originating in this system. VIMS thus extended the model domain beyond London Bridge to include West Neck Creek.

After a series of runs comparing between model results and observed data, it became apparent that the new boundary upstream of West Neck Creek produced better results. Given the proper hydrodynamic results, without much change on the water quality parameters, the water quality model results were satisfactory. Water quality model calibration results for Eastern Branch DEQ stations for 2006 are shown in Figures V.26 through V.32. In all figures comparing modeled and measured water quality parameters, the model predictions are represented as a gray band bounded by daily minimum and maximum predictions.

Results for dissolved oxygen are shown in Figure V.26. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen reasonably well, with only a slight over-prediction at the upstream London Bridge (7-LOB001.79) and Canal No. 2 (7-XBO001.30) stations, where summertime DO measurements fall below 5 mg/l. Figure V.27 presents the predicted versus observed comparisons for chlorophyll-a, catching the trend for all stations, but there were a couple of outliers in the sparse observation data. Figure V.28 shows that the model captures the trend of measured TKN values well for all Eastern Branch DEQ stations. The predictions of ammonium and nitrate-nitrite shown in Figures V.29 and V.30, respectively, have some large diurnal fluctuations, but observed values primarily fall within these ranges. Figure V.31 shows that total phosphorus predictions match observations well overall, although these may slightly under-predict in summer at the mid-branch stations of 7-EBL002.54, 5BWNC010.02, and 7-XBO01.30. Ortho phosphorus measurements are captured reasonably well at all stations, as shown in Figure V.32. An inspection of Figures V.26 through V.32 shows gradual increases of both chlorophyll-a and nutrients in moving from the Inlet upstream to West Neck Creek (5BWNC010.02), and a slight decrease in dissolved oxygen is seen moving upstream in the Eastern Branch.

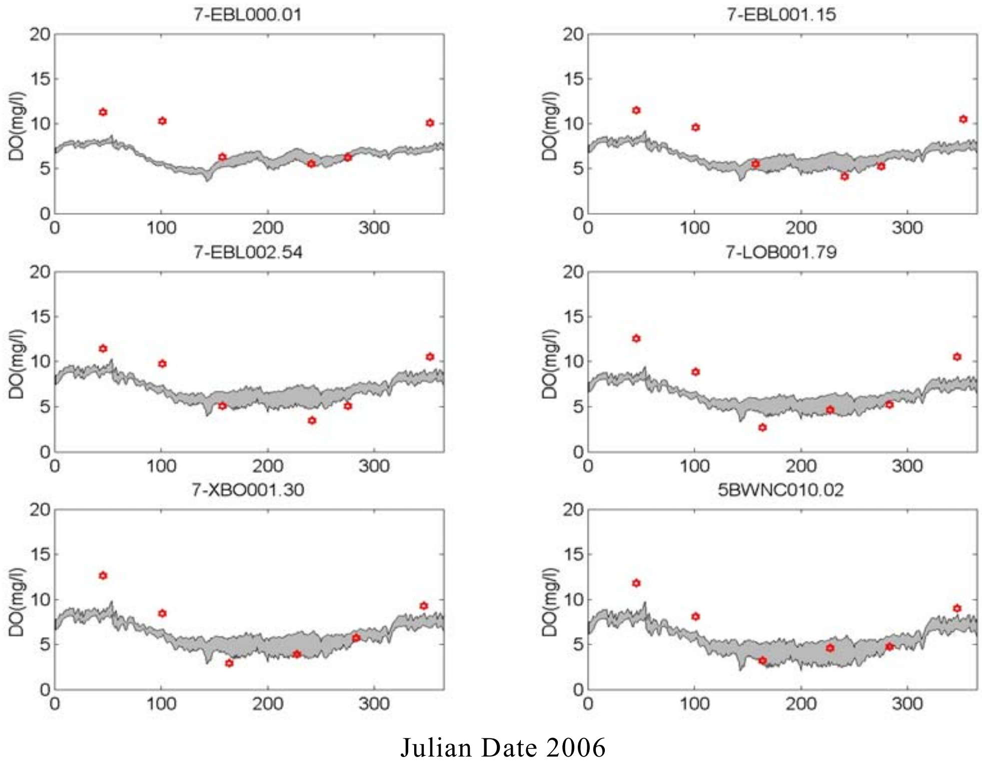


Figure V.26. Predicted vs. observed dissolved oxygen at Eastern Branch DEQ stations for 2006.

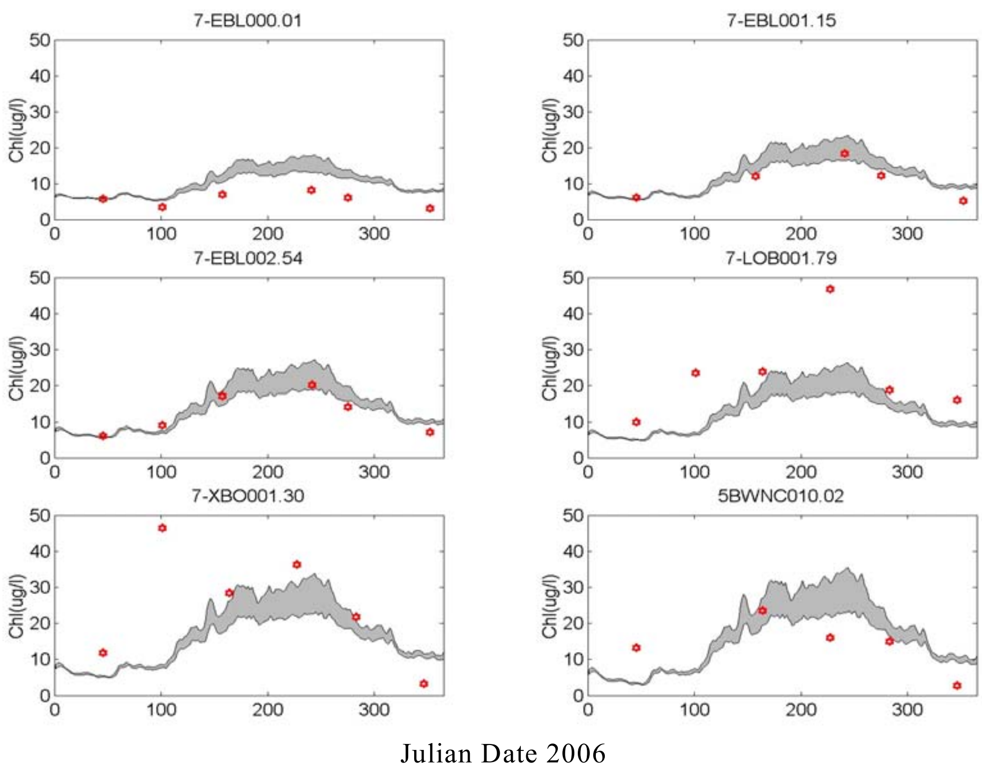


Figure V.27. Predicted vs. observed chlorophyll-a at Eastern Branch DEQ stations for 2006.

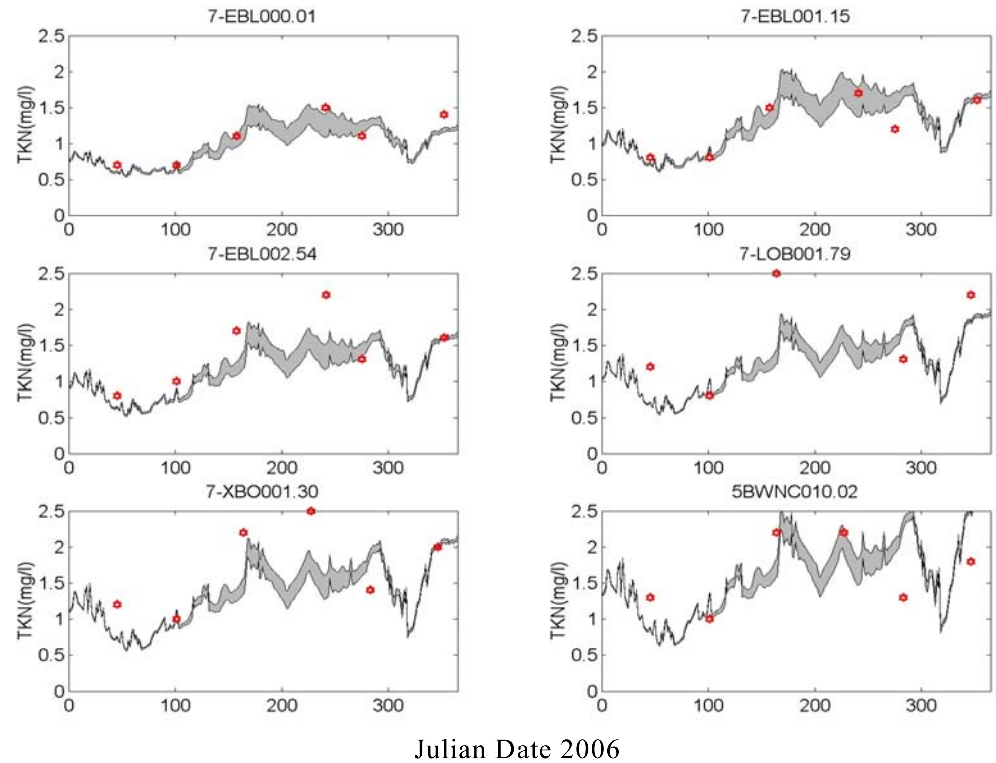


Figure V.28. Predicted vs. observed TKN at Eastern Branch DEQ stations for 2006.

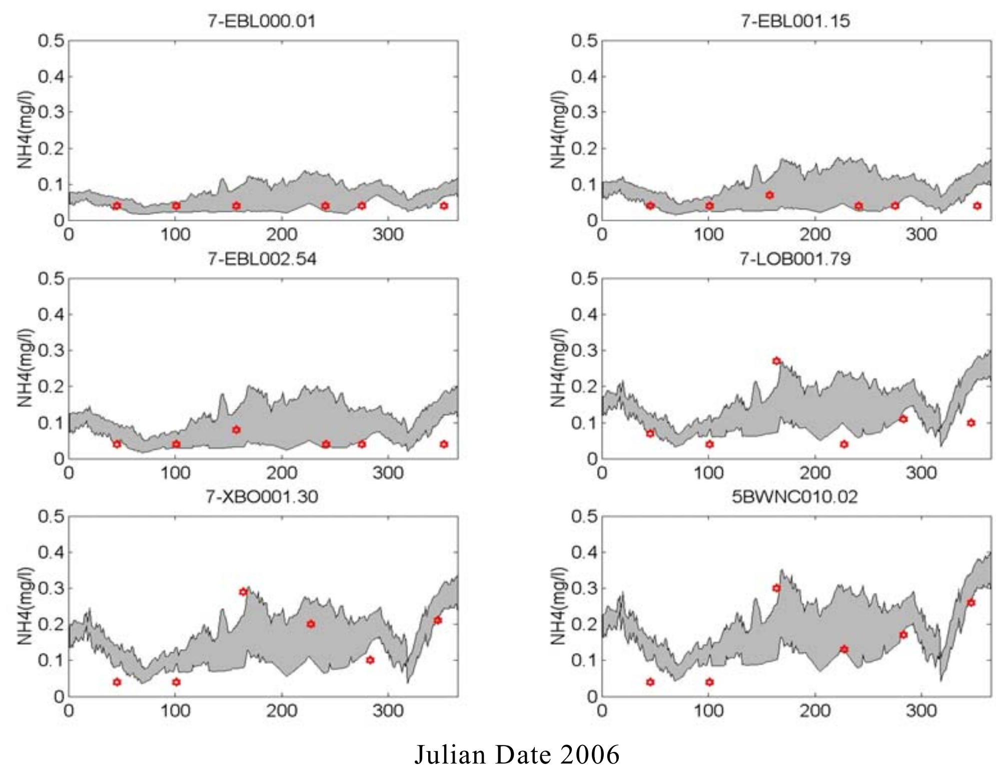


Figure V.29. Predicted vs. observed ammonium at Eastern Branch DEQ stations for 2006.

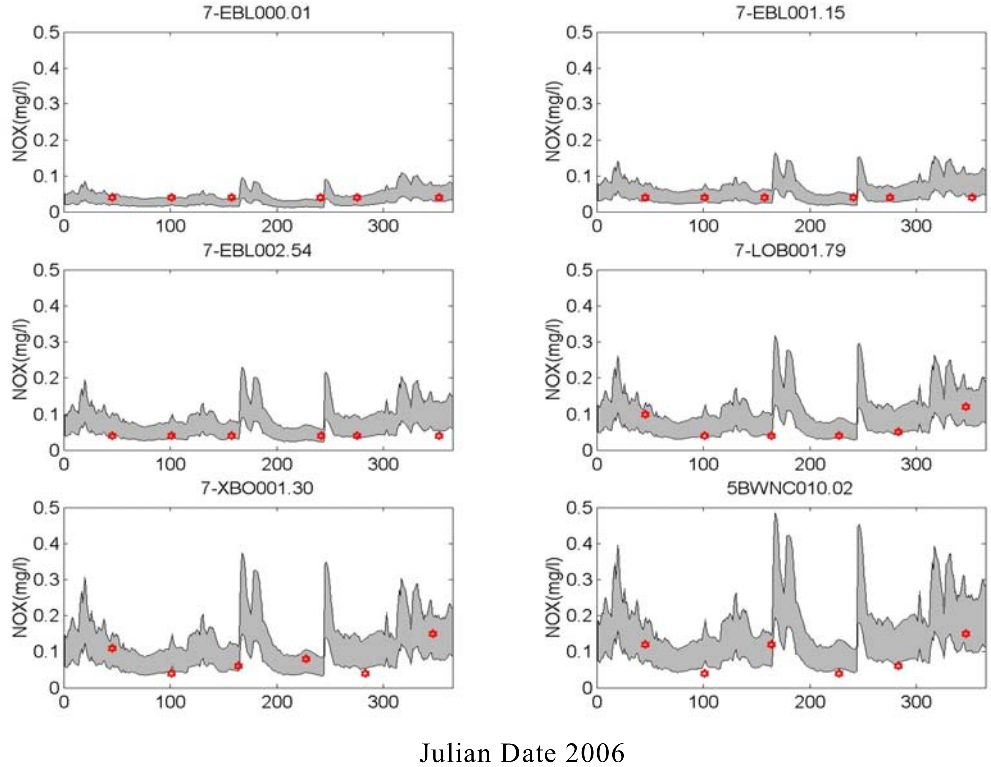


Figure V.30. Predicted vs. observed nitrate-nitrite at Eastern Branch DEQ stations for 2006.

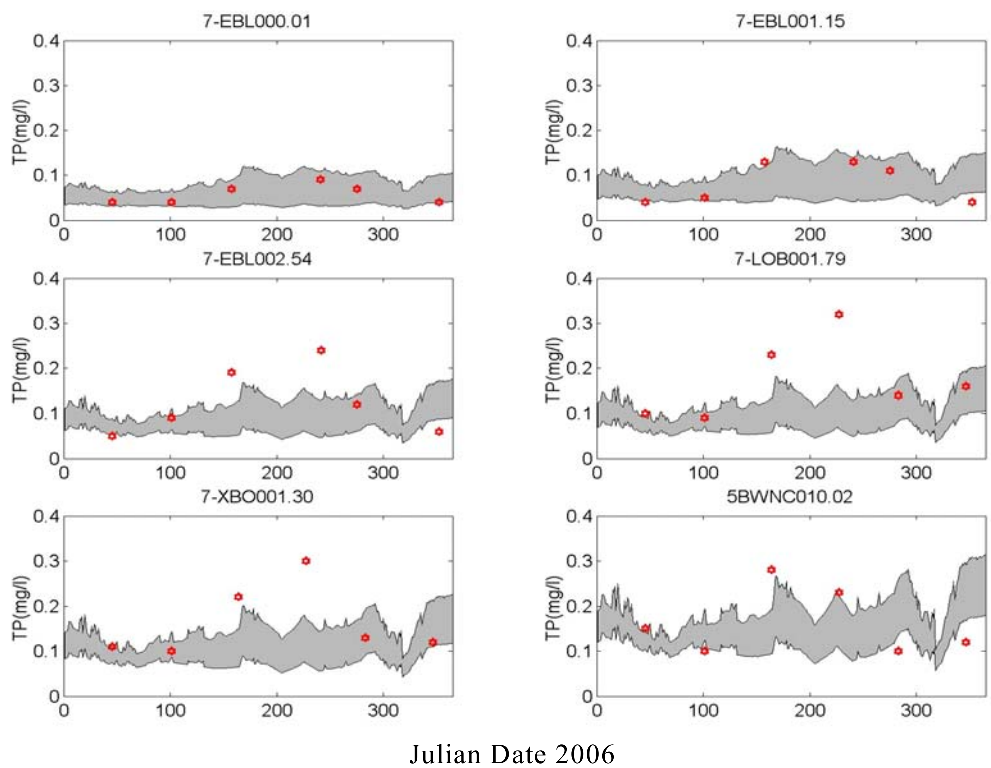


Figure V.31. Predicted vs. observed total phosphorus at Eastern Branch DEQ stations for 2006.

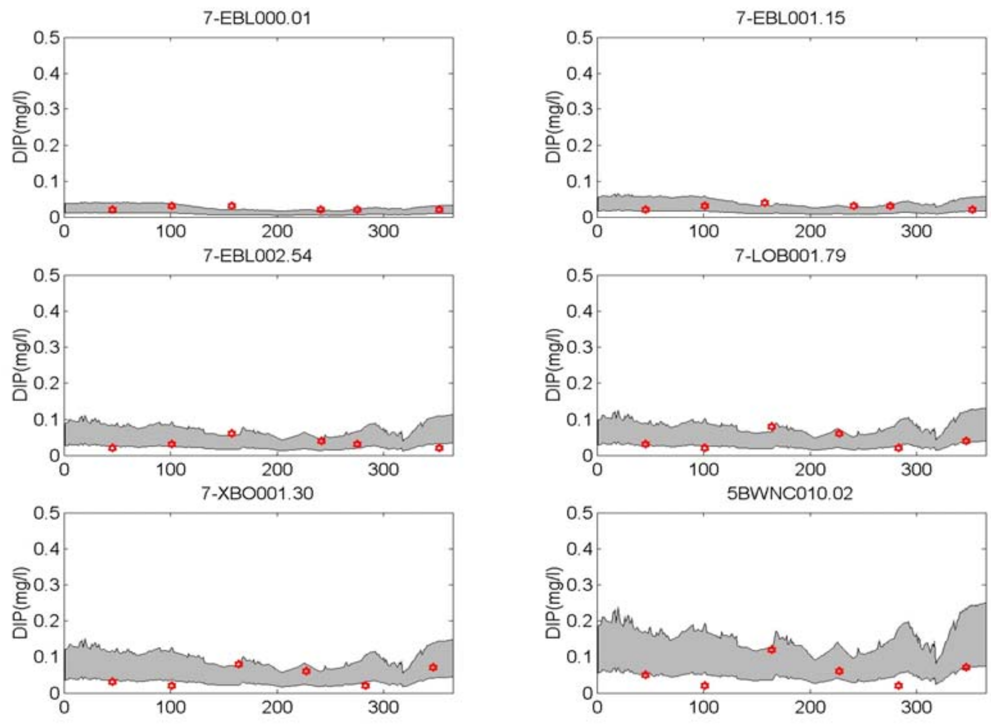


Figure V.32. Predicted vs. observed ortho phosphorus at Eastern Branch DEQ stations for 2006.

C. Broad Bay / Linkhorn Bay Branch DEQ stations calibration results

Water quality model calibration results for Broad Bay /Linkhorn Bay Branch DEQ stations for 2006 are shown in Figures V.33 through V.39. In all figures comparing modeled and measured water quality parameters, the model predictions are represented as a gray band bounded by daily minimum and maximum predictions.

Results for the comparison of modeled versus measured dissolved oxygen at Broad and Linkhorn Bay Branch DEQ stations are shown in Figure V.33. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen extremely well at all 5 DEQ stations in this branch. One may note that all modeled and observed values exceed 5 mg/l throughout the year. Figure V.34 shows reasonably good agreement overall between predicted and observed values for chlorophyll-a, but there may be some over-prediction at upstream stations 7-CRY000.59, 7-LNC000.68, and 7-LKN002.77 beyond Julian Day 280. Figure V.35 shows good agreement between modeled and measured TKN values at all Broad Bay and Linkhorn Bay DEQ stations. The predicted values of ammonium and nitrate-nitrite shown in Figures V.36 and V.37, respectively, match observed values quite well. Figures V.38 and V.39 show that total phosphorus and ortho phosphorus predictions match observations well at all 5 DEQ stations in this branch. An inspection of Figures V.33 through V.39 shows better water quality in this branch than in the Western and Eastern Branches. Finally, there is almost no spatial decrease in dissolved oxygen nor increase in either chlorophyll-a or nutrients in moving from the Inlet upstream to the head of Linkhorn Bay.

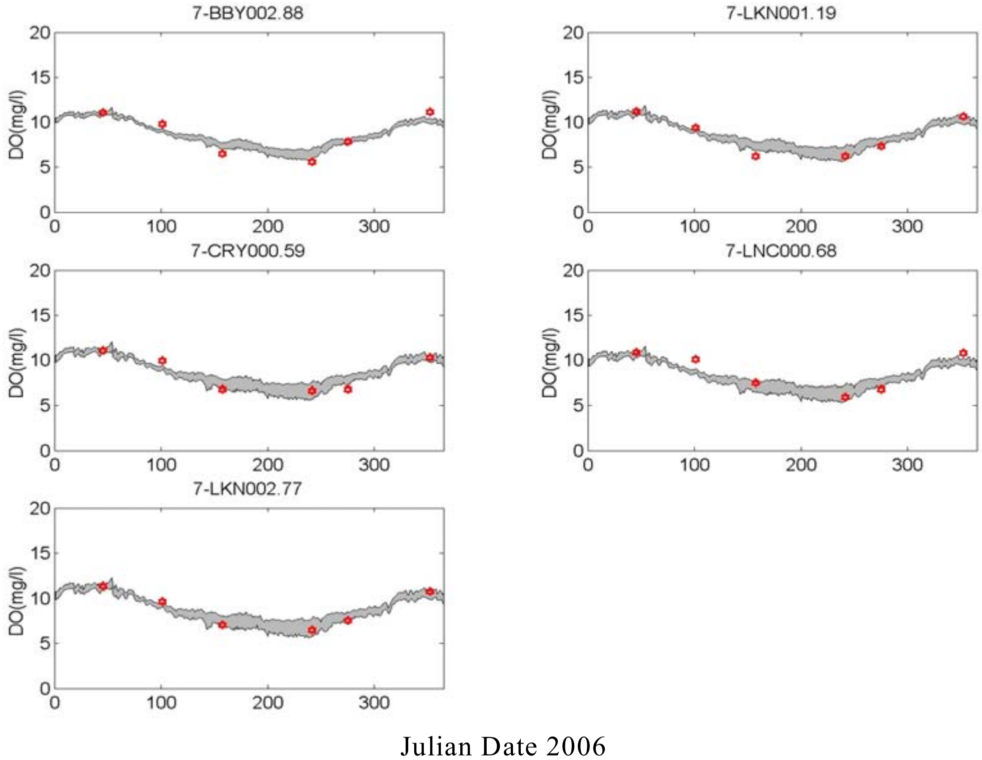


Figure V.33. Predicted vs. observed dissolved oxygen at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

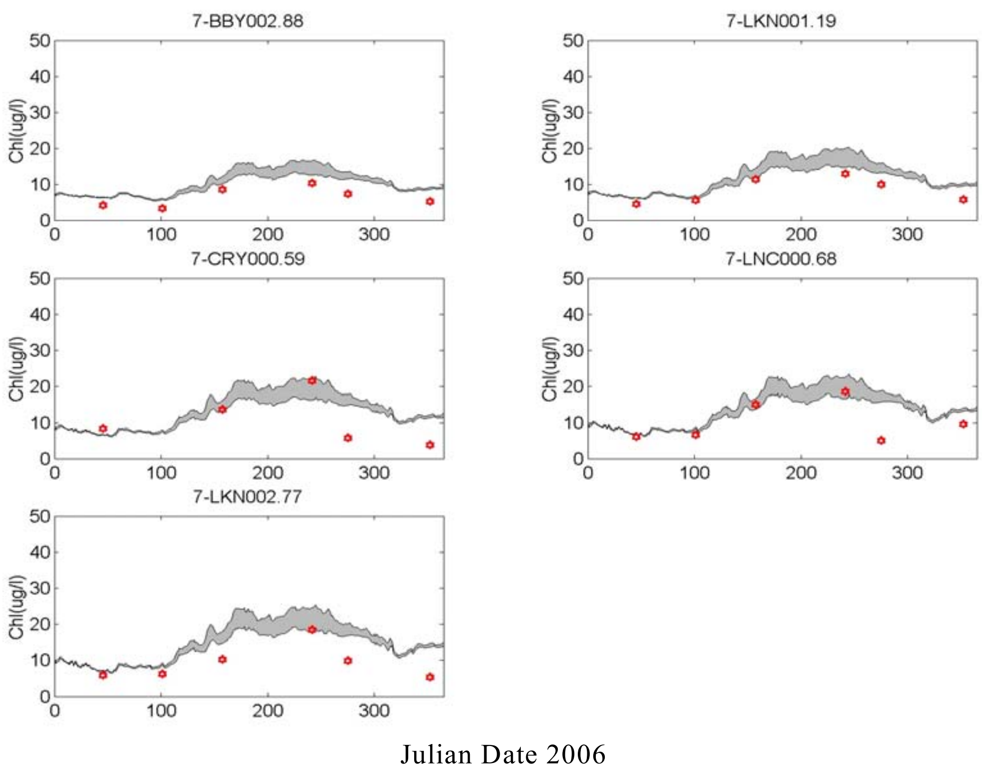


Figure V.34. Predicted vs. observed chlorophyll-a at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

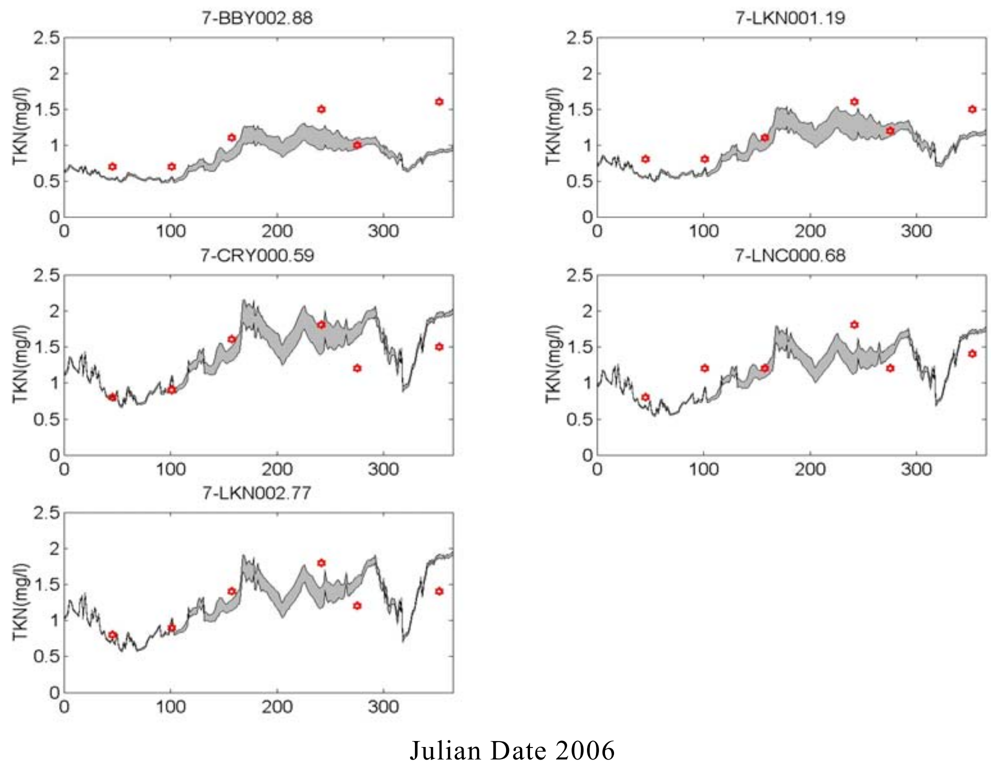


Figure V.35. Predicted vs. observed TKN at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

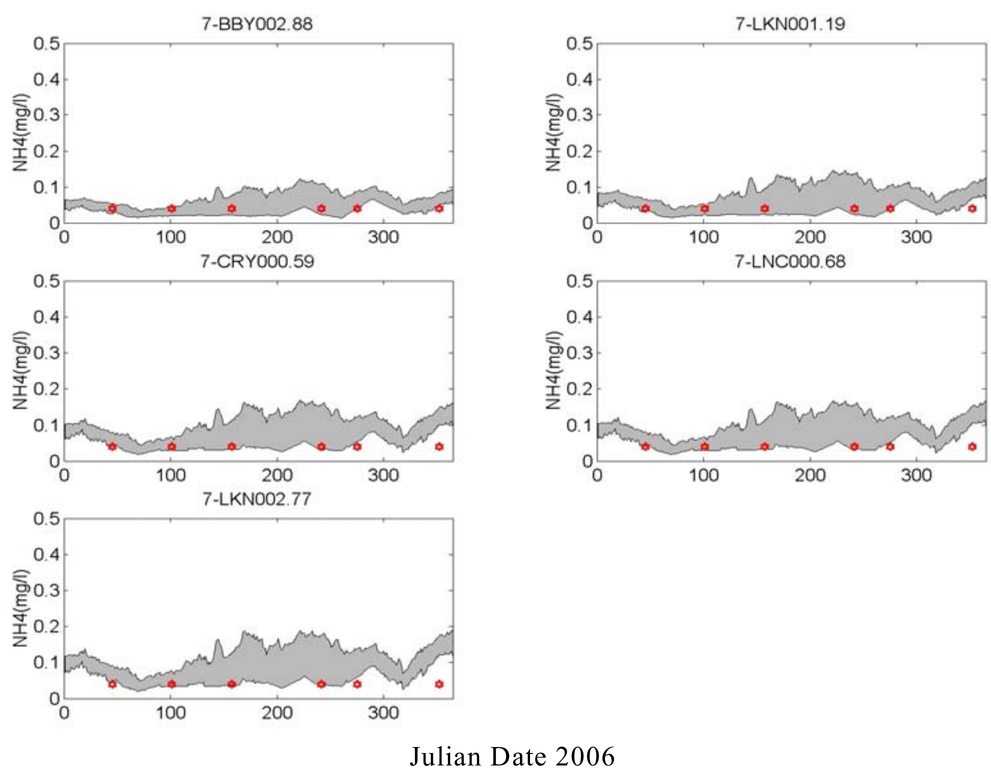


Figure V.36. Predicted vs. observed ammonium at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

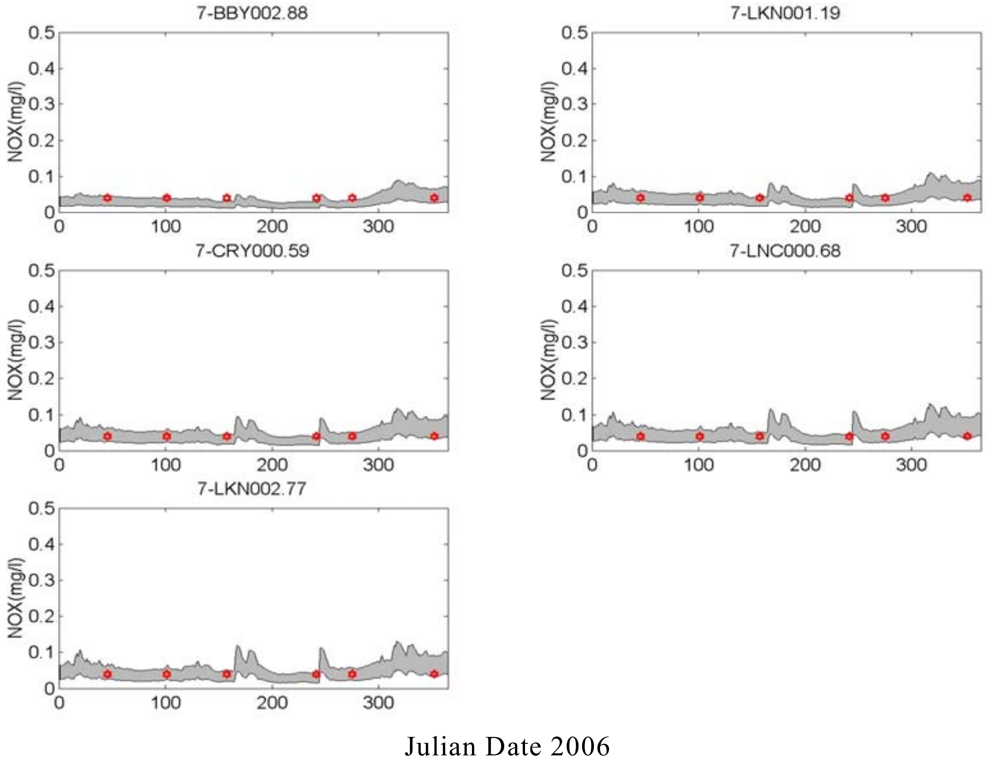


Figure V.37. Predicted vs. observed nitrate-nitrite at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

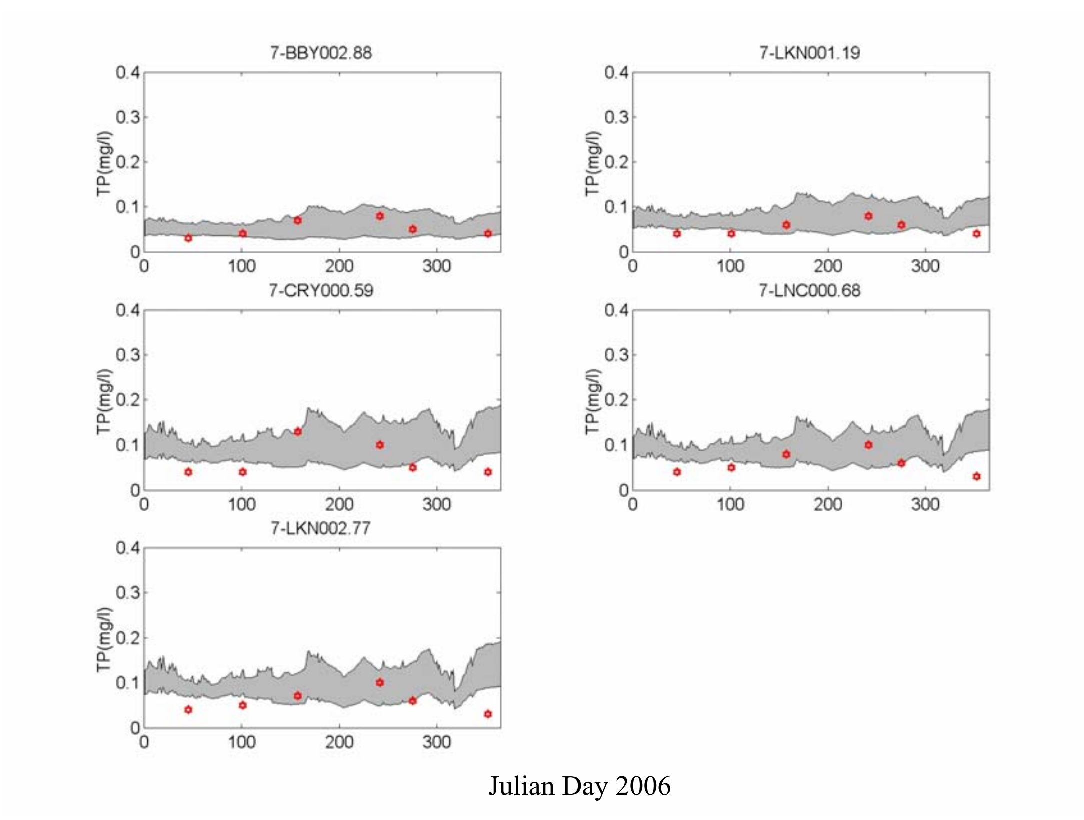


Figure V.38. Predicted vs. observed total phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

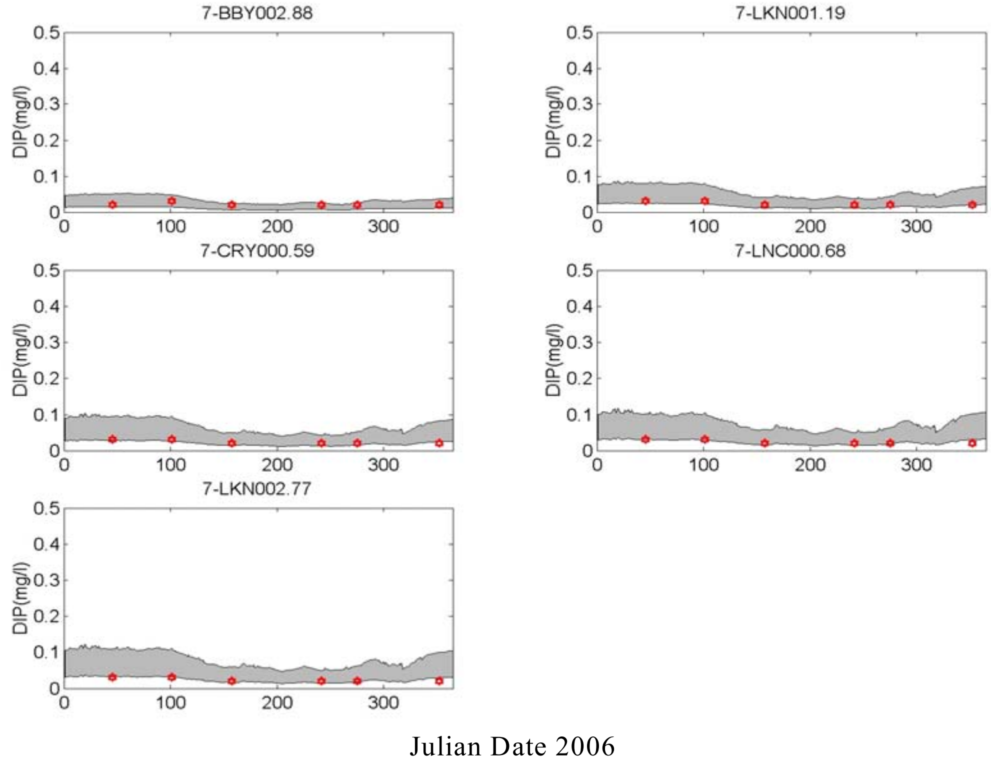


Figure V.39. Predicted vs. observed ortho phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

Summary Statistics of Water Quality Model Calibration Results

In the previous portion of this section, qualitative comparisons between model results and observed values were presented. Although the comparisons indicate that the CE-QUAL-ICM water quality model can reproduce the physical, chemical, and biological processes that affect the eutrophication process in the Lynnhaven River, a more specific measure of the model performance is desirable.

In order to provide a more quantifiable measure of the performance of the water quality model, a statistical analysis was applied to the predicted and observed data of the water quality calibration results.

For model predictions vs. observations of the water quality parameters compared at the surface layer for the year 2006, various error measurements serve to quantify the performance of the water quality model. Error measurements determined include:

1) **Mean error** – The mean error statistic is defined as:

$$ME = \frac{\sum(O - P)}{n}$$

where: ME = mean error, O = observation, P = model predicted result, and *n* = number of observations. The mean error is a summary of the model tendency to overestimate or underestimate the data.

2) **Absolute Mean error** –The absolute mean error statistic is defined as:

$$AME = \frac{\sum |O - P|}{n}$$

where: AME = absolute mean error. The absolute mean error is a measure of the average discrepancy between observations and model results.

3) **Root-Mean-Square Error** – The root-mean-square error statistic is defined as:

$$RME = \sqrt{\frac{\sum (O - P)^2}{n}}$$

where: *RME* = root-mean-square error. The root-mean-square error is an alternate quantification of the average discrepancy between observations and model results.

4) **Relative Error** – The relative error statistic is defined as:

$$RE = \frac{\sum |O - P|}{\sum O}$$

where: *RE* = relative error. The relative error statistic normalizes absolute mean error by the magnitude of the observations.

Additionally, 1:1 plots of predicted results vs. observations show visually how well the model predictions compare with observations and whether the model shows a bias towards either over-prediction or under-prediction.

A. Statistical Analysis of Dissolved Oxygen, Chlorophyll-a, TKN, and Total Phosphorus Results

Statistical analysis of 7 key water quality parameters was performed by comparing predicted and observed results of each parameter for all of the 16 Lynnhaven DEQ stations combined. The every-other-month DEQ measurements taken during the 2006 year thus provided sample sizes of 90, 86, 90, and 90, respectively, for DO, chl-a, TKN, and TP predicted vs. observed comparisons at all Lynnhaven River DEQ stations. The 1:1 plots are shown in Figure V.40 for these 4 comparisons and their corresponding error measures are shown in Table V.12. Overall, predicted and observed DO values compare well. The median value for mean error is about 0.69 mg/l while the absolute mean error is 1.07 mg/l. The root-mean-square error for both surface and bottom DO is about 1.47

mg/l, whereas the relative error is around 13%. These statistics are comparable to other eutrophication model studies such as the Three-dimensional Eutrophication Model Study of the Chesapeake Bay (Cerco and Cole, 1994).

It was also worthwhile to point out that the absolute mean error and root-mean-square error of water quality parameters shown in Table V.12 are well within the range of natural variation in a given season of measurements when compared with available observations, for example, Figures V.19-V.21, V.24, V.26-V.28, V.31, V.33-V.35, and V.38.

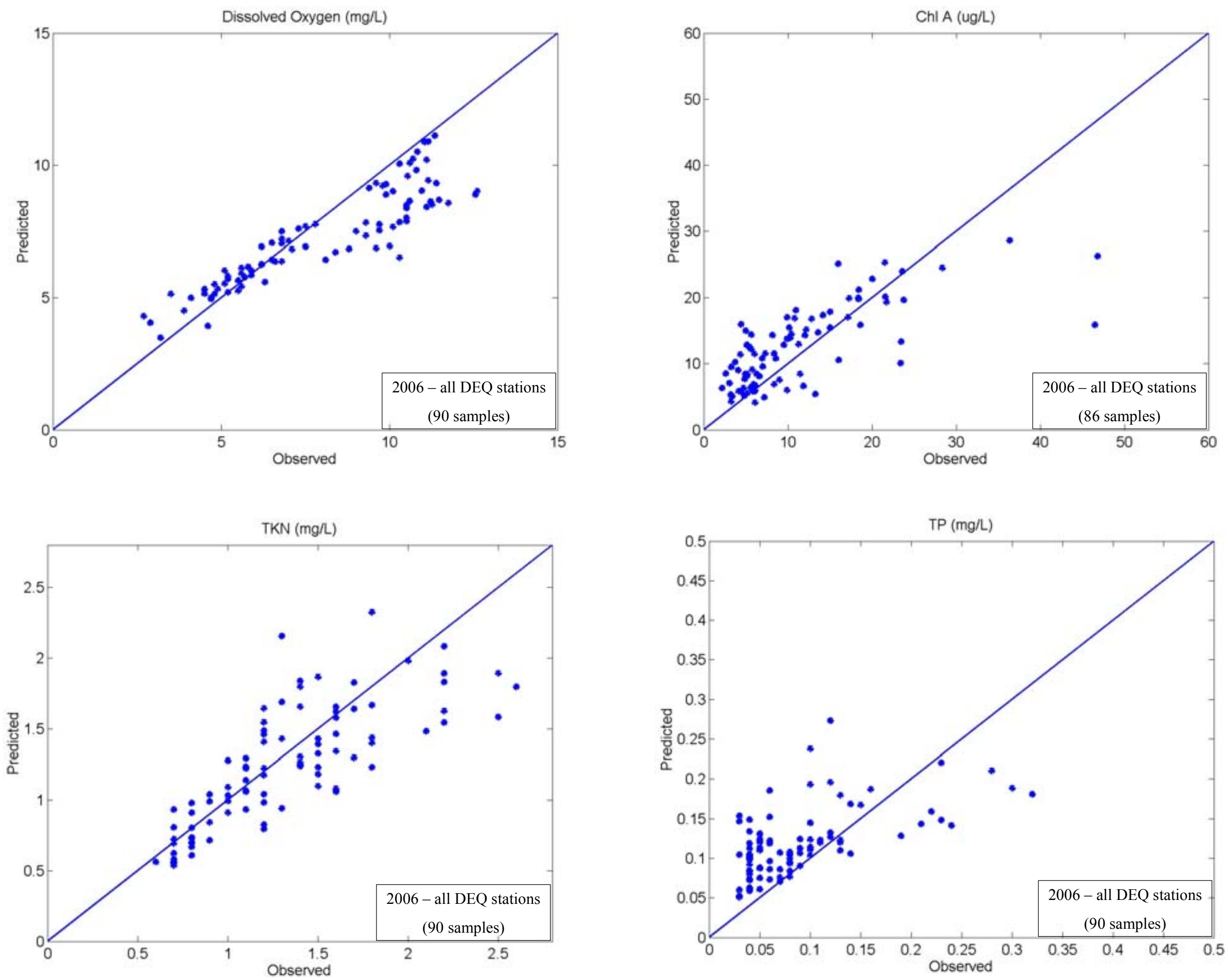


Figure V.40. Plots of 1:1 predicted vs. observed DO, chl-a, TKN, and TP at all 16 Lynnhaven DEQ stations for 2006.

Table V.12. Statistical summary of errors derived by comparing predicted vs. observed surface values of DO, chl-a, TKN, and TP for year 2006.

Surface Comparisons of Predicted vs. Observed Dissolved Oxygen, Chlorophyll-a, TKN, and Total Phosphorus				
	All 16 Lynnhaven DEQ Stations			
	DO	Chl-a	TKN	TP
Sample size	90	86	90	90
Mean Error	0.69	-0.67	0.08	-0.03
Absolute Mean Error	1.07	4.82	0.23	0.05
RMS Error	1.47	8.06	0.31	0.06
Relative Error	0.13	0.40	0.18	0.52
Corr. Coeff. (r)	0.90	0.66	0.79	0.60

B. Statistical Analysis of Ammonia, Nitrate-Nitrite, and Dissolved Inorganic Phosphate

To quantify the comparison between predicted and observed values NH_4, NO_x, and DIP, determination of statistical errors and construction of 1:1 plots were performed for these parameters as well. Table V.13 below shows error values of each parameter for predicted vs. observed comparisons of all 16 Lynnhaven DEQ stations combined for 2006.

The nitrogen and phosphorus are major nutrients that can be used for photosynthesis. In particular, NH_4, NO_x, and dissolved phosphorus are species that can be uptaken directly by the phytoplankton. Therefore, they are important indicators for the environmental quality. Nitrogen's concentration is usually higher than that of phosphorus. The 1:1 plots of predicted vs. observed comparisons of NH_4, NO_x, and DIP are shown in Figure V.41. The summary is shown in Table V.13. The absolute mean error and root-mean-square error of these water quality parameters show the differences between model predictions and observations are within the range of natural variation in a given season of measurements when compared with available observations, for example, as shown in Figures V.22-V.23, V.25, V.29-V.30, V.32, V.36-V.37, and V.39.

Table V.13. Statistical summary of errors derived by comparing predicted vs. observed values of NH_4, NO_X, and DIP for all 16 Lynnhaven DEQ stations for 2006.

Parameter:	NH_4	NO_X	DIP
Sample Size	90	90	90
Mean Error	-0.04	-0.02	-0.02
Absolute Mean Error	0.04	0.03	0.02
RMS Error	0.05	0.04	0.03
Relative Error	0.73	0.57	0.79
Corr. Coeff. (r)	0.74	0.76	0.42

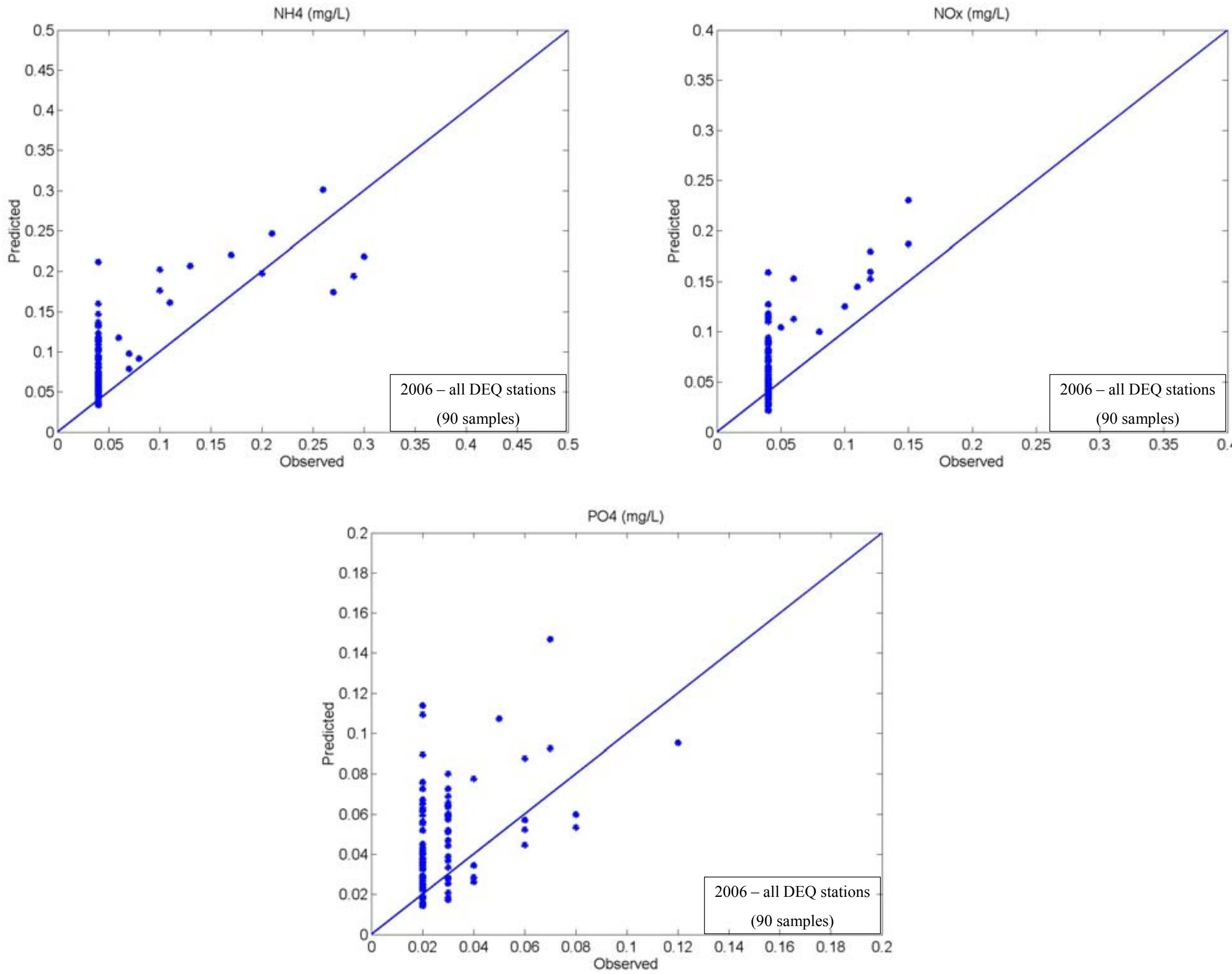


Figure V.41. Plots of 1:1 predicted vs. observed NH_4, NO_x, and DIP.

V-3 Calibration of the Sediment Transport Model

The model was calibrated by adjusting the erosion coefficient M to make the modeled results agree with observation data. The TSS observation data of 2006 collected at the 16 Lynnhaven DEQ stations (locations shown earlier in Figure V.18) were used to calibrate the model. The comparisons between model predictions and observations for TSS are shown in Figures V.42 through V.44, respectively, for the Western, Eastern, and Broad Bay / Linkhorn Bay DEQ stations for calibration year 2006.

Validation of the sediment transport model, using the 2004 and 2005 DEQ data, is shown in Chapter VI, Section VI-3.

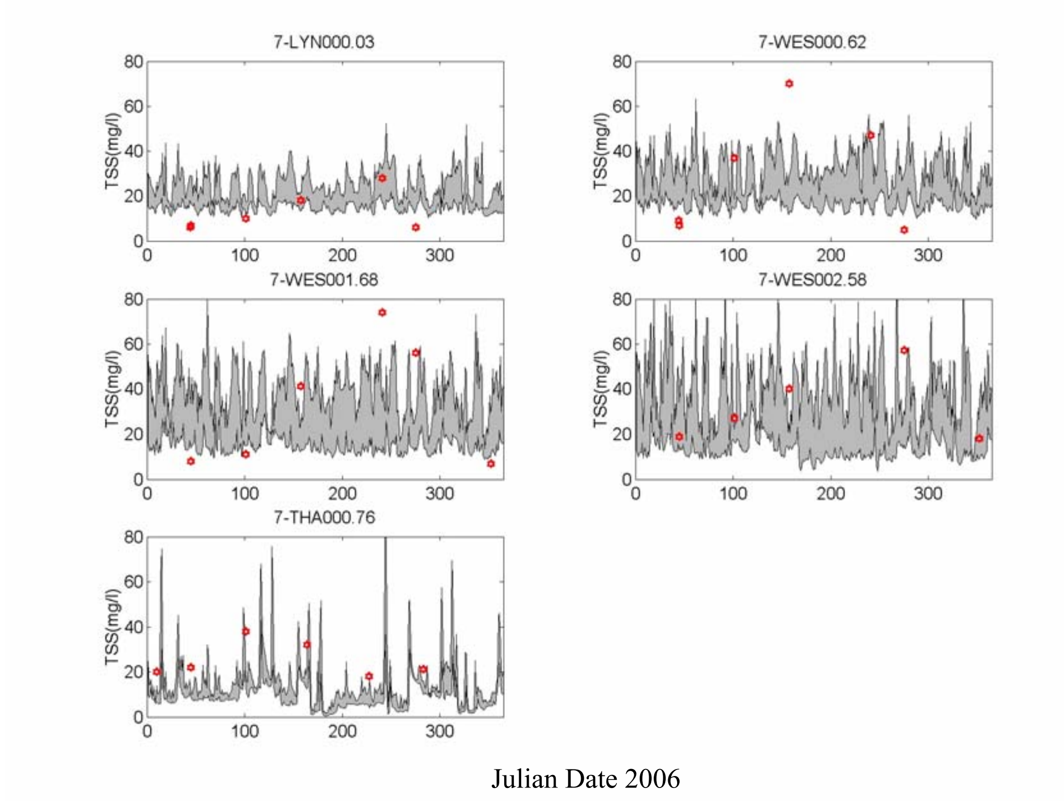


Figure V.42. Predicted vs. observed TSS at Western Branch DEQ stations for 2006.

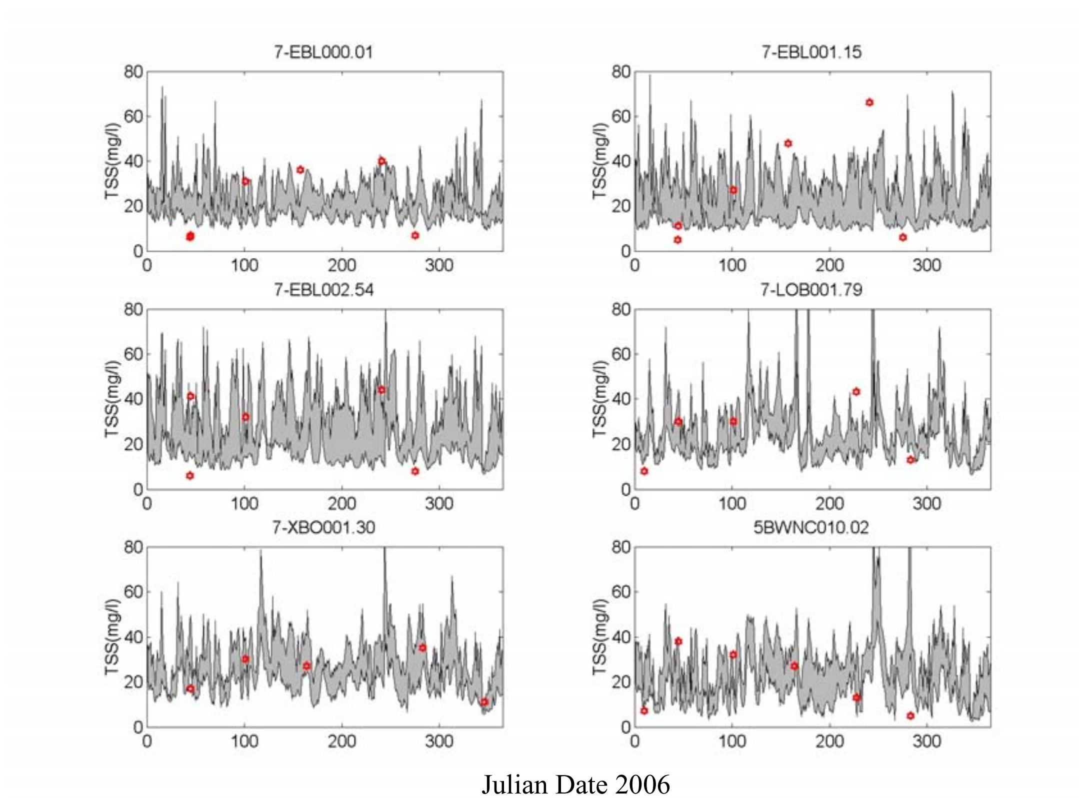


Figure V.43. Predicted vs. observed TSS at Eastern Branch DEQ stations for 2006.

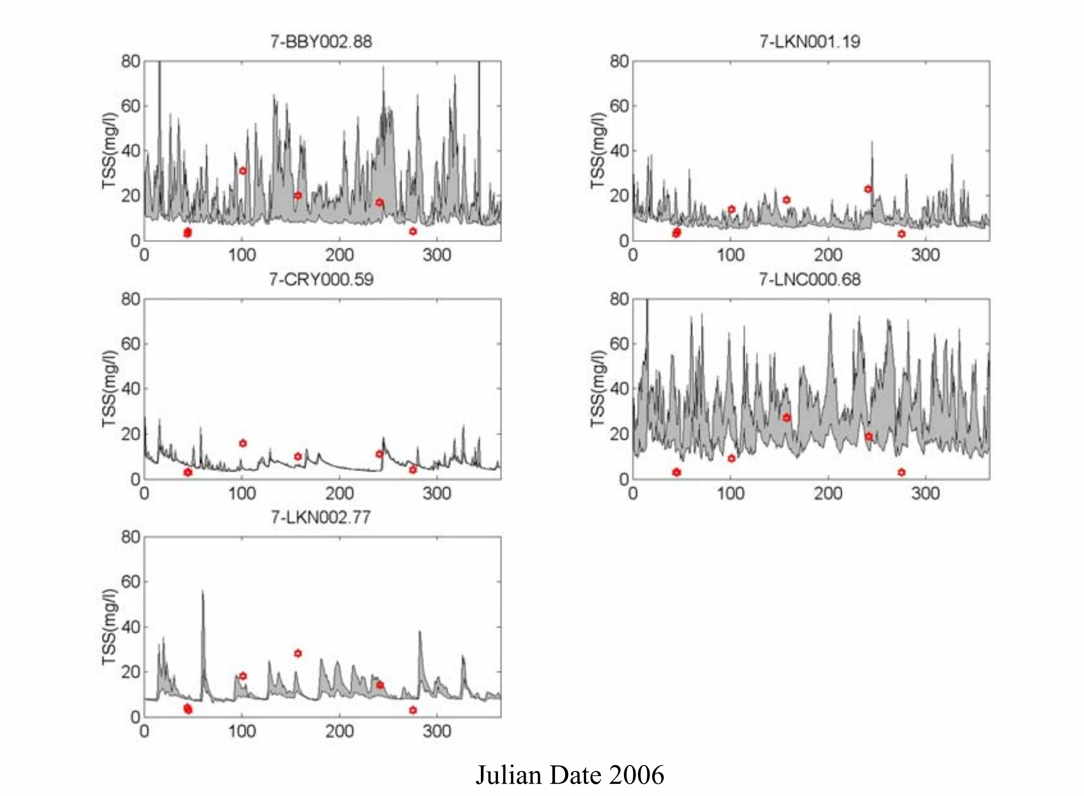


Figure V.44. Predicted vs. observed TSS at Broad Bay / Linkhorn Bay Branch DEQ stations for 2006.

CHAPTER VI. MODEL VALIDATION

The hydrodynamic and water quality models applied to the Lynnhaven River system were developed using the framework outlined in Chapter III. Chapter V describes how the models were calibrated based on 2006 intensive field measured data described. As part of quality control, the model validation is a process for independent checking that the modeling results meet specifications using a different dataset and that it fulfils its intended purpose.

The hydrodynamic model was validated using synoptic data collected in September and November 2005 and the water quality model for the years 2004 and 2005, during which period both the freshwater discharge and the non-point source loading data were provided by the HSPF watershed model in Lynnhaven River, developed by URS Corporation.

VI-1 Validation of the Hydrodynamic Model

It was critical to conduct a systematic, high-frequency hydrodynamic survey, measuring water elevations inside the inlet synoptically with representative currents and salinities in each branch as well as outside of the Inlet (see Section IV-2-A for a full description of the VIMS Lynnhaven hydrodynamic survey). With these data in hand, validation then

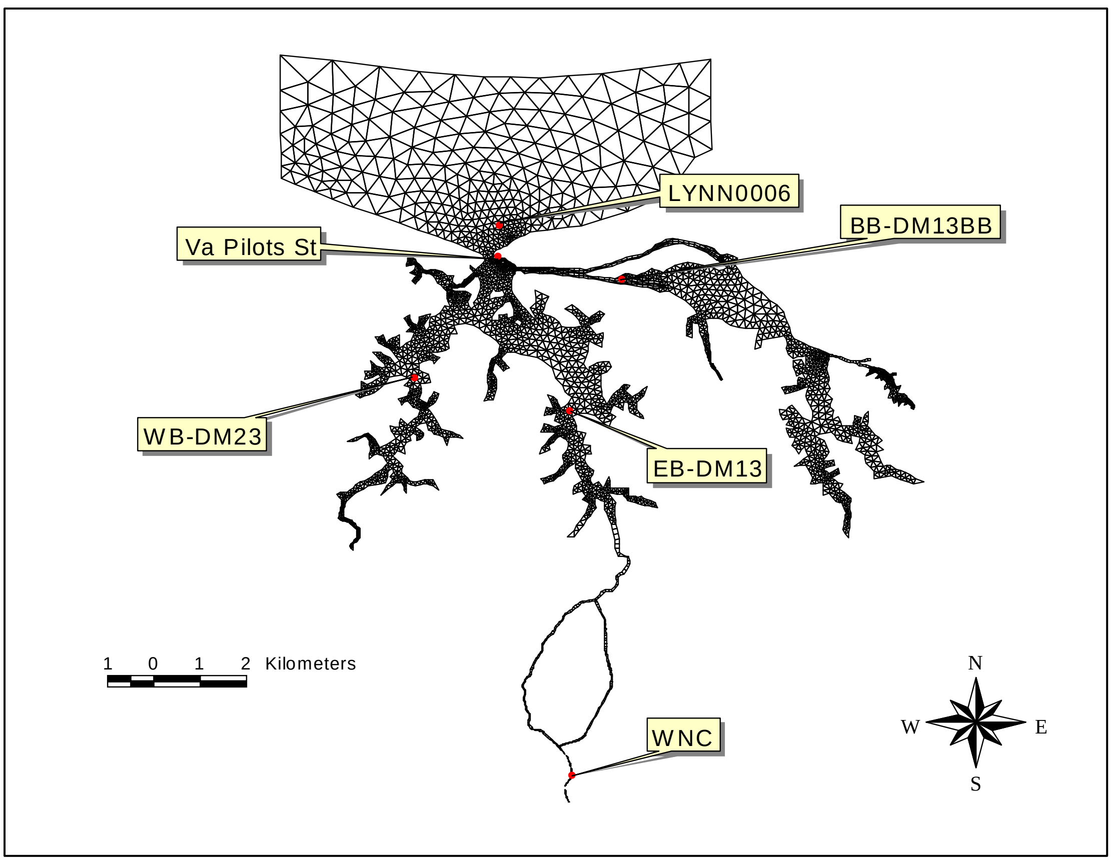


Figure VI.1. Locations of Lynnhaven observation stations (tide and velocity) in 2005.

consisted of a real-time simulation of the prototype condition for periods in September and November, 2005, during which time high-frequency observations of tides, as well as representative high-frequency velocities and salinities in each branch, were available.

VI-1-1 Validation for tidal elevation

In September 2005, a tidal gauge was deployed for 2 weeks in the upper Eastern Branch at West Neck Creek (WNC). In November 2005, a 30-day deployment was made at the Virginia Pilot Station, just inside the Inlet. Locations of these 2 stations are shown in Figure VI.1.

These tidal observations in 2005 were compared to UnTRIM model results from a real-time simulation invoking both the freshwater discharge provided by URS and high frequency wind from the Chesapeake Bay Bridge Tunnel (CBBT) station. The comparison of UnTRIM modeled predictions with observations is shown in Figure VI.2.

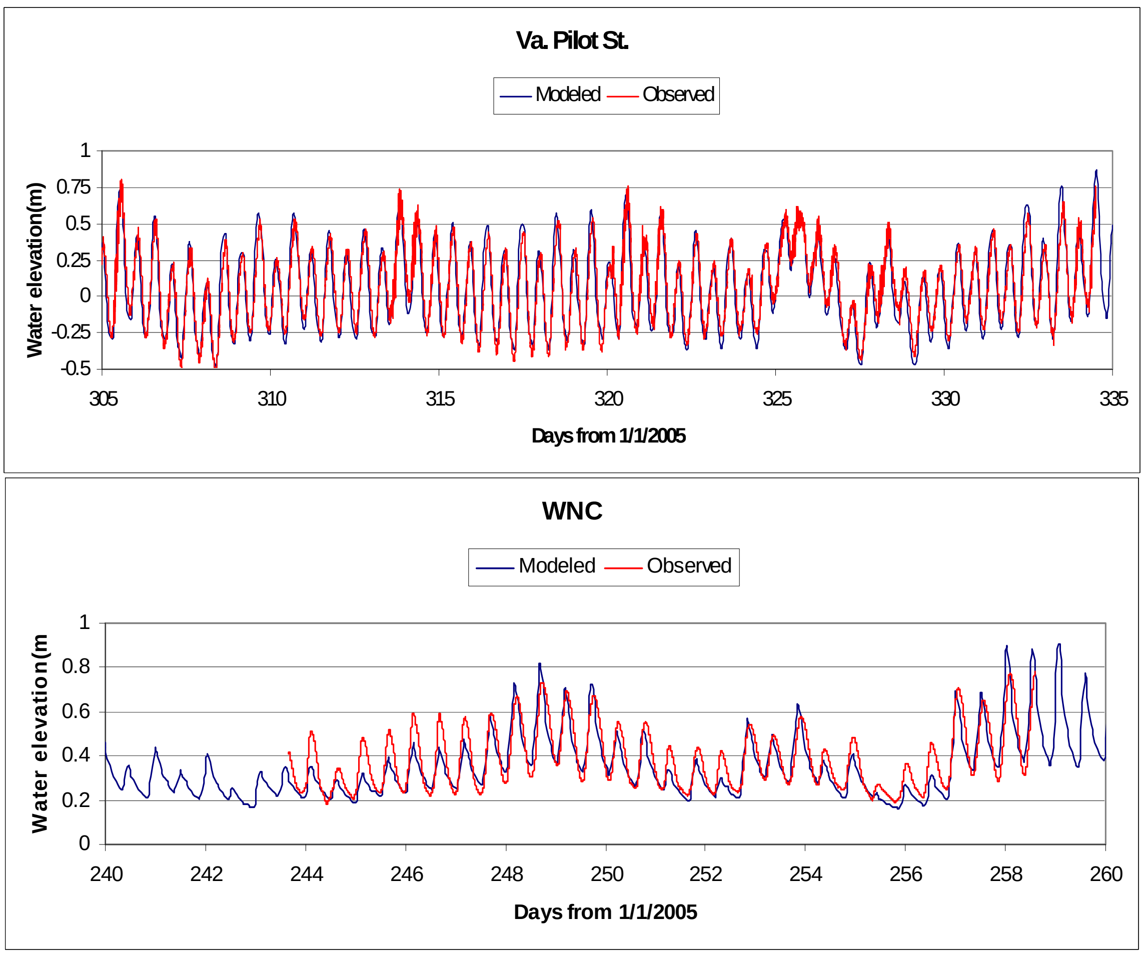


Figure VI.2. Modeled versus observed water elevations at the Virginia Pilot's station (November 2005) and in West Neck Creek (September 2005).

VI-1-2 Validation for velocity

For the VIMS hydrodynamic survey conducted in November 2005, the measurements of tidal velocity were made over a 30-day period using an ADP instrument outside the inlet and an S4 current meter at representative locations of each Lynnhaven branch. Locations of these instruments are shown in Figure VI.3 below.

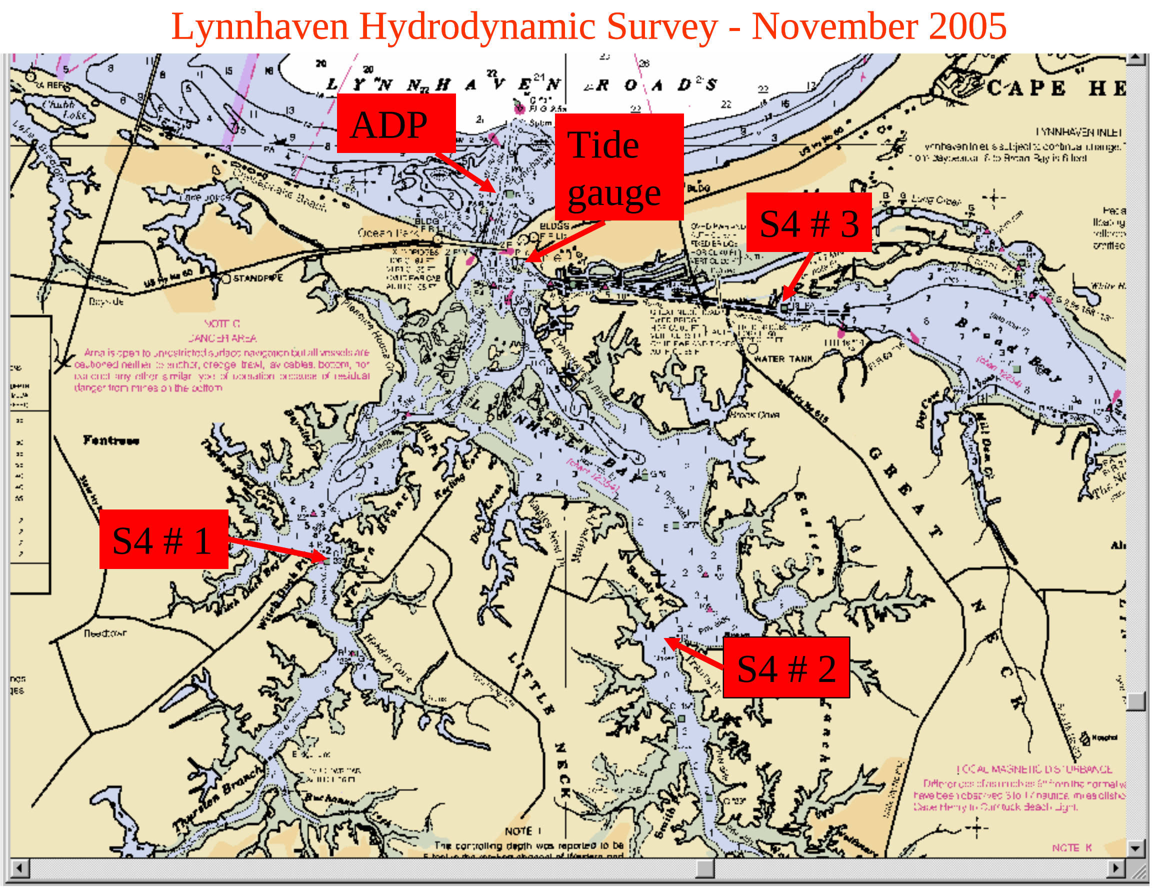


Figure VI.3. Locations of Lynnhaven Velocity Stations, November 2005.

The bottom-mounted ADP outside the Inlet measured velocities at 10 layers in the vertical at a frequency of every 20 minutes for the 30-day deployment. The S4 instruments deployed in each branch measured mid-depth velocity at 30-minute intervals over the deployment.

East-west and north-south component comparisons between observed and predicted currents outside the Inlet are shown in Figure VI.4. The modeled and observed velocity magnitude and direction comparisons are shown for the Western, Eastern, and Broad Bay branches, respectively, in Figures VI.5 through VI.7. In general, good agreement is shown between modeled and observed tidal velocities.

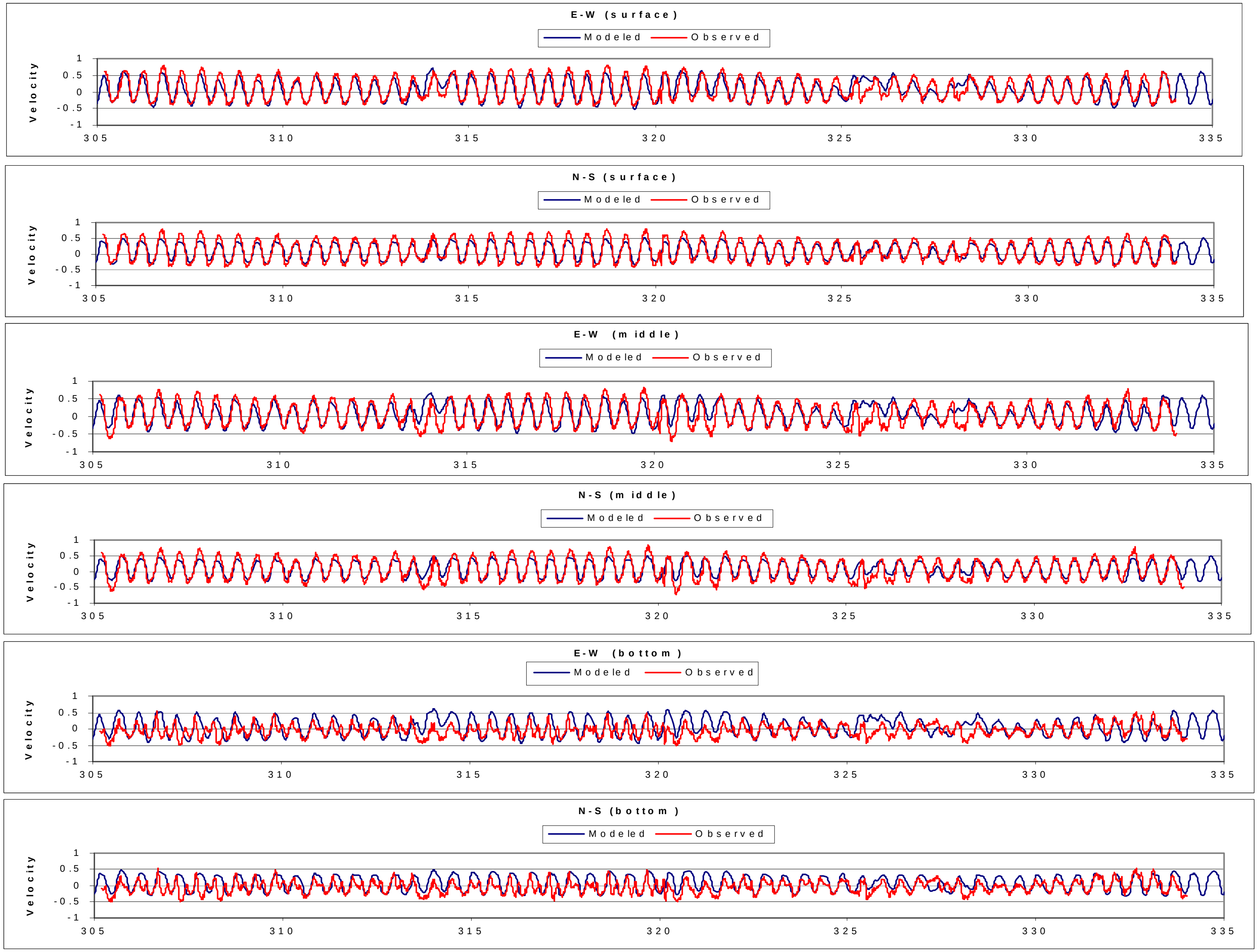
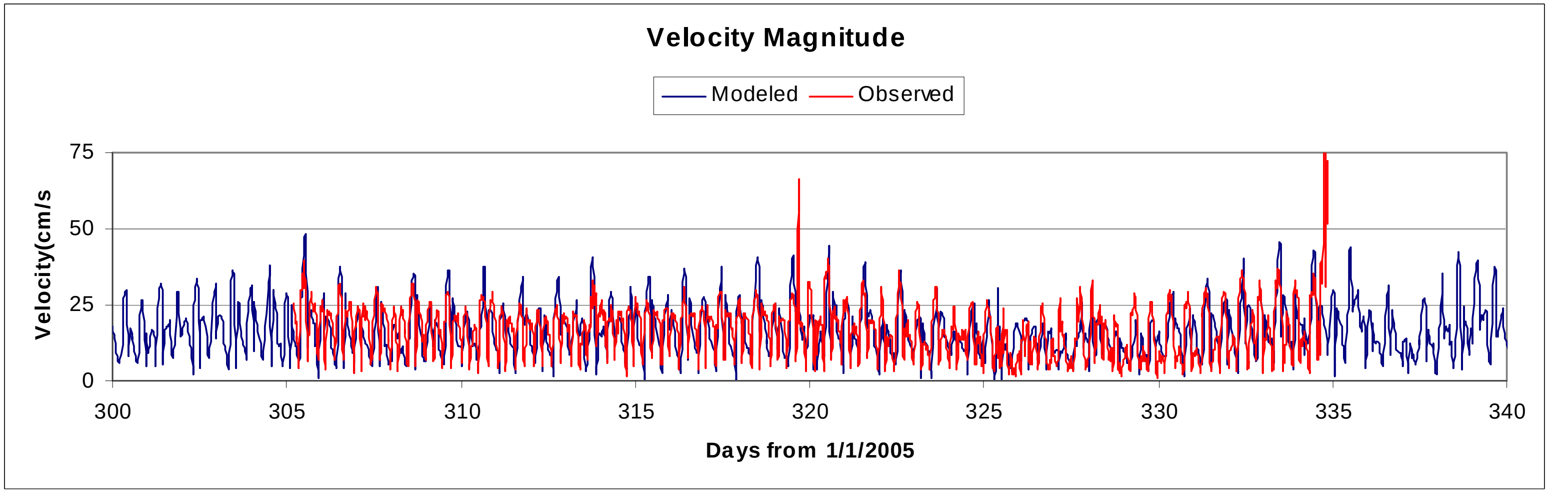


Figure VI.4. East-west and north-south components of measured versus modeled velocity at surface, middle, and bottom layers outside Lynnhaven Inlet.

Comparison of Velocity (Western Branch)



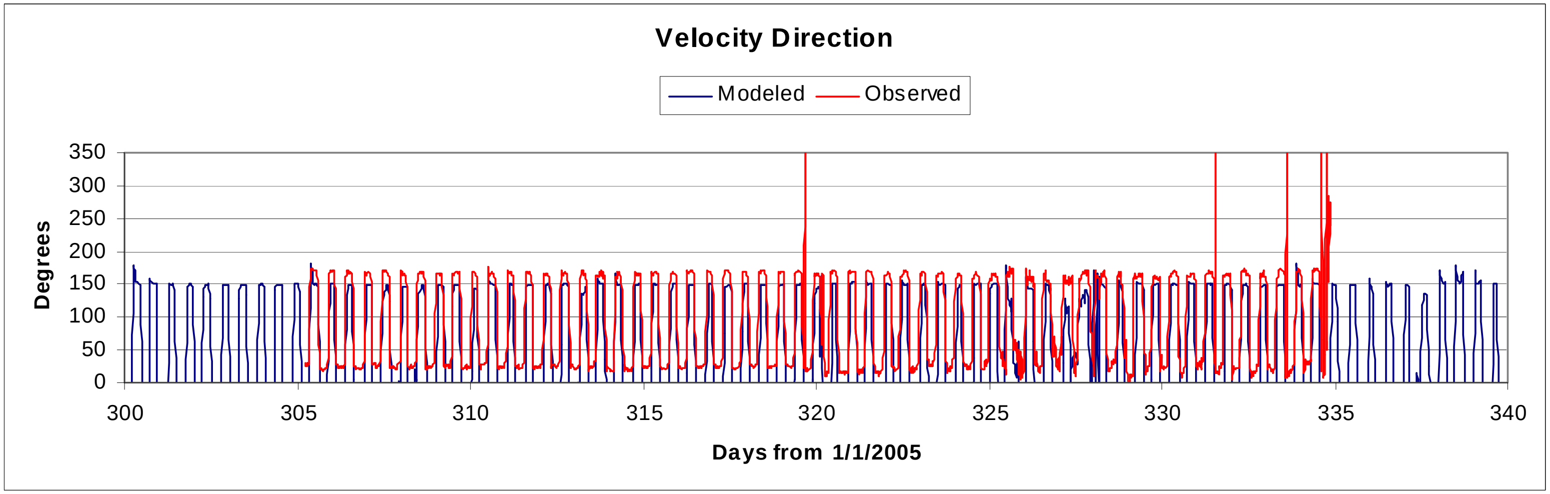
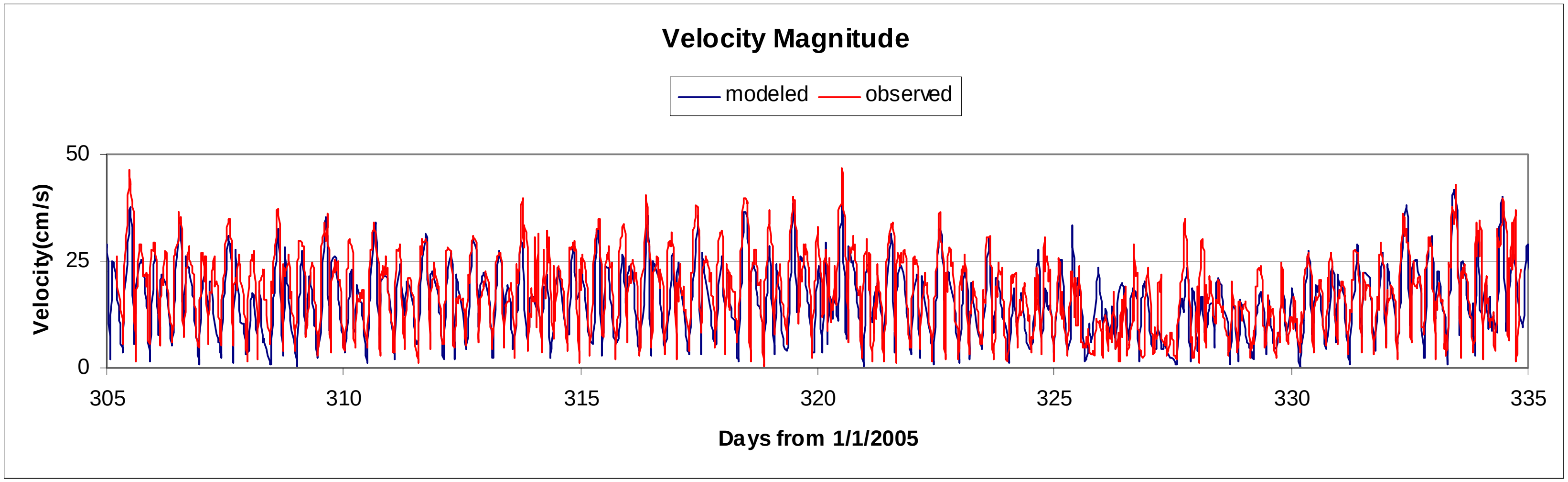


Figure VI.5. Magnitude and direction of measured versus modeled velocity at mid-depth in the Western Branch.

Comparison of Velocity (Eastern Branch)



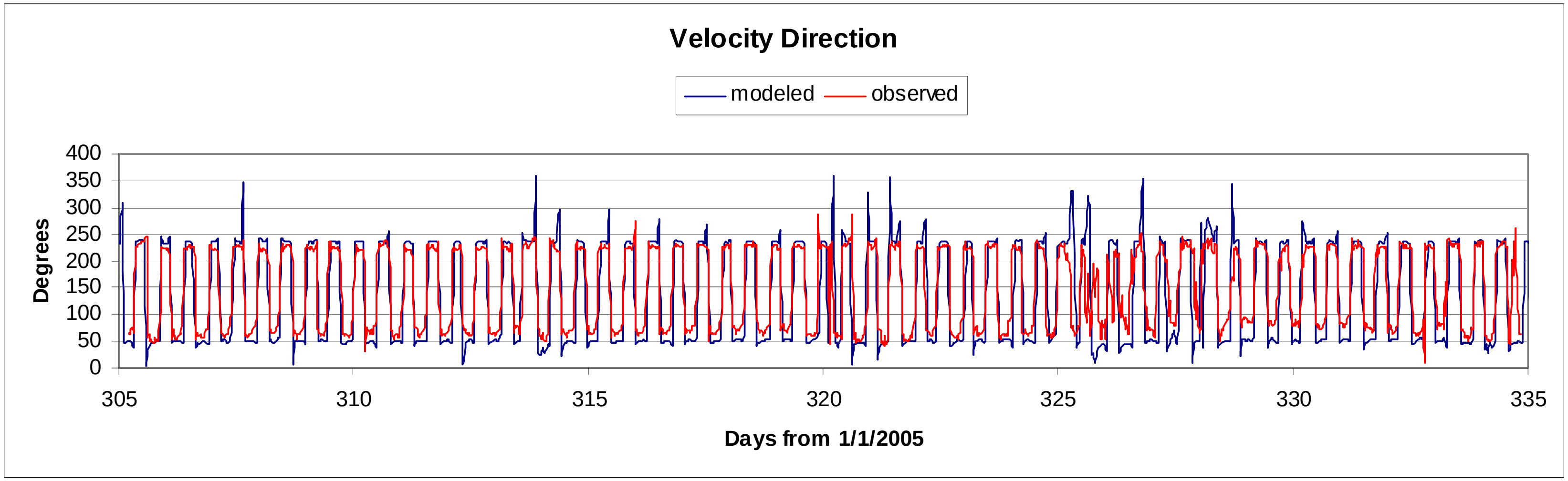
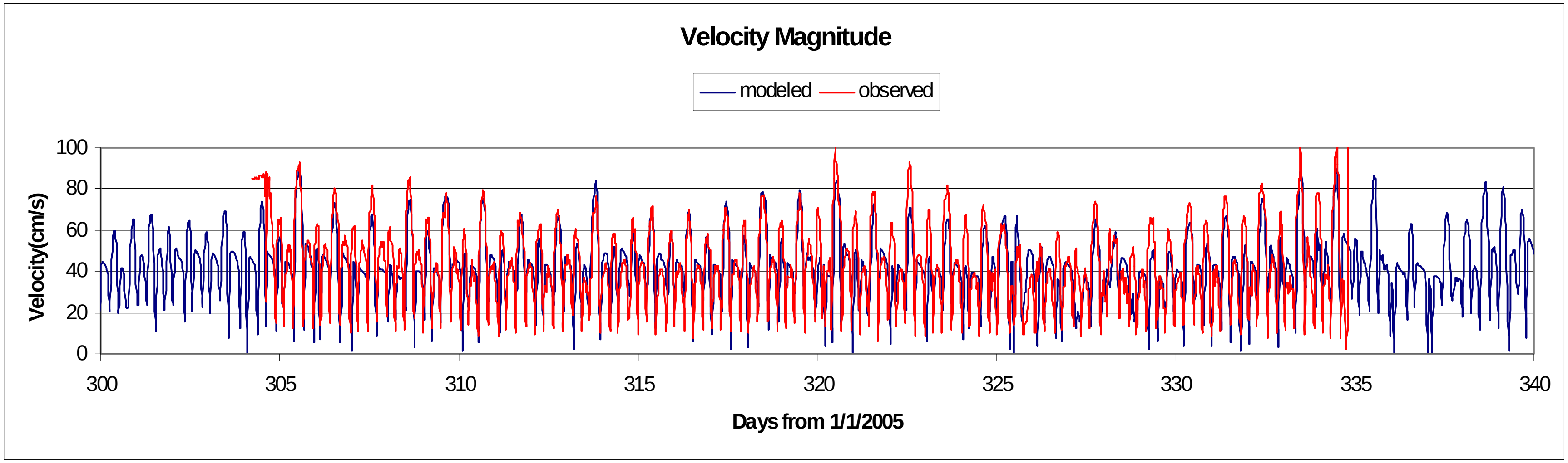


Figure VI.6. Magnitude and direction of measured versus modeled velocity at mid-depth in the Eastern Branch.

Comparison of Velocity (Broad Bay)



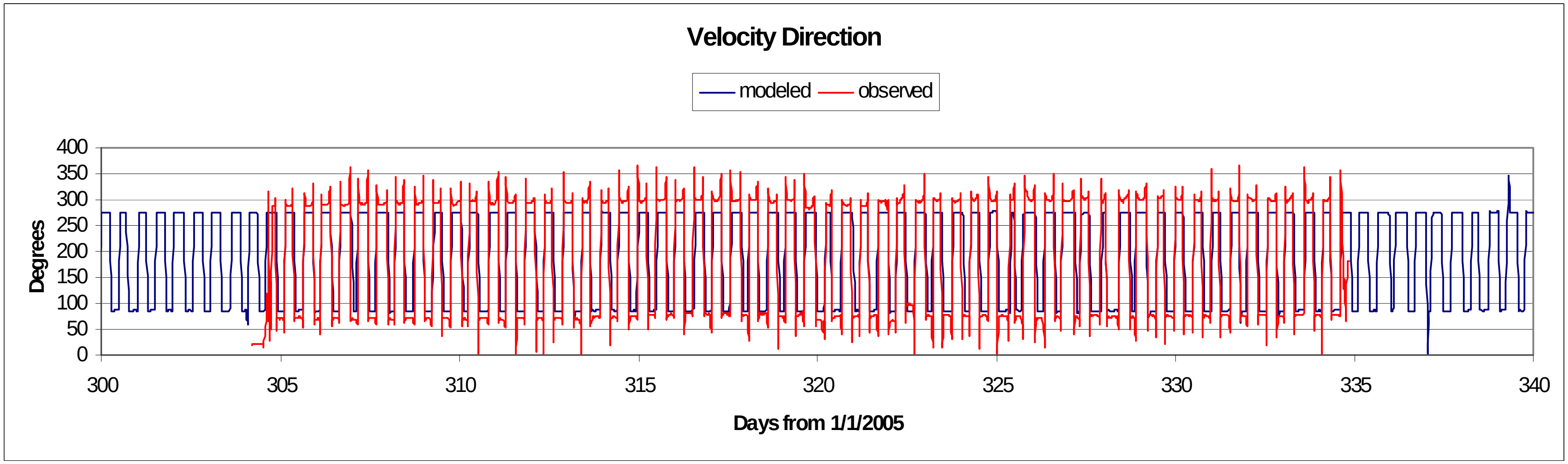


Figure VI.7. Magnitude and direction of measured versus modeled velocity at mid-depth in Broad Bay.

VI-1-3 Validation for salinity

In order to validate salinity predicted by the UnTRIM hydrodynamic model, comparisons between measurements and model predictions were made at all 16 VA-DEQ stations monitored every other month in the Lynnhaven River throughout calendar years 2004 and 2005. Measured data also included those made by the VIMS dataflow surveys during this period (please note that the dataflow coverage did not extend to all 16 stations). The locations of these stations are shown below in Figure VI.8 and the modeled vs. measured salinities for 2004-2005 are shown in Figures VI.9-VI.10, VI.11-VI.12, and VI.13-VI.14, respectively, for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches.

VI-1-4 Validation for temperature

The locations of these stations are shown in Figure VI.8 and the modeled vs. measured temperatures for 2004-2005 are shown in Figures VI.15-VI.16, VI.17-VI.18, and VI.19-VI.20, respectively, for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches.

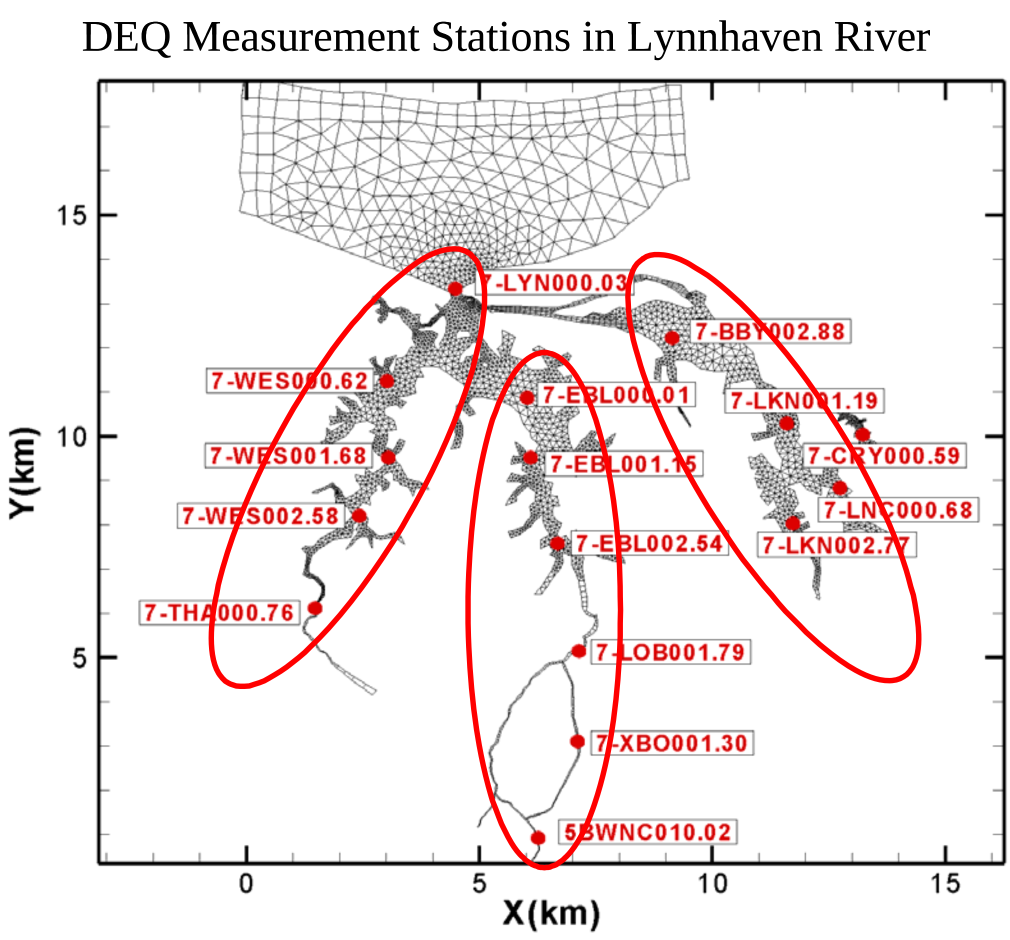


Figure VI.8. Grouping by branch of Lynnhaven DEQ stations as used to compare measured and modeled salinity, temperature, and CE-QUAL-ICM water quality model validation results.

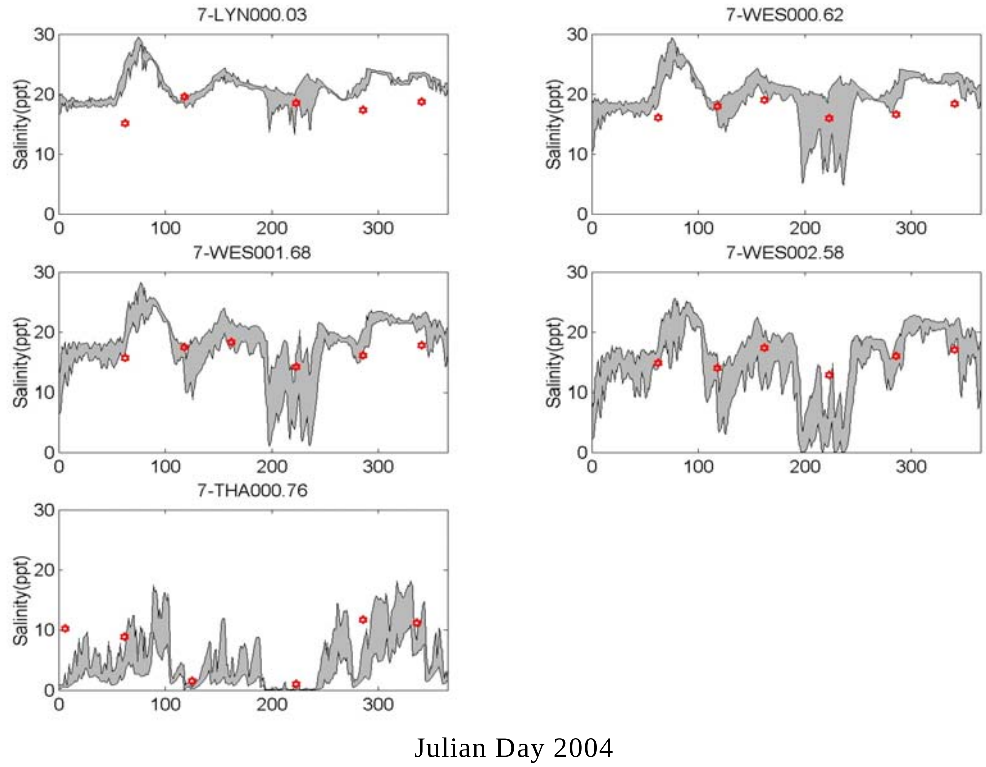


Figure VI.9. UnTRIM modeled versus measured salinities at Western Branch DEQ stations for 2004.

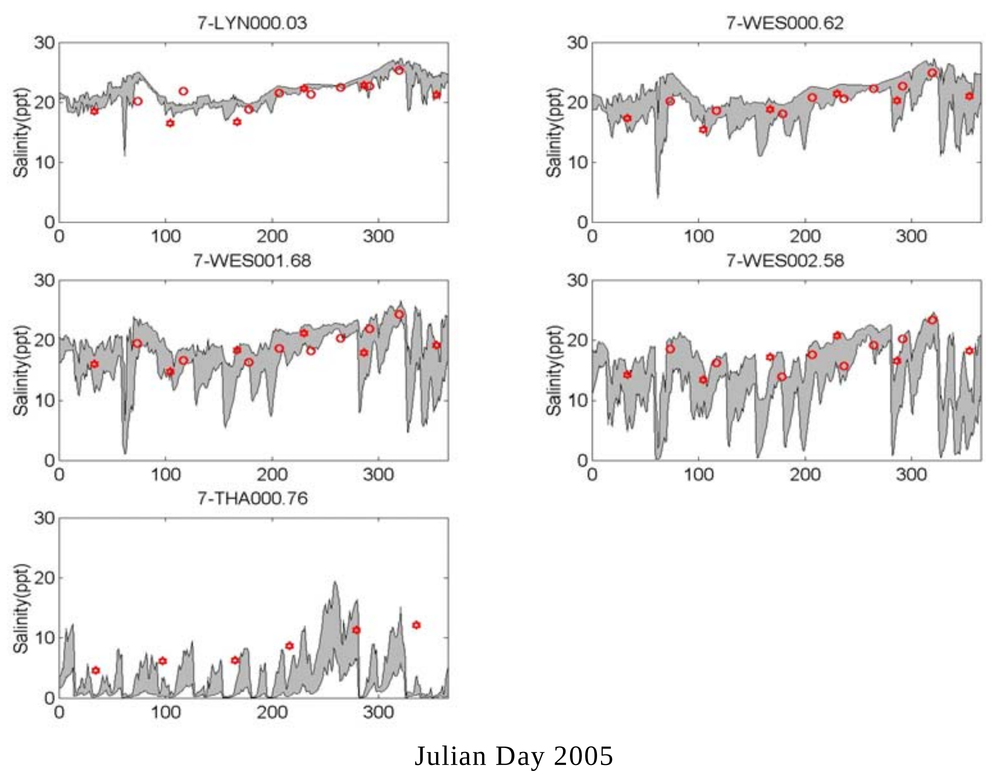


Figure VI.10. UnTRIM modeled versus measured salinities at Western Branch DEQ stations for 2005. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

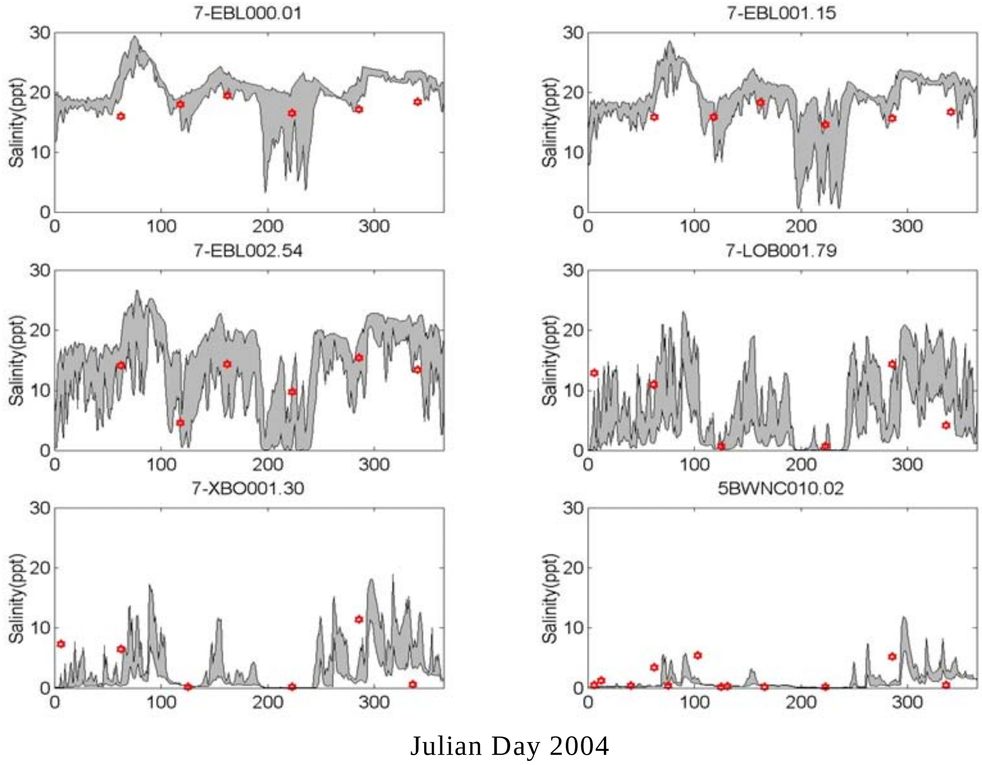


Figure VI.11. UnTRIM modeled versus measured salinities at Eastern Branch DEQ stations for 2004.

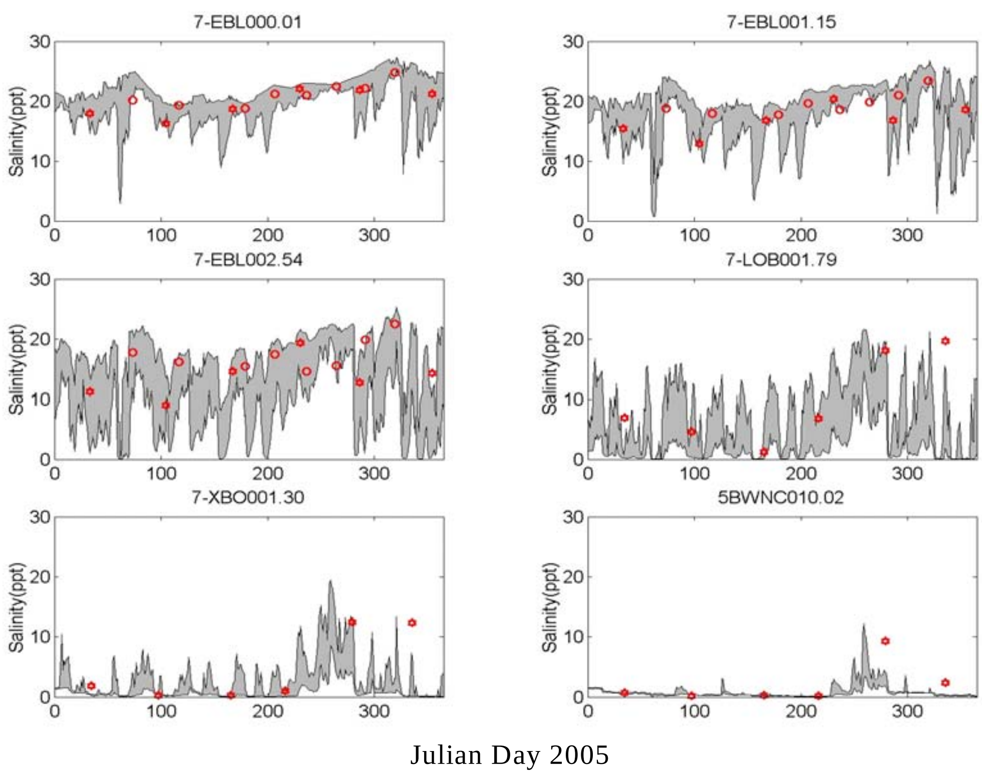


Figure VI.12. UnTRIM modeled versus measured salinities at Eastern Branch DEQ stations for 2005. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

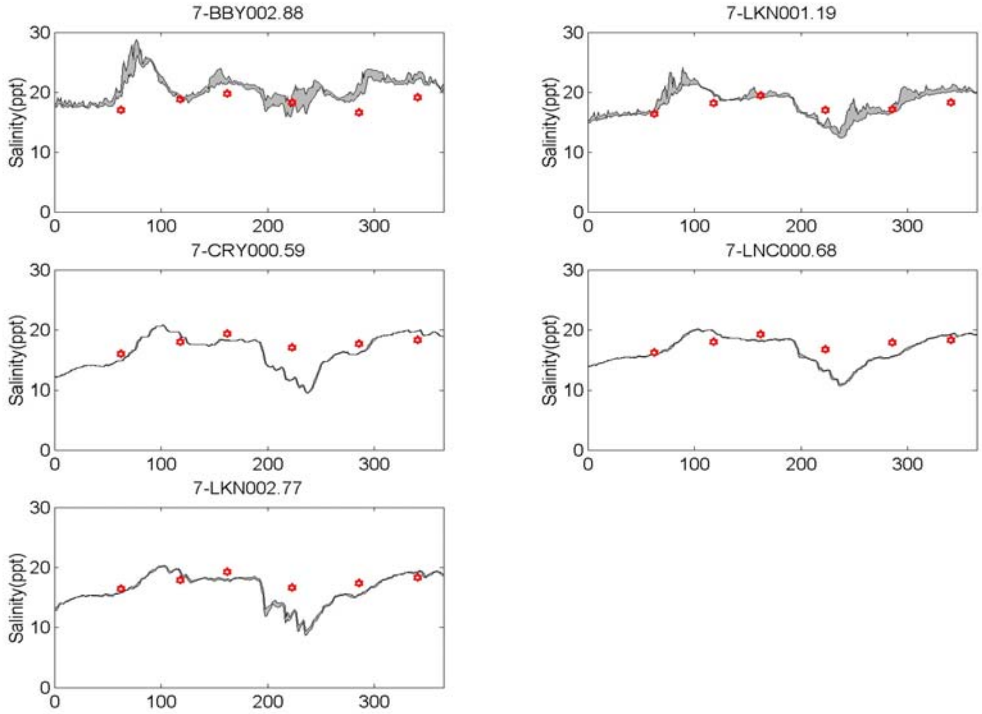


Figure VI.13. UnTRIM modeled versus measured salinities at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

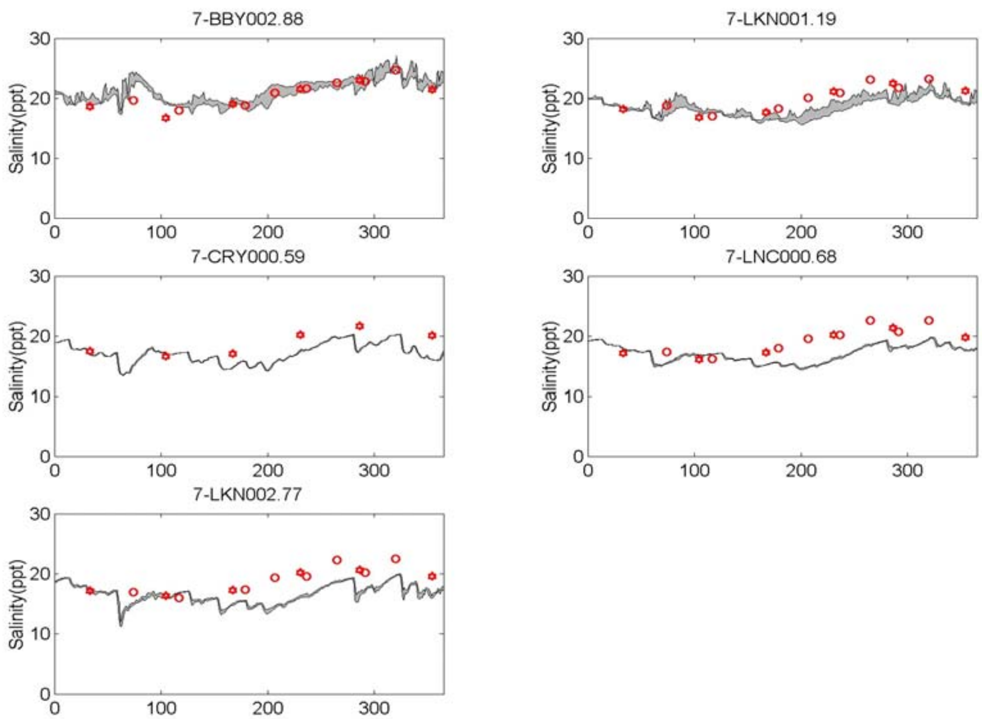


Figure VI.14. UnTRIM modeled versus measured salinities at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005. Red asterisks denote DEQ measurements and red circles denote VIMS dataflow measurements.

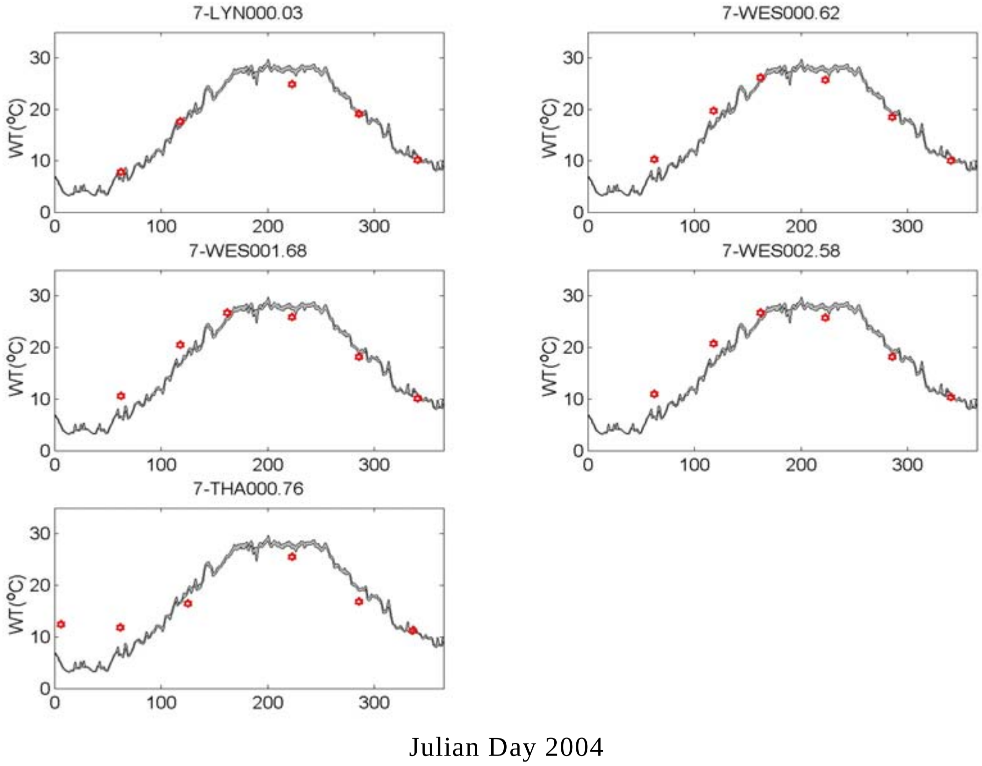


Figure VI.15. UnTRIM modeled versus measured temperatures at Western Branch DEQ stations for 2004.

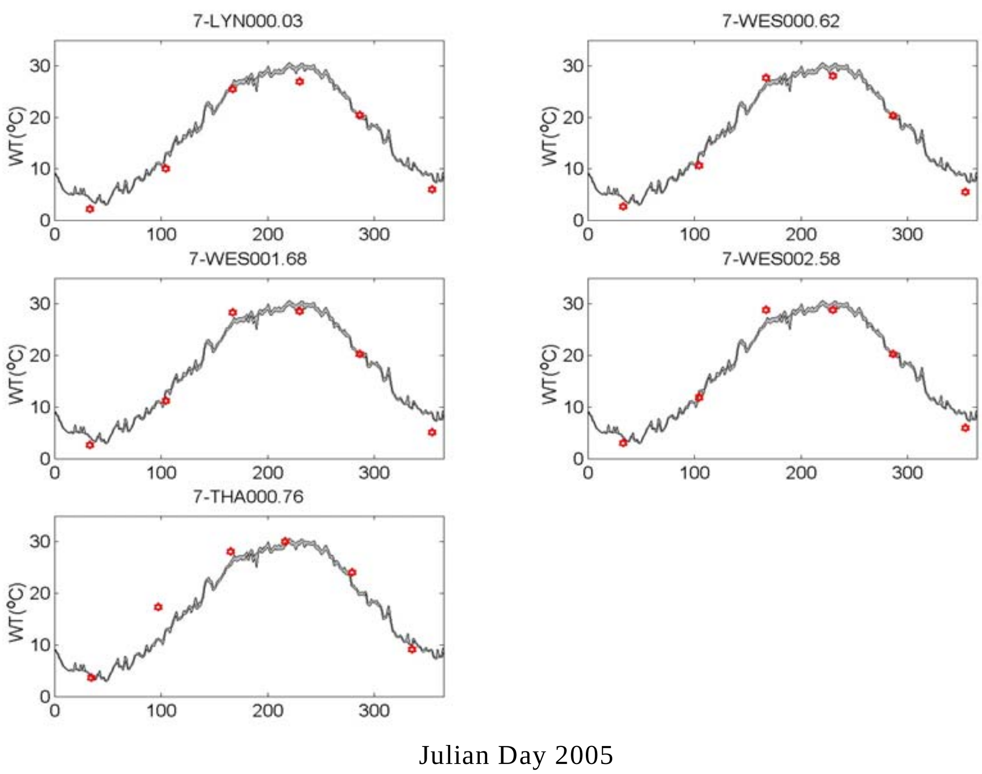


Figure VI.16. UnTRIM modeled versus measured temperatures at Western Branch DEQ stations for 2005.

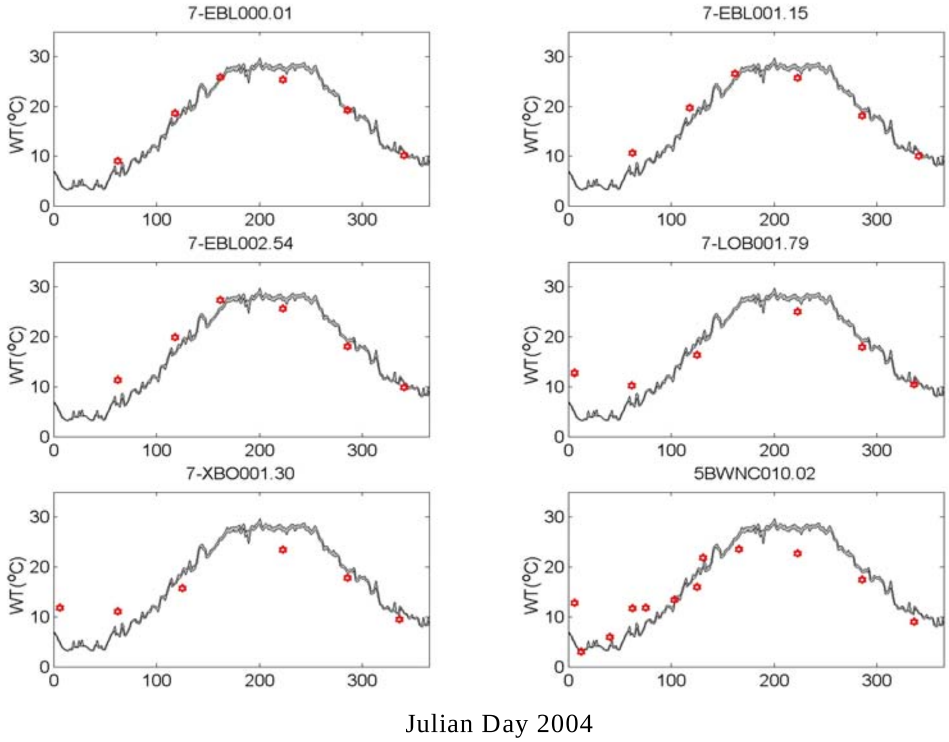


Figure VI.17. UnTRIM modeled versus measured temperatures at Eastern Branch DEQ stations for 2004.

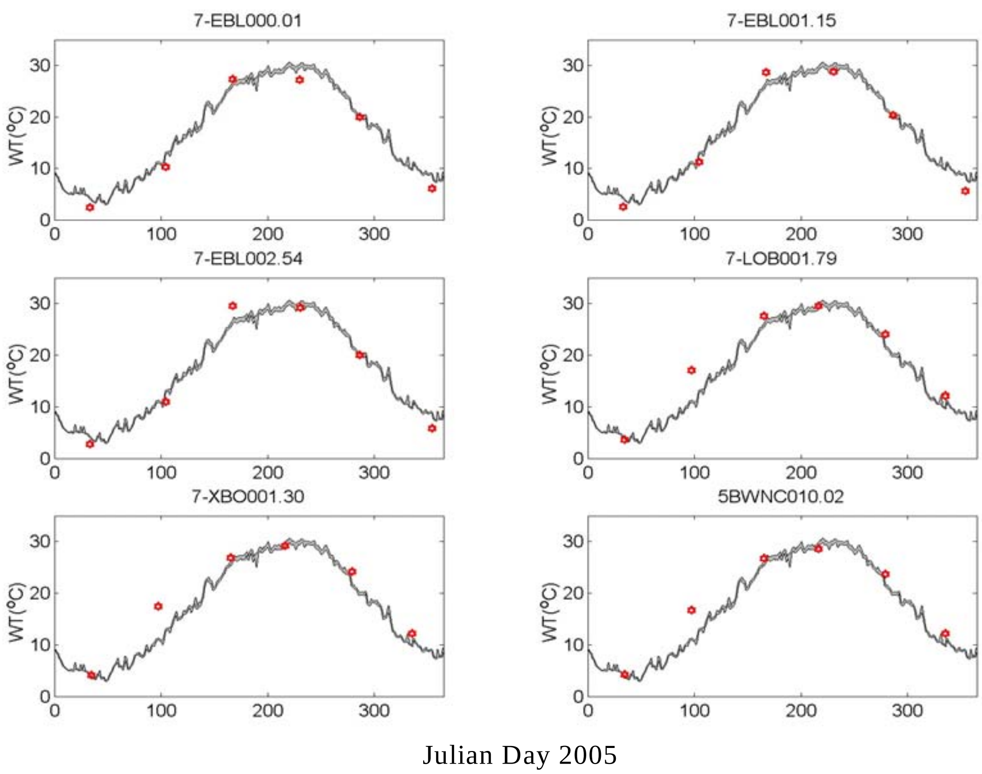


Figure VI.18. UnTRIM modeled versus measured temperatures at Eastern Branch DEQ stations for 2005.

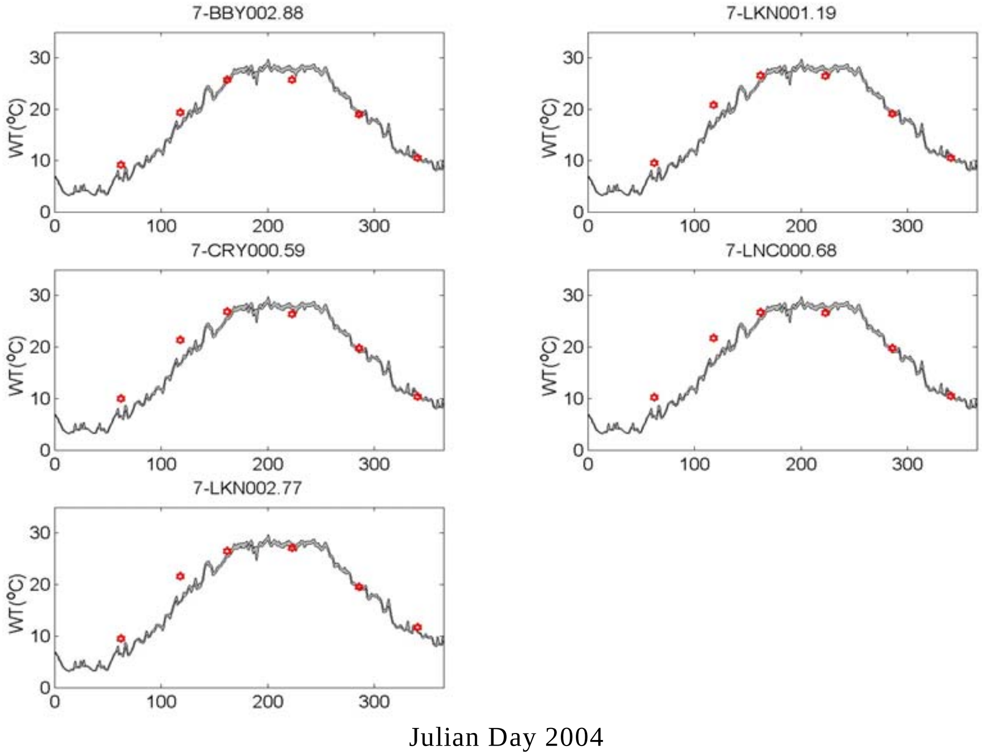


Figure VI.19. UnTRIM modeled versus measured temperatures at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

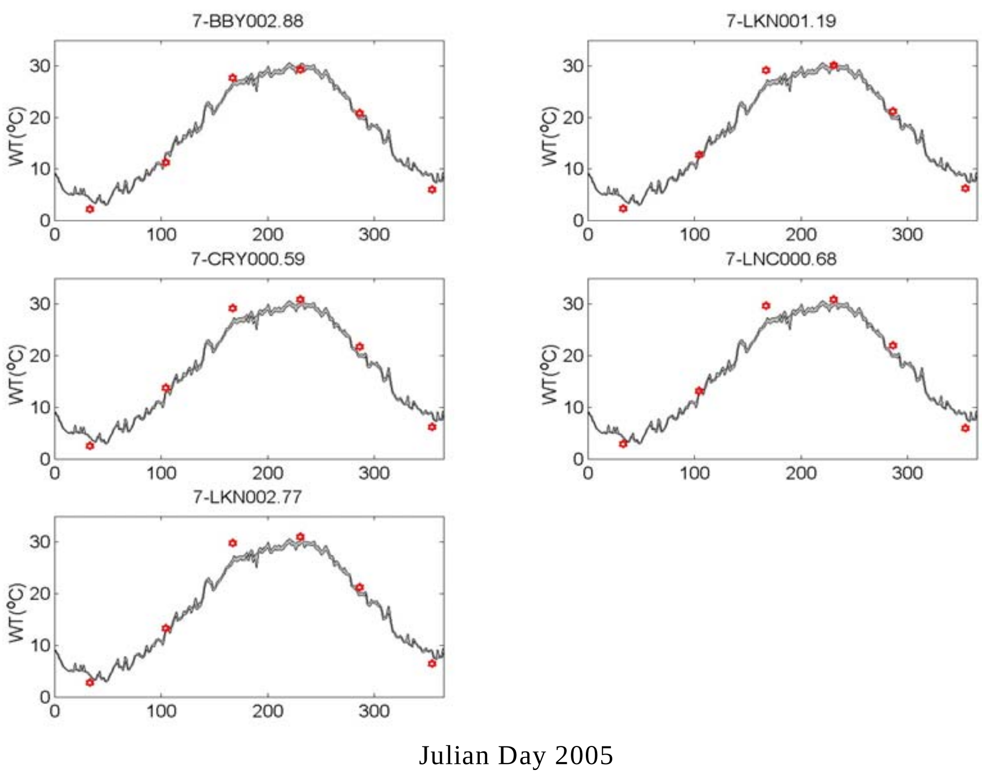


Figure VI.20. UnTRIM modeled versus measured temperatures at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

VI-2 Validation of the Water Quality Model

The overall objective of the model validation procedure is to confirm the predictive capability of the CE-QUAL-ICM model by simulating an entirely different period than that selected for model calibration. Results of the calibration simulation (2006) are shown in Chapter V, Section V-2-5.

Because some parameters were not measured by DEQ in 2004 and in the first half of 2005 due to Virginia State budgetary restrictions that impacted the DEQ monitoring program, the full period of 2004-2005 was selected for model validation.

VI-2-1 Model Validation Results

Lynnhaven hydrologies in 2004 and 2005 differ from that in 2006. On an annual basis, the year of 2004 had higher freshwater input than 2005 and 2005, in turn, had higher input than 2006. In other words, the year 2006 had the lowest freshwater input among 2004, 2005, and 2006. As a result, the salinity of 2006 was the largest and that of 2004 was the smallest. This is part of a long-term trend of decreasing freshwater water input spanning from 2003 to 2008 noted from James River freshwater records.

On the seasonal basis, the year 2004 has a relatively dry winter/spring (from day 70 – 100) but a wet summer (from day 180- 210). On the contrary, the year 2005 had a wet winter/spring (from day 50- 75) and a dry summer/fall (from day 210 – 270). This pattern shift affects the seasonal variation of the water quality within the yearly cycle.

In terms of the annual temperature pattern, the year 2005 had the highest summer water temperature reaching 29.8 degrees Celsius in August, followed by 2006 and 2004. It does not, however, show a significant seasonal shift over the three years 2004-2006. Water quality variables are affected by both salinity and temperature and, thus, it is important to recognize that there are inter-annual, as well as seasonal, variations.

Given that the physical parameters varied from year to year, it is obvious that there will be ramifications on the water quality variables both in terms of their loading as well as the result of chemical kinetics. Validation of the water quality model took place by comparison of time series plots of selected water quality parameters with DEQ observations at the 16 locations shown earlier in Figure VI.8. As was done for the display of calibration results, stations of each Lynnhaven River branch are clustered in the figures comparing observed versus predicted values of each parameter for stations of that branch to facilitate the comparison.

Model simulation results at each station are shown for the full calendar years of 2004 and 2005 and include the primary water quality parameters of dissolved oxygen, chlorophyll-a, TKN, ammonia, nitrate-nitrite, total phosphorus, and ortho phosphorus. Due to the restrictions on monitoring in 2004 and early 2005, validation comparisons of TKN, ammonium, nitrate-nitrite, and ortho phosphorus are limited to the latter half of 2005.

A. Western Branch DEQ stations validation results

As described above, the hydrological conditions in 2004 and 2005 are quite different from those in 2006. After the calibration has been performed for the year of 2006, the validation provides an independent check of whether the modeling results can meet specifications using different hydrological datasets and fulfils its intended purpose.

Keep in mind, however, that between 2004 and 2005, the seasonal patterns are also different. The year of 2004 has a dry spring and wet summer whereas the year of 2005 has a wet spring, but a dry summer. Water quality model validation results for Western Branch DEQ stations for 2004 and 2005 are carried out with different salinity patterns and the reaction constants that are temperature-dependent. The results are shown in Figures VI.21 through VI.34. In all figures, the model predictions are represented as a gray band bounded by daily minimum and maximum.

Results for dissolved oxygen in 2004 and 2005, respectively, are shown in Figures VI.21 and VI.22. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen quite well. The seasonally low DO values (i.e., below 5 mg/l) measured throughout the Western Branch around Julian Day 200 of 2005 were well-captured by model predictions. Figures VI.23 and VI.24 present the predicted versus observed comparisons for chlorophyll-a, catching the trend for the downstream stations, but showing some isolated discrepancies at the upstream stations 7-WES002.58 and 7-THA000.76. Figures VI.25 and VI.26 show model predictions of TKN during 2004 and 2005 for all Western Branch DEQ stations. Observed TKN was only available in latter 2005, but showed good agreement with predictions over this period. The predictions of ammonium shown in Figures VI.27 and VI.28 for 2004 and 2005, respectively, have similar seasonal trends at all stations, and the available observed data from the latter part of 2005 match the predictions reasonably well at all Western Branch DEQ stations. Figures VI.29 and VI.30 show predictions of nitrate-nitrite for 2004 and 2005, respectively, and the available observation measurements of the latter part of 2005 are shown to match reasonably well. An inspection of Figures VI.31 through VI.34 shows that both total phosphorus and ortho-phosphorus measurements are captured reasonably well at all Western Branch DEQ stations.

As in the case of comparisons of observed vs. predicted parameter values for the model calibration (2006) shown in Chapter V, an inspection of Figures VI.21 through VI.34 shows the gradual decrease of dissolved oxygen and increases of both chlorophyll-a and nutrient levels in moving from the Inlet upstream to Thalia Creek. This is a spatial gradient pattern that is consistent with what was observed in the historical data. The shift on the spring and summer pattern basically reflects the difference of the hydrological year. The model does respond truthfully to the real environmental conditions.

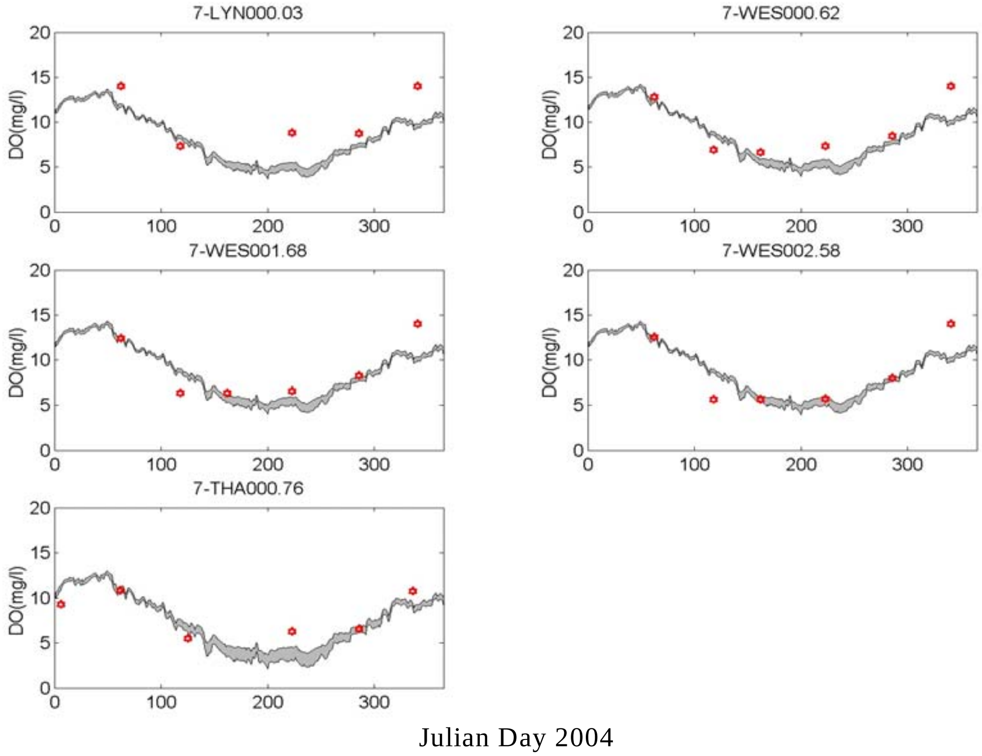


Figure VI.21. Predicted vs. observed dissolved oxygen at Western Branch DEQ stations for 2004.

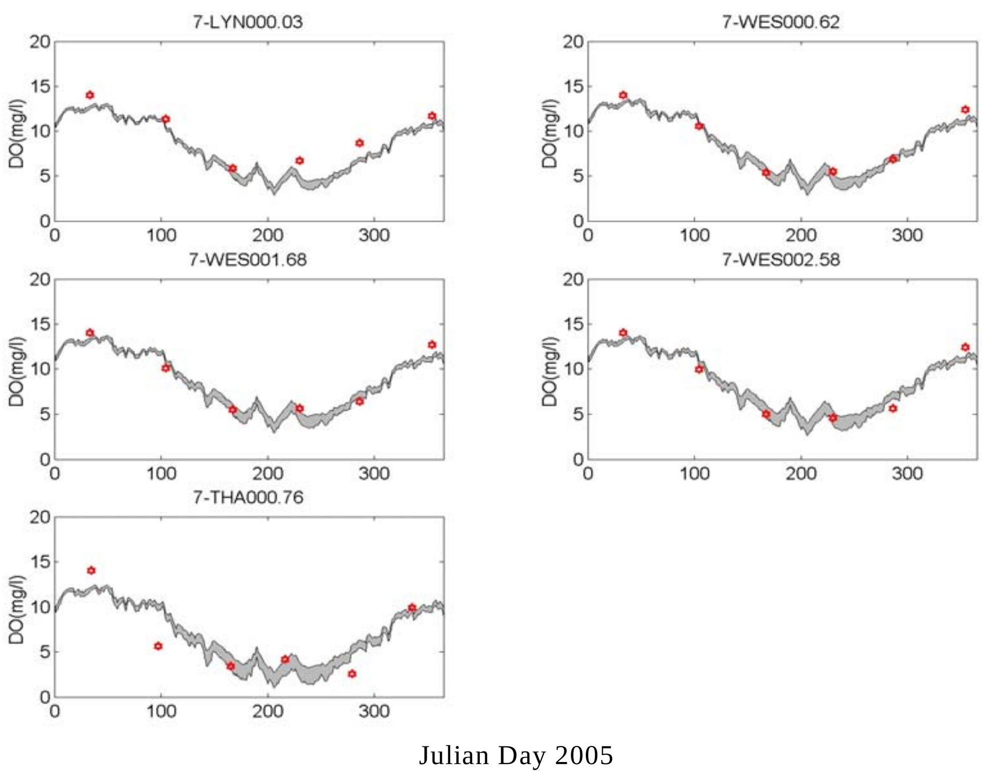


Figure VI.22. Predicted vs. observed dissolved oxygen at Western Branch DEQ stations for 2005.

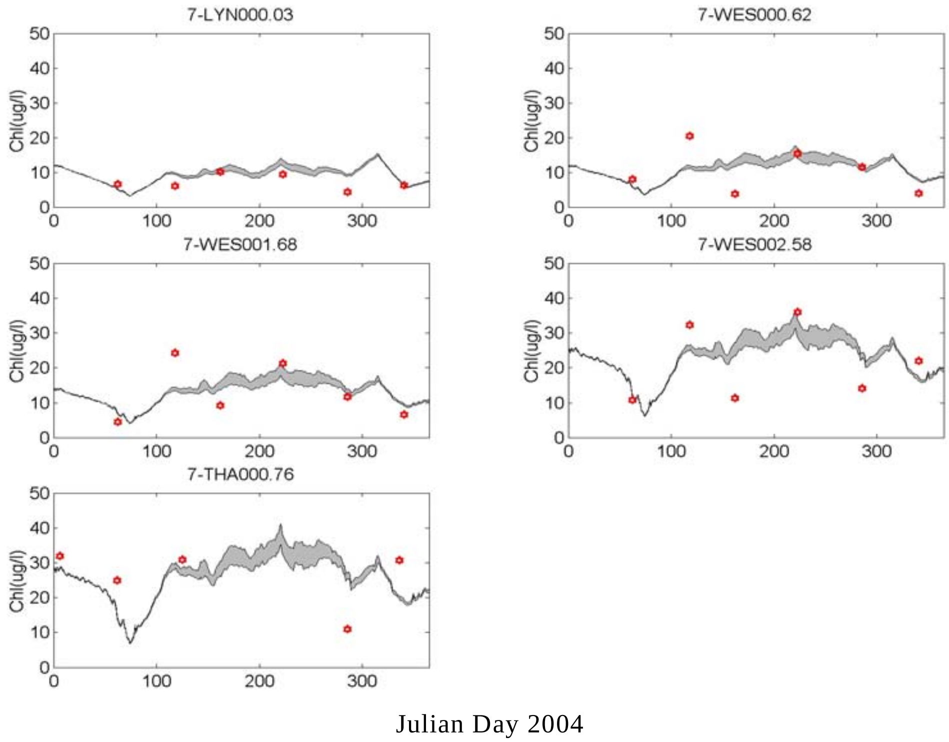


Figure VI.23. Predicted vs. observed chlorophyll-a at Western Branch DEQ stations for 2004.

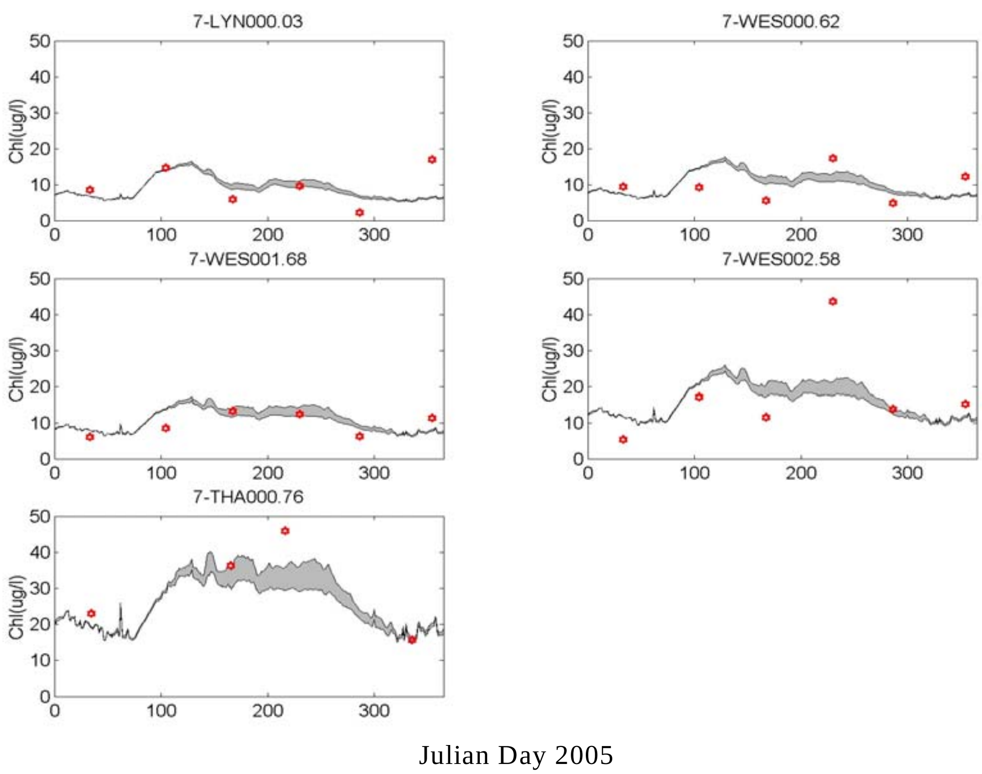


Figure VI.24. Predicted vs. observed chlorophyll-a at Western Branch DEQ stations for 2005.

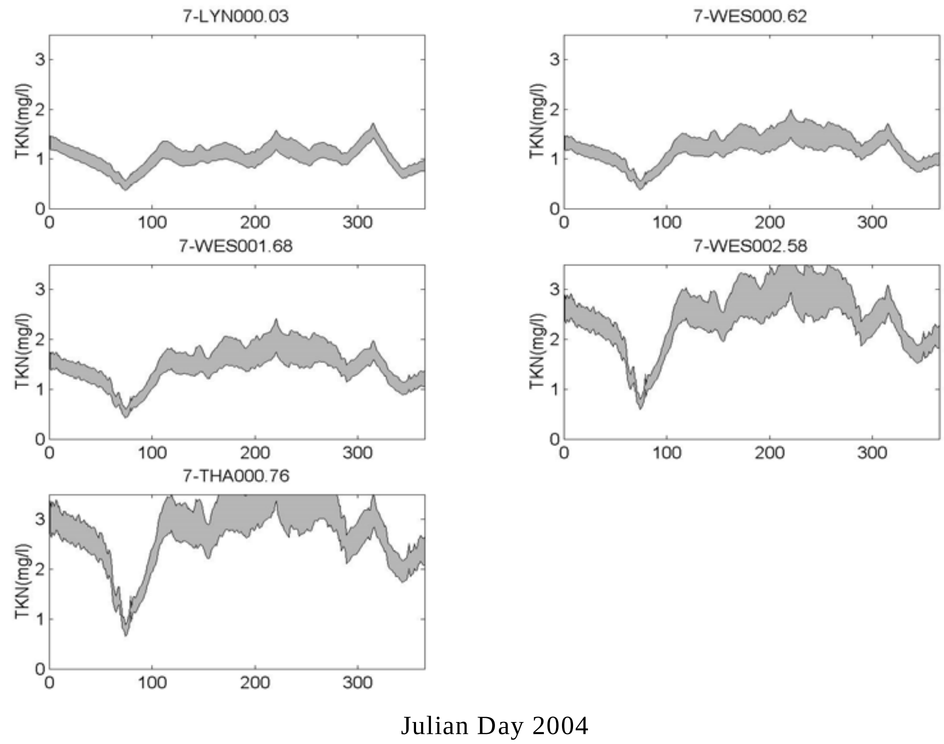


Figure VI.25. Predicted TKN at Western Branch DEQ stations for 2004.

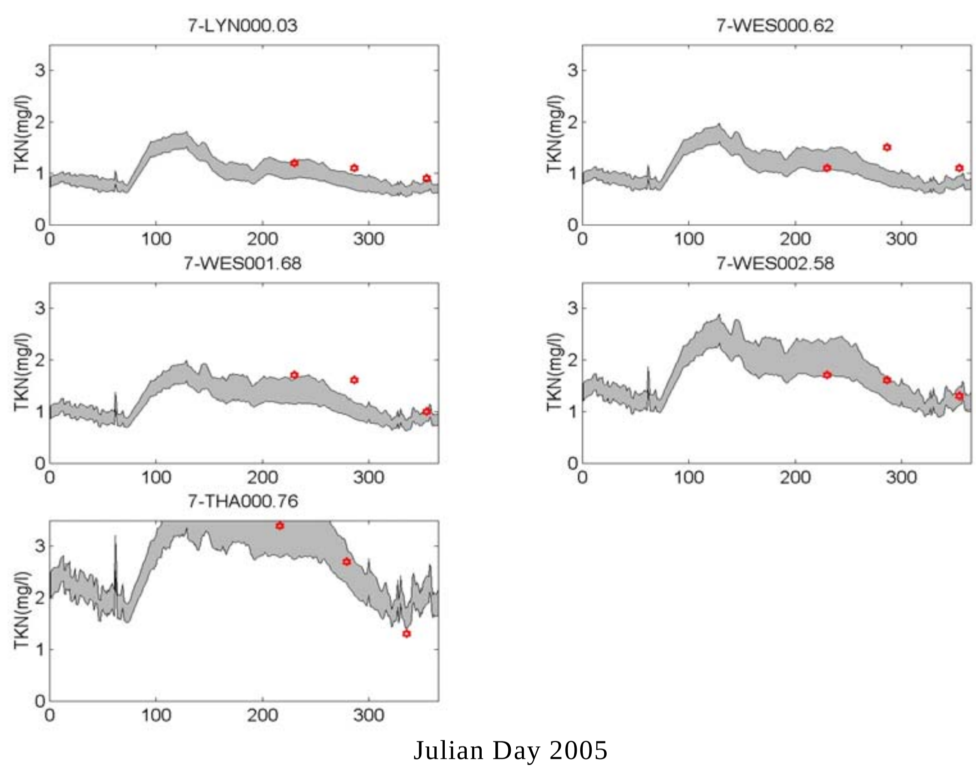


Figure VI.26. Predicted vs. observed TKN at Western Branch DEQ stations for 2005.

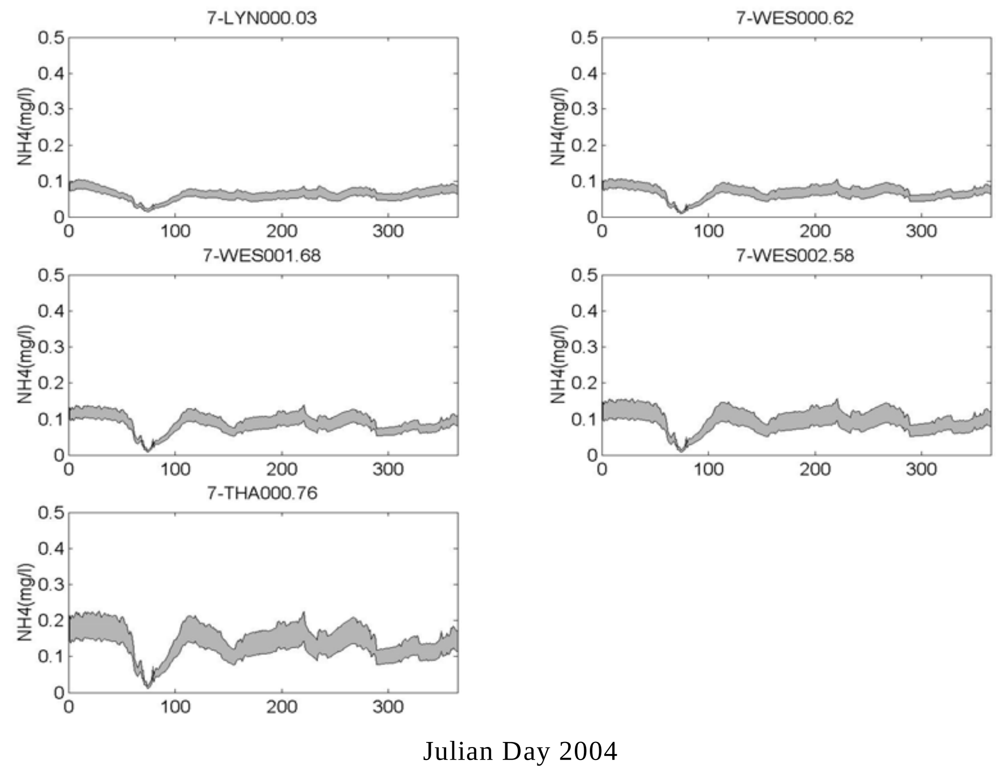


Figure VI.27. Predicted ammonium at Western Branch DEQ stations for 2004.

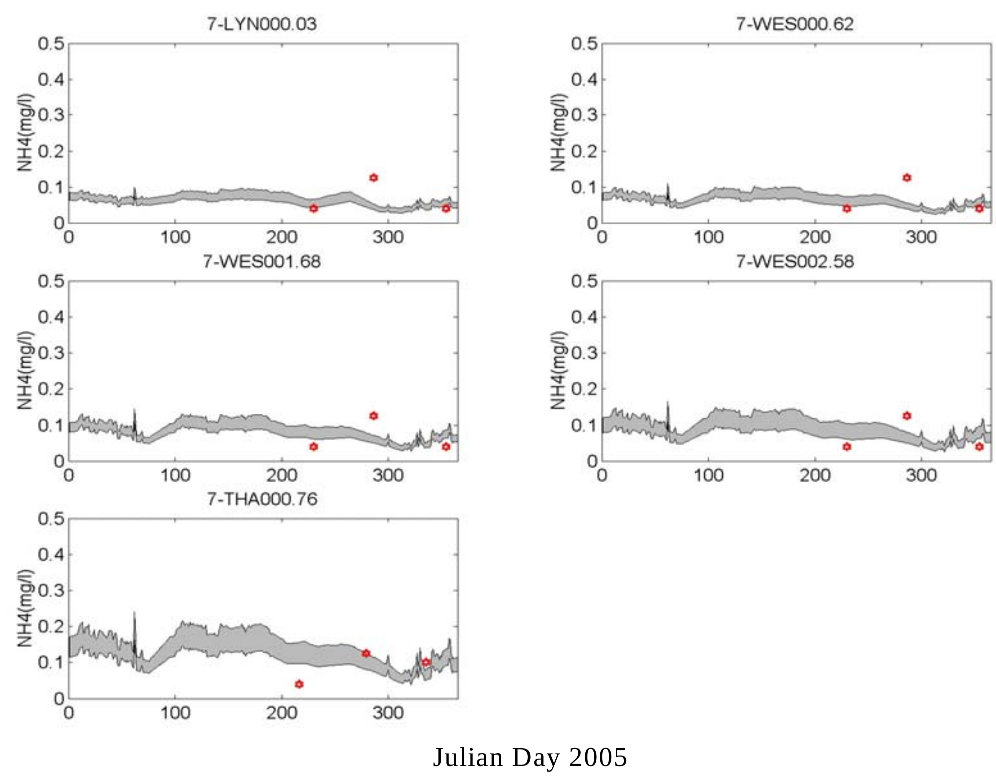


Figure VI.28. Predicted vs. observed ammonium at Western Branch DEQ stations for 2005.

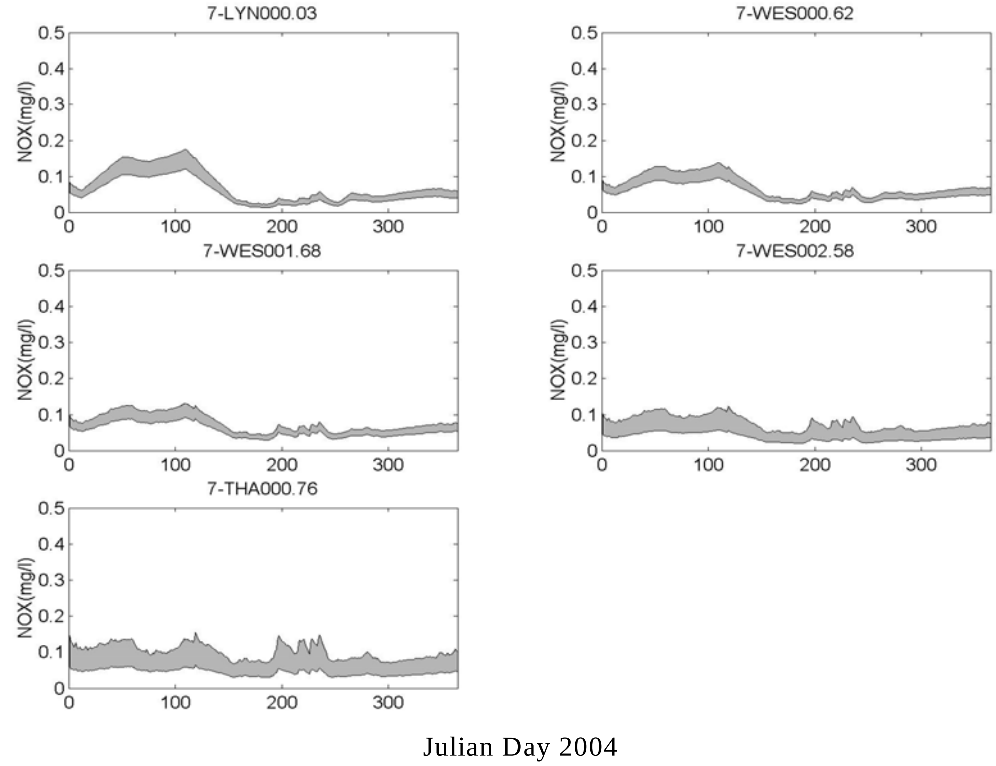


Figure VI.29. Predicted nitrate-nitrite at Western Branch DEQ stations for 2004.

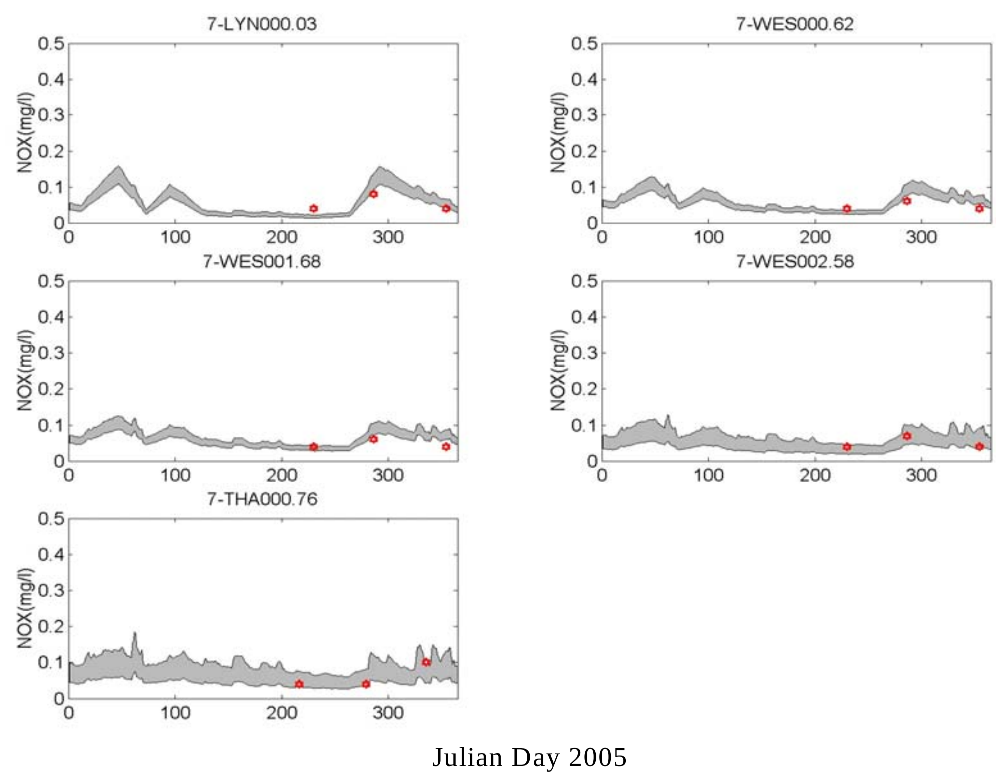


Figure VI.30. Predicted vs. observed nitrate-nitrite at Western Branch DEQ stations for 2005.

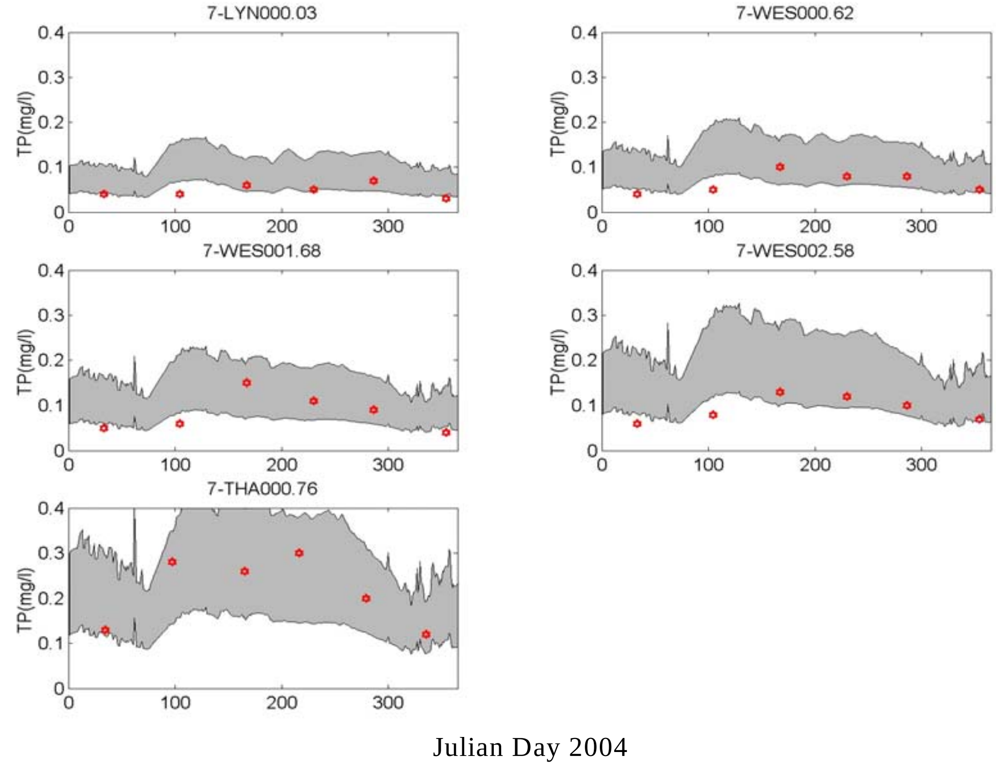


Figure VI.31. Predicted vs. observed total phosphorus at Western Branch DEQ stations for 2004.

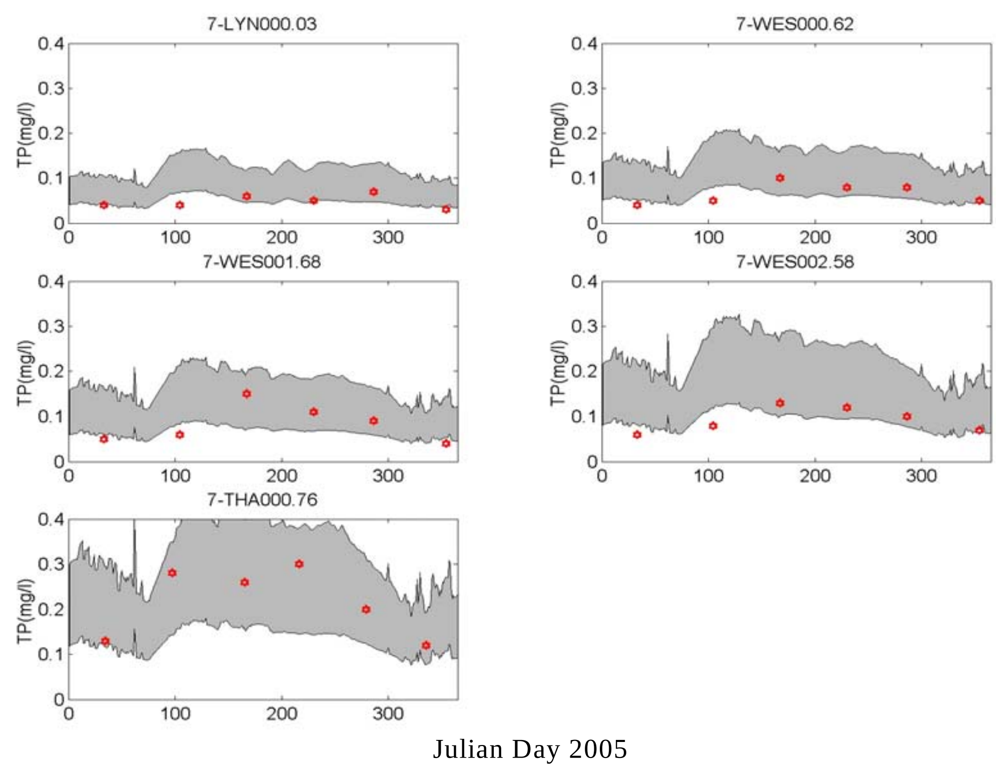


Figure VI.32. Predicted vs. observed total phosphorus at Western Branch DEQ stations for 2005.

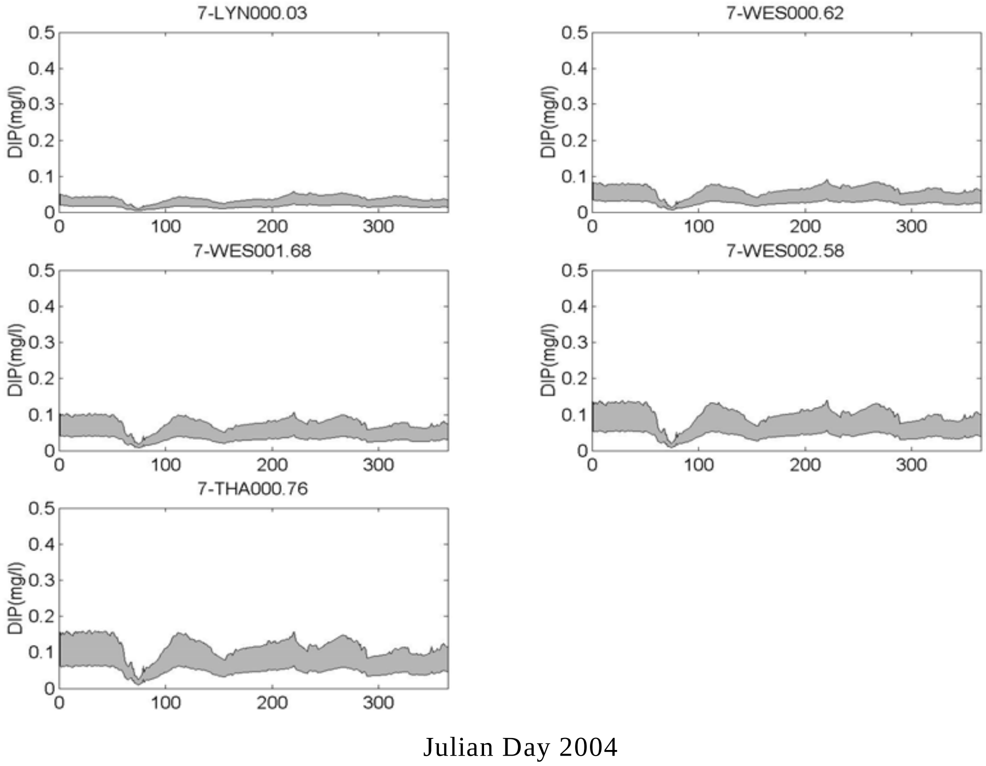


Figure VI.33. Predicted ortho-phosphorus at Western Branch DEQ stations for 2004.

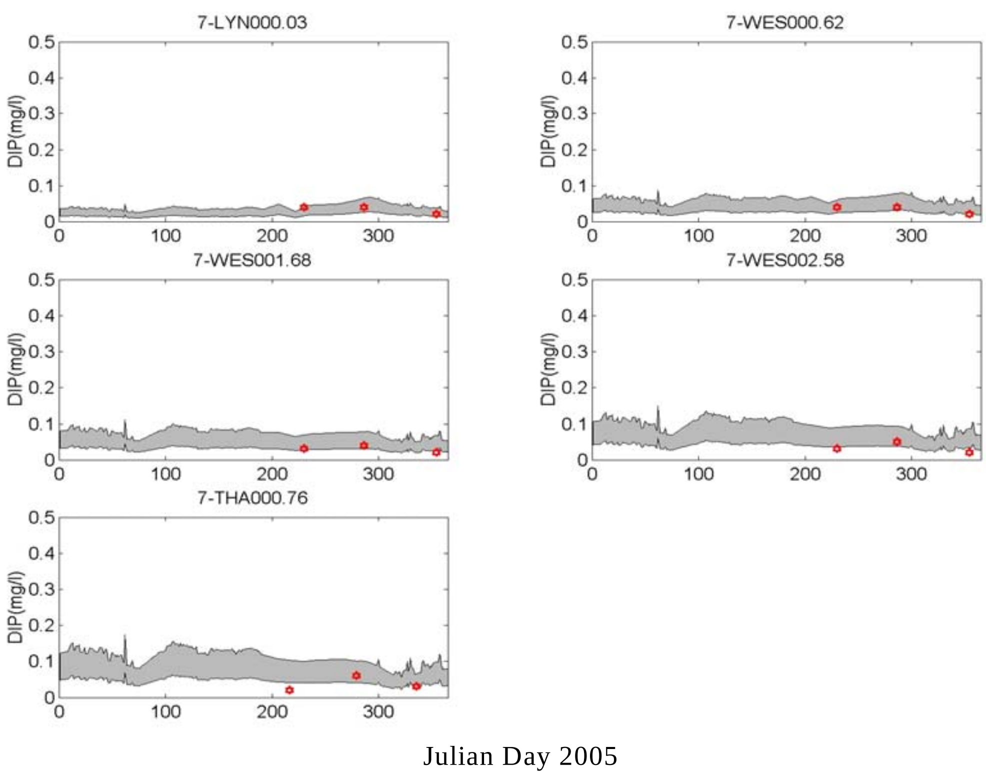


Figure VI.34. Predicted vs. observed ortho-phosphorus at Western Branch DEQ stations for 2005.

B. Eastern Branch DEQ stations validation results

As mentioned, the hydrological condition in 2004 and 2005 are different from those of 2006; between 2004 and 2005, the seasonal patterns also shifted differently. The year 2004 has a dry spring and wet summer whereas the year 2005 has a wet spring, but a dry summer. These conditions applied in the Western Brach as well as in the Eastern Branch. Water quality model validation results for Eastern Branch DEQ stations for 2004 and 2005 are carried out with different salinity patterns and the reaction constants that are temperature-dependent. Water quality model validation results for Eastern Branch DEQ stations for 2004 and 2005 are shown in Figures VI.35 through VI.48. In all figures comparing modeled and measured water quality parameters, the model predictions are represented as a gray band bounded by daily minimum and maximum.

Results for dissolved oxygen in 2004 and 2005, respectively, are shown in Figures VI.35 and VI.36. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen reasonably well, with only occasional over-prediction at the upstream stations of London Bridge (7-LOB001.79) Canal No. 2 (7-XBO001.30), and West Neck Creek (5BWNC010.02), in the latter part of each year. Figures VI.37 and VI.38 present the predicted versus observed comparisons for chlorophyll-a, catching the trend for all stations, but there are a few out-liers in the sparse observation data. Figures VI.39 and VI.40 show reasonable predicted results for 2004 and 2005, respectively, with good agreement with measured TKN values in latter 2005 (Figure VI.40). Predicted values for 2004-2005 ammonium for the Eastern Branch stations are shown in Figures VI.41 and VI.42. Despite some large diurnal fluctuations, these results appear to be reasonable, and agree well with the DEQ measurements taken in latter 2005 shown in Figure VI.42. Figures VI.43 and VI.44 show the 2004-2005 model predictions for nitrate-nitrite. Measured values of nitrate-nitrite in latter 2005 all fall within the daily min-max prediction range. Figures VI.45 and VI.46 show that, whereas total phosphorus predictions have a large diurnal range in the Eastern Branch, all observation data fall within this range. Lastly, the 2004-2005 ortho phosphorus predictions shown in Figures VI.47 and VI.48 appear reasonable and match the observation data shown in Figure VI.48 for latter 2005.

As was the case for the 2006 calibration data for Eastern Branch DEQ stations shown in Chapter V, an overall inspection of Figures VI.35 through VI.48 shows gradual increases of both chlorophyll-a and nutrients in moving from the Inlet upstream to West Neck Creek (5BWNC010.02), and a slight decrease in the summer of dissolved oxygen as seen moving upstream in the Eastern Branch. Overall, the responses in the Eastern Branch are very similar to those in the Western Branch, except that, at the very upstream stations, we consistently observe that Thalia Creek in the Western Branch has slightly, but consistently, higher TKN, NH_4, and chlorophyll values as compared to the stations at London Bridge, Canal No. 2, and West Neck Creek stations. That could contribute to a higher chance of forming localized low DO in the summer.

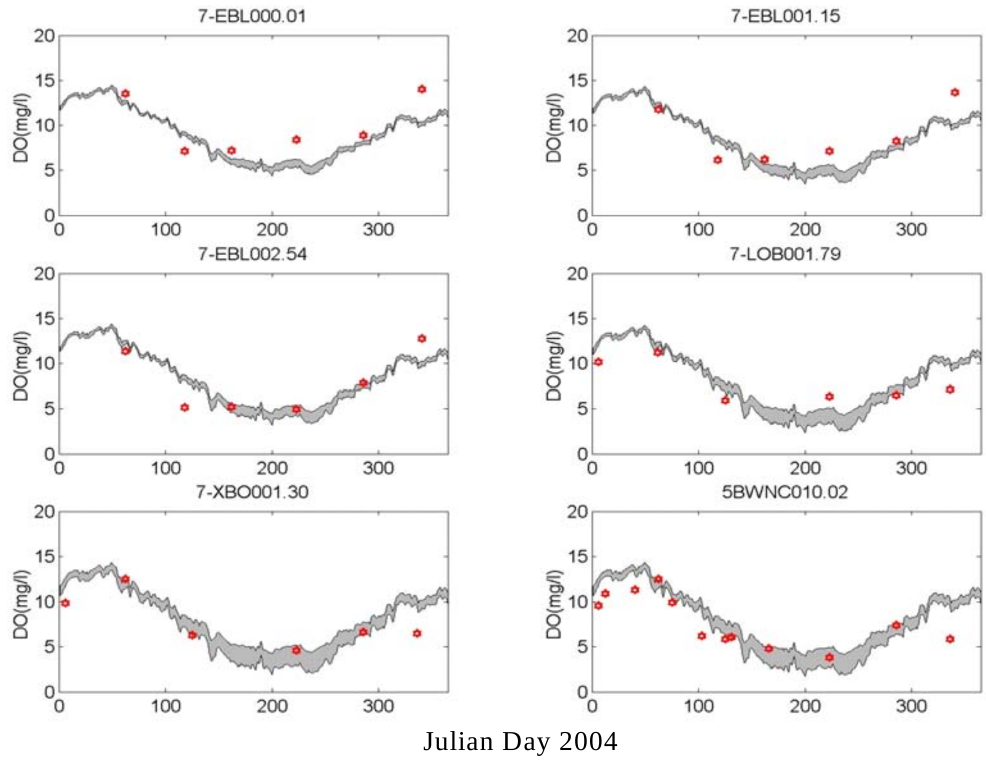


Figure VI.35. Predicted vs. observed dissolved oxygen at Eastern Branch DEQ stations for 2004.

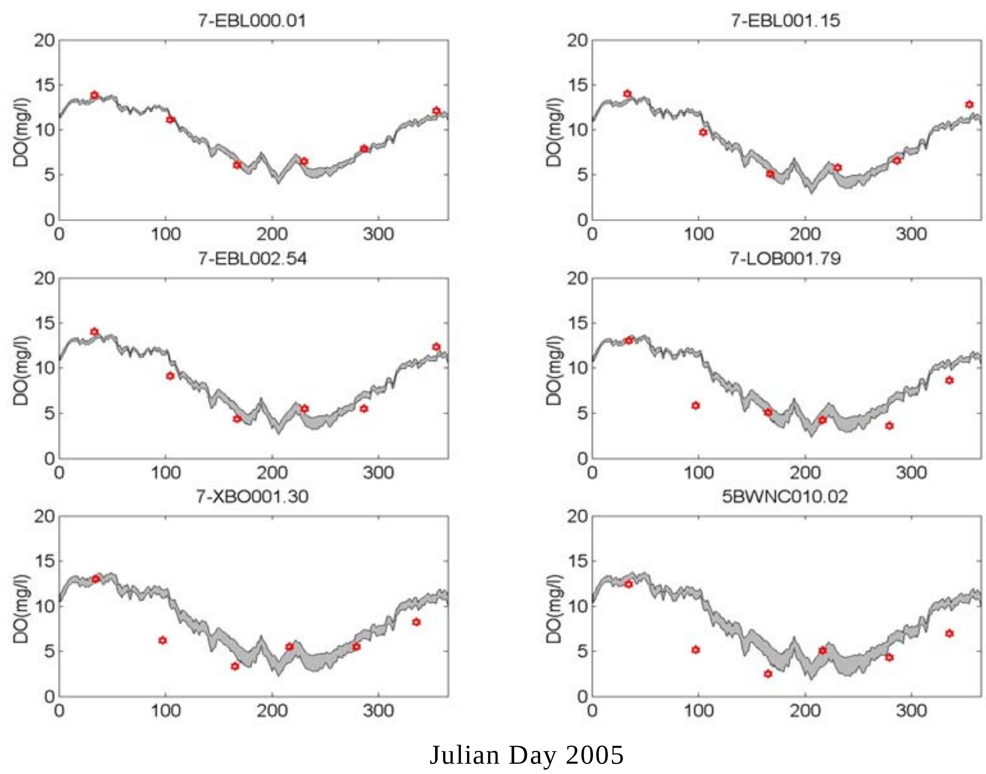


Figure VI.36. Predicted vs. observed dissolved oxygen at Eastern Branch DEQ stations for 2005.

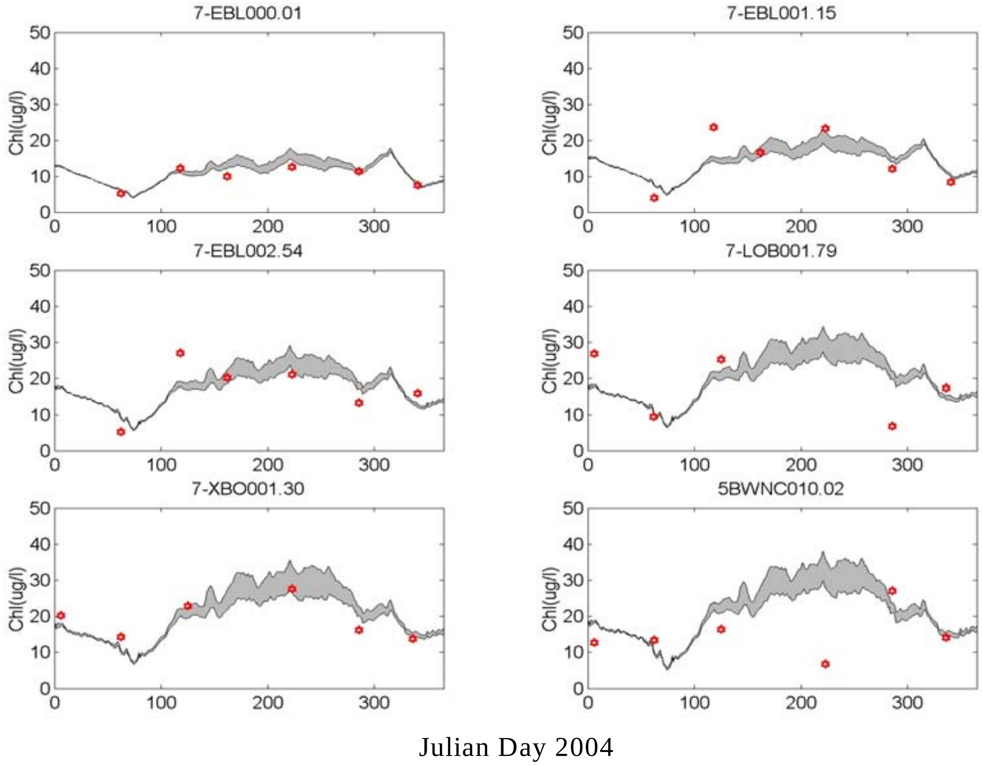


Figure VI.37. Predicted vs. observed chlorophyll-a at Eastern Branch DEQ stations for 2004.

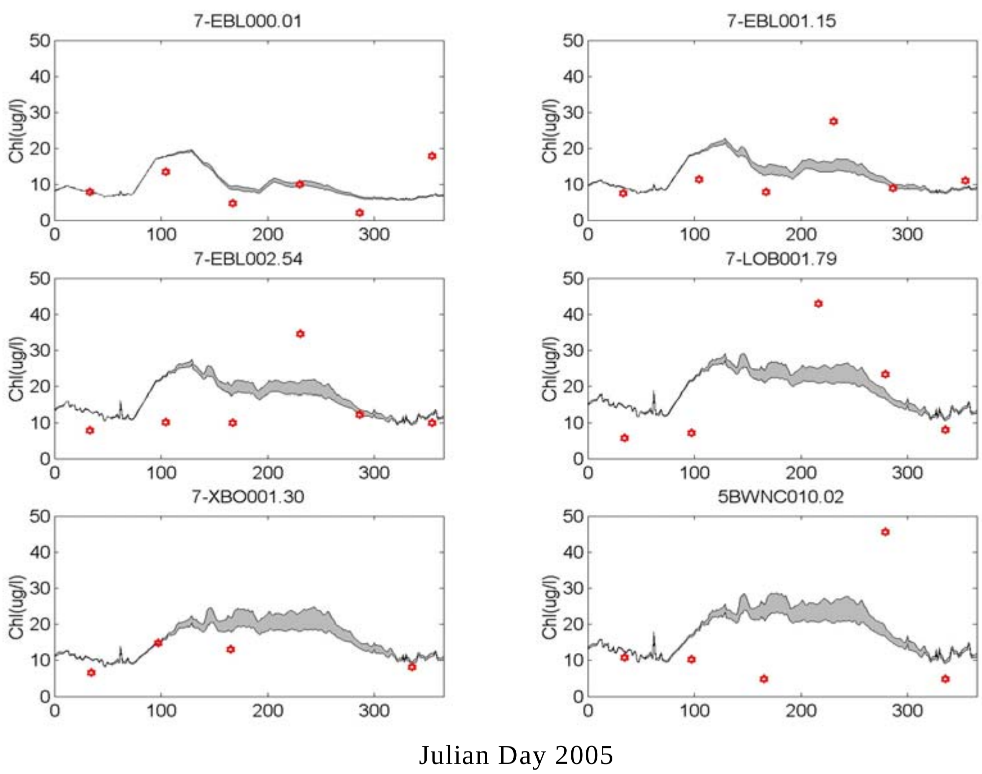


Figure VI.38. Predicted vs. observed chlorophyll-a at Eastern Branch DEQ stations for 2005.

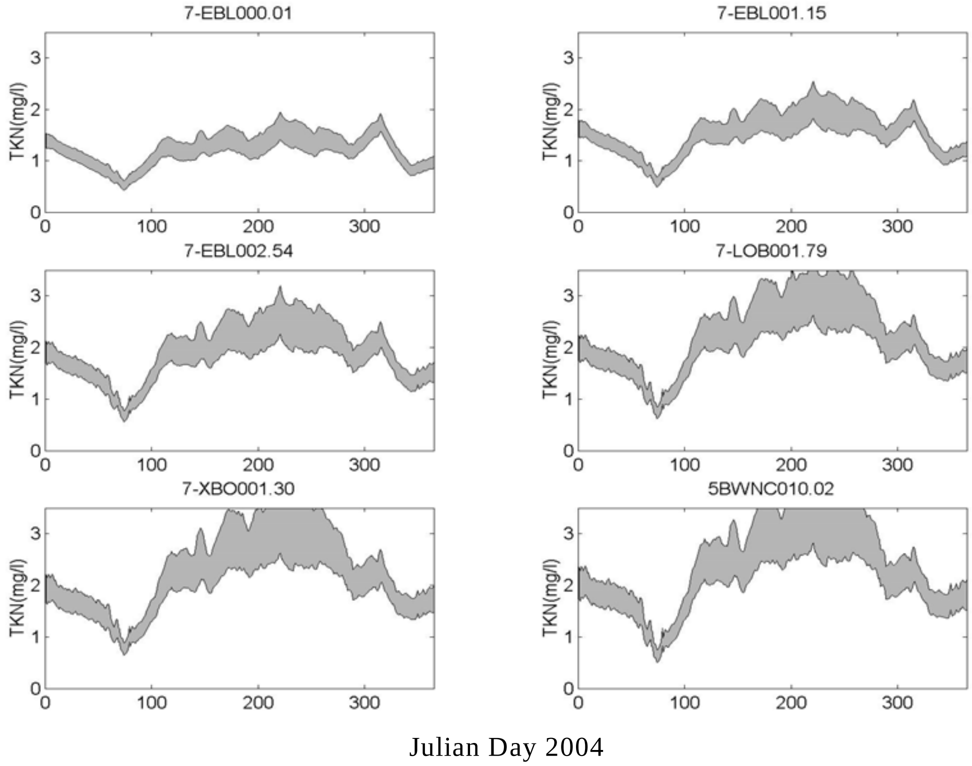


Figure VI.39. Predicted TKN at Eastern Branch DEQ stations for 2004.

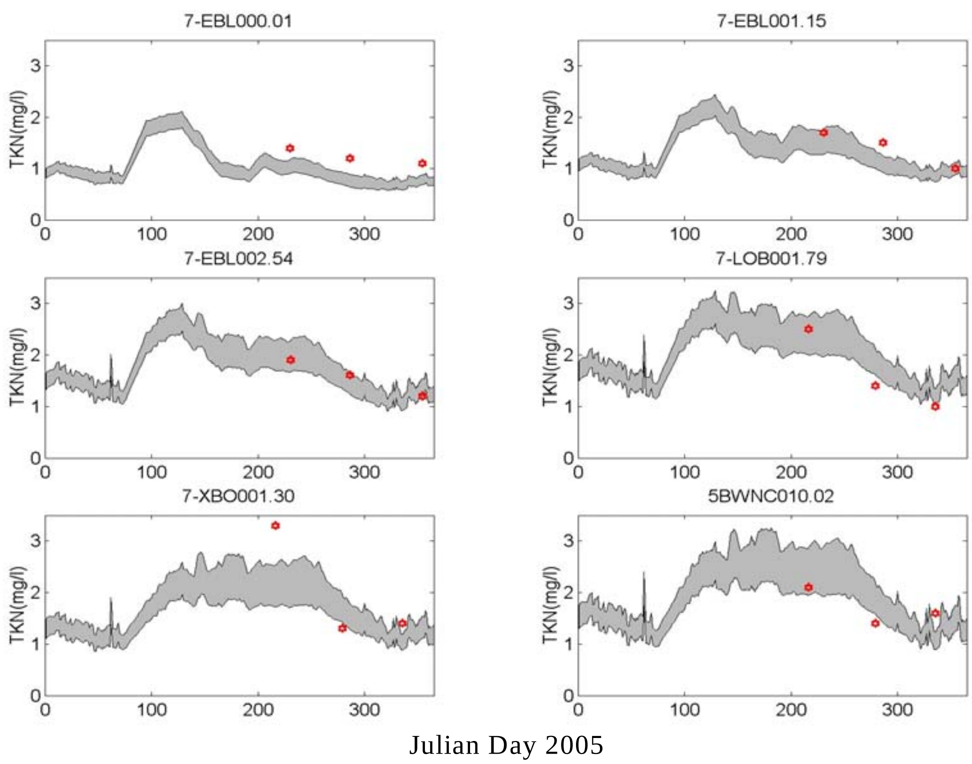


Figure VI.40. Predicted vs. observed TKN at Eastern Branch DEQ stations for 2005.

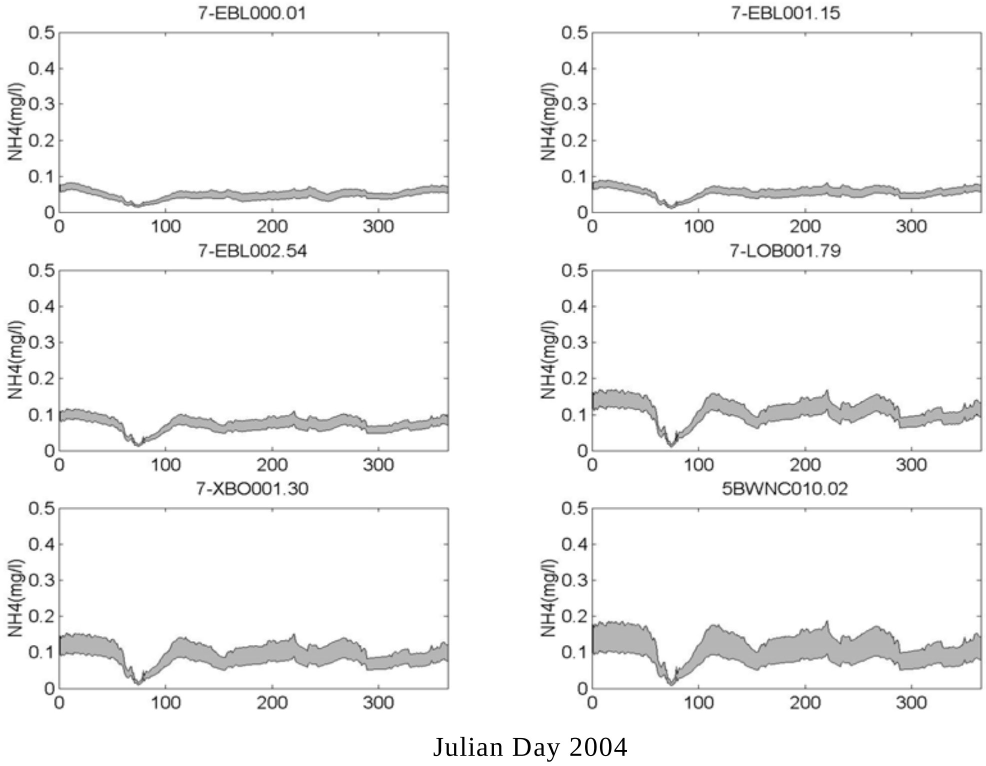


Figure VI.41. Predicted ammonium at Eastern Branch DEQ stations for 2004.

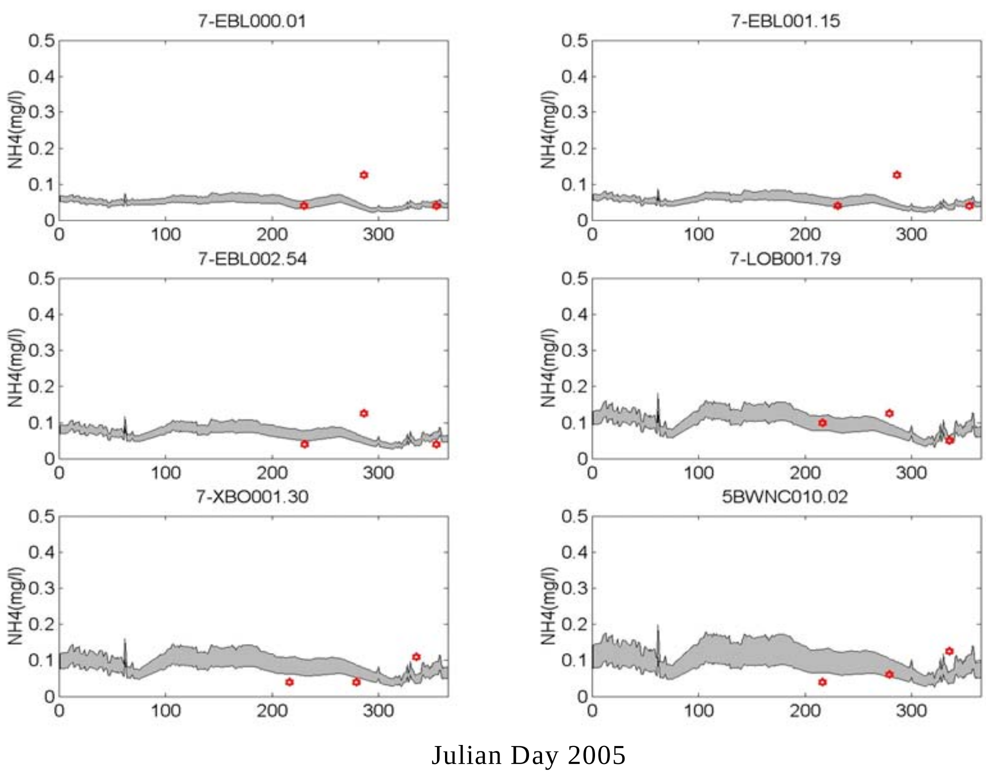


Figure VI.42. Predicted vs. observed ammonium at Eastern Branch DEQ stations for 2005.

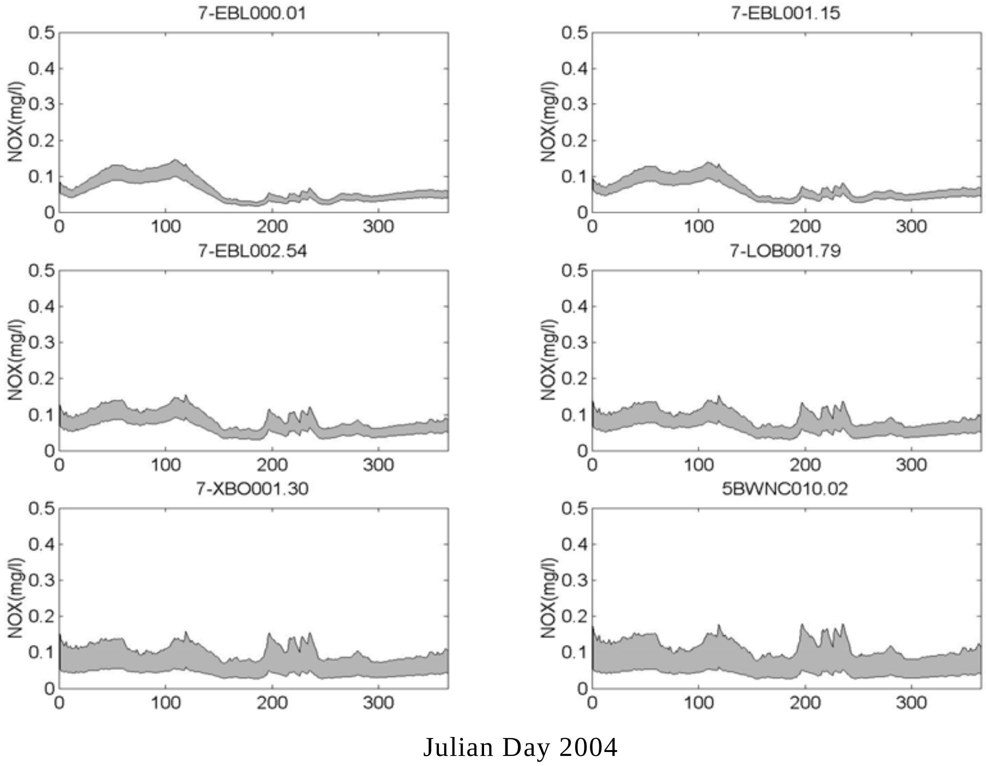


Figure VI.43. Predicted nitrate-nitrite at Eastern Branch DEQ stations for 2004.

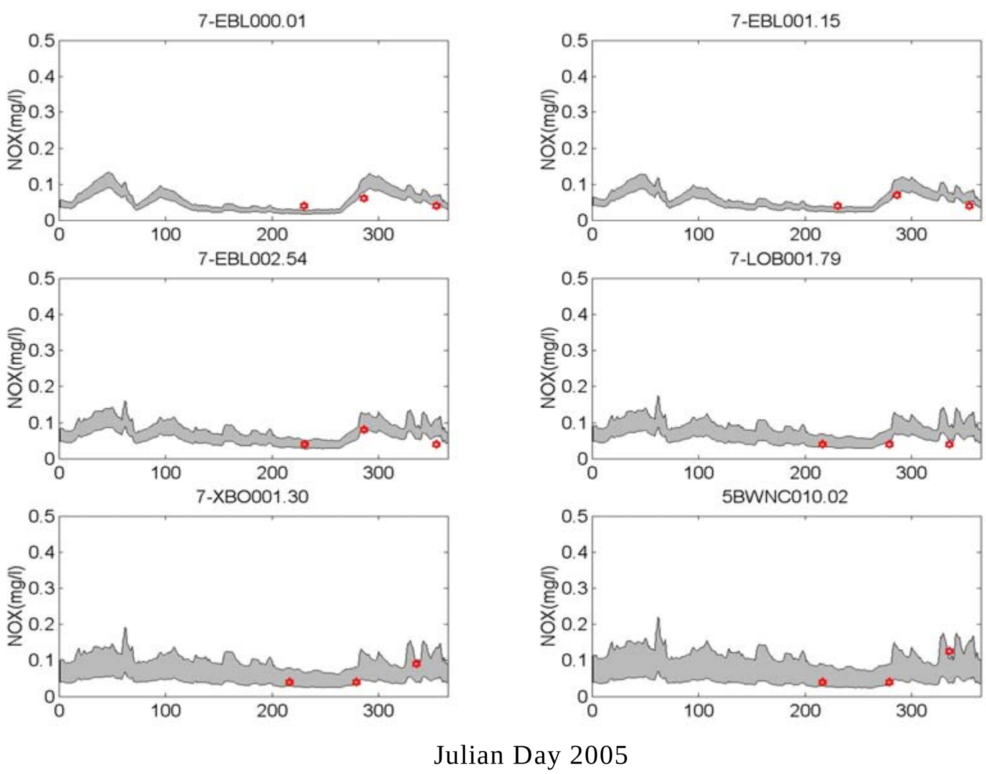


Figure VI.44. Predicted vs. observed nitrate-nitrite at Eastern Branch DEQ stations for 2005.

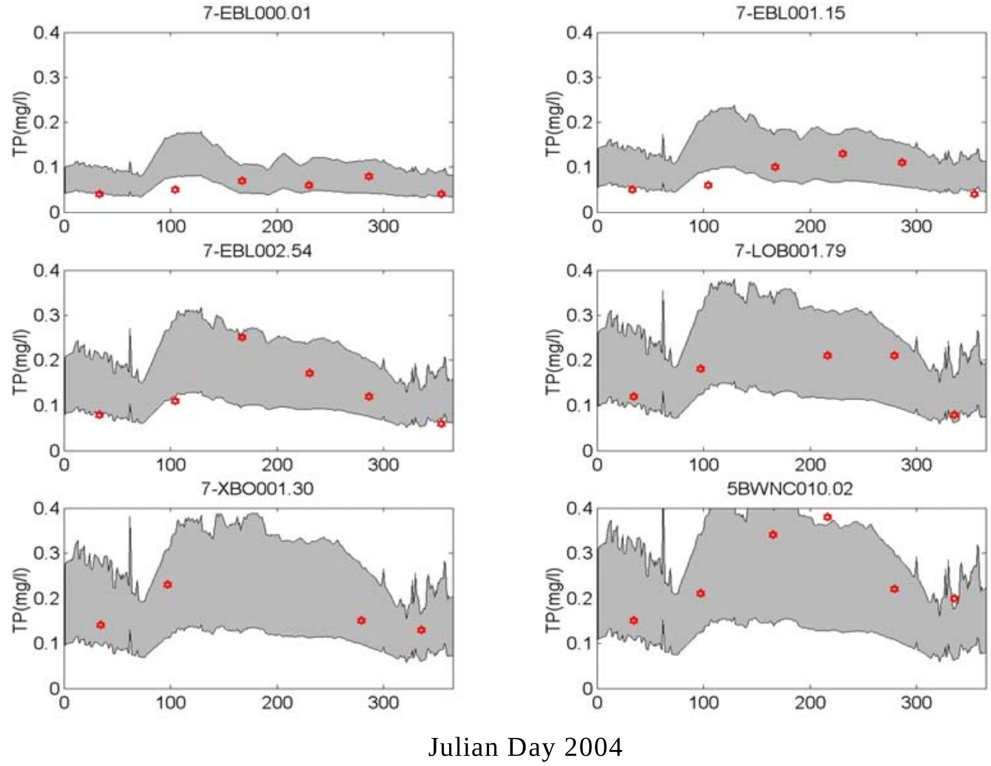


Figure VI.45. Predicted vs. observed total phosphorus at Eastern Branch DEQ stations for 2004.

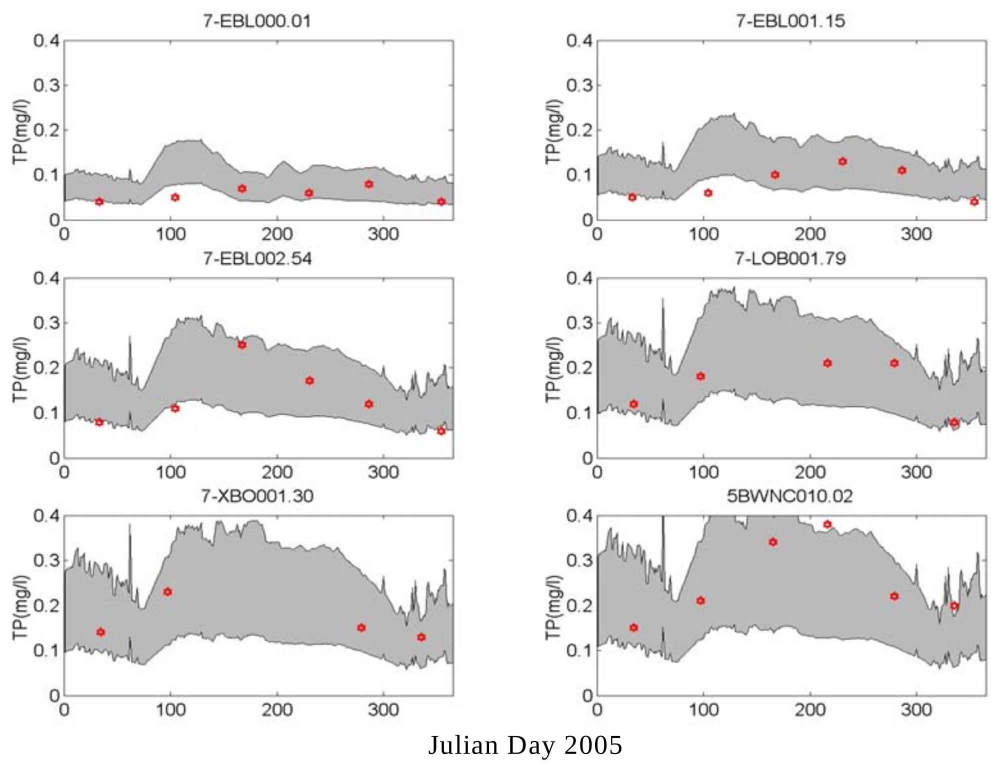


Figure VI.46. Predicted vs. observed total phosphorus at Eastern Branch DEQ stations for 2005.

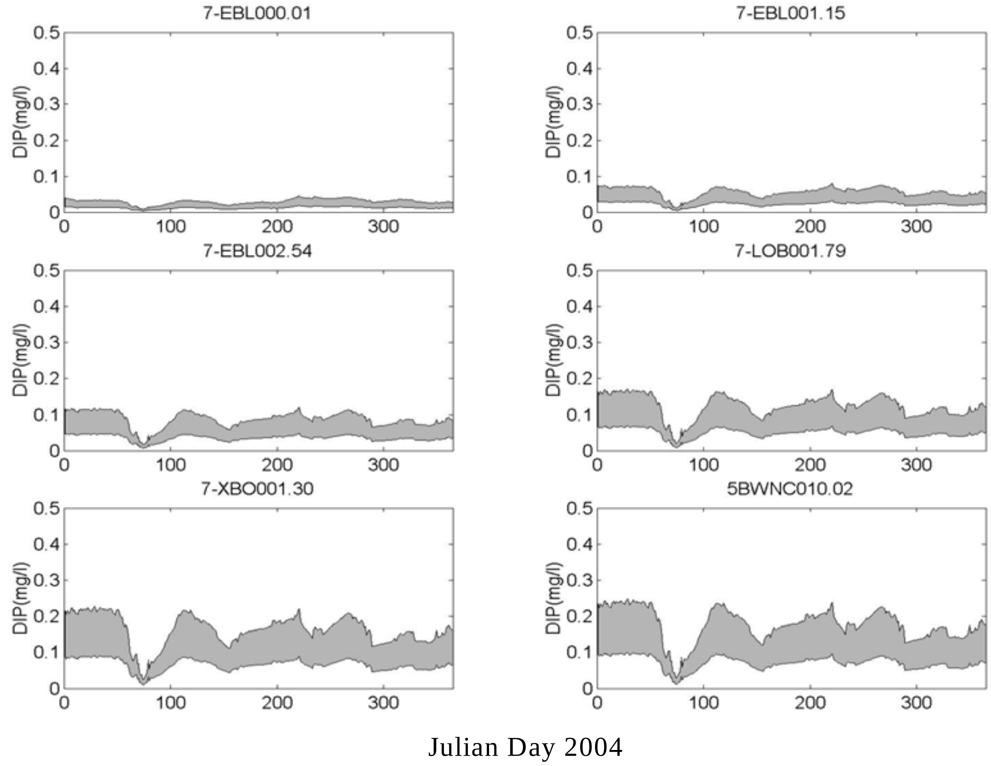


Figure VI.47. Predicted ortho phosphorus at Eastern Branch DEQ stations for 2004.

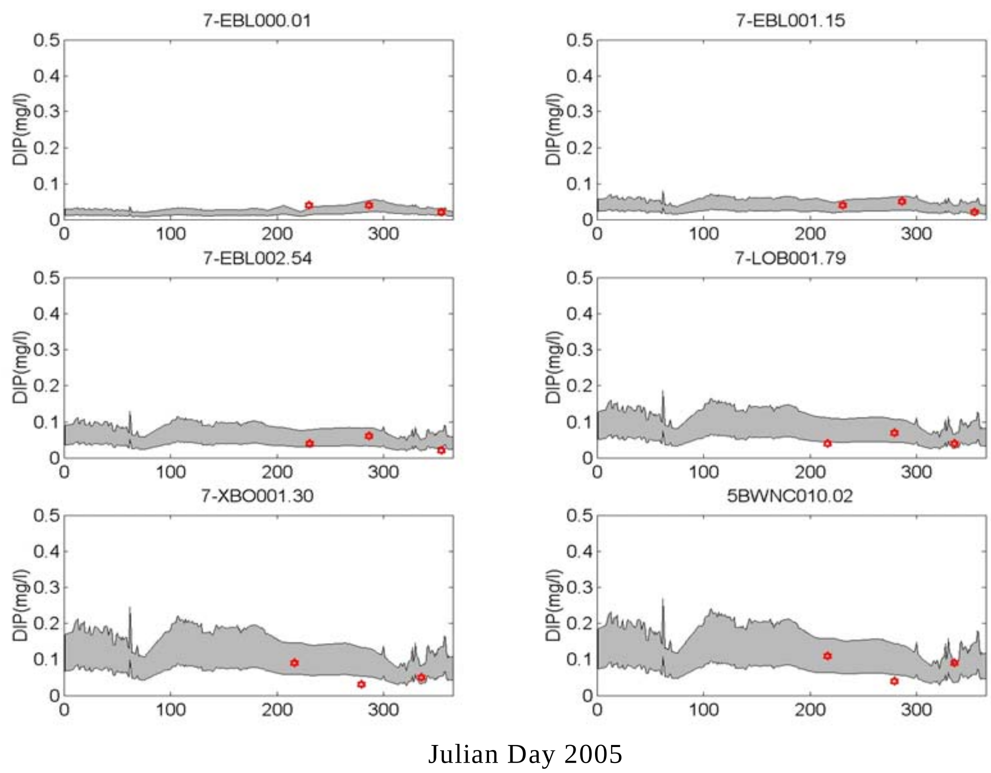


Figure VI.48. Predicted vs. observed ortho phosphorus at Eastern Branch DEQ stations for 2005.

C. Broad Bay / Linkhorn Bay Branch DEQ stations validation results

In the past two sections, we have emphasized that the hydrological conditions in 2004 and 2005 are different from those in 2006. In addition, the year 2004 had a dry spring and wet summer whereas the year of 2005 had a wet spring, but a dry summer. These conditions apply in the Western and Eastern Branches, but do not seem to affect Broad Bay and Linkhorn Bay as much. This is likely because the freshwater inputs in the Broad Bay and Linkhorn Bay are less than those in Eastern and Western Branches and, therefore, the loading was not the single most important reason for the temporal and spatial variability.

Water quality model validation results for Broad Bay/Linkhorn Bay Branch DEQ stations for 2004 and 2005 are carried out with different salinity patterns and the reaction constants that are temperature-dependent. Water quality model validation results for Broad Bay / Linkhorn Bay Branch DEQ stations for 2004 and 2005 are shown in Figures VI.49 through VI.62. In all figures comparing modeled and measured water quality parameters, the model predictions are represented as a gray band bounded by daily minimum and maximum.

Validation results for the comparison of modeled versus measured dissolved oxygen in 2004 and 2005 at Broad and Linkhorn Bay Branch DEQ stations are shown, respectively, in Figures VI.49 and VI.50. As illustrated, the model reproduces the observed temporal distribution of dissolved oxygen extremely well at all 5 DEQ stations in this branch for both years. Figures VI.51 and VI.52 show reasonably good agreement overall between predicted and observed values for chlorophyll-a. Figures VI.53 and VI.54, respectively, show model predictions for 2004 and 2005 for TKN at all Broad Bay and Linkhorn Bay stations, and a good agreement between modeled and measured TKN values can be seen for latter-2005 in Figure VI.54. The 2004 and 2005 predicted values of ammonium are shown in Figures VI.55 and VI.56, respectively, and show good agreement with observations taken in the latter part of 2005 (Figure VI.56). Figures VI.57 and VI.58 show predictions of nitrate-nitrite by the model and match well with available nitrate-nitrite data from latter 2005 (Figure VI.58). Figures VI.59 and VI.60 show that total phosphorus predictions from the model agrees reasonably well with observations at all stations with a slight tendency to over-predict at upstream stations. The model predictions of ortho phosphorus for 2004 and 2005 shown in Figures VI.61 and VI.62 appear reasonable and match the observations available in late 2005 shown in Figure VI.62. Finally, inspection of Figures VI.49 through VI.62 shows that there is almost no spatial decrease in dissolved oxygen nor increase in chlorophyll-a in moving from the Inlet upstream to the head of Linkhorn Bay, similar to what was found for the 2006 calibration data presented in Chapter V. Overall, the Broad Bay and Linkhorn Bay have lower higher TKN, NH_4, TP, and Chlorophyll values as compared to those in the Western and Eastern Branches. Hypoxic conditions in this branch are rare occurrences. On a parallel effort, however, there is evidence that the Mill Dam Creek on the southern shore of Broad Bay can occasionally discharge high concentrations of nitrogen and phosphorus into the system. That is beyond the scope of this study.

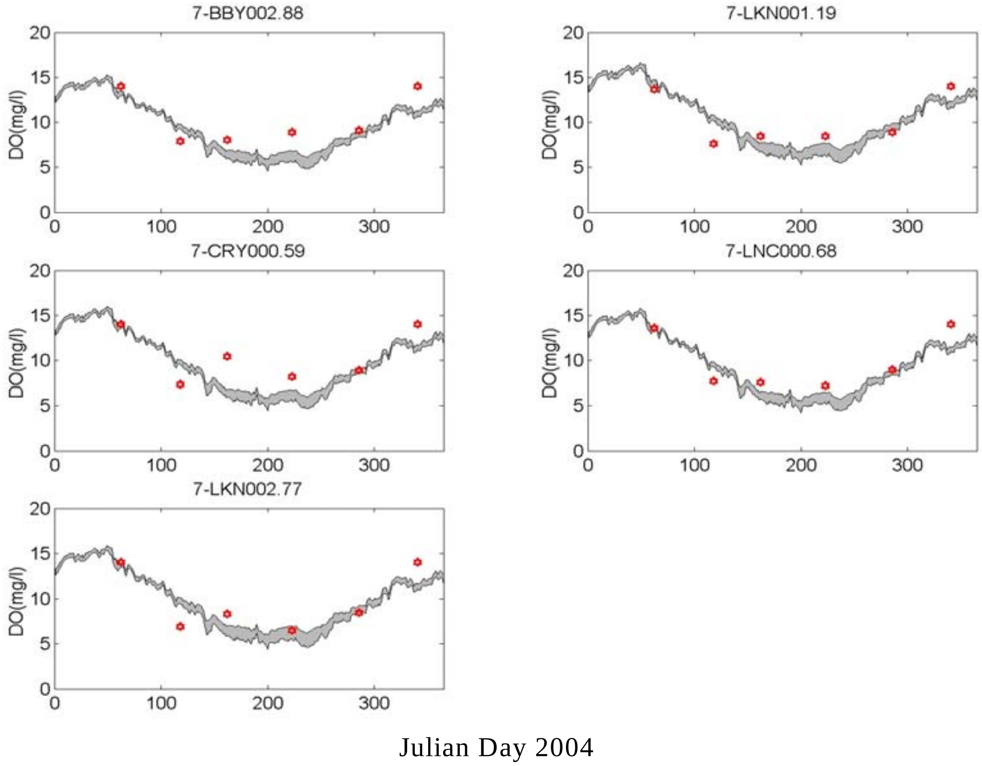


Figure VI.49. Predicted vs. observed dissolved oxygen at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

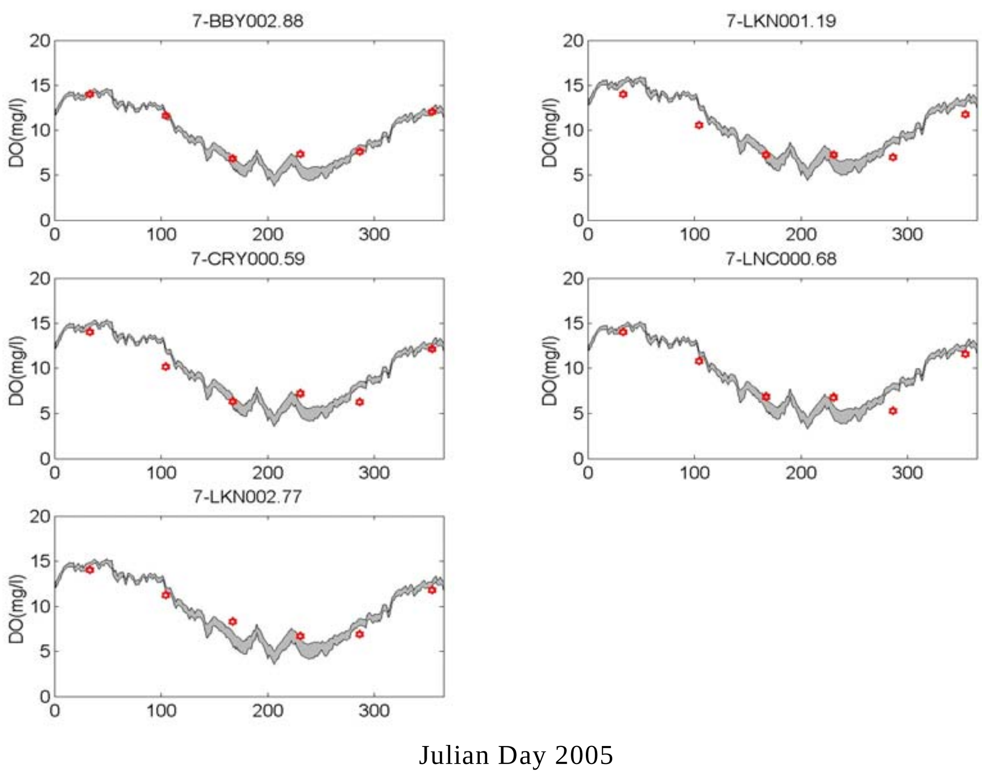


Figure VI.50. Predicted vs. observed dissolved oxygen at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

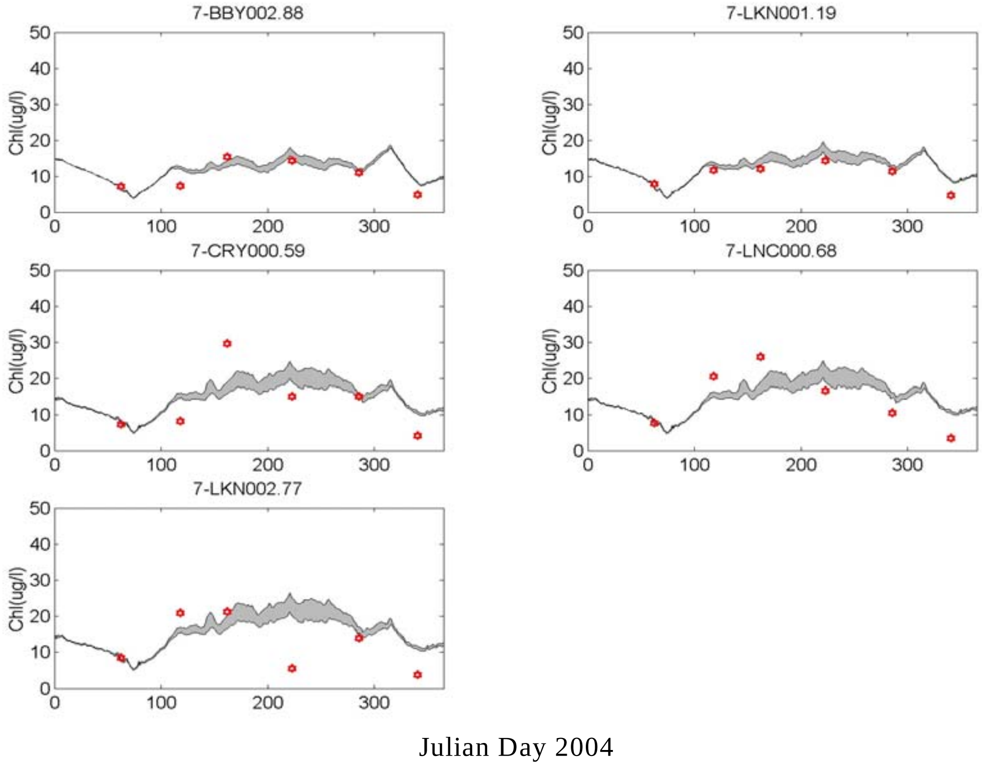


Figure VI.51. Predicted vs. observed chlorophyll-a at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

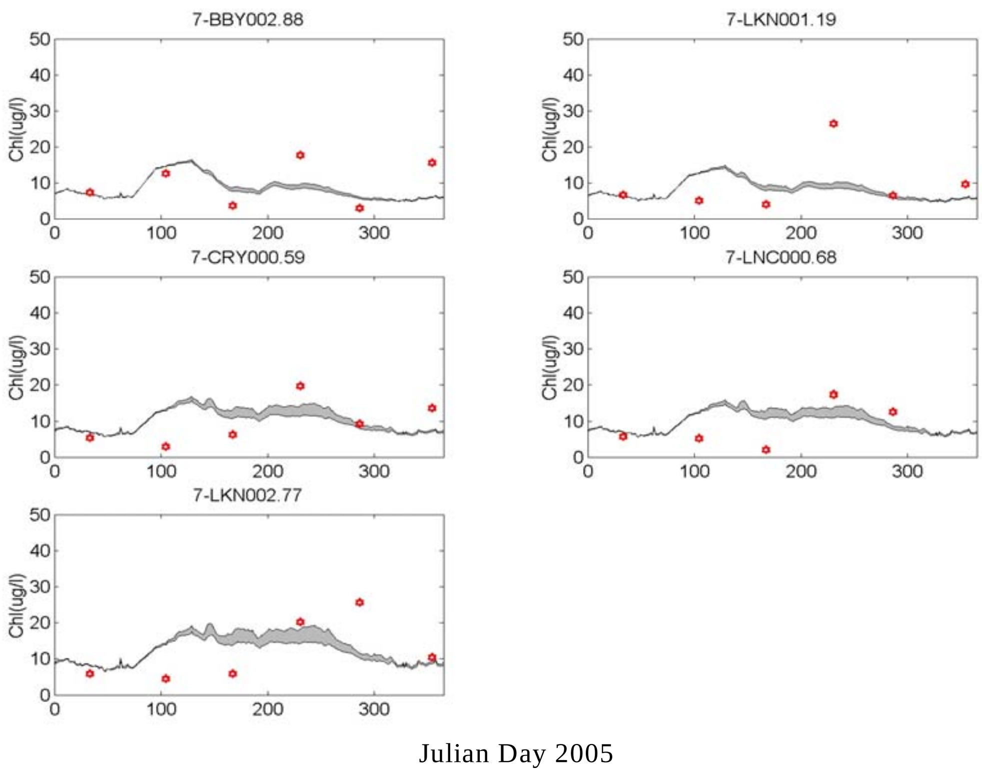


Figure VI.52. Predicted vs. observed chlorophyll-a at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

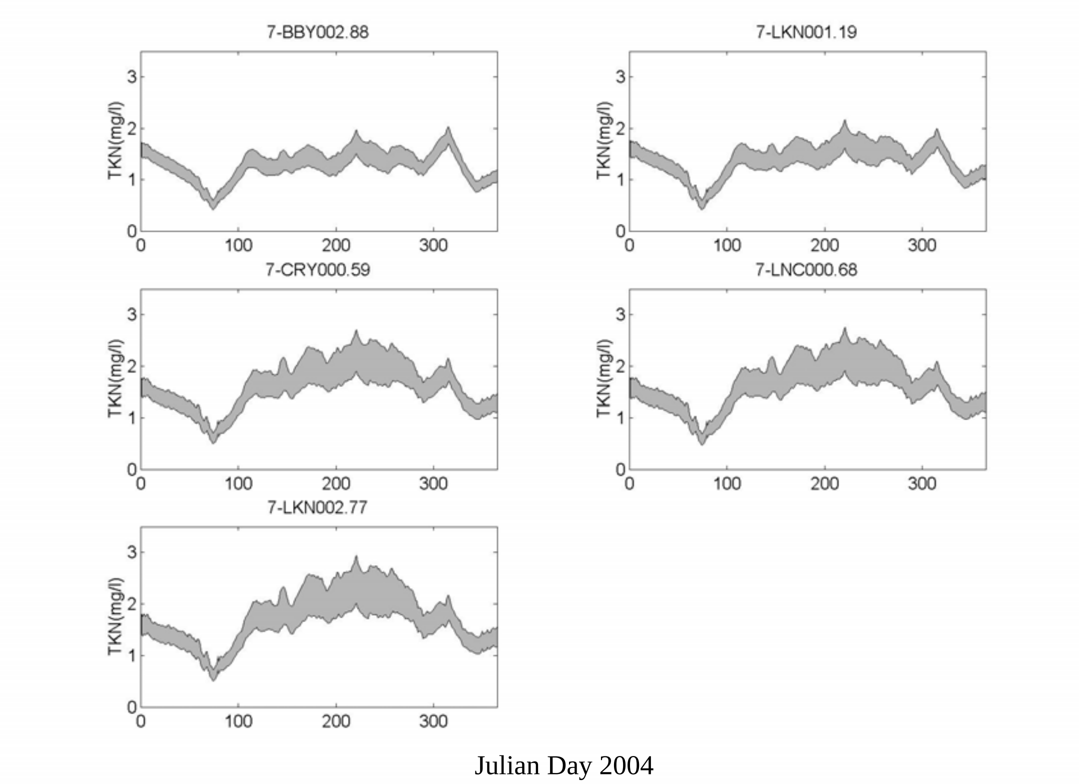


Figure VI.53. Predicted TKN at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

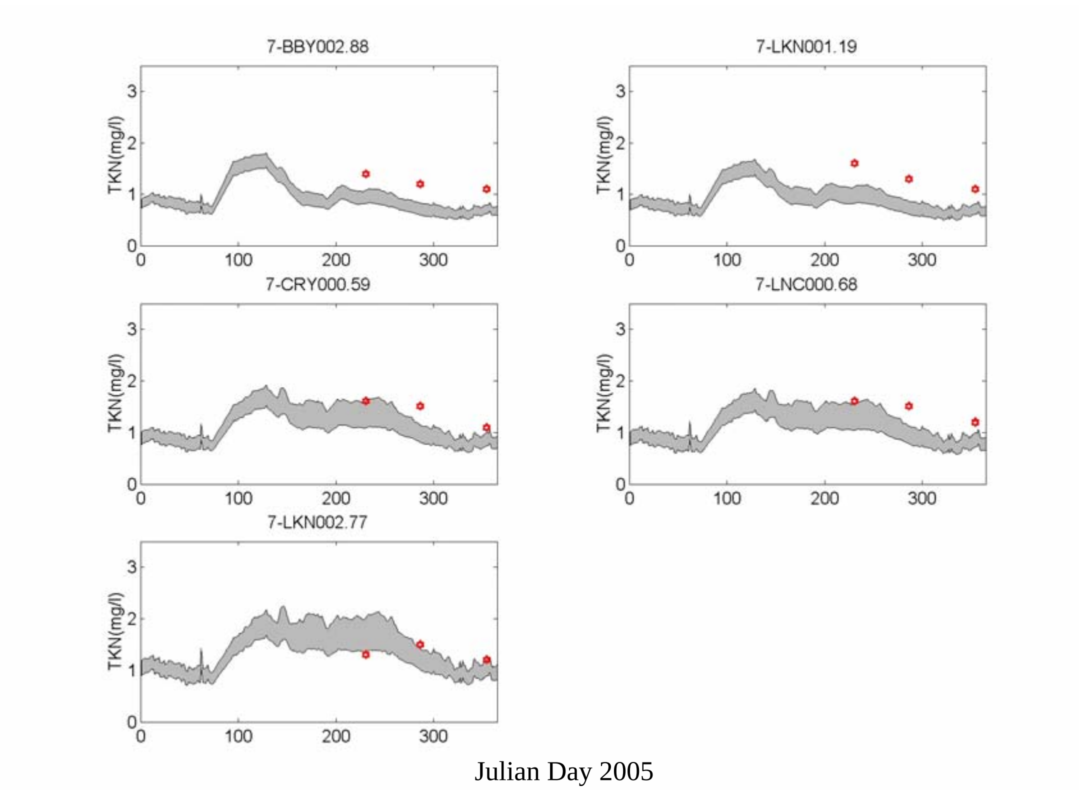


Figure VI.54. Predicted vs. observed TKN at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

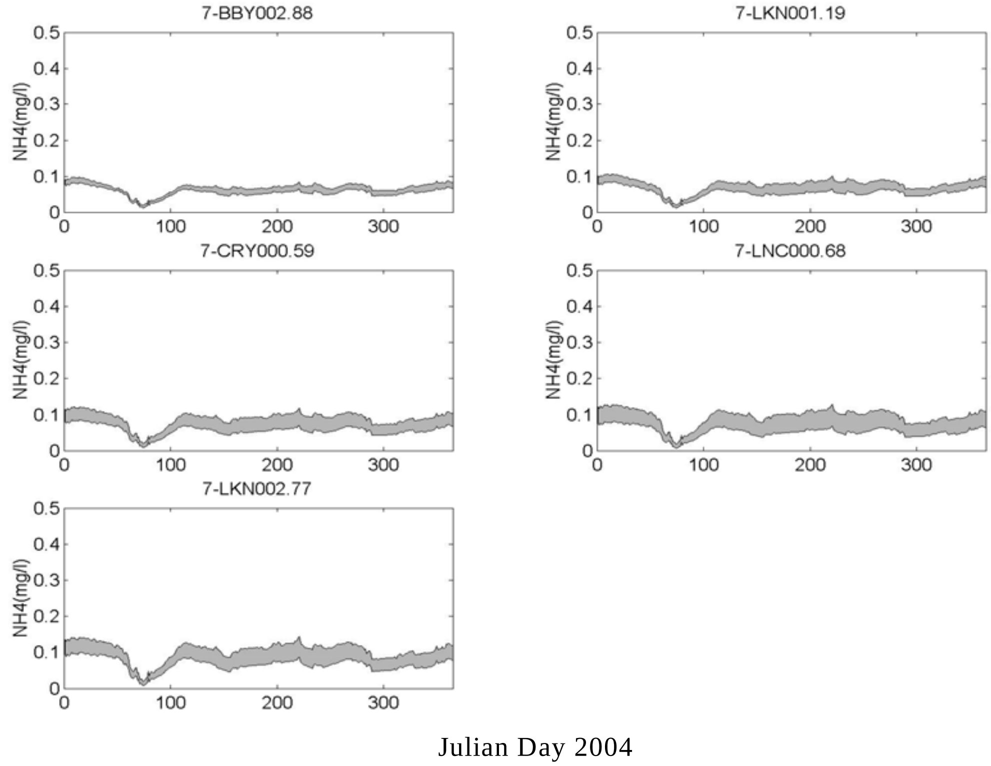


Figure VI.55. Predicted ammonium at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

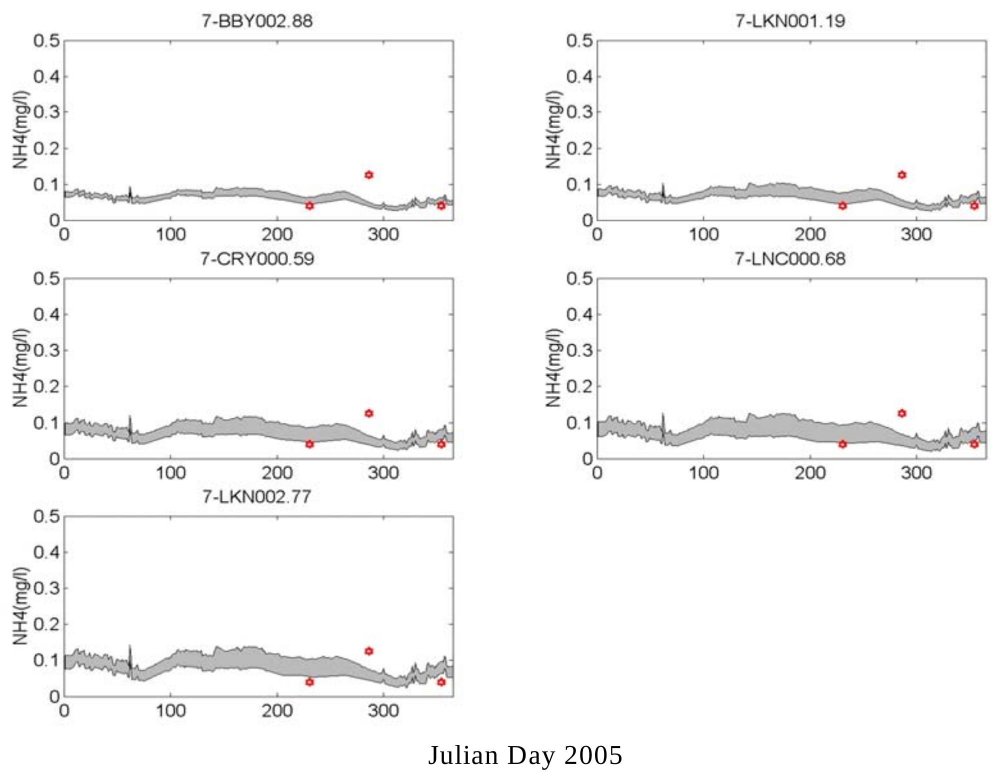


Figure VI.56. Predicted vs. observed ammonium at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

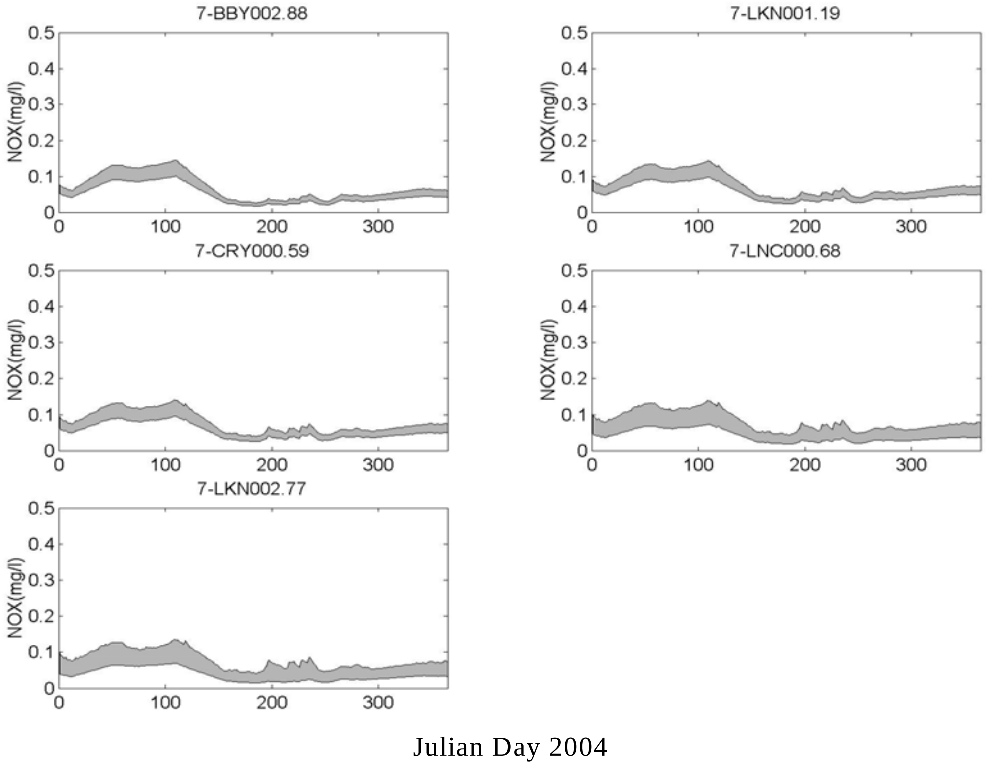


Figure VI.57. Predicted nitrate-nitrite at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

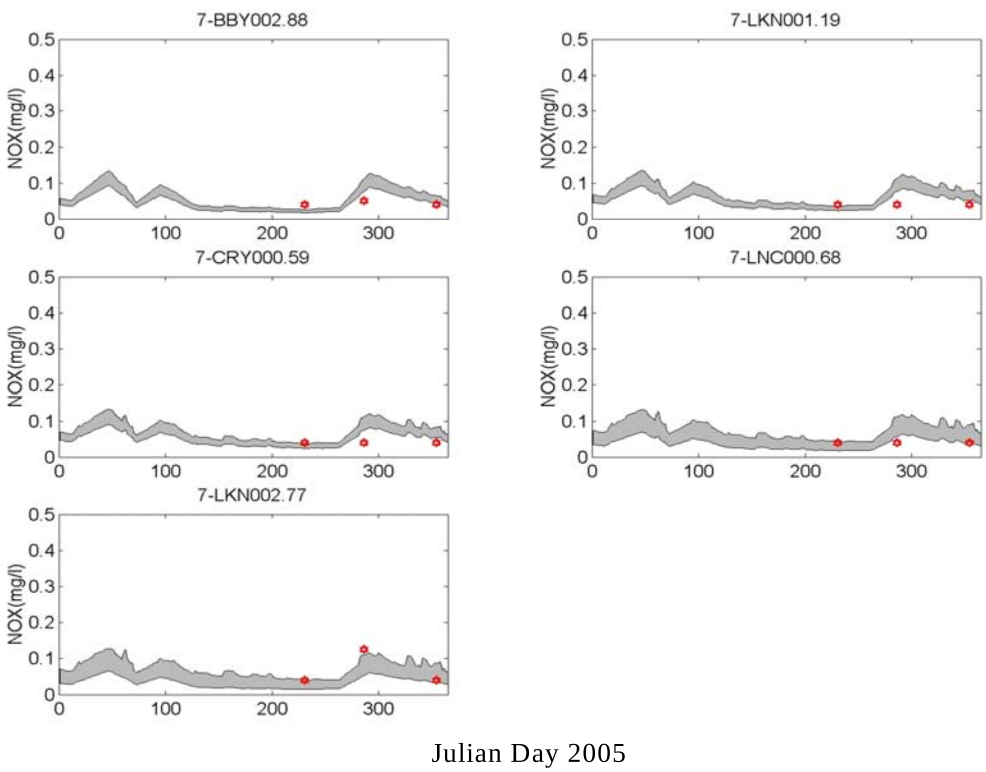
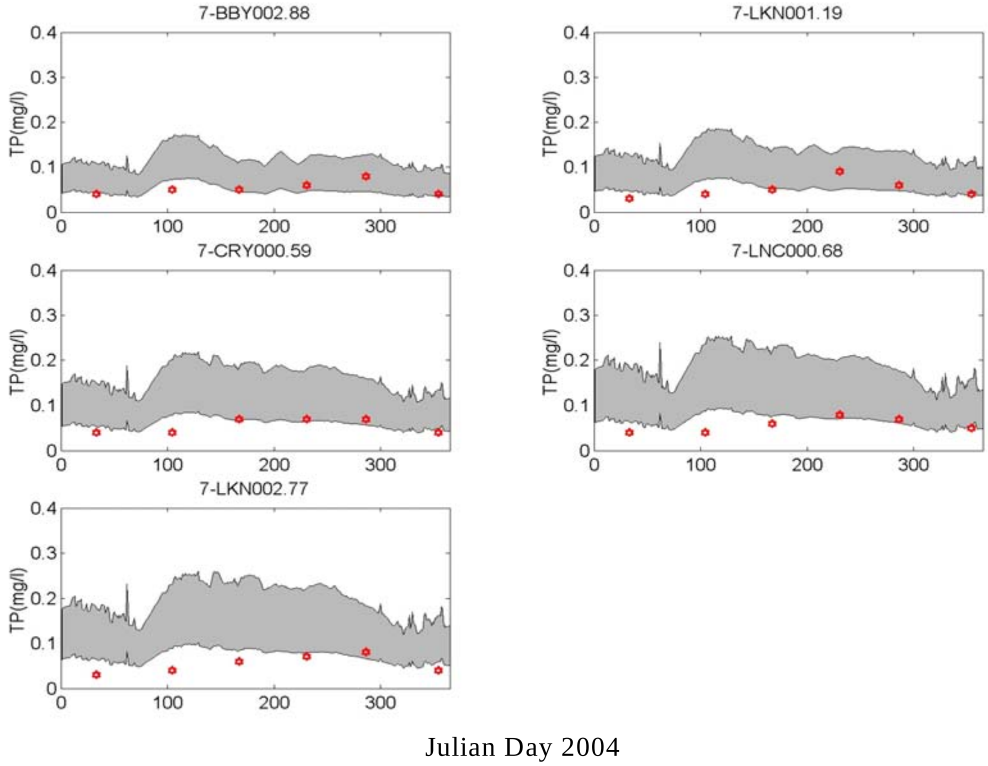
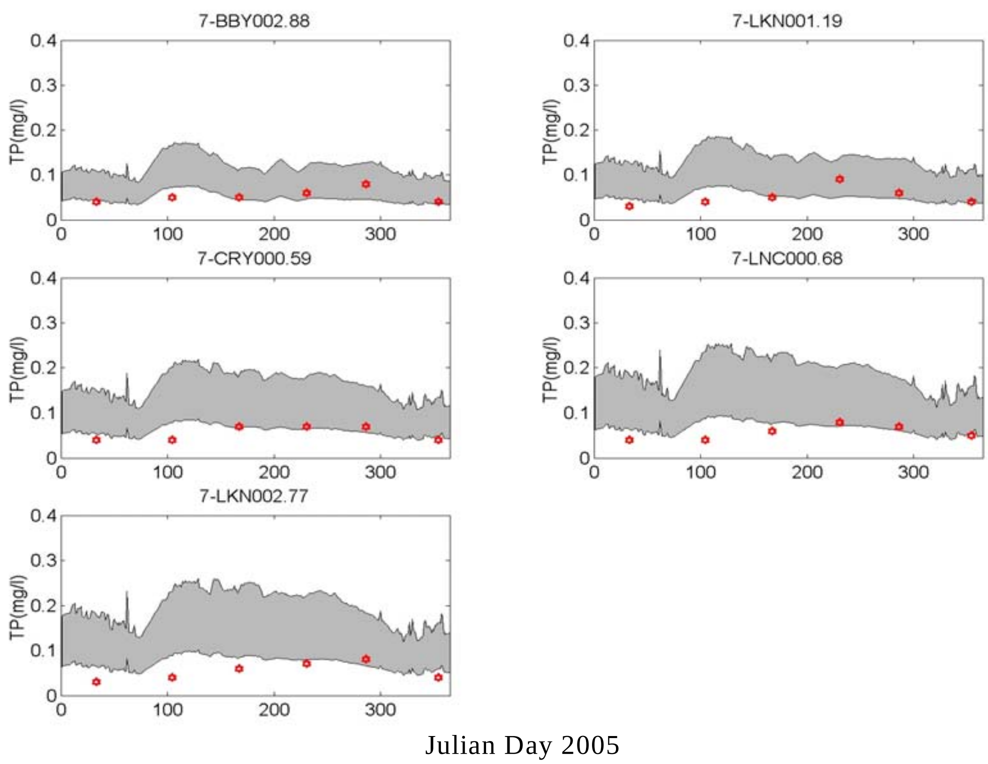


Figure VI.58. Predicted vs. observed nitrate-nitrite at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.



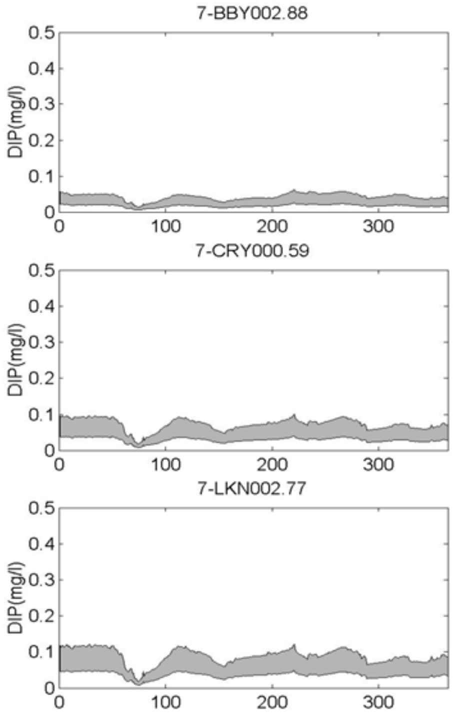
Julian Day 2004

Figure VI.59. Predicted vs. observed total phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.



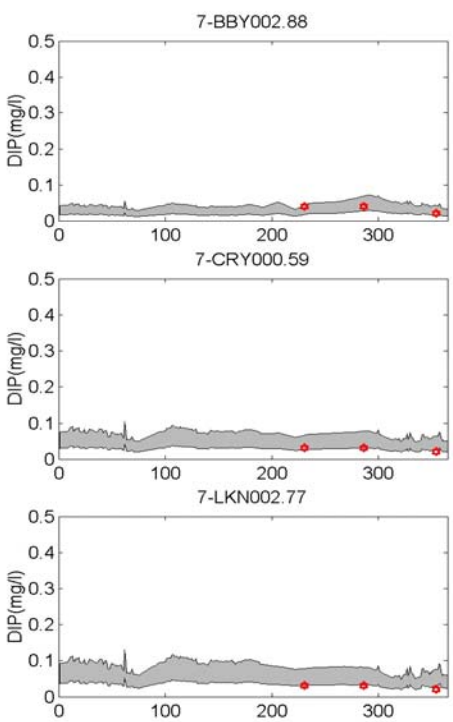
Julian Day 2005

Figure VI.60. Predicted vs. observed total phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.



Julian Day 2004

Figure VI.61. Predicted ortho phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.



Julian Day 2005

Figure VI.62. Predicted vs. observed ortho phosphorus at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

Summary Statistics of Water Quality Model Validation Results

In the previous portion of this section, qualitative comparisons between model results and observed values were presented. As in the case for the model calibration results shown in Chapter V, although the comparisons indicate that the CE-QUAL-ICM water quality model can reproduce the physical, chemical, and biological processes that affect the eutrophication process in the Lynnhaven River, a more specific measure of the model performance is desirable.

In order to provide a more quantifiable measure of the performance of the water quality model during the validation process, a statistical analysis is applied to the comparisons of predicted and observed data of the water quality validation results for 2004 and 2005. Error measurement parameters for these comparisons (i.e., mean error, absolute mean error, root-mean-square error, and relative error) are fully described in Chapter V, which shows the analysis of the performance of the model during calibration.

Additionally, 1:1 plots of predicted results vs. observations show visually how well the model predictions compare with observations and whether the model shows a bias towards either over-prediction or under-prediction.

A. Statistical Analysis of Dissolved Oxygen, Chlorophyll-a, TKN, and Total Phosphorus Results

Statistical analysis of 7 key water quality parameters was performed by comparing predicted and observed results of each parameter for all of the 16 Lynnhaven DEQ stations combined. The every-other-month DEQ measurements taken in 2004 and 2005 thus provided sample sizes of 185, 179, 45, and 18, respectively, for DO, chl-a, TKN, and TP predicted vs. observed comparisons at all Lynnhaven River DEQ stations. The error measures for these 4 comparisons are shown in Table VI.1 below and their corresponding 1:1 plots are shown in Figure VI.63. Overall, predicted and observed DO values compare well. The median value for mean error is about -0.07 mg/l while the absolute mean error is 1.10 mg/l. The root-mean-square error for both surface and bottom DO is about 1.44 mg/l, whereas the relative error is around 12%. It is noted that these statistics compare well with those for the 2006 calibration and that they are comparable to other eutrophication model studies such as the Three-dimensional Eutrophication Model Study of the Chesapeake Bay (Cerco and Cole, 1994).

It was also worthwhile to point out that the absolute mean error and root-mean-square error of water quality parameters shown in Table VI.1 are well within the range of natural variation in a given season of measurements when compared with available observations, for example, Figures VI.21-VI.26, V1.31-VI.32, VI.35-VI.40, VI.45-VI.46, VI.49-VI.54, and VI.59-VI.60.

Table VI.1. Statistical summary of errors derived by comparing predicted vs. observed surface values of DO, chl-a, TKN, and TP for years 2004 - 2005.

Predicted vs. Observed Dissolved Oxygen, Chlorophyll-a, TKN, and Total Phosphorus				
	All 16 Lynnhaven DEQ Stations			
Parameter:	DO	Chl-a	TKN	TP
Sample size	185	179	45	18
Mean Error	-0.07	0.60	0.13	-0.04
Absolute Mean Error	1.10	5.17	0.26	0.05
RMS Error	1.44	10.38	0.30	0.06
Relative Error	0.12	0.36	0.18	0.49
Corr. Coeff. (r)	0.89	0.79	0.80	0.85

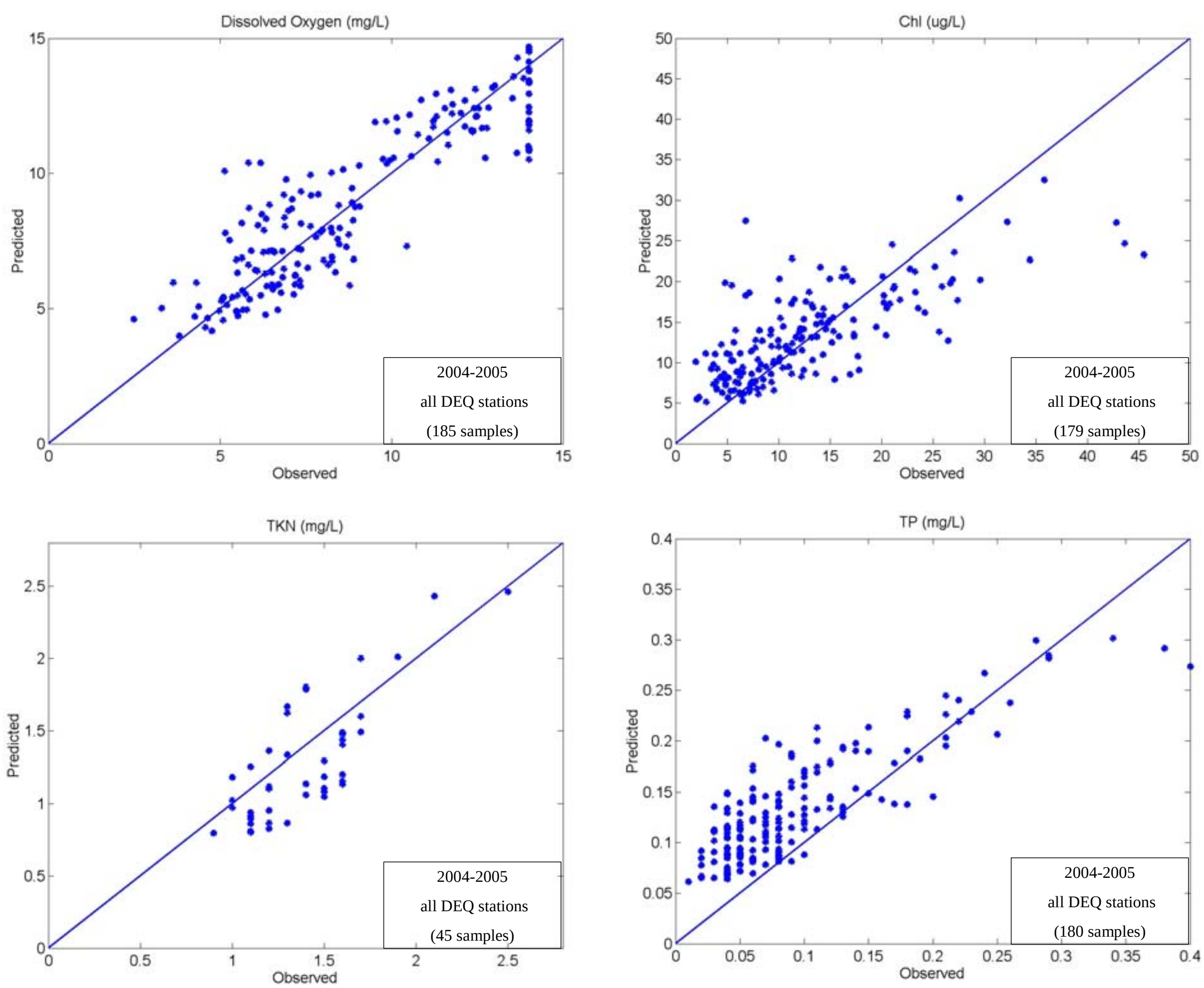


Figure VI.63. Plots of 1:1 predicted vs. observed DO, chl-a, TKN, and TP at all 16 Lynnhaven DEQ stations for 2004 - 2005.

B. Statistical Analysis of Ammonia, Nitrate-Nitrite, and Dissolved Inorganic Phosphate

To quantify the comparison between predicted and observed values NH_4, NO_x, and DIP, determination of statistical errors and construction of 1:1 plots were performed for these parameters as well. Table VI.2 below shows error values of each parameter for predicted vs. observed comparisons of all 16 Lynnhaven DEQ stations combined for 2004 and 2005.

The nitrogen and phosphorus are major nutrients that can be used for photosynthesis. In particular, NH_4, NO_x, and dissolved phosphorus are species that can be uptaken directly by the phytoplankton. Therefore, they are important indicator for the environmental quality. Nitrogen's concentration is usually higher than phosphorus. The 1:1 plots of predicted vs. observed comparisons of NH_4, NO_x, and DIP are shown in Figure VI.64. The absolute mean error and root-mean-square error of these water quality parameters show that the differences between model predictions and observations are within the range of natural variation in a given season of measurements when compared with available observation, for example, Figures VI.27-VI.30, VI.33-VI.34, VI.41-VI.44, VI.47-VI.48, VI.55-VI.58, and VI.61-VI.62.

Table VI.2. Statistical summary of errors derived by comparing predicted vs. observed values of NH_4, NO_X, and DIP for all 16 Lynnhaven DEQ stations for 2004 - 2005.

Parameter:	NH_4	NO_X	DIP
Sample Size	45	45	45
Mean Error	0.00	-0.01	-0.02
Absolute Mean Error	0.03	0.02	0.02
RMS Error	0.04	0.02	0.02
Relative Error	0.48	0.42	0.47
Corr. Coeff. (r)	0.22	0.58	0.70

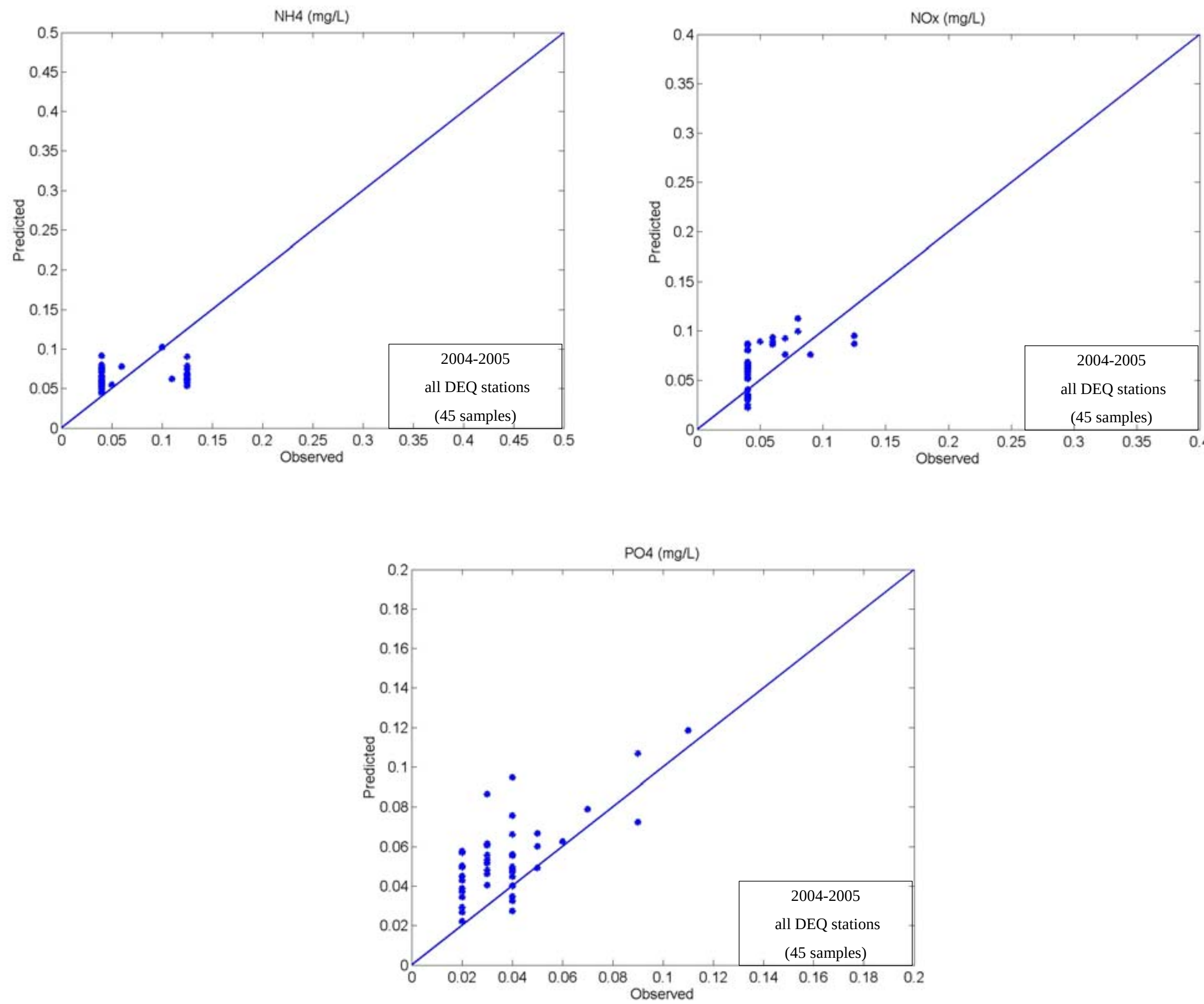


Figure VI.64. Plots of 1:1 predicted vs. observed NH_4, NO_x, and DIP TP at all 16 Lynnhaven DEQ stations for 2004 - 2005.

VI-3 Validation of the Sediment Transport Model

For validation of the sediment transport model, two observation datasets were utilized:

1) High-frequency, continuously measured turbidity time series data from 3 VIMS deployments in 2005 were used to validate the sediment transport model, based on a derived correlation between turbidity and TSS. Station locations for these 3 deployments are shown in Figure VI.65. Comparisons of the modeled TSS values and those derived from these high-frequency turbidity measurements are shown in Figure VI.66. Whereas the magnitudes of the modeled sediment concentration generally agreed with those derived from turbidity measurements, detailed variations did not completely match, probably due to the uncertainty between observed turbidity and TSS.

2) To confirm the model performance over the full spatial domain, predictions from model simulations for both 2004 and 2005 were used to compare to DEQ data at all 16 Lynnhaven stations. These comparisons are shown in Figures VI.67-VI.68, VI.69-VI.70, and VI.71-VI.72, respectively, for the Western, Eastern, and Broad Bay/Linkhorn Bay Branch DEQ stations of the Lynnhaven.

Inspection of Figures VI.67 through VI.72 shows that the model, in general, reproduced TSS concentrations at all stations reasonably well. It should be noted that no parameters were altered for the simulations of validation years 2004 and 2005.

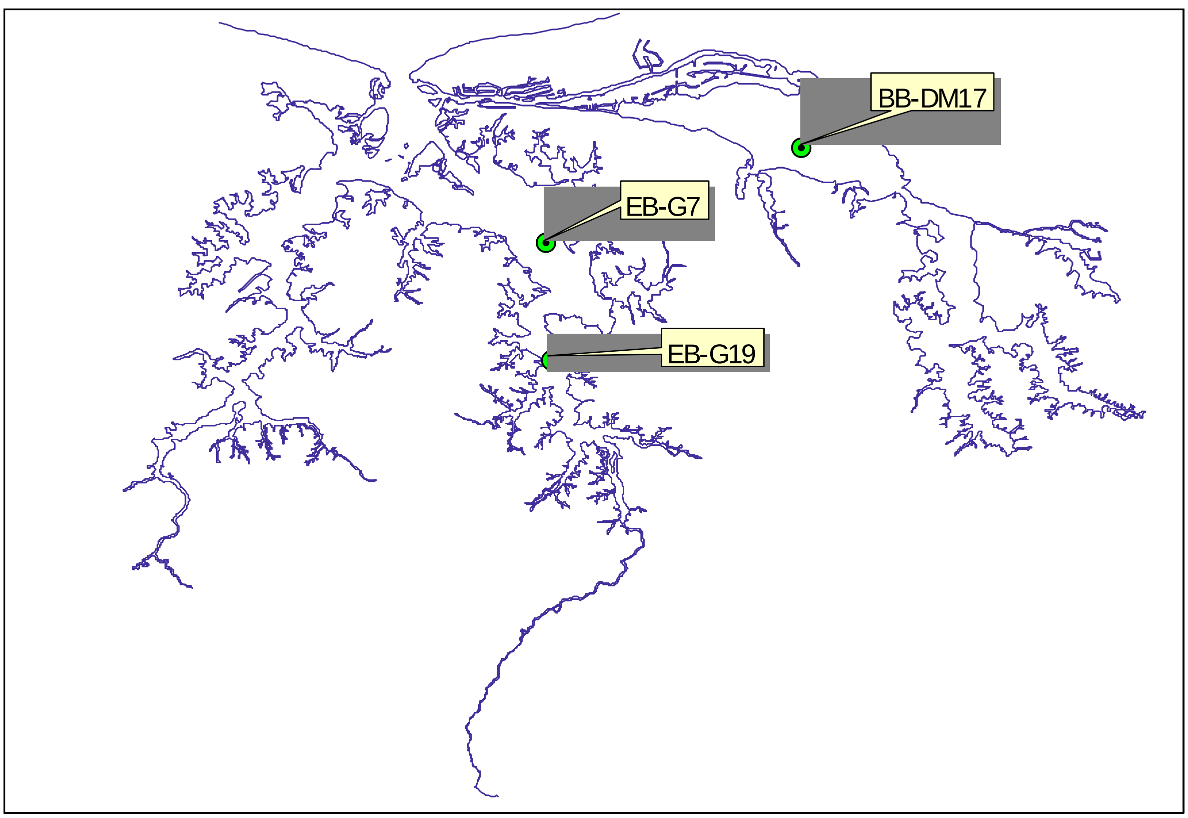


Figure VI.65. Station locations for high-frequency measurements of turbidity in 2005 in the Lynnhaven River system.

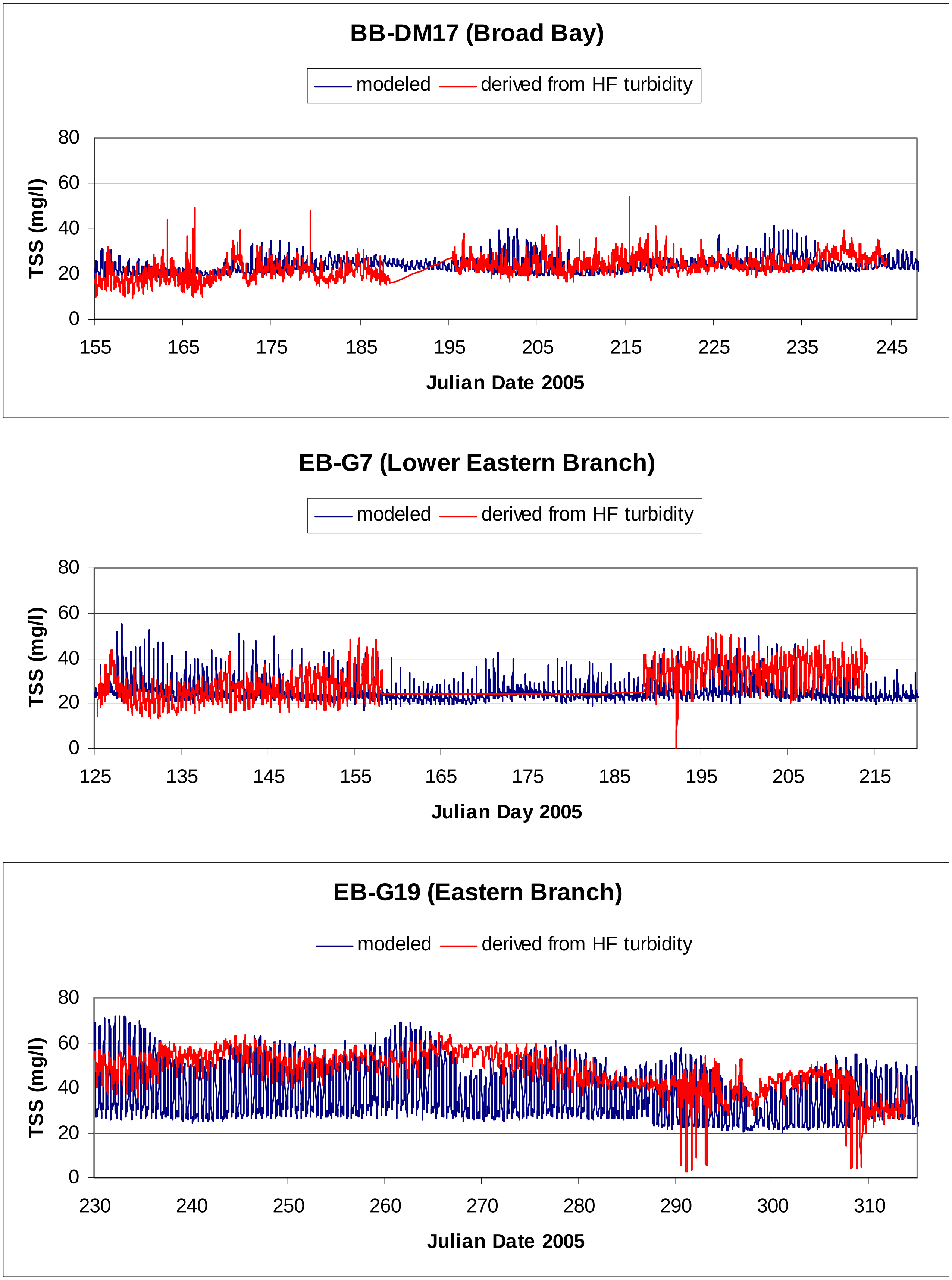


Figure VI.66. Predicted TSS vs. TSS derived from high-frequency turbidity measurements at 3 locations in the Lynnhaven in 2005.

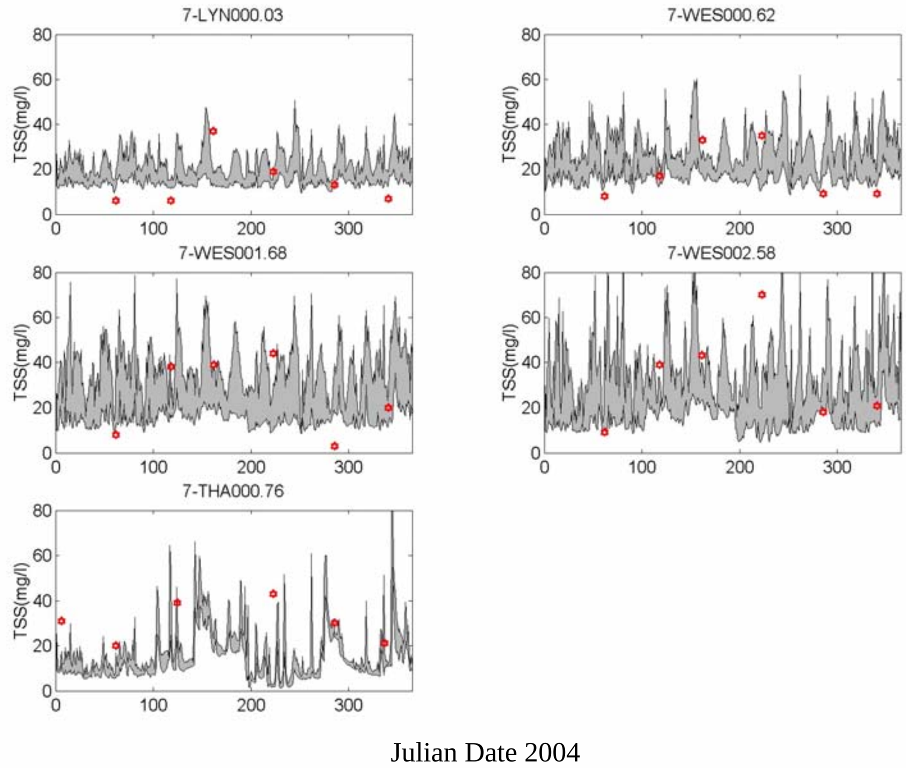


Figure VI.67. Predicted vs. observed TSS at Western Branch DEQ stations for 2004.

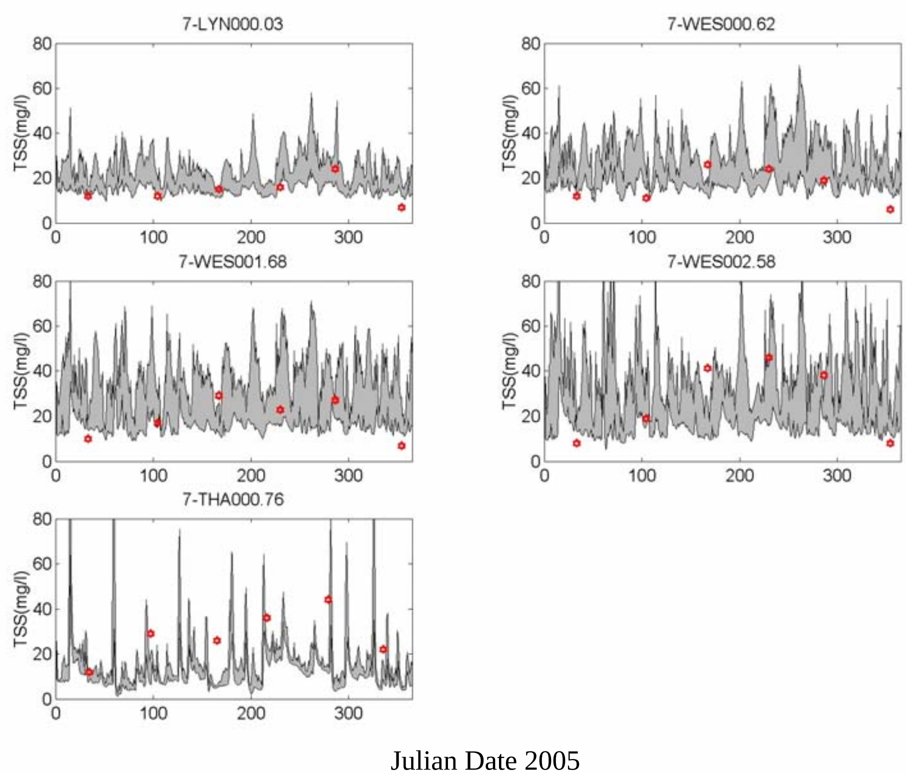


Figure VI.68. Predicted vs. observed TSS at Western Branch DEQ stations for 2005.

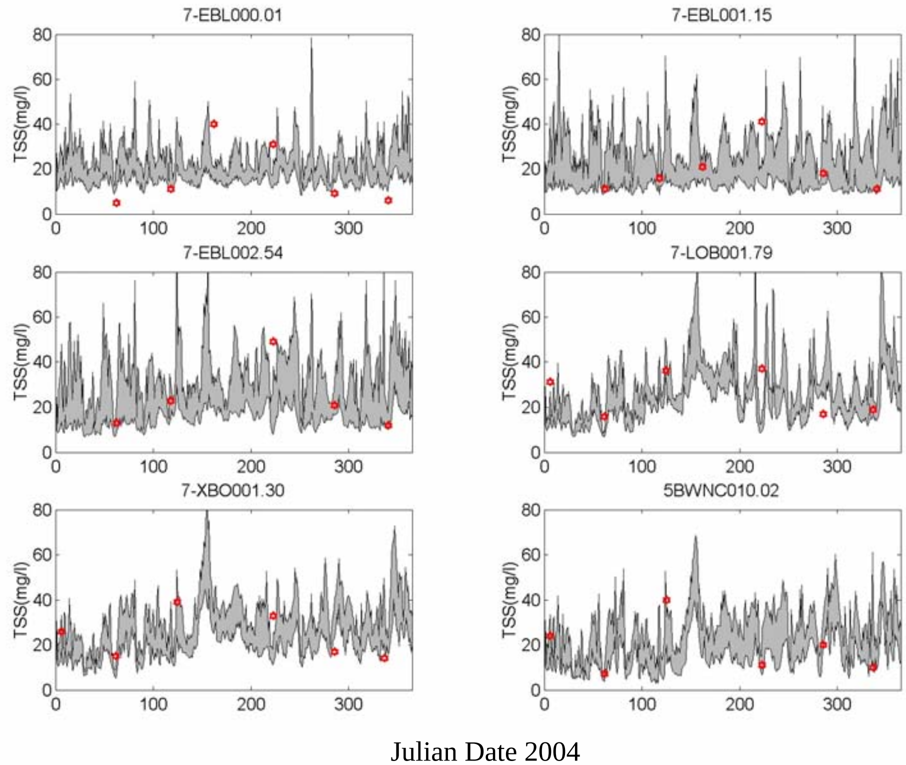


Figure VI.69. Predicted vs. observed TSS at Eastern Branch DEQ stations for 2004.

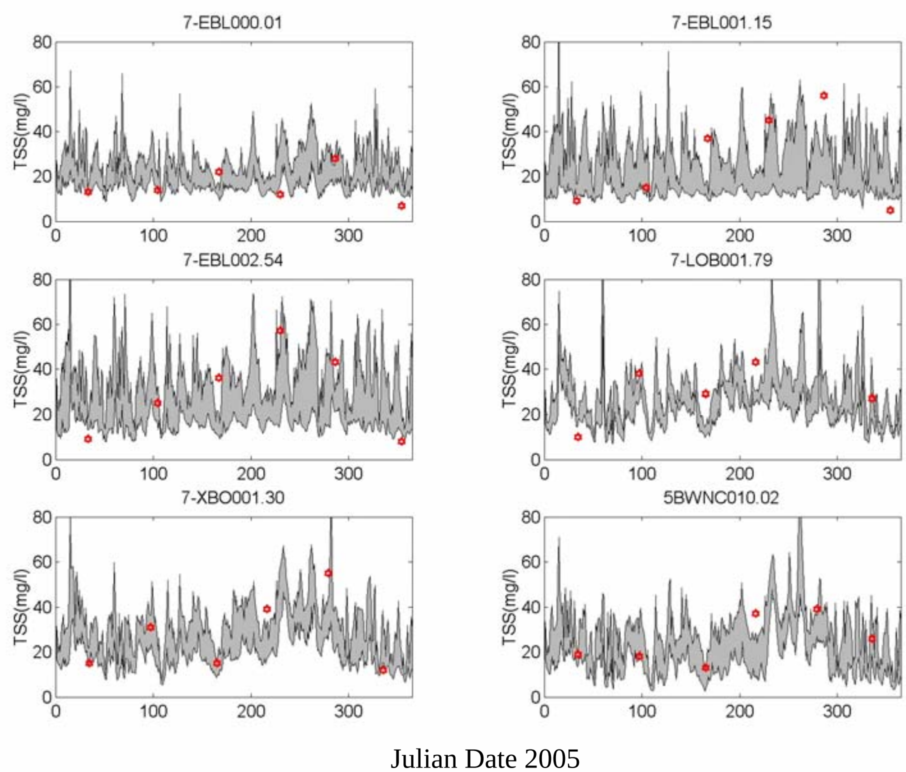


Figure VI.70. Predicted vs. observed TSS at Eastern Branch DEQ stations for 2005.

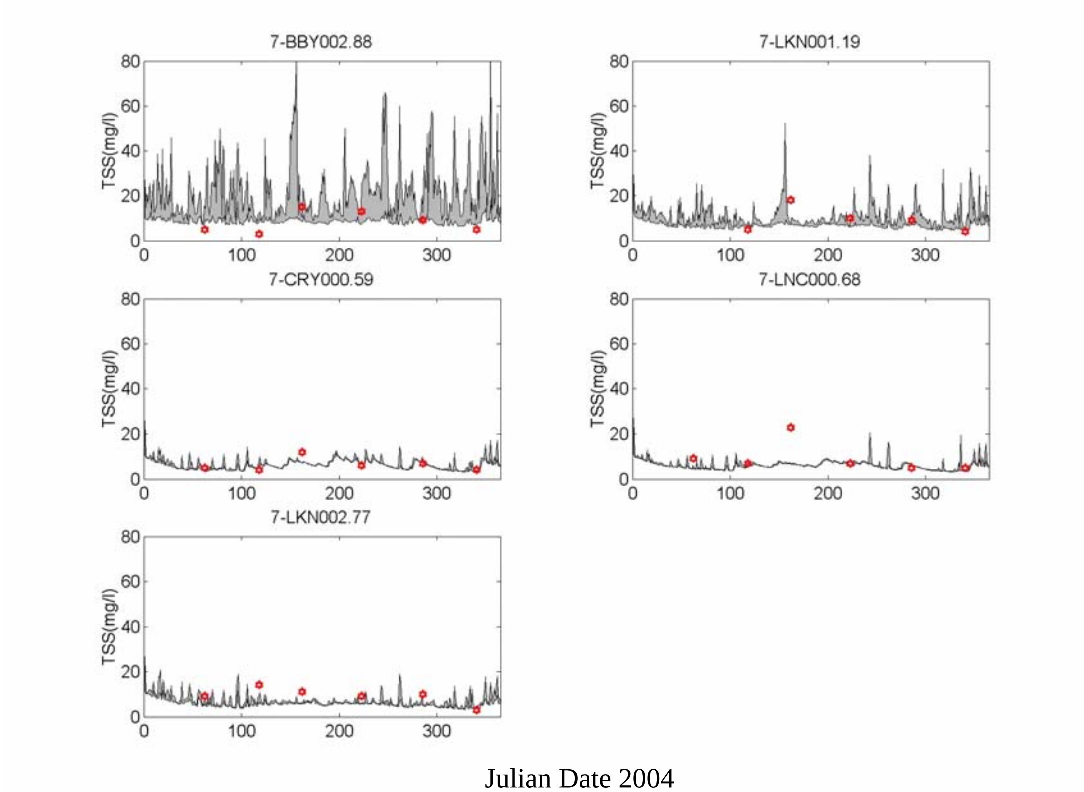


Figure VI.71. Predicted vs. observed TSS at Broad Bay / Linkhorn Bay Branch DEQ stations for 2004.

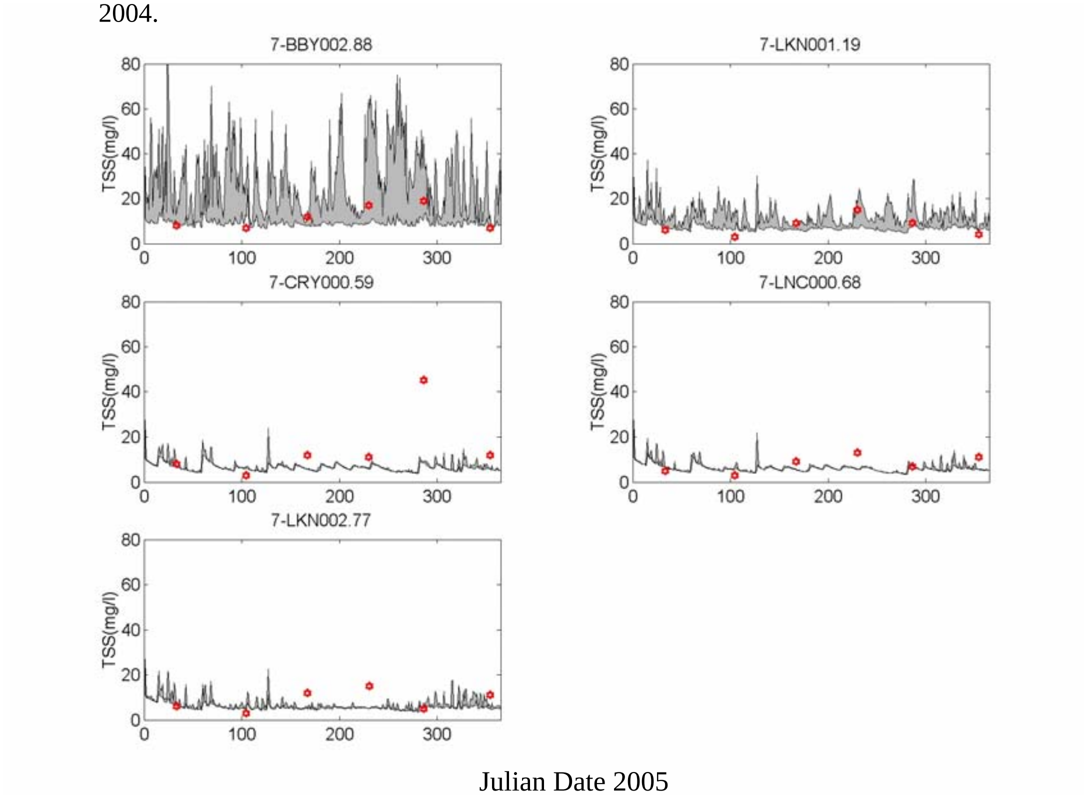


Figure VI.72. Predicted vs. observed TSS at Broad Bay / Linkhorn Bay Branch DEQ stations for 2005.

CHAPTER VII. SENSITIVITY ANALYSIS ON BENTHIC MICROALGAE DYNAMICS

The shallow water region (SWR) of coastal marine ecosystems, such as the Lynnhaven River system with depths less than 3-5 meters, encompasses the land-water margin and serves as the buffer zone for the transport of nutrients between land and water. When light can penetrate through the water column and reach the bottom, it triggers benthic microalgae (BMA) to perform photosynthesis, resulting in oxygen and nutrient benthic-pelagic exchange fluxes. BMA and their consumers are essential components of the Lynnhaven ecosystem; they uptake more nutrients and are more labile than vascular plants, and thus are clearly a source for fueling secondary primary production.

VII-1 Benthic Microalgae Model Formulation

The present model framework for benthic microalgae was inspired by the previous studies by Cerco and Seitzinger (1997) and Blackford (2002). The key variables determining the biomass of BMA are irradiance at the sediment surface, the self-shading of BMA, nutrients in the water column and sediment concentration, temperature, metabolism, and grazing rate. Figure VII.1 presents the conceptual diagram of the BMA model. BMA dynamics influence several biochemical processes: oxygen and nutrient fluxes between the water column and sediments, oxic layer thickness in the sediment, and the particulate organic material concentration in the sediment. All these processes have been built into the CE-QUAL-ICM model for its application to the Lynnhaven River system.

VII-1-1 Modeling biomass of BMA

BMA reside in a thin layer between the water column and sediments and its biomass is determined by the balance of production, respiration, and predation:

$$\frac{\delta B}{\delta t} = \left(P - BM - PR\right)B \qquad \text{(VII-1)}$$

where:
B = BMA biomass, as carbon (gm C m^{-2})
P = production rate (d^{-1})
BM = basal metabolism (respiration) rate (d^{-1})
PR = predation rate (d^{-1})

The production (growth) was determined by available light, nutrients, and ambient temperature:

$$P = P^{B}m * f(I) * f(N) * f(T) \qquad \text{(VII-2)}$$

where:
$P^{B}m$ = maximum production rate under optimal conditions (g C g^{-1} Chl d^{-1})

f(I) = effect of suboptimal light conditions
f(N) = effect of limited nutrient availability
f(T) = effect of temperature

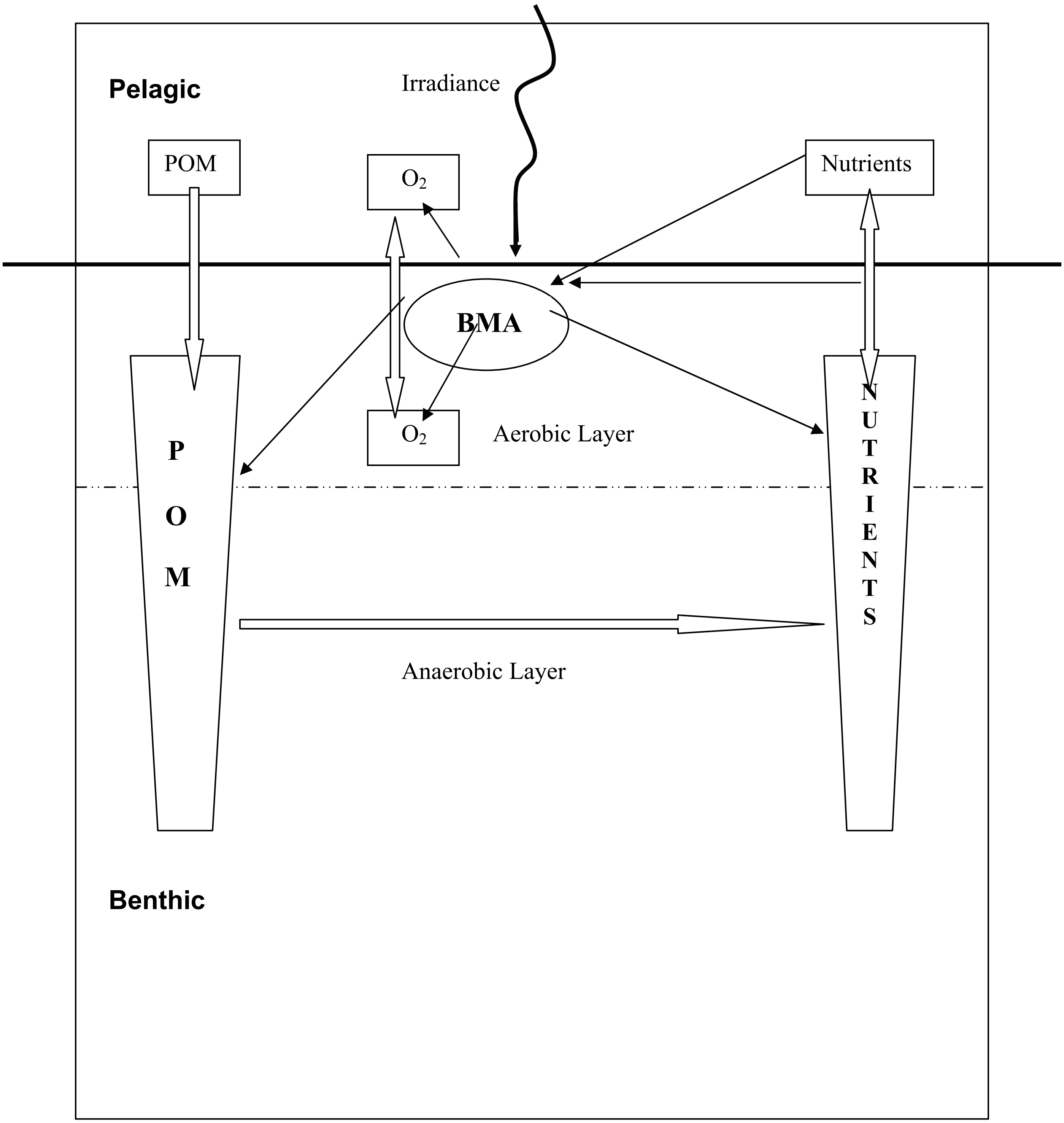


Figure VII.1. Framework of benthic algae model.

Light effect

Available light for BMA photosynthesis is the key factor to control the biomass of BMA. For example, the BMA biomass variability in the Southeastern Kattegat is 70% controlled by light availability (Sundbäck, 1984). The effect of light on production is expressed as:

$$f(I) = \frac{I}{\sqrt{I^2 + IK^2}} \qquad \text{(VII-3)}$$

where:
I = local irradiance

As is done for phytoplankton, the parameter Ik is defined as the irradiance at which the initial slope of the production vs. irradiance relationship intersects the value of $P^B m$:

$$IK = \frac{P^B m}{\alpha} \qquad \text{(VII-4)}$$

where:
α = initial slope of production vs. irradiance relationship (g C g^{-1} Chl (E $m^{-2})^{-1}$)

Local irradiance varies within the BMA layer due to BMA self-shading and extinction due to sediment solids:

$$I = I_s e^{-Ks*z} \qquad \text{(VII-5)}$$

where:
Is = irradiance at surface of BMA layer (same as irradiance at bottom of water column)
Ks = light attenuation within BMA layer due to BMA self-shading and sediment (m^{-1})
z = local coordinate measured down from surface of algal layer

Self-shading has been cited as an important factor influencing BMA (Cahoon and Cooke, 1992). Consequently, it is reasonable to separate K_s (light attenuation) into two terms; one is self-shading related to the BMA biomass, and the other is sediment solids extinction. The mean light within the BMA layer is represented as:

$$I_{mean} = I_o e^{-Ksed} \frac{1 - e^{-Ka \lg ae * B}}{Ka \lg ae * B} \qquad \text{(VII-6)}$$

where:
I_{mean} = available light within BMA layer
Io = irradiance at the surface of sediment
K_{sed} = attenuation due to sediment solid
K_{algae} = attenuation due to benthic microalgae self-shading ($m^2 g^{-1}$C)
B = benthic microalgae biomass (g C m^{-2})

Equation (VII-6) mainly constrains unlimited growth of BMA. When the biomass of BMA becomes larger, the mean light within the BMA layer will be smaller. As a result, BMA growth will be limited. Irradiance at the surface of the BMA layer is calculated from the irradiance at the surface of the water column through the following equation:

$$\mathrm{Ke} = \mathrm{a}_1 + \mathrm{a}_2 * TSS + \mathrm{a}_3 * CHL \tag{VII-7}$$

where:

a_1 = background attenuation (m^{-1})
a_2 = attenuation by inorganic suspended solids ($m^2\ g^{-1}$)
a_3 = attenuation by organic suspended solids ($m^2\ gm^{-1}$ CHL)
TSS = total suspended solids concentration ($g\ m^{-3}$)
CHL = chlorophyll-a concentration (mg CHL m^{-3})

Nutrients

The influence of nutrients on BMA production is represented by the Monod formulation:

$$f(N) = \frac{N}{Kh + N} \tag{VII-8}$$

where:
N = concentration of nutrient available for BMA uptake (g m m^{-2})
Kh = nutrient concentration at which algal uptake is halved (g m m^{-2})

There are two nutrient sources for BMA, one from the water column and the other from returned nutrients as they diffuse from the sediment into the overlying water column. A nutrient concentration available on an areal basis is calculated as follows:

$$N = Nflux * \Delta t + Nwater * Hwater \tag{VII-9}$$

where:
N*flux* = sediment nutrient release ($g\ m^{-2}\ d^{-1}$)
Δt = discrete time step (day)
N*water* = nutrient concentration in overlying water ($g\ m^{-2}$)
H*water* = depth of bottom layer (m)

Two nutrients potentially limit BMA production: dissolved inorganic nitrogen and phosphorus. As in the case for phytoplankton, Liebig's "law of the minimum" (Odum, 1971) is used. Therefore, nutrient limitation is determined by the most limiting nutrient. Based on the reported value, half-saturation constants were set as $K_{hn} = 0.01$ g N m^{-2} for nitrogen and $K_{hp} = 0.001$ g P m^{-2} for phosphorus (Cerco and Seitzinger, 1997). It is assumed that silica is not a limiting factor in the present BMA model, even though benthic diatoms can uptake silica.

Temperature
Temperature is also shown to have a strong effect on production, respiration, and grazing rates. For example, temperature was recognized to account for up to 70% of the variability of microphytobenthic populations (Uthicke and Klumpp, 1998). The effect of temperature on algal production is represented by a function similar to a Gaussian probability curve:

$$\begin{aligned} f(T) &= \exp\left(-KTG1[T - TM]^2\right) \quad \text{when } T \leq TM \\ &= \exp\left(-KTG2[TM - T]^2\right) \quad \text{when } T > TM \end{aligned} \qquad \text{(VII-10)}$$

where:
TM = optimal temperature for BMA growth (°C)
KTG1 = effect of temperature below TM on BMA growth ($°C^{-2}$)
KTG2 = effect of temperature above TM on BMA growth ($°C^{-2}$)

As a result, BMA production increases as a function of temperature until an optimum temperature is attained, and then decreases with temperature after an optimum temperature is reached.

Basal metabolism (Respiration)
Basal metabolism is commonly considered to be an exponentially increasing function of temperature:

$$BM = BMR * \exp[KTB(T - TR)] \qquad \text{(VII-11)}$$

where:
BMR = metabolic rate at reference temperature TR (day^{-1})
KTB = effect of temperature on metabolism ($C^{\circ -1}$)
TR = reference temperature for metabolism (C°)

Predation
Predation is calculated by a relationship identical to that for respiration:

$$PR = BPR * \exp[KTB(T - TR)] \qquad \text{(VII-12)}$$

where:
BPR = predation rate at TR (day^{-1})
KTB = effect of temperature on predation ($C^{\circ -1}$)
TR = reference temperature for predation (C°)

The rates of both metabolism and predation for BMA both increase with temperature. The differences lie in the parameter values, and their distribution.

VII-2 Nutrient Budgets in the Lynnhaven River

A nutrient budget provides a basis for assessing potential effects of system responses in the context of various sources and sinks. The purposes for constructing the nutrient budget were: (1) to present the nutrient pathway on an annual basis, especially under the scenarios of with and without the effects from BMA, (2) to evaluate the relative importance of the various sources and sinks of nitrogen and phosphorus during the seasonal cycle from the monthly nutrient budget, (3) to estimate recycling processes in order to allow estimates of turnover times and the relative importance of "new" versus "recycled" nutrients, and (4) to quantify nutrient export to the coastal ocean and losses from the sediment on an annual basis comparing with results from deep water systems (Nixon et al., 1996).

In order to quantify the nutrient budget in an estuary, both nutrient storage in sediments and nutrient exchange with the ocean and the atmosphere must be quantified. Nutrient storage in sediments is difficult to measure in the field due to large spatial and temporal gradients (Boynton et al., 1995). Nutrient exchange with the outside ocean is complicated by tidal currents, with large temporal and spatial gradients (Kjerfve and Proehl, 1979). Therefore, the nutrient budget calculation from a well-calibrated numerical model represents one of the most efficient and accurate ways to achieve the goal.

VII-2-1 Annual nutrient budget in Lynnhaven River system

This Lynnhaven hydrodynamic/water quality model comprises the estimate of major inputs, exports, storages, and recycling of TN and TP in the Lynnhaven River proper and its branches. There are two types of nutrient inputs into the system including nonpoint loading from watershed and atmospheric sources. Loss terms include burial of TN and TP in sediments in depositional portions of study areas, denitrification of N in sediments, and net exchanges of N and P at the mouth of the river. Since it is probably a small source as is the case in most nutrient-rich estuarine systems, nitrogen fixation is not evaluated (Howarth et al., 1988).

The conceptual model of the nutrient budget can be expressed as differential equations for TN and TP both in the water column and in the sediment based on Boynton et al. (1995). In the water column, the time rates of change of TN and TP vary with nonpoint, atmospheric and depositional fluxes, and oceanic sources:

$$\frac{dTN_w}{dt} = TN_{nonpoint} + TN_{atm} - TN_{dp} + TN_{flux} + TN_{ocean} \quad \text{(VII-13)}$$

$$\frac{dTP_w}{dt} = TP_{nonpoint} + TP_{atm} - TN_{dp} + TN_{flux} + TN_{ocean} \quad \text{(VII-14)}$$

In the sediment, the important processes impacting the time rates of changes of TN and TP include deposition, flux, burial, and denitrification:

$$\frac{dTN_s}{dt} = TN_{dp} - TN_{flux} - TN_{burial} - TN_{denitri} \quad \text{(VII-15)}$$

$$\frac{dTP_s}{dt} = TP_{dp} - TP_{flux} - TP_{burial} \quad \text{(VII-16)}$$

where:

TN_w , TP_w = total nitrogen, phosphorus in water column
TN_s, TP_s = total nitrogen, phosphorus in sediment
$TN_{nonpoint}$, $TP_{nonpoint}$ = total nitrogen, phosphorus loading from nonpoint source
TN_{atm}, TP_{atm} = total nitrogen, phosphorus loading from atmosphere
TN_{dp}, TP_{dp} = total nitrogen, phosphorus deposition into sediment
TN_{flux}, Tp_{flux} = total nitrogen, phosphorus flux from sediment into water column
TN_{ocean}, TP_{ocean} = net total nitrogen, phosphorus exchange with adjacent seaward system
TN_{burial}, TP_{burial} = total nitrogen, phosphorus burial in deep sediment
$TN_{denitri}$ = total nitrogen, phosphorus denitrified in sediment

Annual nutrient budget in the mainstem of Lynnhaven River

The mean annual water quality budget in the Lynnhaven River was studied first. It was assumed that, on an annual basis, the nutrient species are in an equilibrium condition. Consequently, $\frac{dTN_w}{dt}$, $\frac{dTP_w}{dt}$, $\frac{dTN_s}{dt}$ and $\frac{dTP_s}{dt}$ are equal to zero by definition. The results of annual nutrient budgets are shown in Figure VII.2 and Figure VII.3 (values in parentheses denote results without BMA).

Annual TN and TP budgets, reported in units per square meter of surface area of Lynnhaven River, show the loading of nutrients from the watershed we calculated is slightly less than that for Chesapeake Bay (Boynton et al., 1995). Our loading for Lynnhaven River is 27.79 (mg N m^{-2} d^{-1}) for TN and 2.08 (mg P m^{-2} d^{-1}) for TP. In a previous comparison with Chesapeake Bay loading of nutrients from its watershed, TN loading was 36.01 (mg N m^{-2} d^{-1}) and TP loading was 2.67 (mg P m^{-2} d^{-1}). The ratio of the Lynnhaven River watershed (166 km^2) to the surface area of the receiving waters (18.1 km^2) is 9.2. This ratio for Chesapeake Bay is 14.4 (165,760 km^2 watershed area, 11,542 km^2 surface area of its receiving waters). The atmosphere deposition directly deposited through the surface of the river contributed only 9.5% for TN and 4.4% for TP. While direct atmospheric deposition represents a very small nutrient source compared to nonpoint sources from the watershed, the influence of atmospheric deposition on primary production may be larger. The reason for this is that a substantial fraction of TN and TP entering from watershed sources is in a form not directly available to phytoplankton, being either dissolved organic nutrient or a form of particulate material. However, virtually all of the nitrogen and phosphorus deposited from the atmosphere is immediately available for phytoplanktonic uptake.

Figure VII.2 and Figure VII.3 show the results of the water quality model simulation and indicate that, over lengthy time scales, benthic algae can influence most terms of the nutrient budget in the water column. The presence of BMA reduced the export of nutrients into Chesapeake Bay. There are two reasons: 1) a larger quantity of particulate nitrogen and phosphorus deposit into the sediment in the presence of BMA and 2) for nitrogen flux between the water column and sediment with BMA, the flux direction changed from traditional flux in that the BMA uptake dissolved nutrients both from the sediment and the water column, which causes the net dissolved nitrogen flux to occur from the water column into the sediment. For phosphorus flux between the water column and the sediment with BMA, the flux direction does not change, but less dissolved phosphorus is released from the sediment due to BMA uptake. The nutrients that are uptaken by BMA are stored in the sediment in winter and spring, and released from the sediment as dissolved nutrient in summer and autumn. Simulations indicate that larger quantities of dissolved nitrogen are incorporated into the sediments in the presence of benthic algae. Deposition of particulate nitrogen computed in the presence of benthic algae also increases. Enhanced deposition results from the stimulation of primary production in the water column by summer nutrients released in the presence of benthic algae.

The computed net annual flux of dissolved phosphorus is from the sediments to the water column, both with and without the effects of benthic algae (Figure VII.3). Annual average sediment release is diminished when algae are present, however, due to uptake during periods of benthic production. The simulation indicates that Lynnhaven River would export more phosphorus to the ocean in the absence of benthic algae.

Figure VII.2 and Figure VII.3 also indicate that benthic algae can influence burial and denitrification in sediment. For both particulate nitrogen and particulate phosphorus, computed deposition and burial is increased in the presence of benthic algae. As a result of the uptake by BMA and enhanced deposition, more nitrogen and phosphorus are buried into deep, unavailable sediments instead of being exported into Chesapeake Bay without benthic algae. The denitrification rate also increased due to BMA. In general, the annual averaged denitrification rates with BMA and without BMA are within the range 5 to 250 μmol N m^{-2} h^{-1} (1.68 mg N m^{-2} d^{-1} to 84 mg N m^{-2} d^{-1}) reported for several estuarine systems (Andersen et al., 1984; Seitzinger, 1988; 1990; Rysgaard et al., 1993; 1995; Nowicki et al., 1997; Sundbäck et al., 2000). The highest denitrification rate, 98 mg N m^{-2} d^{-1}, occurred in the late summer during the simulation including BMA. There are also several studies that show extremely high denitrification rates of approximately 500 to 1300 μmol N m^{-2} h^{-1} (168 to 437 mg N m^{-2} d^{-1}) in some estuarine sediments (Seitzinger, 1988; 1990; Ogilvie et al., 1997; Dong et al., 2000).

<u>Annual nutrient budget in the three tributaries of Lynnhaven River</u>

In the Lynnhaven River, there are three major branches: Western Branch, Eastern Branch, and Broad Bay. Their dynamics are different. It is valuable to characterize the difference between these three branches. For example, which tributary receives the majority of the nutrient loading from the watershed? Which tributary exports the largest quantities of nutrients into Chesapeake Bay? Using the same methodology described earlier, nutrient budgets in the three branches of Lynnhaven River were calculated (Figure VII.4 and Figure VII.5).

The results show that the Western and Eastern Branches receive significantly more nutrients than does Broad Bay. While the combined surface areas of the Western and Eastern Branches (11.1 km^2) comprise only 61% of the entire system (18.1 km^2), the percentage for nutrient loadings are 85% for TN and 83% for TP contributed from the watershed. The largest areal loadings of TN and TP are in Western Branch, which are almost 5 times and 4 times those in Broad Bay for TN and TP, respectively.

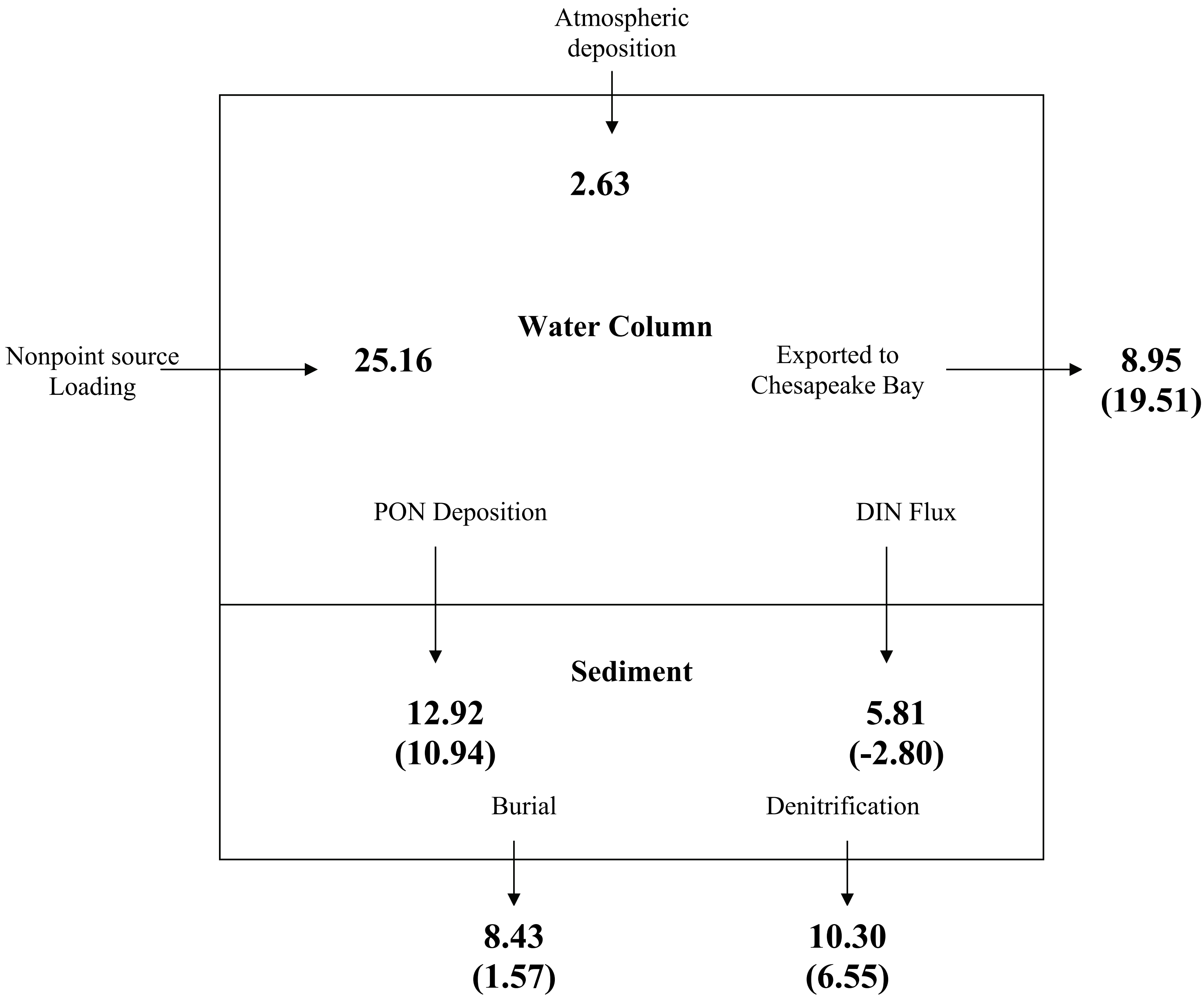


Figure VII.2. Annual Total Nitrogen budget (mg N m^{-2} d^{-1}) for Lynnhaven River (Values in parentheses indicate results without BMA)

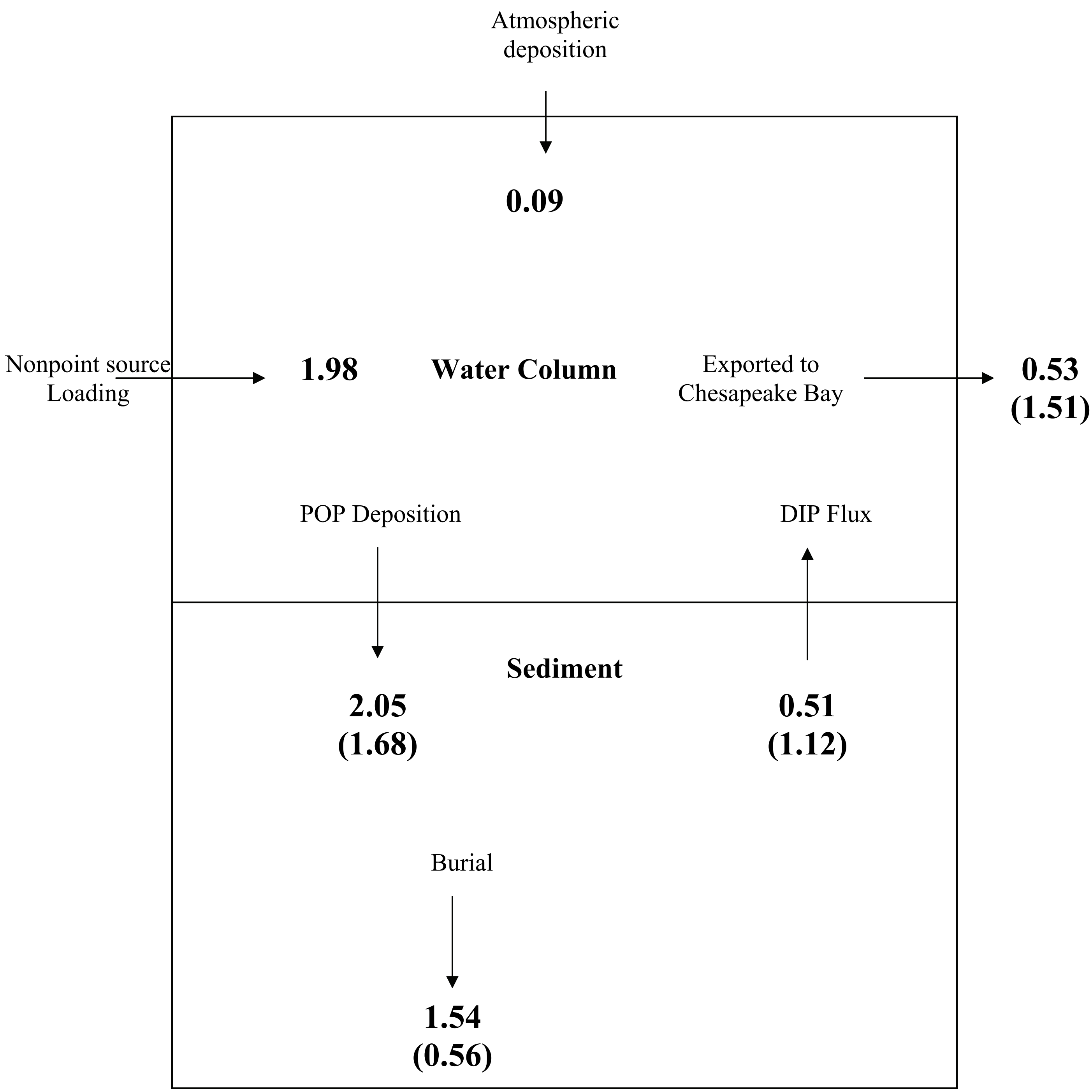


Figure VII.3. Annual Total Phosphorus budget (mg P m^{-2} d^{-1}) for Lynnhaven River (Values in parentheses indicate results without BMA)

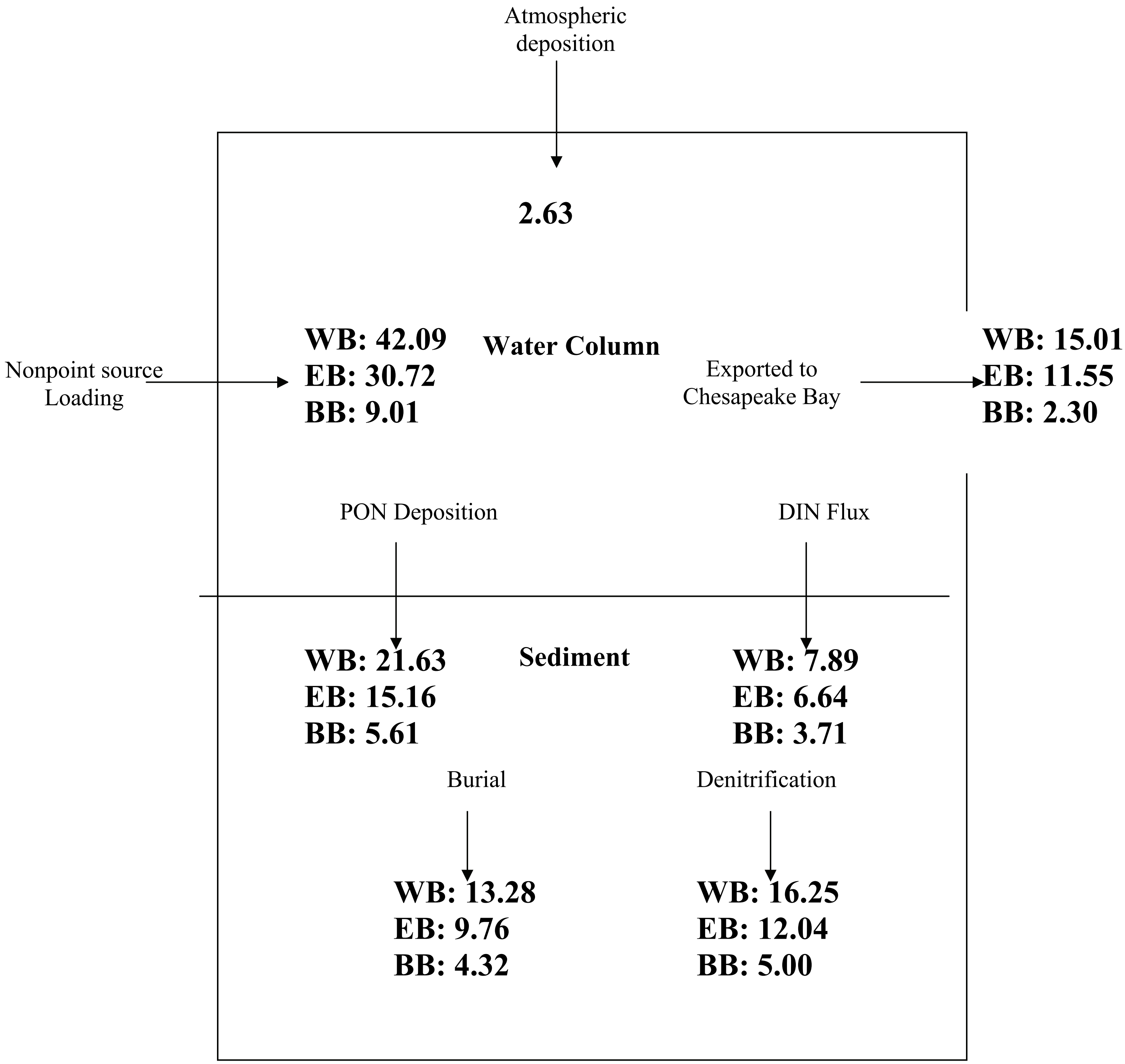


Figure VII.4. Annual Total Nitrogen budget (mg N m^{-2} d^{-1}) in three branches of Lynnhaven River (WB: Western Branch, EB: Eastern Branch, BB: Broad Bay)

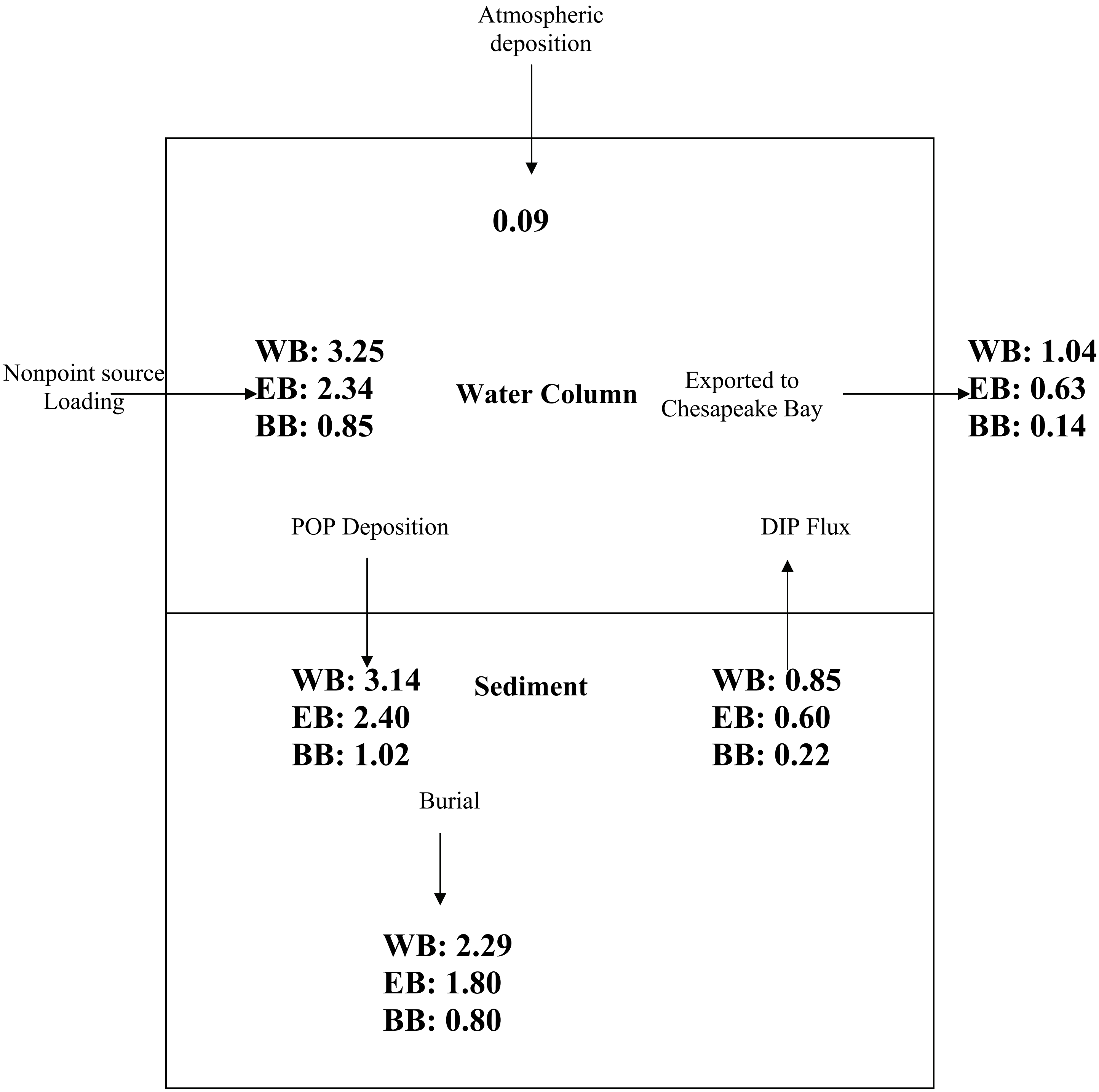


Figure VII.5. Annual Total Phosphorus budget (mg P m^{-2} d^{-1}) in three branches of Lynnhaven River (WB: Western Branch, EB: Eastern Branch, BB: Broad Bay)

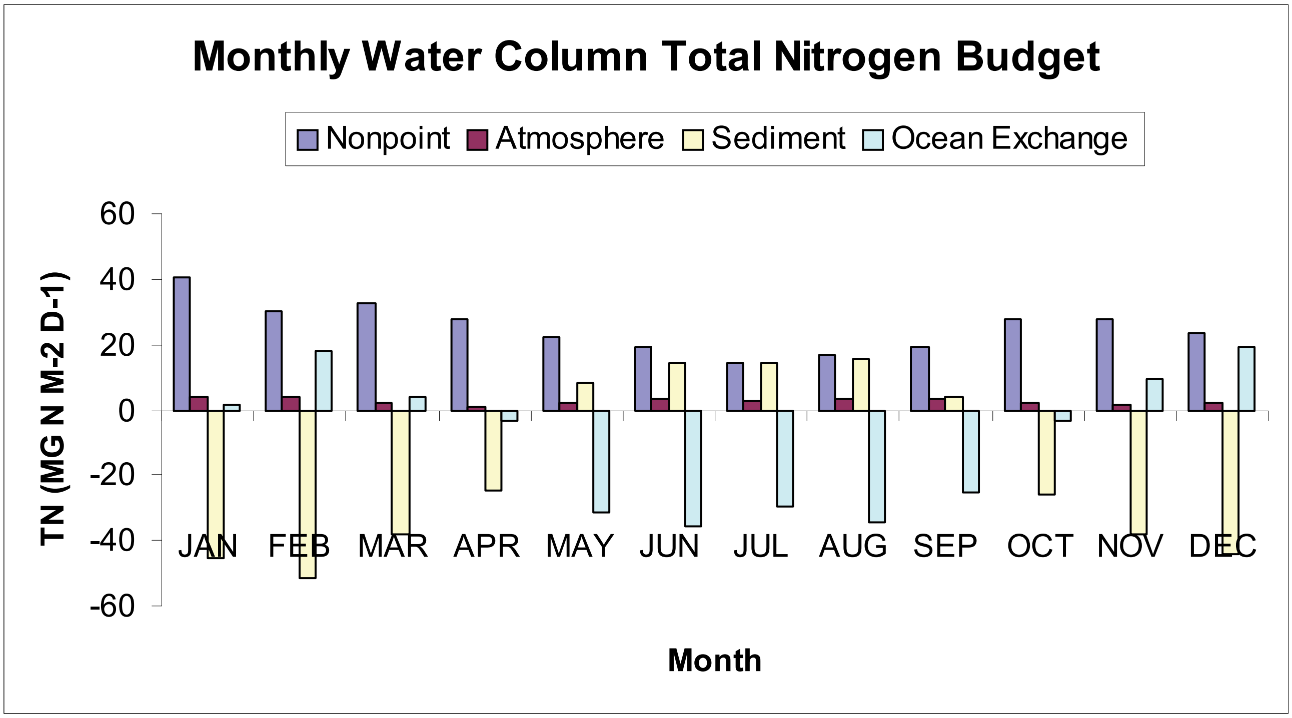
It is not surprising that most nutrients exported from the Lynnhaven into Chesapeake Bay are from the Western and Eastern Branches. With larger nutrient loadings, the Western and Eastern Branches contribute approximately 90% of TN and 89% of TP exported into Chesapeake Bay. The removal of nutrients via ocean exchange, as a percentage of TN input to the estuary, also varies between the three branches. The Western Branch exports 34% of its TN loading and 31% of its TP loading, the Eastern Branch exports 35% of its TN loading and 29% of its TP loading, and Broad Bay only exports 20% of its TN loading and 15% of its TP loading.

The difference appears to be due to different residence times for the three branches. From the results of an "age-of-water" investigation, we know that the residence time of either the Western or Eastern Branch is approximately 12 days for the mean flow condition, which is much smaller than that of Broad Bay, 72 days. Nixon (1996) showed that the net transport of nutrients through a system to the outside ocean is inversely correlated with the residence time of water in the system. With larger nutrient loading, the Western and Eastern Branches also show larger values of particulate nutrient deposition, dissolved nutrient flux, final burial into deep sediment, and denitrification rates than these values for Broad Bay.

VII-2-2 The monthly nutrient budget for the Lynnhaven River system

There are other time scales, such as seasonal time scales, that are important for the nutrient budget. The monthly nutrient budget was calculated using the formula presented above. For the water column, the monthly budget for the entire year is shown in Figure VII.6. It indicates that nonpoint sources account for most external loadings of nitrogen and phosphorus to the Lynnhaven River through the entire year. Atmospheric nitrogen and phosphorus loadings are almost constant throughout the year. From October through April, the sediment is the major sink of nitrogen from the water column. From May to September, sediments release remineralized nitrogen to the water column and function as a source. During July and August, sediment-released nitrogen is larger than the nonpoint source loading. From November through March, Lynnhaven River exports nitrogen to the Chesapeake Bay. During the rest of the year, nitrogen imports from the ocean are substantial. The monthly budget for phosphorus also reveals a similar pattern. From October through March, the sediment is the major sink. From April to September, sediments act as a source by releasing phosphorus to the water column. From October through February, the Lynnhaven River exports phosphorus to the Chesapeake Bay. Similar monthly patterns of the nutrient budget were found by Cerco and Seitzinger (1997) for their analysis of the Indian River-Rehoboth Bay system.

The sediment nutrient budget was also calculated (Figure VII.7). During winter and spring, sediments are net sinks of nutrients from the water column. Settling of nutrients in particulate form is one component of the nutrient budget during these months. In addition, BMA also uptake dissolved inorganic nutrients. Benthic fluxes of total dissolved nutrients are dominated by uptakes throughout the spring and winter. Benthic microalgae can assimilate a large proportion of the nitrogen and phosphorus and produce oxygen in the sediments (Ferguson et al., 2004).



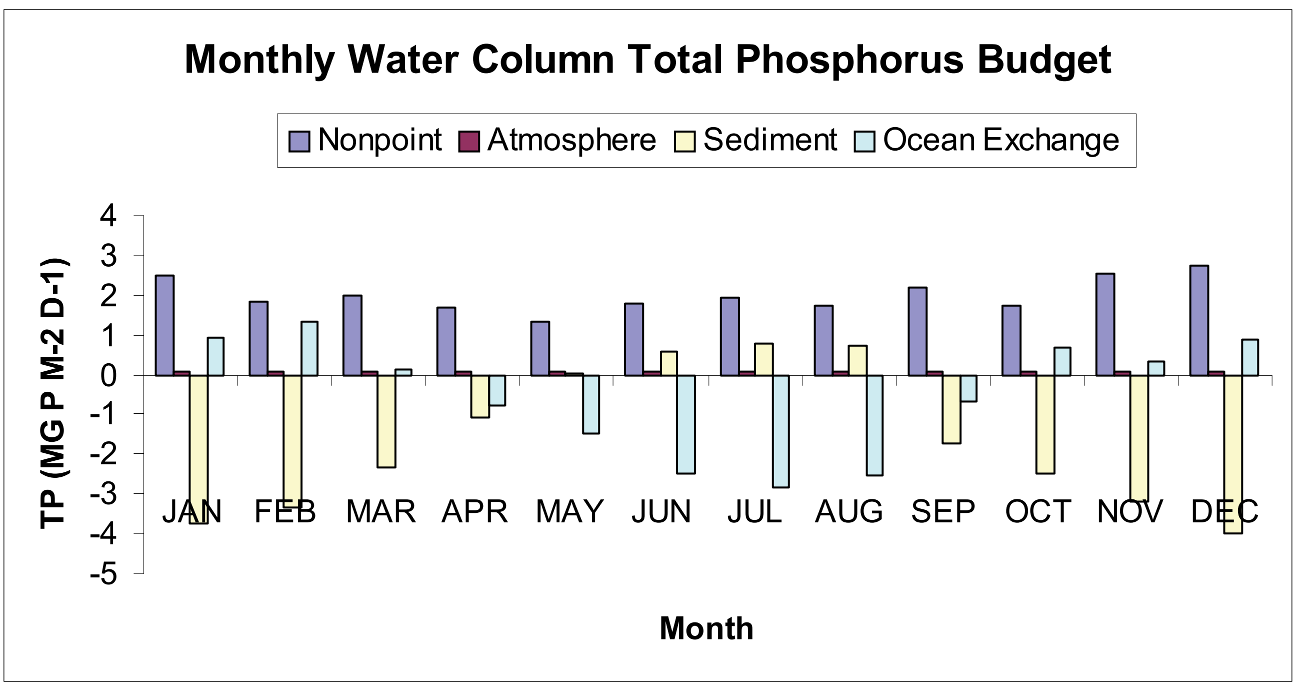
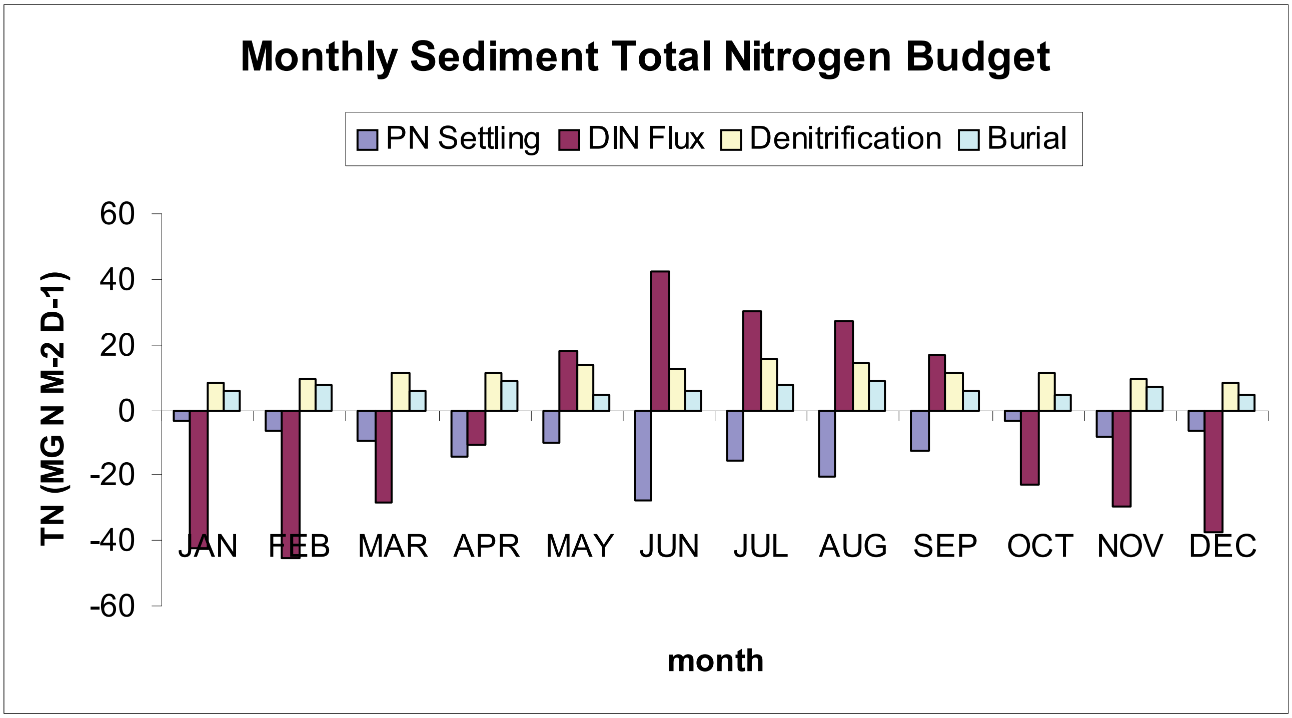


Figure VII.6. Monthly Total Nitrogen budget (mg N m^{-2} d^{-1}) and Total Phosphorus budget (mg P m^{-2} d^{-1}) in the water column for Lynnhaven River (positive means entering the water column, and negative means leaving the water column)



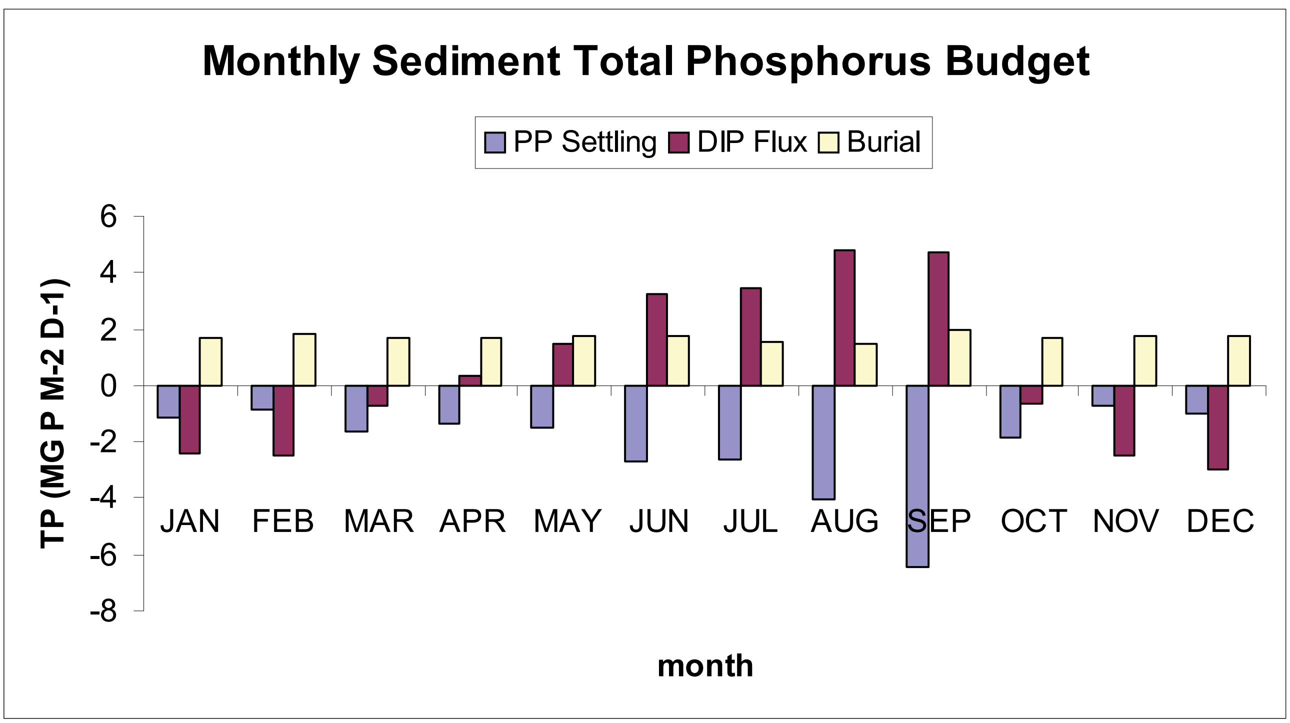


Figure VII.7. Monthly Total Nitrogen budget (mg N m^{-2} d^{-1}) and Total Phosphorus budget (mg P m^{-2} d^{-1}) in sediment for Lynnhaven River (positive values indicate leaving sediment, negative values indicate entering sediment)

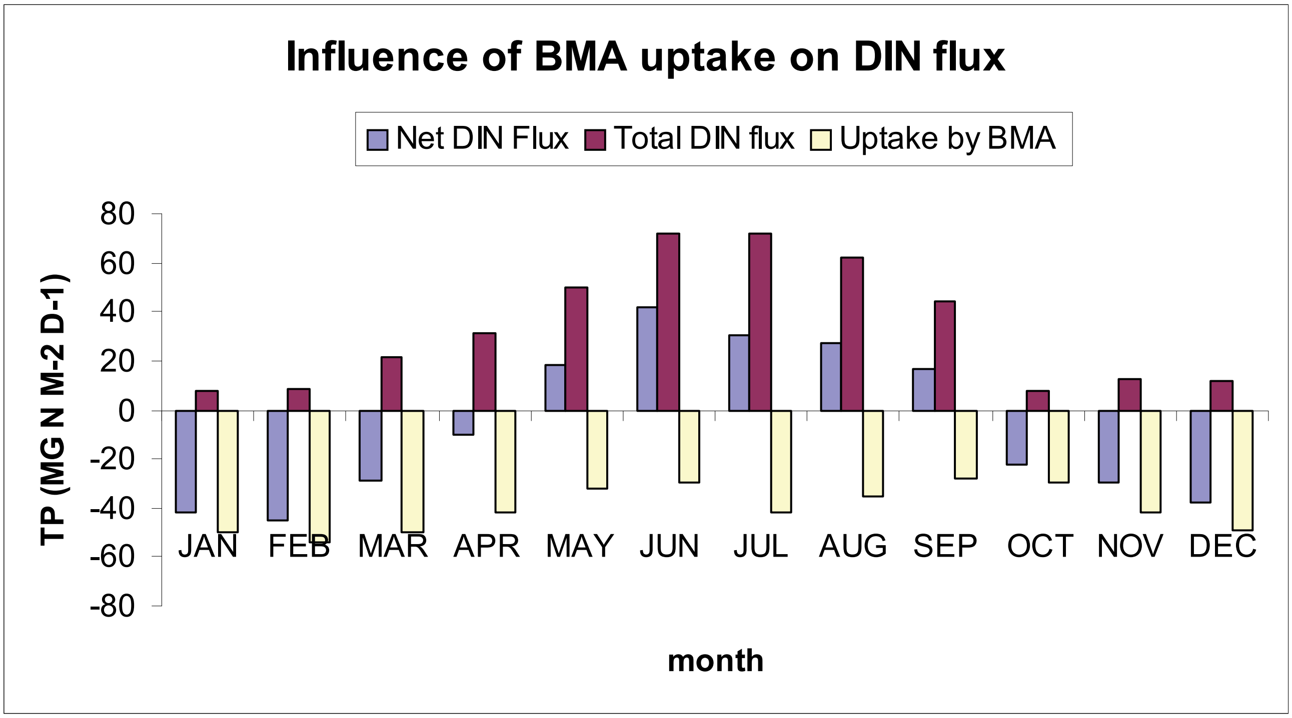
In April or May, the system undergoes a change as the sediment begins to release nutrients. It is possible that, in this condition, the extra pelagic production and resulting light extinction would decrease BMA production, leaving an unsustainable benthic respiratory requirement. Meanwhile, phytoplankton assimilate dissolved nutrients in the water column, which lowers the concentration of dissolved nutrients. The coupled effects cause sediments to release dissolved nutrients into the water column. Cerco and Seitzinger (1997) also indicated that this change is caused by phytoplankton shading out benthic algae and primary production in the water column exceeding production in the sediments. When temperatures become relatively high during this period, phytoplankton in the water column receive more light than BMA in the sediment. Mineralization of the organic matter in the sediments also increases with high temperature in summer, and dissolved inorganic nutrients are released from the sediment and support the primary production in the water column. Phytoplankton growth exceeds BMA, since light available to BMA decreases due to shading by phytoplankton. In summer and autumn, the sediments are a net source of nutrients to the water column.

In order to illustrate the influence of BMA uptake on sediment dissolved nutrient flux, Figure VII.8 shows the monthly dissolved nitrogen and phosphorus assimilated by BMA with the total and net nutrient fluxes. The total nutrient flux, without BMA uptake, indicates that sediment released both nitrogen and phosphorus over the entire year. The most intense period of release of nutrients from the sediment occurred in summer. The dissolved nutrients assimilated by BMA exceeded the released nutrients in winter and spring, while the released nutrients from the sediment dominated in summer and autumn. In summary, BMA could reverse the direction of nutrient sediment flux in early spring and late autumn.

VII-3 Comparison of Nutrient Budget between Shallow and Deep Water Systems

In deep estuaries, sediment-regenerated nutrients often account for the majority of the total nutrients regenerated. For example, the annual sediment releases of nitrogen and phosphorus ranged from 55% to 233% and 44% to 2140%, respectively, of their annual terrestrial plus atmospheric inputs. The most intense sediment nutrient flux from the sediment into the water column occurred in summer. In Lynnhaven River, however, the annual sediment flux of nitrogen is from the water column into the sediment. From monthly budget results, it is clear that the sediment still releases nitrogen in summer and fall as in deep estuaries, but the BMA in the sediment uptake nitrogen from the water column in winter and spring. The overall effect of annual sediment nitrogen flux is from the water column into the sediment. Meanwhile, the uptake effect of BMA also reduces the magnitude of the phosphorus flux from the sediment into the water column.

In most estuaries, nutrient loadings are dominated by freshwater inputs during spring. With abundant nutrients in the water column, phytoplankton usually bloom in spring, for example, in Chesapeake Bay (Kemp and Boynton, 1984; Malone et al., 1988). After phytoplankton decay and sink into the sediment, the recycling of nutrients from the sediments then supports further phytoplankton productivity in the summer (Kemp and Boynton, 1984; Rysgaard et al., 1995). It appears that nutrient cycling in these systems



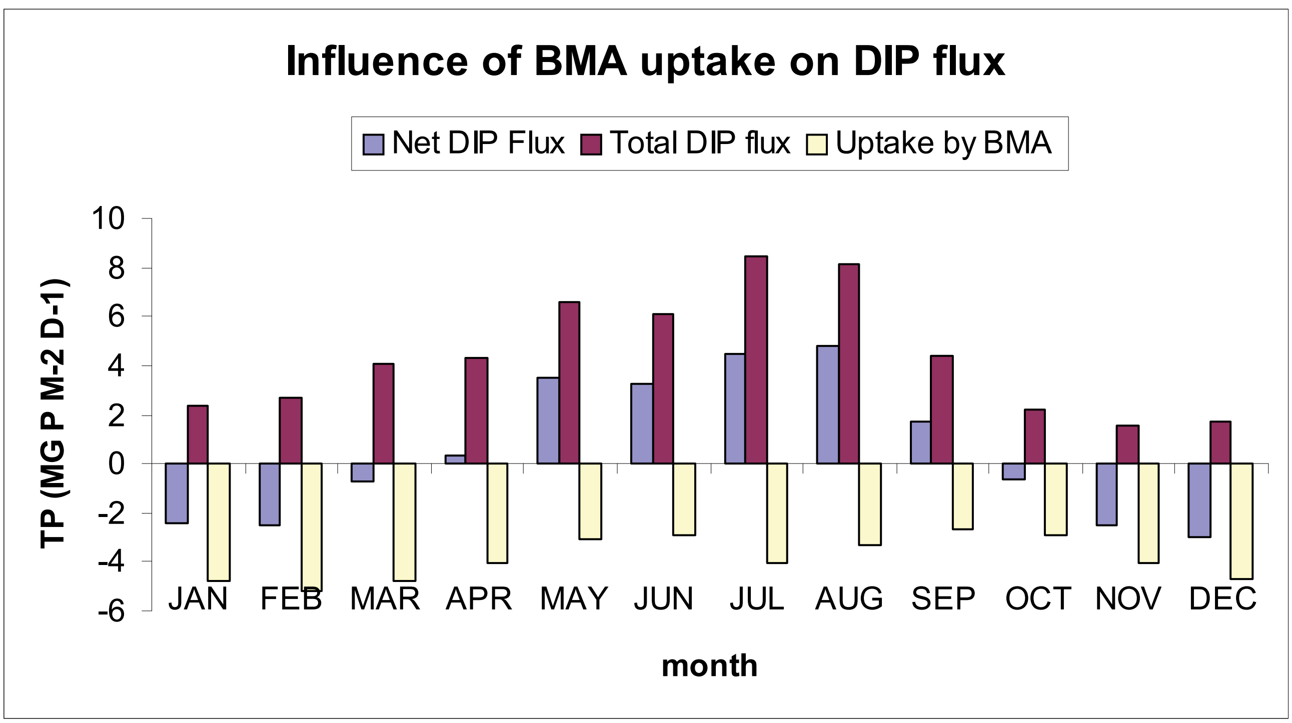


Figure VII.8. Monthly BMA uptake contribution to sediment flux nitrogen and phosphorus for Lynnhaven River (Positive values indicate leaving sediment, negative values indicate entering sediment) occurs over reasonably broad, seasonal time scales. In Chesapeake Bay, nutrients are removed from the water column during the spring phytoplankton bloom and are subsequently deposited in the sediments as detritus. A spring phytoplankton bloom has not been observed in the Lynnhaven River. However, the benthic algal bloom plays the role of the phytoplankton bloom in the deeper system. After BMA assimilates nutrients in winter and spring, nutrients stored in particulate form enter into the sediment. The microbial processes are responsible for nutrient regeneration in sediments, which are sensitive to temperature and oxygen conditions. In summer, nutrients are released from the sediment and support the water column primary production. Overall, mineralization of the organic matter stored in the sediments by BMA supports the summer maximum in the annual primary production.

Nixon et al. (1996) showed that the net transport of nutrients through estuaries to the continental shelf is inversely correlated with residence time of water in the system. Without BMA, the annual nutrient budget indicates that 70% of TN and 73% of TP, respectively, entering from land and atmosphere would be exported into Chesapeake Bay. These estimations of the efficiency of nitrogen and phosphorus transports through the Lynnhaven River fit well with the findings of Nixon et al. (1996), assuming that the residence time of water in the Lynnhaven River is 35 days (Figure VII.9). With the BMA, however, only 32% of TN and 26% of TP entering would be exported into Chesapeake Bay. This indicates that, as nutrients transported through the Lynnhaven River, more nutrients could be removed from the water column due to BMA uptake and subsequently through the buried and denitrified in sediments. This provides an alternative mechanism for the nutrient pathway in the shallow water system.

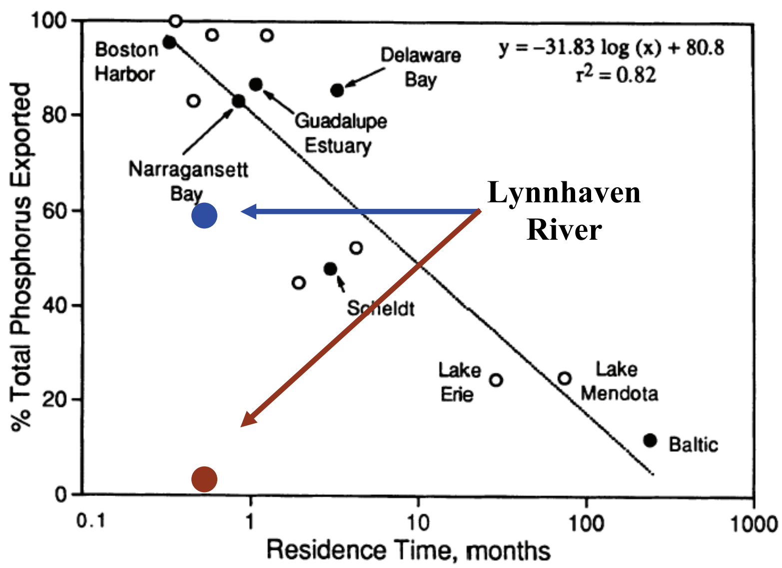


Figure VII.9. The percent of total nitrogen and phosphorus input from land and atmosphere that is exported from a sample of estuaries and lakes as a function of mean residence time in the system. Estuarine data marked as solid points; lake data marked as open circles (Nixon et al., 1996; modified); regression equations calculated by Nixon et al. (1996) (Blue dot shows results without BMA; red dot shows results with BMA)

CHAPTER VIII. DISCUSSION AND CONCLUSIONS

The Virginia Institute of Marine Science (VIMS) has successfully developed an integrated numerical modeling framework for the Lynnhaven system, a shallow water coastal bay in the City of Virginia Beach, Virginia. This framework combines a high-resolution 3D hydrodynamic model (UnTRIM) that provides the required transport for a water quality model (CE-QUAL-ICM) that, in turn, provides intra-tidal predictions of 23 water quality state variables. A suspended sediment transport model was also developed and incorporated into the modeling framework.

The hydrodynamic model UnTRIM is a state-of-the-art numerical model using an un-structured grid, which is able to follow complex shoreline geometry more closely than the traditional structured grid. This feature is particularly important for application to a shallow water body like the Lynnhaven system. The percent error in water volume due to any inaccuracy of the fitting of the model grid to the shoreline is amplified when the relative volume of deeper water decreases with decreasing overall depth. The UnTRIM model employs an Eulerian-Lagrangian approach and a semi-implicit numerical scheme to solve the momentum equation, thus eliminating the constraint of Courant's condition and allowing a much larger time step (of the order of 10 minutes) in numerical computation. This is advantageous over the hydrodynamic model using the Eulerian approach, since the model needs to run for an extended period, normally longer than the annual cycle, to supply transport to the water quality model for evaluating seasonal variations in water quality conditions. The selection of CE-QUAL-ICM was based on its history of application to the Chesapeake Bay system. However, it was later deemed necessary to modify it by including the benthic microalgae for the application to the Lynnhaven system.

Prior to the inception of the model development, all available historical Lynnhaven hydrodynamic and water quality data were amassed in a MicroSoft ACCESS database and analyzed for model calibration suitability and long-term trends. These data were collected from monitoring programs of the Virginia Department of Environmental Quality (VA-DEQ) and the Virginia Health Department, Shellfish Sanitation Division (VA-DSS), intensive surveys conducted by VIMS and Malcolm Pirnie Environmental Engineers, and tidal surveys conducted by the National Oceanic and Atmospheric Administration (NOAA).

A strategy of project-specific field surveys and laboratory experiments was devised based on which measurements would complement the existing historical data and be most useful to the model calibration and validation processes. These field surveys and experiments included the following:

- a hydrodynamic survey of synoptic measurements of times series of surface elevations plus currents and salinities in all Lynnhaven branches and outside the Inlet

- seasonal sediment flux measurements at the Inlet and in all branches to determine the spatial and seasonal variations of the fluxes from the water column to the sediment (and vice versa) of dissolved oxygen, ammonia, nitrate-nitrite, and phosphate

- sediment flux measurements of dissolved oxygen, ammonia, nitrate-nitrite and phosphate in the laboratory under controlled environments

- critical shear stress measurements at multiple sites in the basin to determine the spatial and seasonal variations to the erodibility of bottom sediments

- high-frequency time series measurements of chlorophyll-a, turbidity, Colored Dissolved Organic Matter (CDOM), and dissolved oxygen (DO) to evaluate water quality conditions with high temporal resolution

The analyses of sediment flux data of laboratory experiments clearly have indicated that benthic microalgae (BMA) play a significant role in the pelagic-benthic exchange process in the Lynnhaven system. The importance of the BMA process in shallow waters has been documented by other studies in various water bodies. Therefore, a microalgae model was developed based on the experimental data and literature formulations, and incorporated into the water quality model CE-QUAL-ICM. The BMA growth can reduce the rates, or even reverse the directions, of nutrient and oxygen exchanges between the water column and sediment, and significantly affect the nutrient budget of a water body. The photosynthesis of BMA would assimilate nutrients from the water column, store them in the sediment, and further bury them into deep sediment, or nitrify them in the case of nitrogen. Therefore, fewer nutrients would be exported out of the system. The VIMS model study indicated that 32% of total nitrogen and 26% of total phosphorus inputs into the Lynnhaven system were exported to the Chesapeake Bay.

The hydrodynamic portion of the integrated model was calibrated using historical datasets and NOAA tide predictions. The water quality portion of the model was calibrated using the 2006 data set collected by the VA-DEQ. The calibration parameters were adjusted, within their literature ranges, to achieve the best agreement between the model predictions and observation data.

Validation of the hydrodynamic model was made by comparing the 2005 simulation results with observations collected in VIMS hydrodynamic surveys of that year. Validation of the water quality model was conducted with a two-year model run simulating the water quality conditions of 2004-2005. The model predictions were compared with the monitoring data of VA-DEQ. Satisfactory agreements between the model predictions and field observations were achieved without altering any values of calibration parameters that were set in the calibration process.

The sediment transport model was developed utilizing the equilibrium critical shear stress defined at the interface between layers, and incorporated into the modeling framework. The values of some model parameters were derived from the critical shear stress measurements conducted specifically for the project, and the others were from literature reports. This model was calibrated by comparing its predictions of total suspended solids (TSS) with observations at the 16 Lynnhaven VA-DEQ stations during 2006 and validated by comparing the 2004-2005 model results with VA-DEQ observations for those years. Additionally, the validation compared model predictions with TSS values derived from VIMS high-frequency measurements of turbidity at 3 locations in 2005.

The model sensitivity analyses showed that 70% of total nitrogen and 73% of total phosphorus would have been exported if there were no BMA growth in the system. The CE-QUAL-ICM could not have successfully simulated the water quality conditions in the Lynnhaven system without the modification of including BMA. The BMA model developed by VIMS accurately predicted the oxygen and nutrient water-sediment flux measurements in the laboratory for various seasons and different locations. The addition of BMA model enabled the CE-QUAL-ICM to successfully simulate the water quality conditions in the Lynnhaven system.

There are two water quality problems identified through data analyses and model simulations. One is the degraded water clarity due to significant concentrations of suspended sediment. The other is the localized summertime low dissolved oxygen in headland areas. The modeling framework developed by VIMS is ready for its application in conducting scenario runs. The model should be used as a management tool to assess the effectiveness of alternative managing practices to mitigate these problems.

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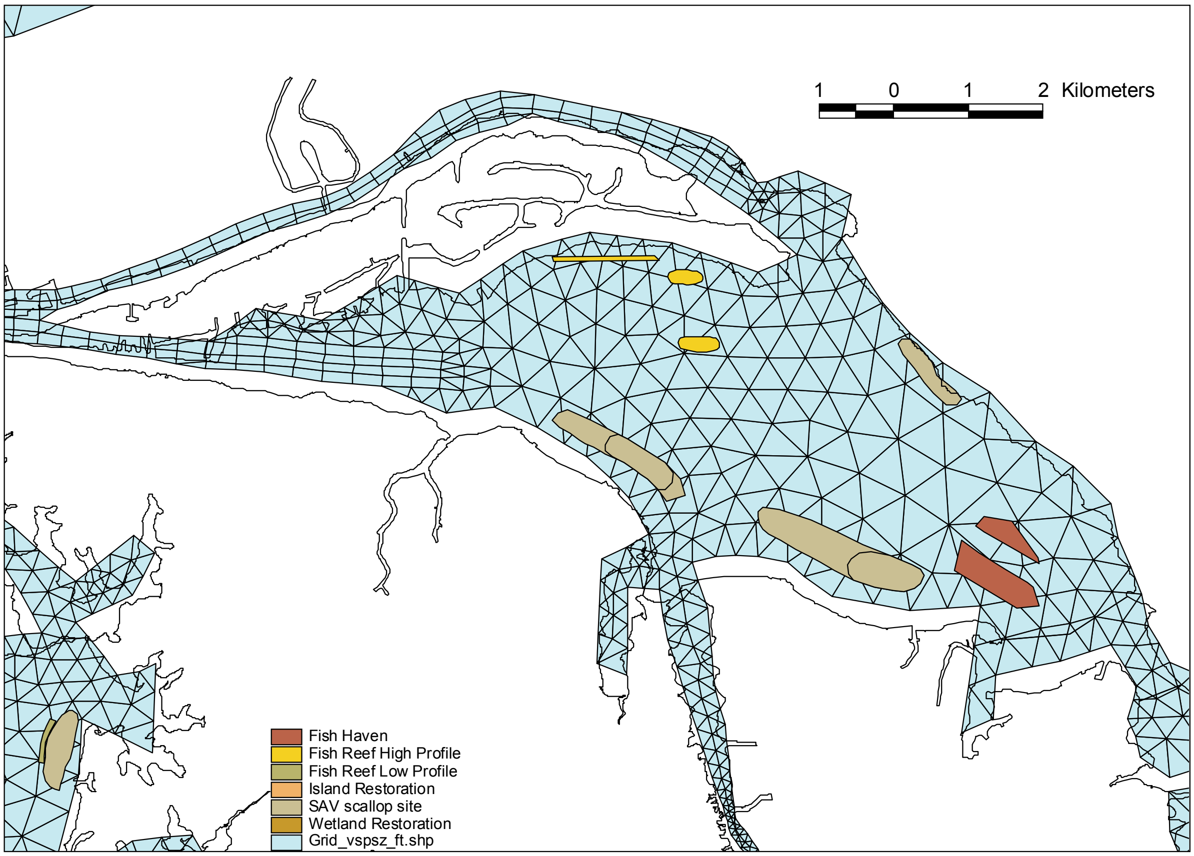
APPENDIX A

ATTACHMENT 2

NUMERICAL MODELING SCENARIO RUNS TO ASSESS TSS AND CHLOROPHYLL REDUCTIONS CAUSED BY ECOSYSTEM RESTORATION, LYNNHAVEN RIVER

Numerical Modeling Scenario Runs to Assess TSS and Chlorophyll Reductions Caused by Ecosystem Restoration, Lynnhaven River



Mac Sisson, Yuepeng Li, Harry Wang, and Albert Kuo

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I. Background and Introduction

The Lynnhaven River System, comprised of the Eastern and Western Branches, Long Creek, Broad Bay, and Linkhorn Bay, is located in Virginia Beach, Virginia, on the south shore of the Chesapeake Bay. It flows northerly and empties into the Chesapeake Bay about 10 miles east of Norfolk. Due to its narrow entrance and greater influence by the tide of the Bay than by river discharge, it is technically considered as a tidal inlet system. The watershed of the Lynnhaven River system is approximately 50 square miles in southeastern Virginia. The Lynnhaven River system was once a highly productive ecosystem, supporting a large oyster population and various shallow water organisms.

Like many Chesapeake Bay small coastal basins, however, the water quality conditions in Lynnhaven River system have deteriorated. A Reconnaissance Report issued by the U. S. Army Corps of Engineers (2002), cited a number of problems in water quality deterioration, siltation, sedimentation, and habitat management in the Lynnhaven. In 2005, the Army Corps of Engineers, along with the City of Virginia Beach, commissioned the Virginia Institute of Marine Science (VIMS) to develop a comprehensive three-dimensional hydrodynamics and water quality modeling capability for the Lynnhaven River System.

During that project, entitled "Development of 3D hydrodynamic and water quality models in the Lynnhaven River System", VIMS personnel developed an unstructured grid serving as the platform for executing its hydrodynamic model UnTRIM in the Lynnhaven. The modeling domain exterior boundary was selected with the intent to cover all significant receiving waters of the Lynnhaven (i.e., Western Branch, Eastern Branch, and Broad Bay and Linkhorn Bay). The model domain, along with the locations of DEQ stations at which the UnTRIM hydrodynamic and CE-QUAL-ICM water quality models were calibrated and validated, is shown in Figure 1.

The development of these models has provided the Corps and the City of Virginia Beach with a means of quantifying measures (e.g., nutrient load reductions) needed for the restoration of the system. It has also helped those involved with the restoration to identify and address the most troubling water quality "*hot spots*" of the system, such as Mill Dam Creek – Dey Cove and Thalia Creek – Thurston Branch.

Over this same period, the Army Corps has achieved a great deal of progress in its focus of restoring a viable critical mass of oyster reefs while implementing the most recent theories of successful reef construction. The next question is: "will this success of oyster population restoration have a positive feedback effect on the water quality of the Lynnhaven?"

As part of the ecosystem restoration of the Lynnhaven, the Corps is proposing to develop structure-based restorations of the following items: oyster reefs, scallops, SAV, and wetlands at selected locations spanning all 3 branches of the Lynnhaven. The locations of these proposed restoration sites are shown in the map in Figure 2. On this figure, the habitat types are color-coded with essential fish habitats (EFHs) shown in blue, SAV/Scallop sites shown in orange, and wetland restoration sites shown in green.

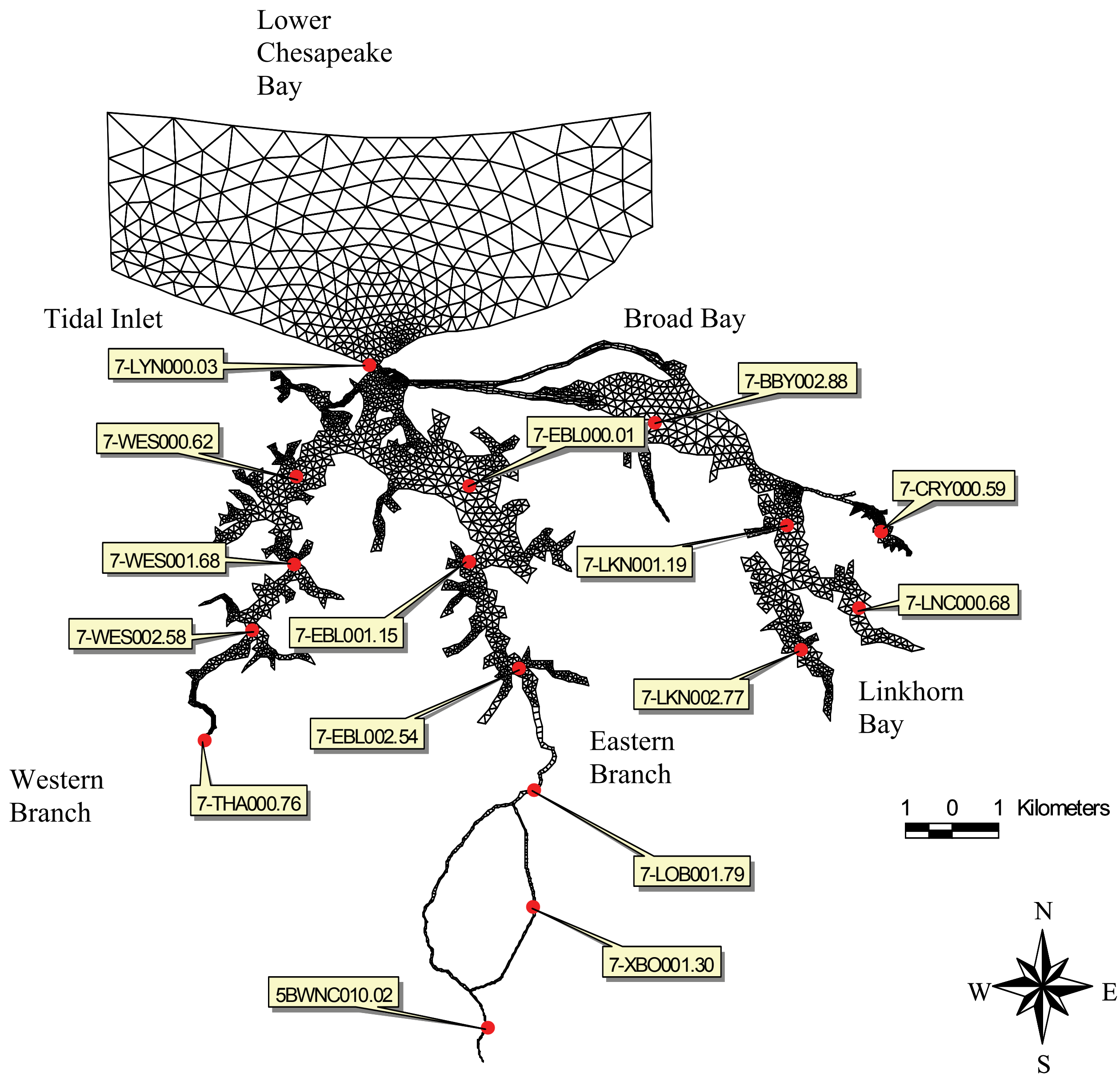

Figure 1. The unstructured grid for Lynnhaven River System and the locations of the 16 Lynnhaven stations monitored by the Virginia Department of Environmental Quality.

An important part of the restoration planning effort is to determine a metric for which the benefits of restoration site construction can be assessed. It is known that established restoration sites will remove total suspended solids (TSS) from the water column, including the volatilized portion of TSS (i.e., organic matters such as phytoplankton). Additionally, it can be shown that chlorophyll uptake rates at restoration sites are correlated with secondary productivity (Schulte, 2010). Given that the Army Corps of Engineers' plan for restoring SAV, scallops, and oyster reefs has a large potential to reduce total suspended solids (TSS) and chlorophyll levels, measurements of these reductions over the temporal and spatial scales that are present may not be feasible. In contrast, a calibrated model that has been properly formulated is capable of addressing "*what-if*" questions and quantifying the impact in a Lynnhaven basin-wide scale. This justifies the use of hydrodynamic and water quality models to perform the task if both the TSS reduction and the secondary production rates can be estimated (e.g., in units of kg/acre/month), and if the acreages and locations of each restoration habitat type are known, it is possible to incorporate these rates into the computations made by the hydrodynamic and water quality models. This may be done by adding sink terms into the UnTRIM hydrodynamic model that represent TSS removal and sink terms into the CE-QUAL-ICM water quality model that represent chlorophyll-a removal.

VIMS has worked with the Army Corps of Engineers to develop a methodology to assess the impact of proposed restoration plans, including SAV, scallops, and fish reefs (including oyster reefs) on the TSS and chlorophyll levels near these restoration sites.

II. Methodology

II-1. Modeling Phytoplankton Kinetics and TSS concentration

The kinetic equations for algae are:

$$\frac{\delta B_x}{\delta t} = \left(P_x - BM_x - PR_x\right) B_x - WS_x \frac{\delta B_x}{\delta z}$$

where:
B_x = algal biomass (g C m^{-3})
t = time
P_x, BM_x, PR_x = production, basal metabolism, and predation rates of algae, respectively (day^{-1})
z = the vertical coordinate and WS_x = algal settling velocity (m day^{-1}).
The subscript, **x**, is used to denote three algal groups: **f** for dinoflagellates, **d** for diatoms, and **g** for greens.

(a) Growth (Production)

Algal growth depends on nutrient availability, ambient light, and temperature. The effects of these processes are considered to be multiplicative as follows:

$$P_x = PM_x \cdot f(N) \cdot f(I) \cdot f(T)$$

where:
PM_x = maximum production rate under optimum conditions (day^{-1})
f(N), f(I), f(T) = effect of sub-optimal nutrient, light intensity, and temperature, respectively.

Effect of nutrients on growth

$$f(N) = \text{minimum}\left\{\frac{NH4 + NO3}{KHN_x + NH4 + NO3}, \frac{PO4d}{KHP_x + PO4d}, \frac{SAd}{KHS_d + SAd}\right\}$$

where:
NH4, NO3 = ammonium and nitrate nitrogen concentrations, respectively (g N m^{-3})
PO4d = dissolved phosphate concentration (g P m^{-3})
SAd = dissolved silica concentration (g Si m^{-3})
KHN_x = half-saturation constant for algal nitrogen uptake (g N m^{-3})
KHP_x = half-saturation constant for algal phosphorus uptake (g P m^{-3})
KHS_d = half-saturation constant for silica uptake by diatoms (g Si m^{-3})

Effects of light on growth

$$f(I) = \frac{1}{KESS \cdot \Delta z} \ln\left(\frac{IH_x + I_{TOP}}{IH_x + I_{BOT}}\right)$$

Where:

$$I_{TOP} = I_{SFC}\, e^{-KESS \cdot Z_T}$$

$$I_{BOT} = I_{SFC}\, e^{-KESS(Z_T + \Delta z)}$$

$$I_{SFC} = \frac{I_{TOTAL}}{FD} \frac{\pi}{2} \sin\left(\pi \frac{t_D - t_U}{FD}\right)$$

$$KESS = KE_B + KE_{CHL} \cdot \sum_x \frac{B_x}{CCHL_x} + KE_{TSS} \cdot TSS$$

KESS = light extinction coefficient (m^{-1})
Z_T = distance from surface to the top of model layer (m)
IH_x = half-saturation light intensity for algal growth (langleys day^{-1})

I_{TOP}, I_{BOT} = light intensities at the top and bottom of model layer, respectively (langleys day^{-1})
I_{SFC} = light intensity at surface at time t (langley day^{-1})
I_{TOTAL} = total daily light intensity at surface (langley day^{-1})
FD = fractional daylength
t_D = time of day (in fractional days)
t_U = time of sunrise (in fractional days)
KE_B = background light extinction coefficient (m^{-1})
KE_{CHL} = light extinction coefficient for chlorophyll a (m^{-1} per mg CHL m^{-3})
$CCHL_x$ = carbon-to-chlorophyll ratio in algae (g C per g CHL)
KE_{TSS} = light extinction coefficient due to TSS (m^{-1} per g m^{-3})

The effect of light on algal growth was simulated using the Steele function, which always results in photo-inhibition at the surface under high light intensity. To relieve photo-inhibition, a Monod-type function with half-saturation light intensity is used in the present model. The present model also has the total suspended solids state variable, the light extinction coefficient is expressed to consist of three terms: background extinction, algal self-shading and extinction due to total suspended solids.

Effect of temperature on growth

$$f(T) = \exp\left(-KTG1_x [T - TM_x]^2\right) \quad \text{when } T \leq TM_x$$
$$= \exp\left(-KTG2_x [TM_x - T]^2\right) \quad \text{when } T > TM_x$$

where:
TM_x = optimal temperature for algal growth (°C)
$KTG1_x$ = effect of temperature below TM_x on algal growth (°C^{-2})
$KTG2_x$ = effect of temperature above TM_x on algal growth (°C^{-2}).

(b) Basal Metabolism

Basal metabolism is commonly considered to be an exponentially increasing function of temperature:

$$BM_x = BMR_x \cdot \exp\left(KTB_x [T - TR_x]\right)$$

where:
BMR_x = metabolic rate at reference temperature TR_x (day^{-1})
KTB_x = effect of temperature on metabolism ($C^{\circ -1}$)
TR_x = reference temperature for metabolism (C°)

(c) Predation

The predation formulation is identical to basal metabolism. The difference in predation and basal metabolism lies in the distribution of the end products of these processes.

$PR_x = BPR_x \exp(KTB_x (T - TR_x))$
BPR_x = predation rate at TR_x (day $^{-1}$)
KTB_x = effect of temperature on predation ($C^{\circ -1}$)
TR_x = reference temperature for predation (C°)

(d) Settling velocity

Reported algal settling rates typically range from 0.1 to 5 m d^{-1} (Bienfang et al., 1982; Riebesell, 1989; Waite et al., 1992). In part, this variation is a function of physical factors related to algal size, shape, and density (Hutchinson, 1967). The variability also reflects regulation of algal buoyancy as a function of nutritional status (Bienfang et al., 1982; Richardson and Cullen, 1995) and light (Waite et al., 1992). The algal settling rate employed in the model represents the total effect of all physiological and behavioral processes that result in the downward transport of phytoplankton. The settling rate employed, from 0.1 m d^{-1} to 0.9 m d^{-1}, was used in the model to optimize agreement of predicted and observed algae.

The calculation of TSS was based on the Sanford (2008) formulation of the sediment transport model described in Section III-4 of the report entitled: "Development of Hydrodynamic and Water Quality Models for the Lynnhaven River System" submitted to the Army Corps of Engineers, Norfolk District in March, 2009.

II-2. The Implementation of Habitat Restoration Plans

For this project, a total of 4 scenarios were executed in order to determine the impact of the removal of TSS and chlorophyll on two habitat restoration plans. These plans are known as "Plan A" (also the "Selected Plan") and "Plan B". Descriptions of the 4 scenarios are as follows:

- Scenario 1 – execute UnTRIM to assess the impact of TSS removal caused by "Plan A"
- Scenario 2 – execute UnTRIM to assess the impact of TSS removal caused by "Plan B"
- Scenario 3 – execute ICM to assess the impact of chlorophyll removal caused by "Plan A"
- Scenario 4 – execute ICM to assess the impact of chlorophyll removal caused by "Plan B"

Tables 1 and 2 show the acreages associated with each restoration site (locations for which are shown in Figure 2) for "Plan A" and "Plan B", respectively. Additionally, estimates of both the TSS removal rates (kg (TSS removed)/acre/month) and secondary production rates (kg (ash-free dry weight of animal biomass)/acre/month) are listed in Table 3 for all 3 types of habitat restoration. As these uptake rates vary seasonally, estimates are provided for each month of the year.

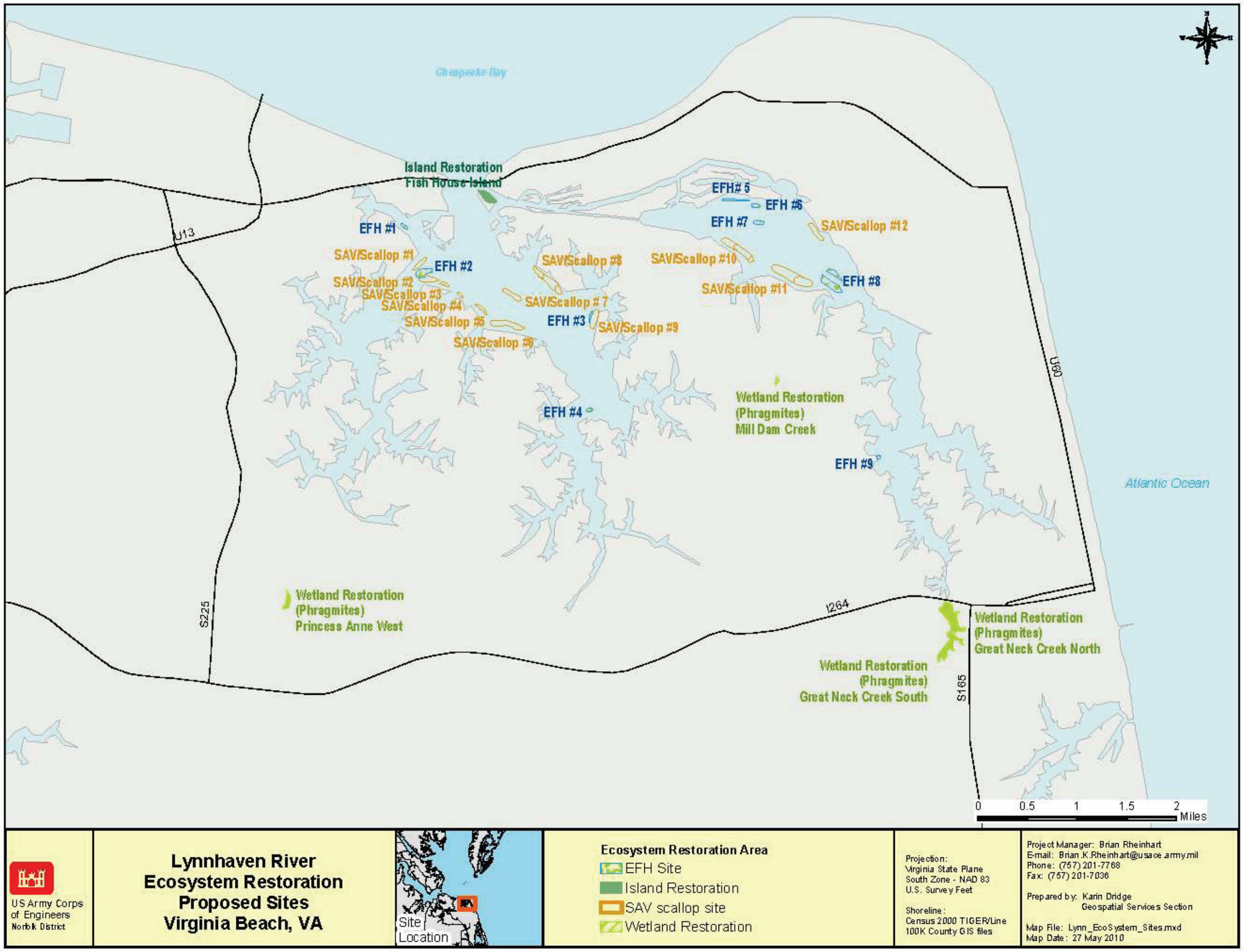

Figure 2. Lynnhaven River Ecosystem Restoration Proposed Sites (Courtesy, Norfolk District COE)

Table 1. Site names (locations of which are shown in Figure 2) and acreages for each site of the 3 habitat types for "Plan A". (source: Norfolk District COE).

Restoration Type	DESCRIPTION	Site_Name on Map	Min_Max	ACRES
SAV	Western Branch Lynn 1	SAV/Scallop #1	Max	3.985
SAV	Western Branch Lynn 2	SAV/Scallop #2	Max	6.672
SAV	Eastern Branch Lynn 1	SAV/Scallop #3	Max	1.393
SAV	Eastern Branch Lynn 2	SAV/Scallop #4	Max	1.049
SAV	Eastern Branch Lynn 3	SAV/Scallop #5	Max	2.351
SAV	Eastern Branch Lynn 4	SAV/Scallop #6	Max	10.859
SAV	Eastern Branch Lynn 5	SAV/Scallop #7	Max	5.248
SAV	Eastern Branch Lynn 6	SAV/Scallop #8	Max	13.618
SAV	Brock Cove SAV	SAV/Scallop #9	Max	6.935
SAV	Broad Bay 1	SAV/Scallop #10	Max	13.655
SAV	Broad Bay 3	SAV/Scallop #11	Max	22.424
SAV	Broad Bay 2	SAV/Scallop #12	Max	5.574
			Total SAV Acreage	93.763
Scallop	Eastern Branch Lynn 6	SAV/Scallop #8	Min	5.959
Scallop	Broad Bay 1	SAV/Scallop #10	Min	6.935
Scallop	Broad Bay 3	SAV/Scallop #11	Min	8.695
			Total Scallop Acreage	21.589
Fish Reef Low Profile	Pleasure House Creek	EFH #1		1.214
Fish Reef	Hill Point	EFH #2		6.865
Fish Reef Low Profile	Brock Cove	EFH #3		0.964
Fish Reef Low Profile	Brown Cove	EFH #4		1.525
Fish Reef High Profile	Broad Bay north	EFH #5		1.796
Fish Reef High Profile	Broad Bay north	EFH #6		1.794
Fish Reef High Profile	Broad Bay center	EFH #7		2.265
Fish Reef	Broad Bay Cove	EFH #8		14.306
Fish Reef High Profile	Linkhorn Bay	EFH #9		0.688
			Total Fish Reef Acreage	31.417

Table 2. Site names (locations of which are shown in Figure 2) and acreages for each site of the 3 habitat types for "Plan B" (source: Norfolk District COE).

Rest_Type	DESC	Site_Name on Map	Min_Max	ACRES
SAV	Western Branch Lynn 1	SAV/Scallop #1	Max	3.985
SAV	Western Branch Lynn 2	SAV/Scallop #2	Max	6.672
SAV	Eastern Branch Lynn 1	SAV/Scallop #3	Max	1.393
SAV	Eastern Branch Lynn 2	SAV/Scallop #4	Max	1.049
SAV	Eastern Branch Lynn 3	SAV/Scallop #5	Max	2.351
SAV	Eastern Branch Lynn 4	SAV/Scallop #6	Max	10.859
SAV	Eastern Branch Lynn 5	SAV/Scallop #7	Max	5.248
SAV	Eastern Branch Lynn 6	SAV/Scallop #8	Max	13.618
SAV	Brock Cove SAV	SAV/Scallop #9	Max	6.935
SAV	Broad Bay 1	SAV/Scallop #10	Max	13.655
SAV	Broad Bay 3	SAV/Scallop #11	Max	22.424
SAV	Broad Bay 2	SAV/Scallop #12	Max	5.574
			Total SAV Acreage	93.763
Scallop	Eastern Branch Lynn 6	SAV/Scallop #8	Min	5.959
Scallop	Broad Bay 1	SAV/Scallop #10	Min	6.935
Scallop	Broad Bay 3	SAV/Scallop #11	Min	8.695
			Total Scallop Acreage	21.589
~~Fish Reef Low Profile~~	~~Pleasure House Creek~~	~~EFH #1~~		0
~~Fish Reef~~	~~Hill Point~~	~~EFH #2~~		0
~~Fish Reef Low Profile~~	~~Brock Cove~~	~~EFH #3~~		0
~~Fish Reef Low Profile~~	~~Brown Cove~~	~~EFH #4~~		0
Fish Reef High Profile	Broad Bay north	EFH #5		1.796
Fish Reef High Profile	Broad Bay north	EFH #6		1.794
Fish Reef High Profile	Broad Bay center	EFH #7		2.265
Fish Reef	Broad Bay Cove	EFH #8		14.306
Fish Reef High Profile	Linkhorn Bay	EFH #9		0.688
			Total Fish Reef Acreage	20.849

Table 3. Estimates of TSS reduction rates and secondary production numbers for each habitat type in the Lynnhaven restoration (source: Norfolk District COE).

	Habitat Type							
Time (mos.)	SAV		Scallops		Fish Reefs (including oyster reefs)			
					Low Relief Reefs		High Relief Reefs	
	TSS	Secondary Production	TSS	Secondary Production	TSS	Secondary Production	TSS	Secondary Production
1 – January	6.07	80.94	22.09	20.23	446.60	72.50	552.65	89.71
2 – February	6.07	80.94	22.09	20.23	446.60	72.50	552.65	89.71
3 – March	12.14	161.87	44.19	40.46	893.06	144.99	1105.14	179.42
4 – April	18.21	242.81	66.28	60.70	1339.79	217.49	1657.95	269.13
5 – May	30.35	323.75	118.06	108.16	2232.98	362.48	2763.24	448.55
6 – June	54.63	678.33	185.13	169.62	3742.07	629.26	4630.70	778.69
7 – July	54.63	728.64	198.86	182.19	4019.36	652.46	4973.84	807.39
8 – August	54.63	728.64	198.86	182.19	4019.36	652.46	4973.84	807.39
9 – September	30.35	323.75	118.06	108.16	2232.98	362.48	2763.24	448.55
10 – October	18.21	242.81	66.28	60.70	1339.79	217.49	1657.95	269.13
11 – November	12.14	161.87	44.19	40.46	977.37	144.99	1209.46	179.42
12 – December	6.07	80.94	22.09	20.23	446.60	72.50	552.65	89.71
Total (annually)	**607**	**3835.29**	**1106.18**	**1013.33**	**22136.5**	**3601.55**	**27393.3**	**4456.82**
Avg. (monthly)	**50.58**	**319.61**	**92.18**	**84.44**	**1844.71**	**300.13**	**2282.77**	**371.40**

Notes: 1) All secondary production numbers are in ash-free dry weight of animal biomass and in kilograms/acre/month
2) All TSS reduction numbers are in kilograms of TSS removed/acre/month
3) The literature suggests a 10% trophic level transfer from primary to secondary level
4) For modeling purposes, one assumption is that there is 1% chlorophyll A per unit weight of plankton
5) The dry weight conversion of phytoplankton used is 10% of the wet weight.

There were 3 important setup steps that were required prior to performing these scenario runs:

Step 1 - Enhancements of model codes for the UnTRIM hydrodynamic model and the CE-QUAL-ICM water quality model were made, respectively, by adding sink terms to the equations computing the TSS and phytoplankton (in terms of carbon in biomass) concentrations. Sink term were added to the equation for the bottom layer only. Since most of the restoration sites are in shallow waters, the bottom layer is the entire water column in most affected model cells.

$(C'*\acute{V}' - C*V)/\Delta t$ = advection terms + diffusion terms + growth & death terms (in case of phytoplankton carbon) – Sink term due to restored habitats
′

Where C' and C are the concentrations (in gram per cubic meter) at new and old time steps respectively; V' an V are the volume (in cubic meters) of the grid cell at new and old time steps, respectively: Δt is the time interval, in second, between the computation time steps. The first three groups of terms on the right hand side of the above equation exist in the original model formulation. The last term was computed with values provided by the Corps as shown in Table 3. For TSS reduction, the sink term in grams per second is:

$$\text{Sink term} = (1000*R)*A / (30*86400)$$

Where R is the TSS reduction rate in kg/acre/month, and varies monthly as shown in Table 3, and A is the area, in acres, of the restored habitat in the model computation cell.

For the chlorophyll reduction, the sink term, in terms of grams of carbon per second is

$$\text{Sink term} = (1000*SP/TE)*A/ (30*86400)$$

Where SP is the secondary production provided in Table 3, and TE is the tropic transfer efficiency, assumed to be 0.1 (10%, note in Table 3). The computed phytoplankton biomass is transferred to chlorophyll assuming a carbon to chlorophyll ratio of 60, which was determined in the calibration of the Lynnhaven River water quality model.

Step 2 - Using GIS technology, the physical extents of all restoration sites were superimposed onto the UnTRIM model grid to numerically characterize each relevant model cell.

The exact locations and spatial extents of the restoration sites could then be recorded. By intersecting the restoration site GIS layer with the VIMS model grid, we were able to identify exactly which cells among the more than 5,000 cells of the UnTRIM unstructured grid for the Lynnhaven River (Figure 1) fall entirely or partially within the area of restoration sites and to determine the acreage of restoration habitat in each of these cells.

Step 3 – Perform a year-long base case run for both hydrodynamic and water quality models using the calibration year of 2006. For the hydrodynamic base case execution, TSS concentrations at all 16 Lynnhaven VA-DEQ monitoring stations are saved throughout calendar year 2006. For the water quality base case execution, chlorophyll concentrations at all 16 Lynnhaven VA-DEQ monitoring stations are saved throughout calendar year 2006. These base case results are then later compared to the results from Scenario Runs 1-4 to assess the impacts caused by the restoration sites.

III. Scenario run results

III-1. TSS removal

The prediction of TSS by the Lynnhaven UnTRIM hydrodynamic model used calendar year 2006 for its calibration. This calibration occurred by comparing TSS observations against model predictions at the 16 Lynnhaven River VA-DEQ stations shown in Figure 1. These comparisons throughout 2006 are shown for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches, respectively, in Figures 3 through 5. This calibration simulation of the model, not invoking any TSS removal due to habitat construction, was then used as the “base case” to compare to Scenarios 1 and 2 to assess TSS removal.

III-1-1. TSS removal resulting from “Plan A” habitat restoration – Scenario 1

The UnTRIM hydrodynamic model was used to simulate Scenarios 1 and 2 for calendar year 2006 for comparison to the base case. The impact of “Plan A” is the difference (Plan A minus base case) for the VA-DEQ Lynnhaven stations grouped branch-by-branch (Figures 6 through 8). This difference, in effect, represents the removal of TSS due to the habitat restoration modeled for “Plan A”. One way to assess the TSS removal is to compare the average of this difference over the entire year for each Lynnhaven VA-DEQ station with the average predicted base case value for that station, as shown in Tables 4 through 6.

Tables 4 and 5 display the average predicted base case TSS at VA-DEQ stations in the Western and Eastern Branches of the Lynnhaven and it can be seen that these range from 11 to 22 mg/l. The removal of TSS resulting from the Plan A restoration ranges from 0.3 to 8.0 mg/l at stations in these 2 branches, and the percentage of TSS removal ranges up to 44% in the Lower Eastern Branch. In general, the reduction percentage decreases moving upstream.

In contrast, Table 6 shows average predicted base case TSS values in the Broad Bay/Linkhorn Bay Branch as much lower, ranging from 6.1 to 9.5 mg/l. TSS reductions resulting from the Plan A restoration remain high, however, ranging from 3.0 to 7.1 mg/l. Consequently, in this branch, the percentage of reduction is quite high, ranging from 46% to 74%, and is generally increasing moving downstream.

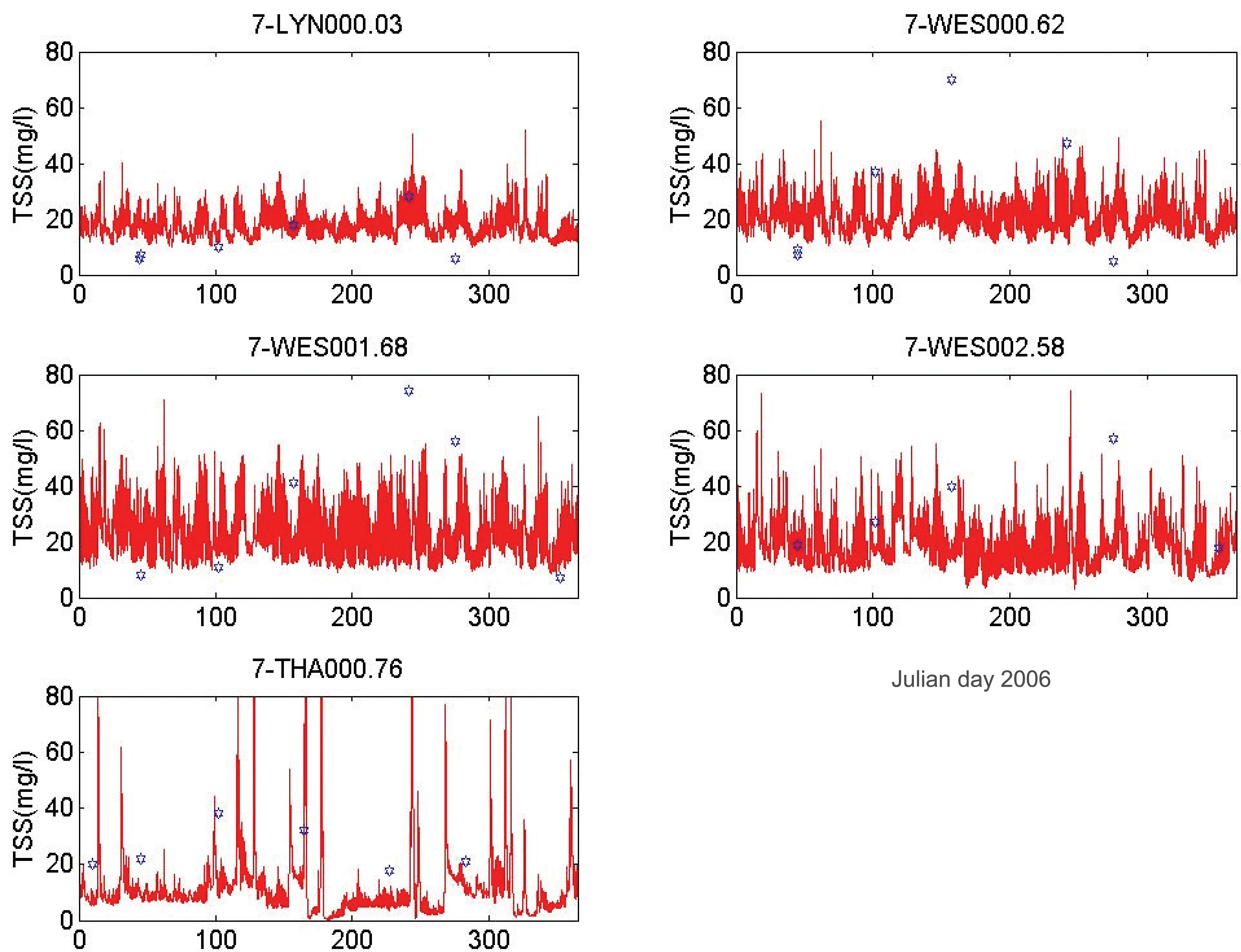

Figure 3. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Western Branch stations for 2006.

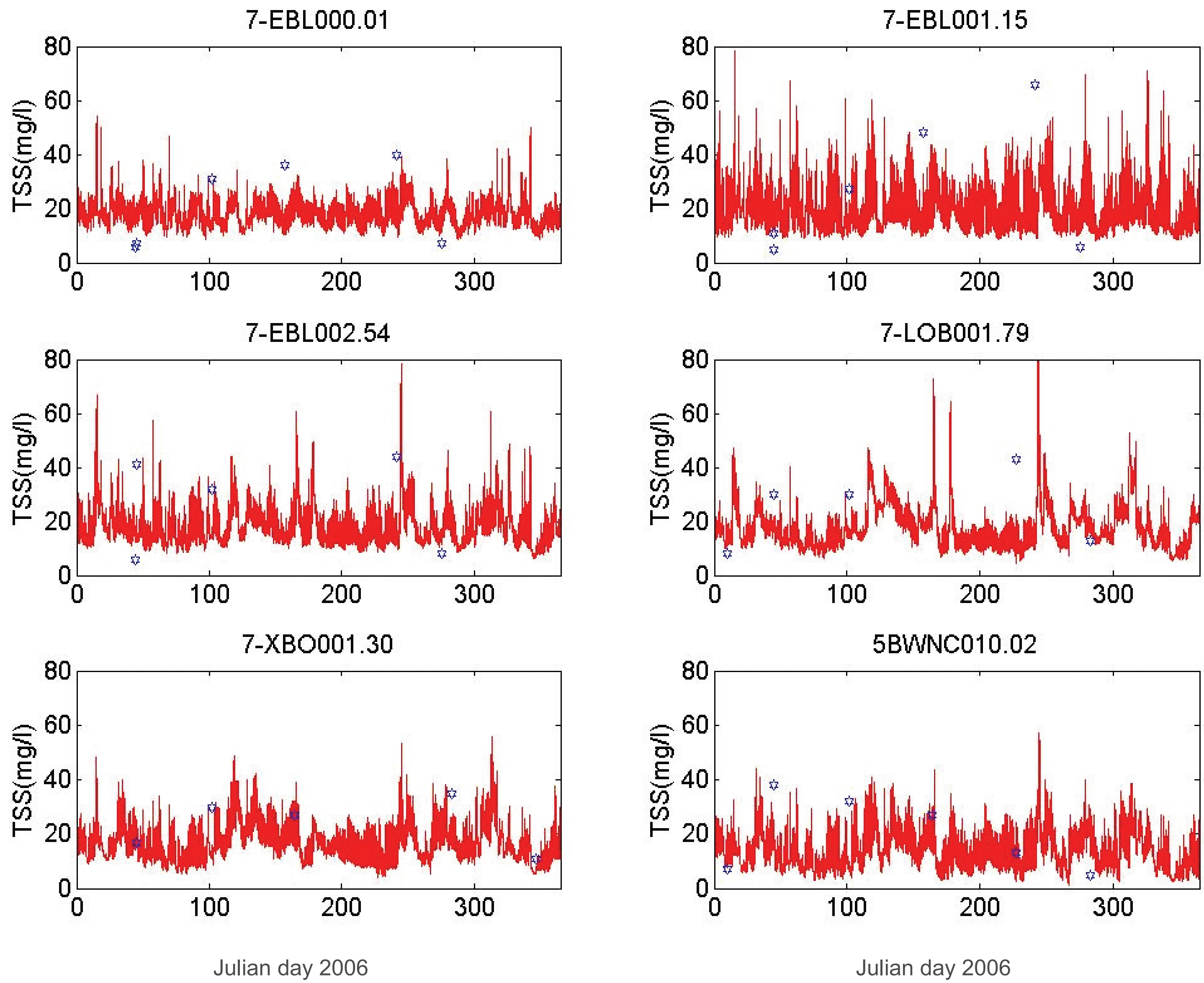

Figure 4. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Eastern Branch stations for 2006.

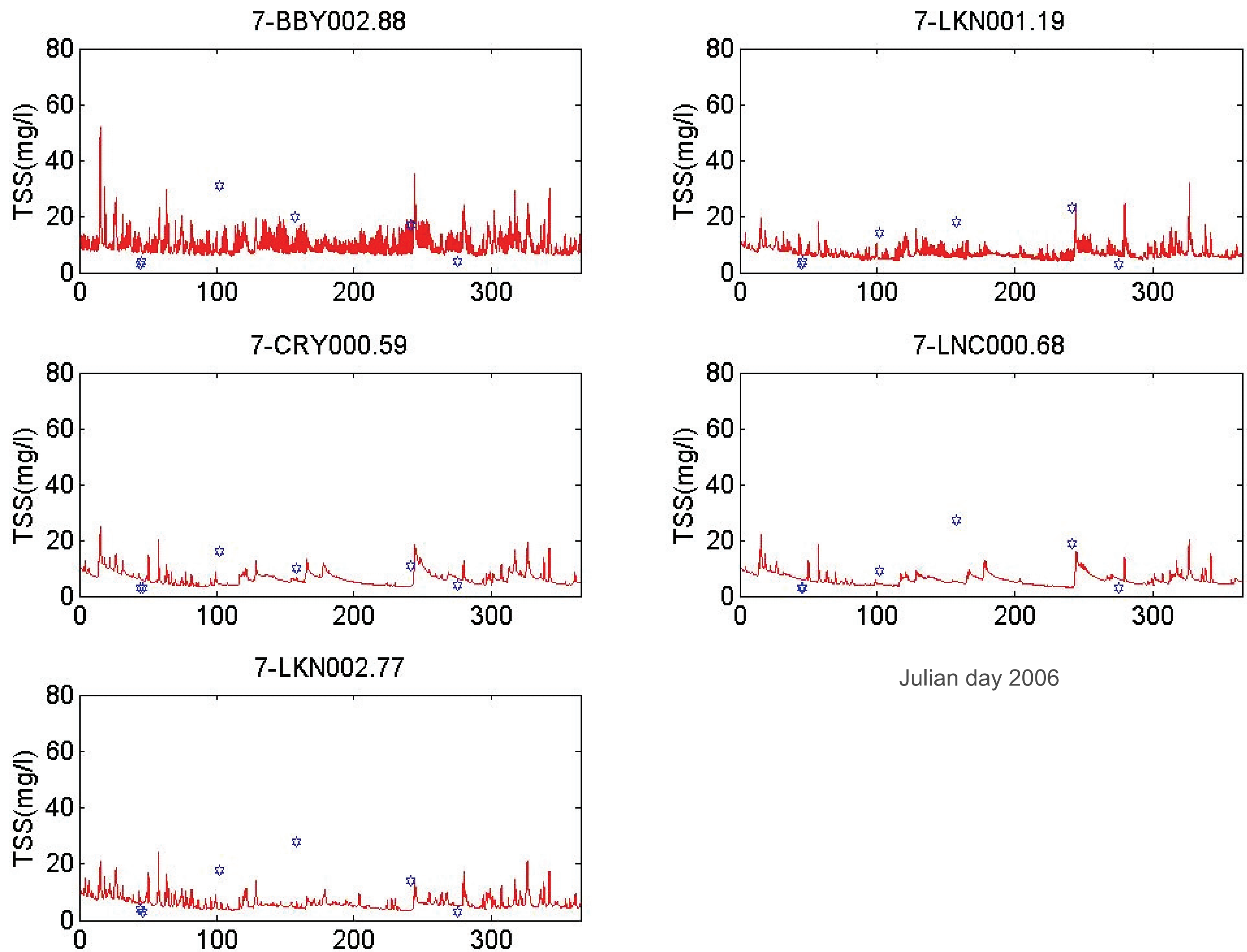

Figure 5. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Broad Bay/Linkhorn Bay Branch stations for 2006.

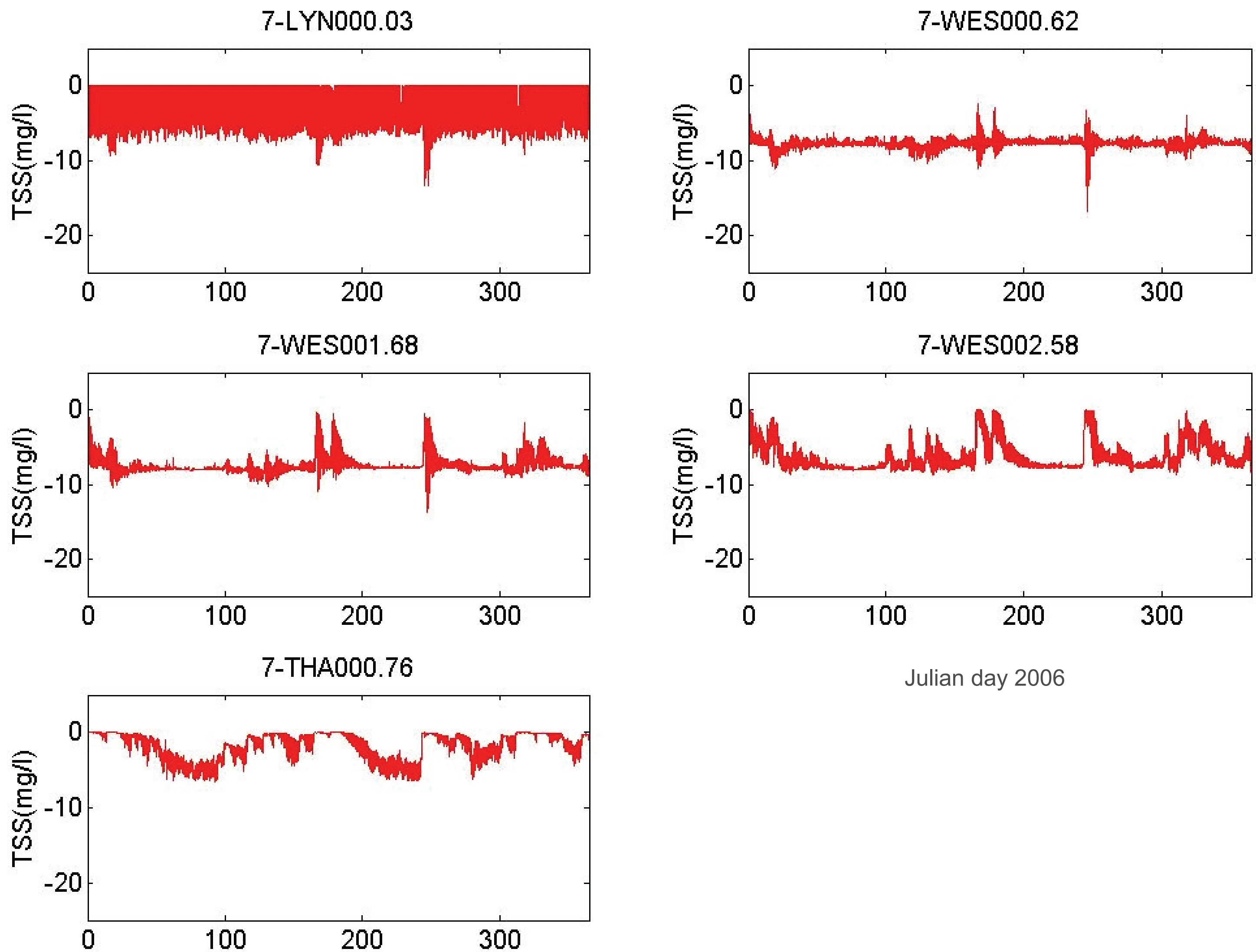

Figure 6. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

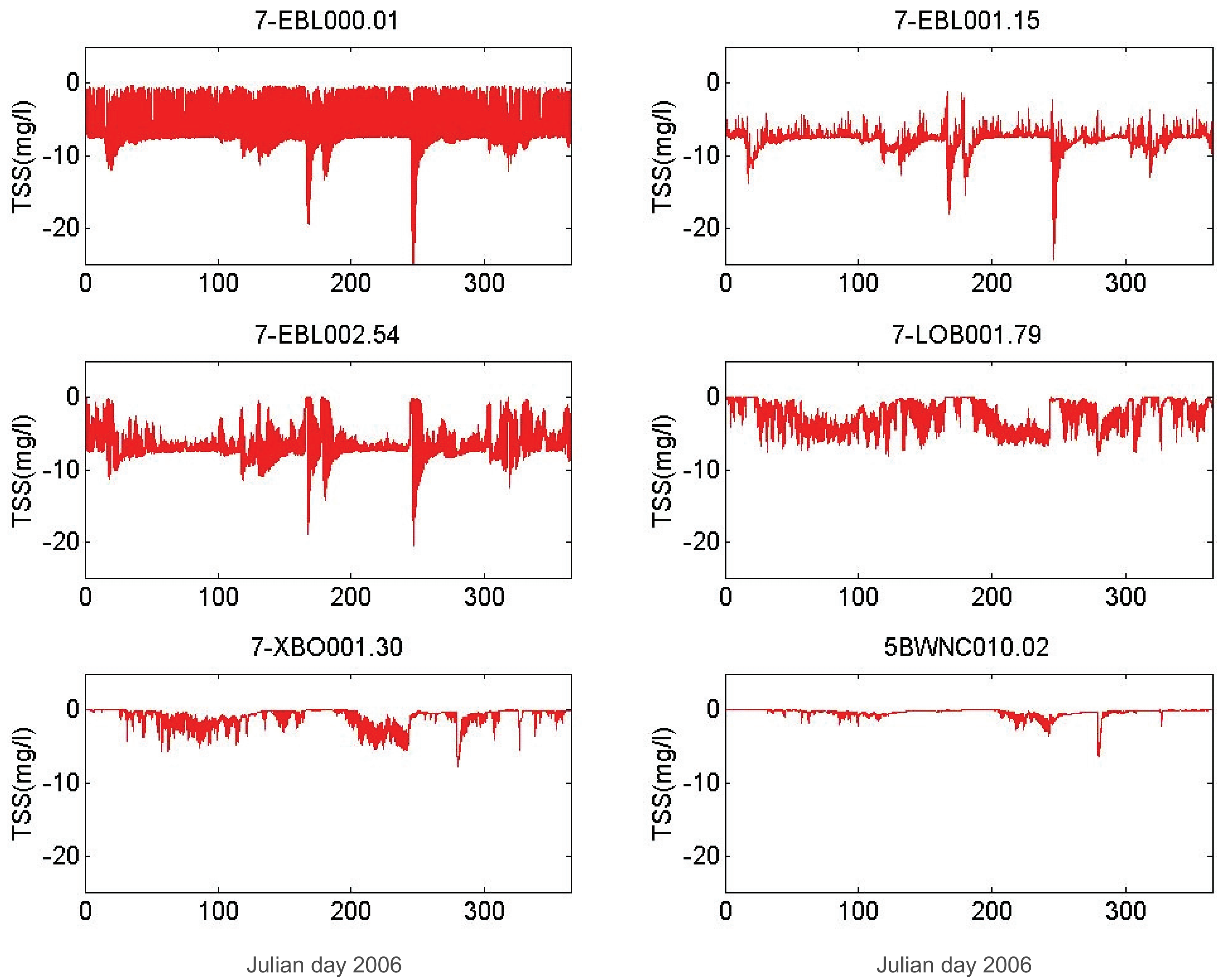

Figure 7. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

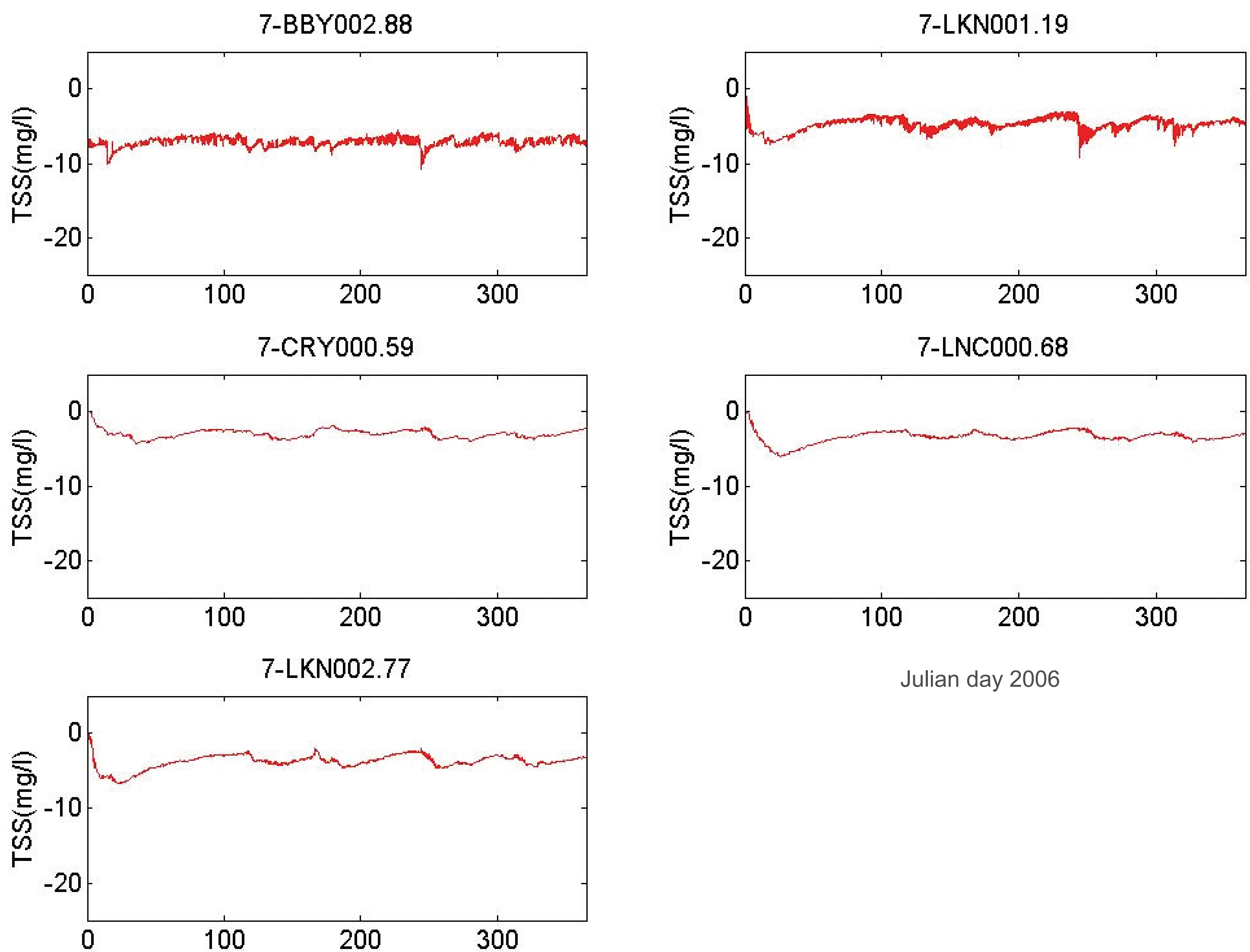

Figure 8. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

Table 4. The average TSS reduction at Lynnhaven River Western Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-LYN000.03	18	3.1 (BC*)	17%
7-WES000.62	21	7.8	38%
7-WES001.68	22	7.3	33%
7-WES002.58	18	6.1	36%
7-THA000.76	11	1.8	16%

BC* - Suspected impact from fixed boundary condition in the Bay

Table 5. The average TSS reduction at Lynnhaven River Eastern Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-EBL000.01	18	5.9	33%
7-EBL001.15	18	8.0	44%
7-EBL002.54	18	6.4	36%
7-LOB001.79	18	2.4	14%
7-XBO001.30	16	1.0	6.1%
5BWNC010.02	14	0.3	2.5%

Table 6. The average TSS reduction at Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-BBY002.88	9.5	7.1	74%
7-LKN001.19	7.0	4.8	68%
7-CRY000.59	6.5	3.0	46%
7-LNC000.68	6.1	3.4	55%
7-LKN002.77	6.3	3.8	60%

III-1-2. TSS removal resulting from "Plan B" habitat restoration – Scenario 2

First, it should be noted that Plan B differs from Plan A only in that the former excludes the 4 low profile fish reefs (EFH#1, EFH#2, EFH#3, and EFH#4) listed in Tables 1 and 2. These sites are all located near the Inlet and the Lower Eastern Branch. The impact of the "Plan B" restoration on TSS removal is shown by the differences of the time series (Plan B minus base case) plotted from 2006 simulations. These differences are plotted for all 16 VA-DEQ Lynnhaven stations and are grouped branch-by-branch in Figures 9, 10, and 11, respectively, for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches.

As was done for the assessment of the Scenario 1 (i.e., "Plan A") results, part of the assessment of the TSS removal impact of Scenario 2 (i.e., "Plan B") is to compare the average of this difference over the entire year for each Lynnhaven VA-DEQ station with the average predicted base case value for that station, as shown in Tables 7 through 9.

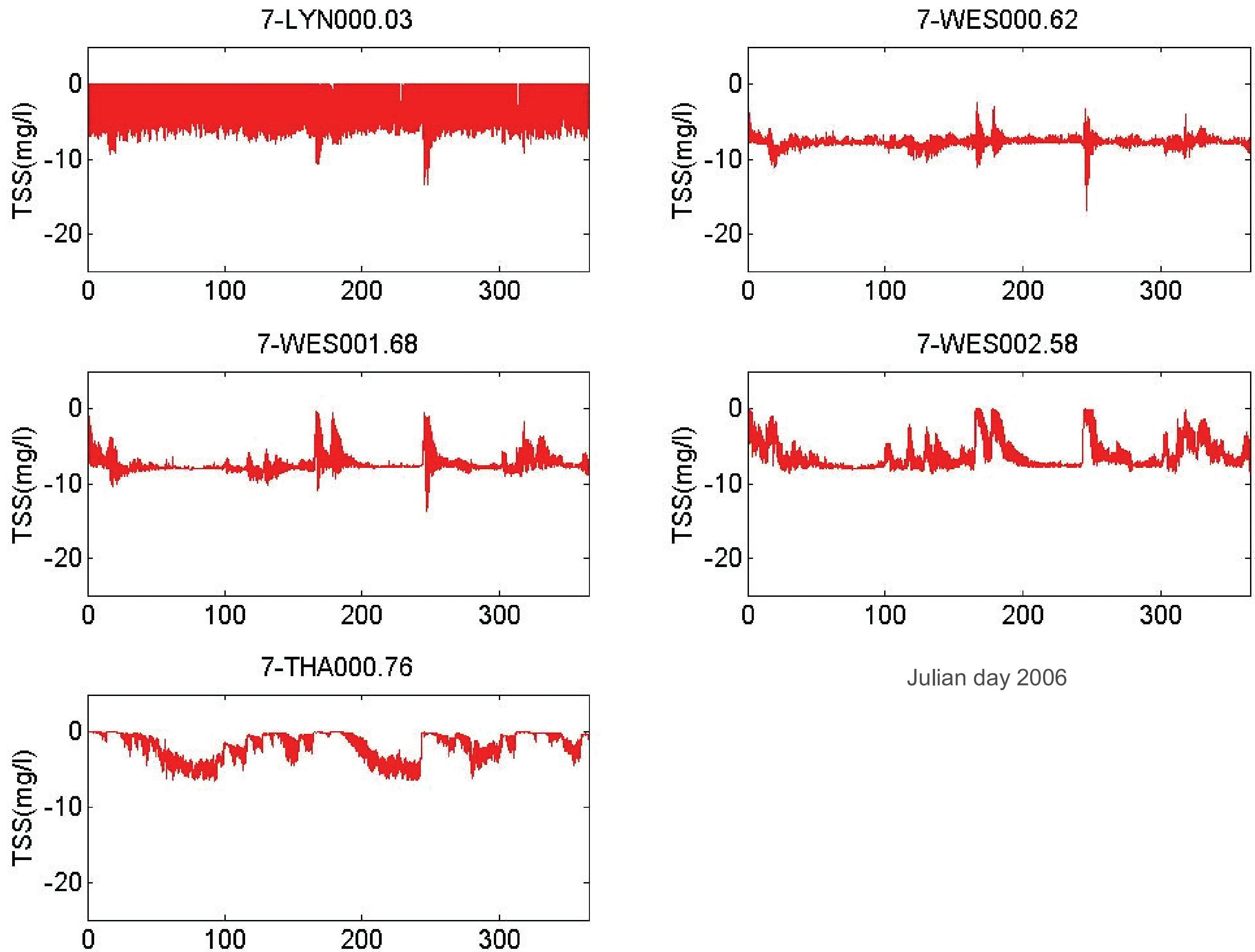

Figure 9. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

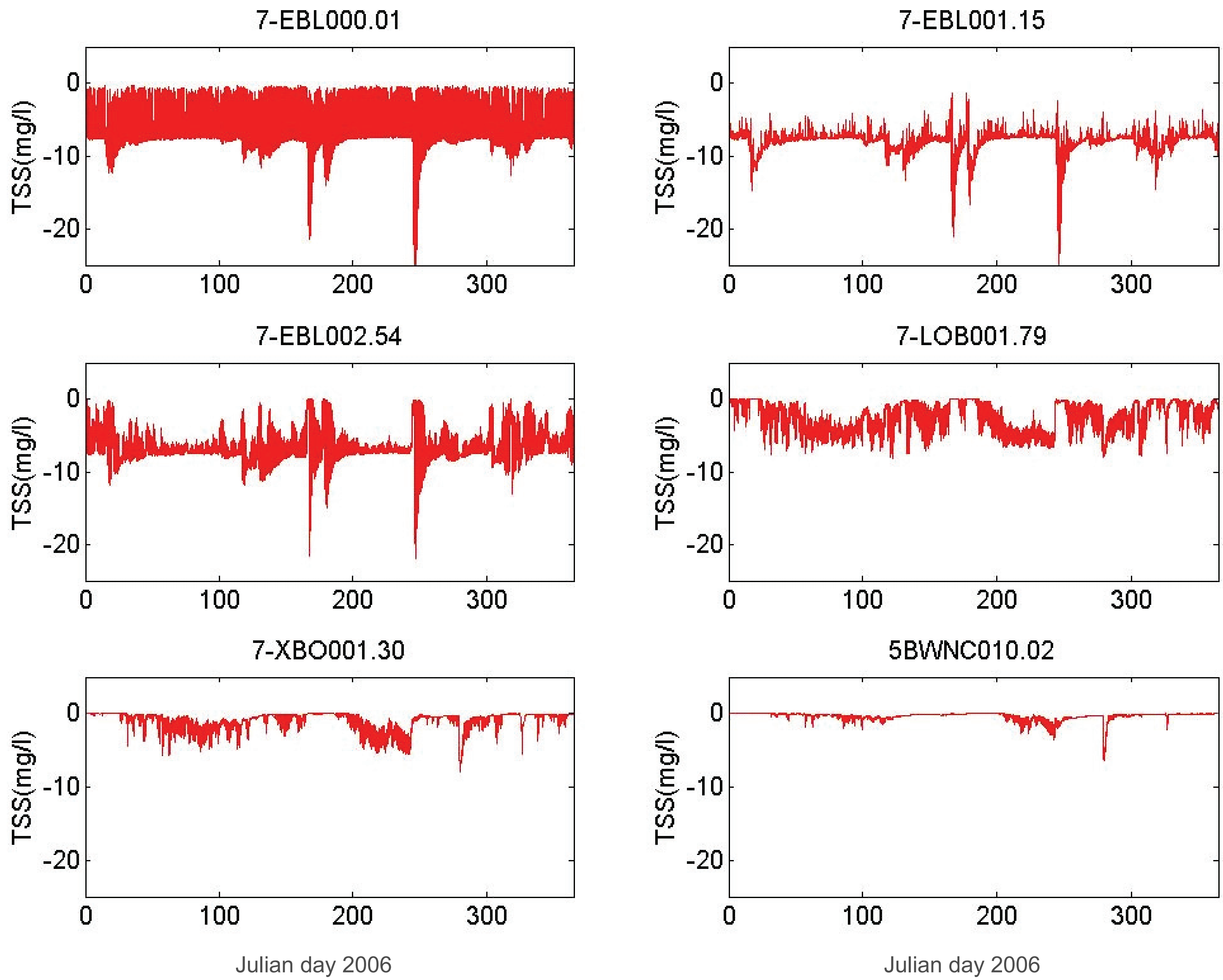

Figure 10. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

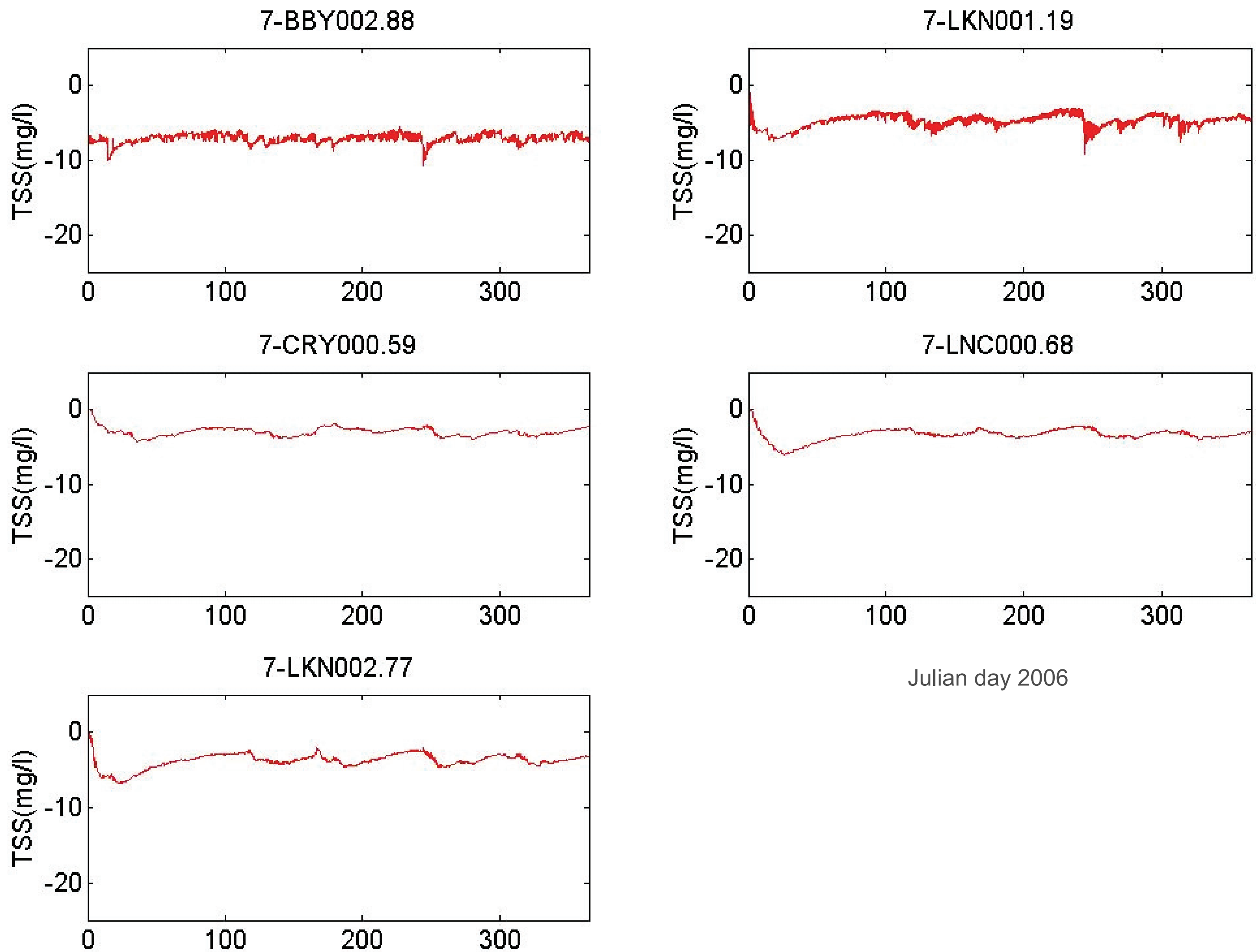

Figure 11. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

Table 7. The average TSS reduction at Lynnhaven River Western Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-LYN000.03	18	3.1 (BC*)	17%
7-WES000.62	21	7.8	38%
7-WES001.68	22	7.3	33%
7-WES002.58	18	6.1	36%
7-THA000.76	11	1.8	16%

BC* - Suspected impact from fixed boundary condition in the Bay

Table 8. The average TSS reduction at Lynnhaven River Eastern Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-EBL000.01	18	5.9	33%
7-EBL001.15	18	7.9	43%
7-EBL002.54	18	6.3	36%
7-LOB001.79	18	2.4	14%
7-XBO001.30	16	1.0	6.0%
5BWNC010.02	14	0.3	2.4%

Table 9. The average TSS reduction at Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case TSS (mg/l)	TSS Reduction (mg/l)	Percentage of Reduction
7-BBY002.88	9.5	7.1	74%
7-LKN001.19	7.0	4.8	68%
7-CRY000.59	6.5	3.0	46%
7-LNC000.68	6.1	3.4	55%
7-LKN002.77	6.3	3.8	60%

III-2. Chlorophyll removal

The prediction of chlorophyll by the Lynnhaven CE-QUAL-ICM water quality model used calendar year 2006 for its calibration. This calibration occurred by comparing chlorophyll observations against model predictions at the 16 Lynnhaven River VA-DEQ stations shown in Figure 1. These comparisons throughout 2006 are shown for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches, respectively, in Figures 12 through 14. This calibration simulation of the model, not invoking any chlorophyll removal due to habitat construction, was then used as the "base case" to compare to Scenarios 3 and 4 to assess chlorophyll removal.

As part of the specifications for Scenarios 3 and 4, in addition to the "Plan A" and "Plan B" restoration design specifications, the results of the assessed impacts of these plans on TSS levels (i.e., results of Scenarios 1 and 2) were factored in. This was done by reducing the sediment load by 40% throughout the domain for both Scenarios 3 and 4.

III-2-1. Chlorophyll removal resulting from "Plan A" habitat restoration – Scenario 3

The CE-QUAL-ICM water quality model was used to simulate Scenarios 3 and 4 for calendar year 2006 for comparison to the base case. The impact of "Plan A" is the difference (Plan A minus base case) for the VA-DEQ Lynnhaven stations grouped branch-by-branch (Figures 15 through 17). This difference, in effect, represents the removal of chlorophyll due to the habitat restoration modeled for "Plan A". One way to assess the chlorophyll removal is to compare the average of this difference over the entire year for each Lynnhaven VA-DEQ station with the average predicted base case value for that station, as shown in Tables 10 through 12.

Tables 10, 11, and 12 display the average predicted base case chlorophyll concentrations at VA-DEQ stations, respectively, in the Western, Eastern, and Broad Bay/Linkhorn Bay Branches of the Lynnhaven and it can be seen that these range from 7.7 to 15.0 µg/l for calendar year 2006. The removal of chlorophyll resulting from the Plan A restoration ranges from 1.4 to 4.0 µg/l at stations in these 3 branches, and the percentage of chlorophyll removal ranges from 12 to 30% over these 3 branches.

Compared with the results of the TSS reductions ranges shown in Section III-1, the chlorophyll reductions showed much less variation from branch to branch. Averages of the percentages of reduction shown in Tables 10 through 12 at the DEQ stations in the Western, Eastern, and Broad Bay/Linkhorn Bay Branches, respectively, are 25.2%, 17.7%, and 22.4%.

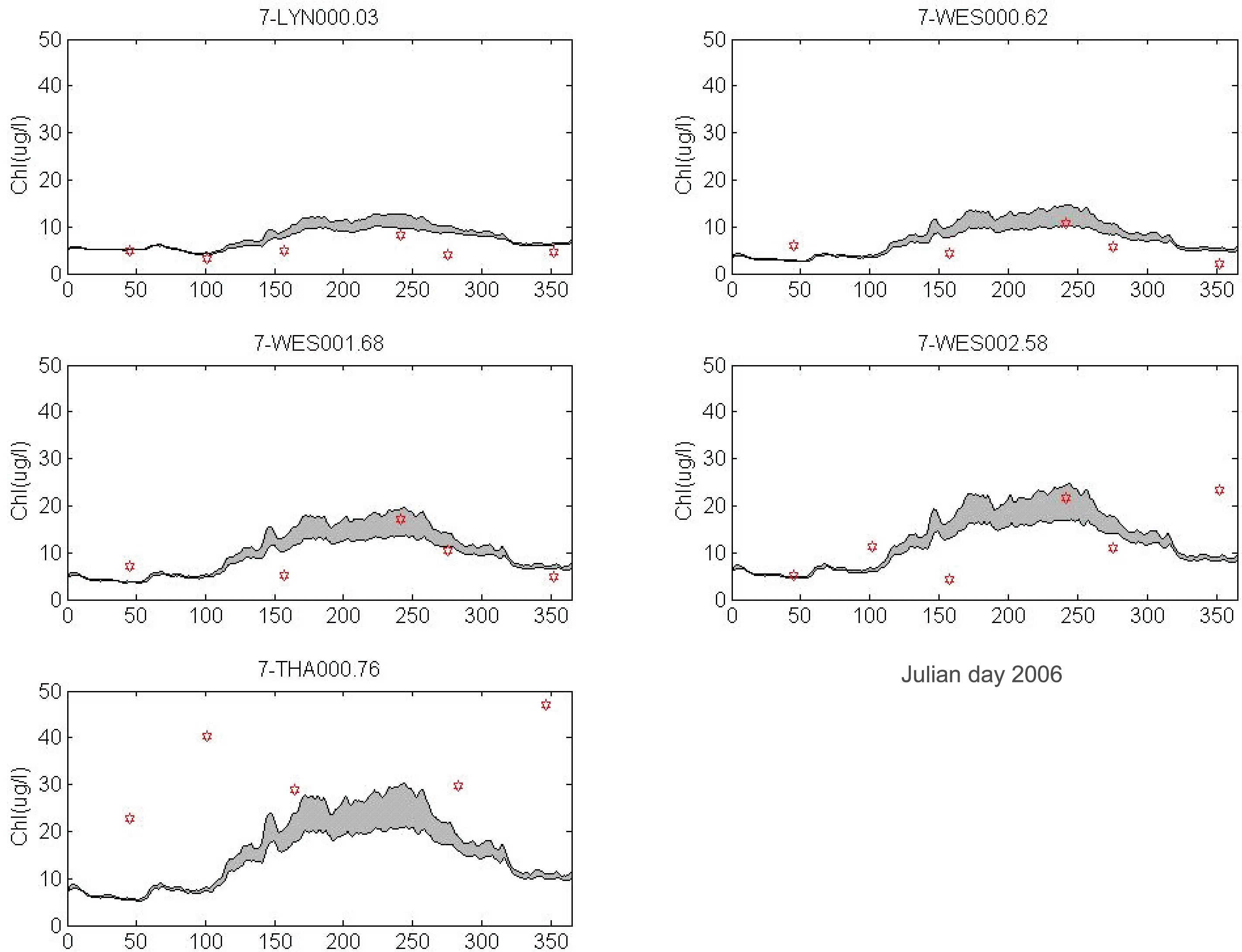

Figure 12. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Western Branch stations for 2006.

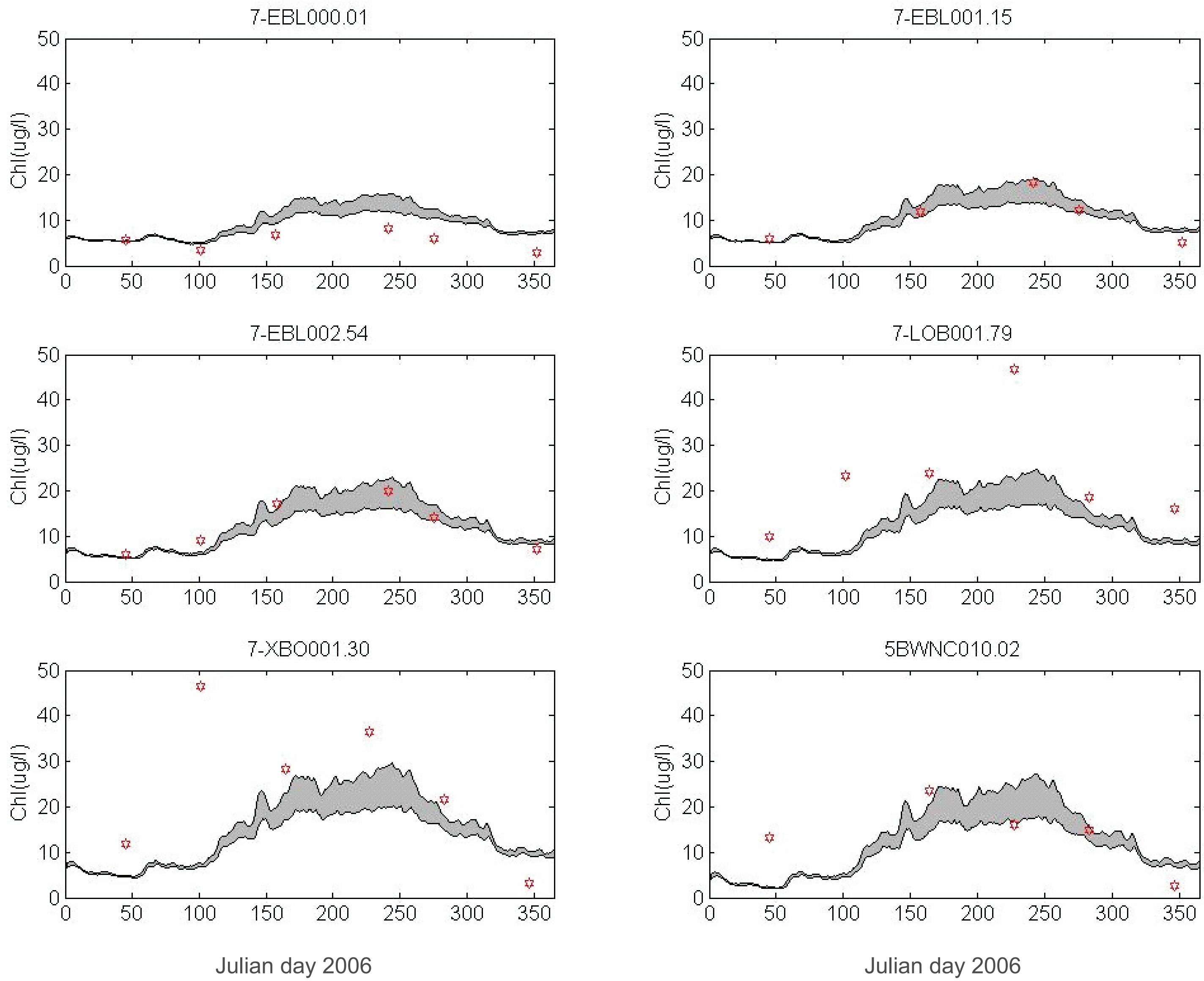

Figure 13. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Eastern Branch stations for 2006.

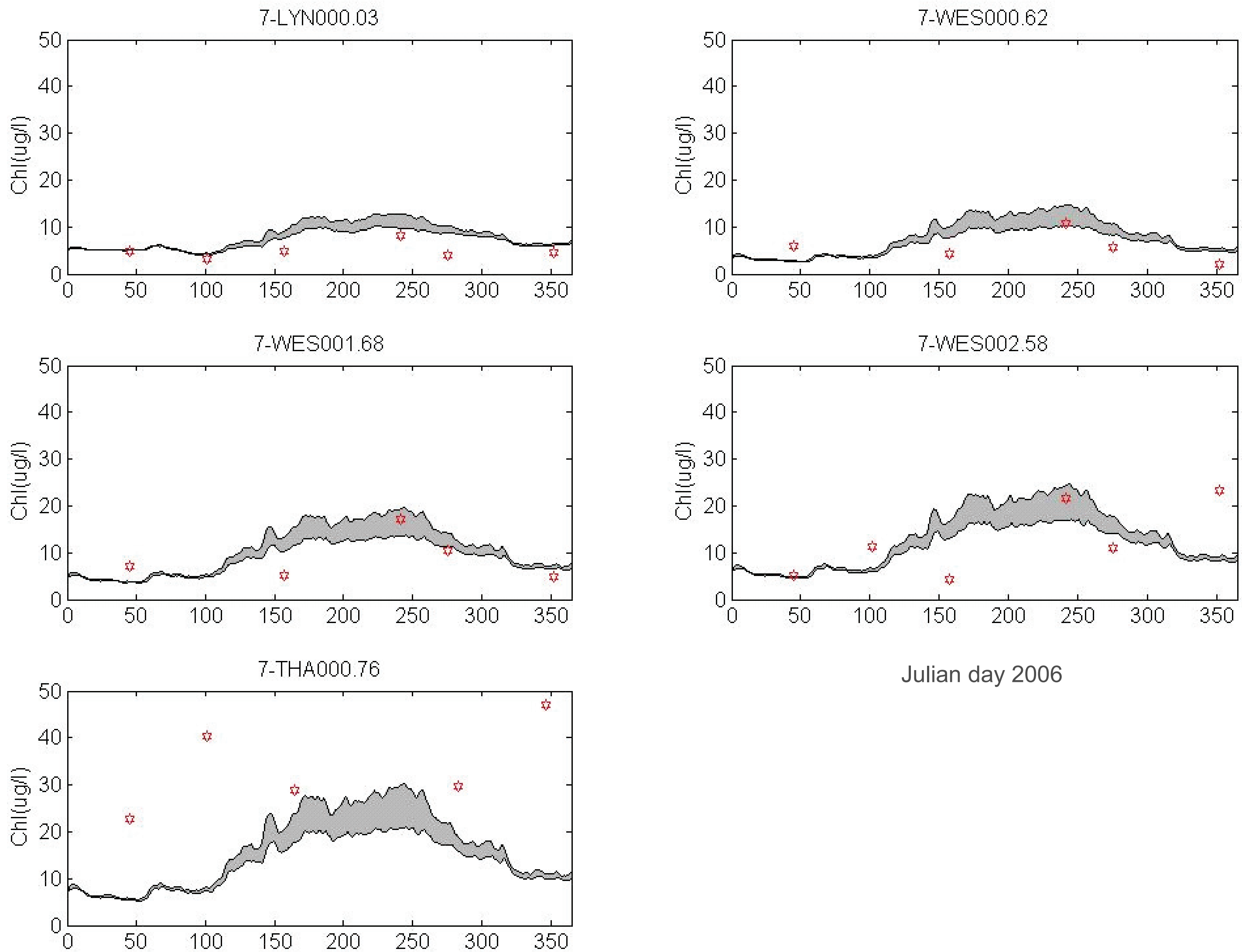

Figure 14. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Broad Bay/Linkhorn Bay Branch stations for 2006.

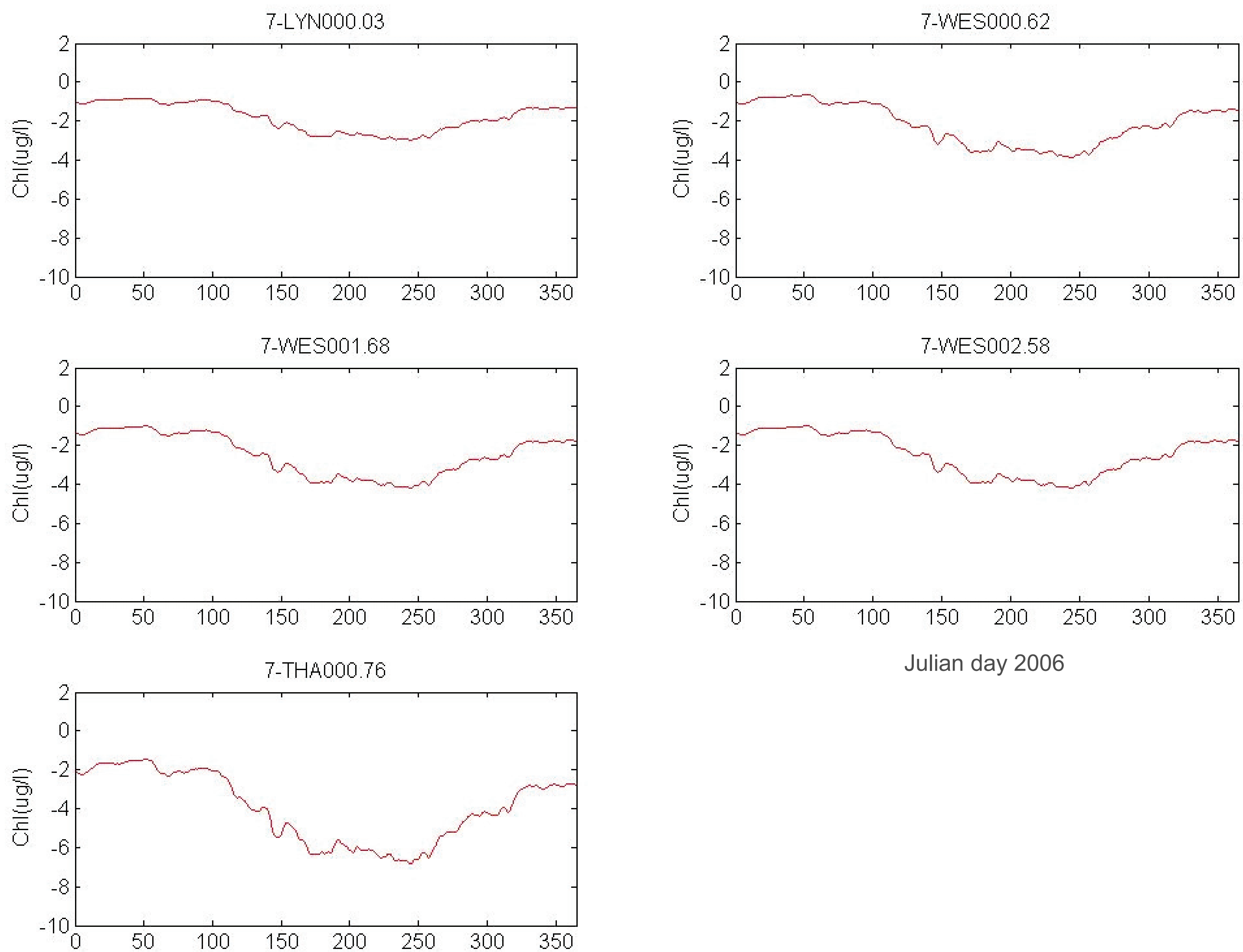

Figure 15. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

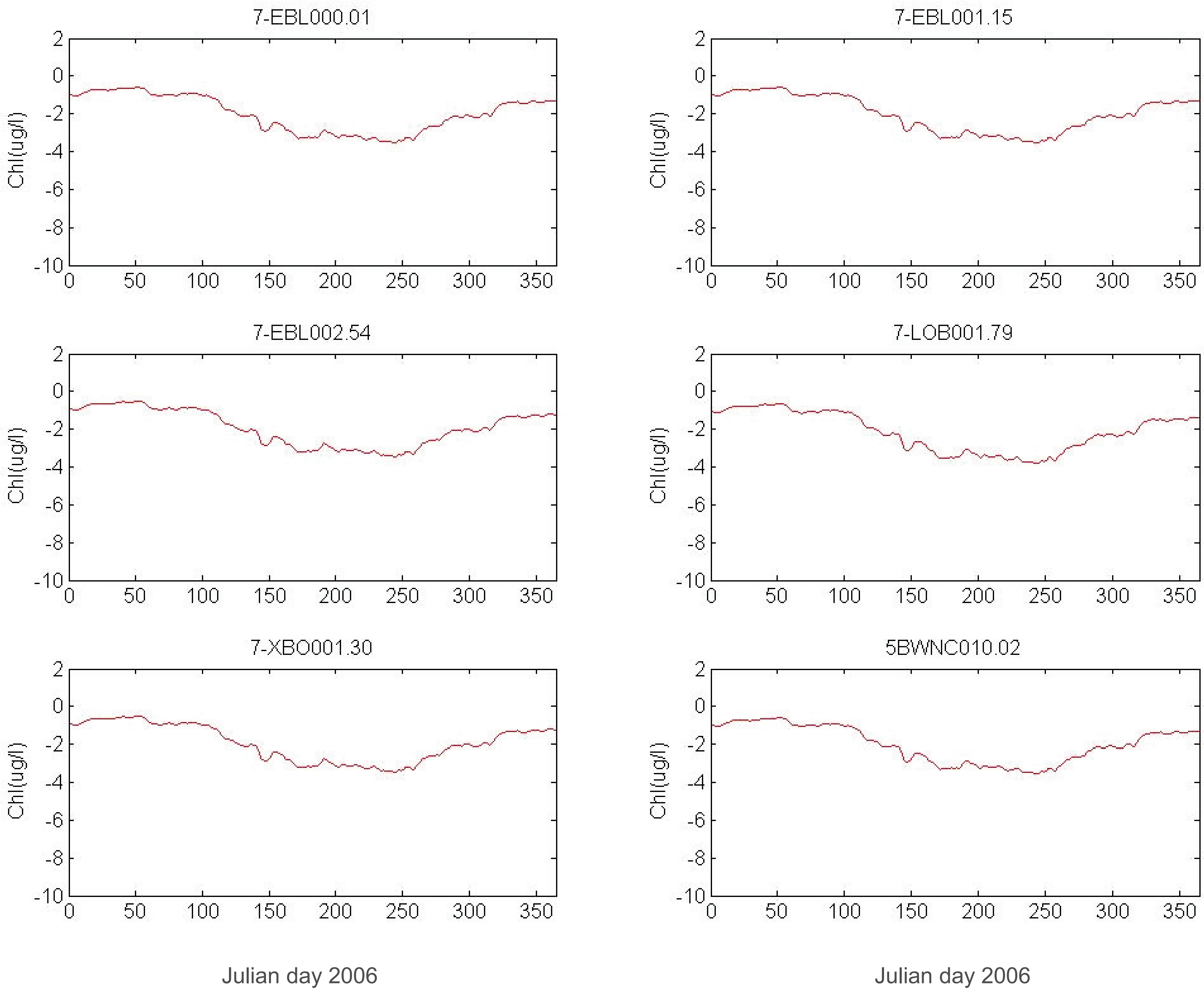

Figure 16. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

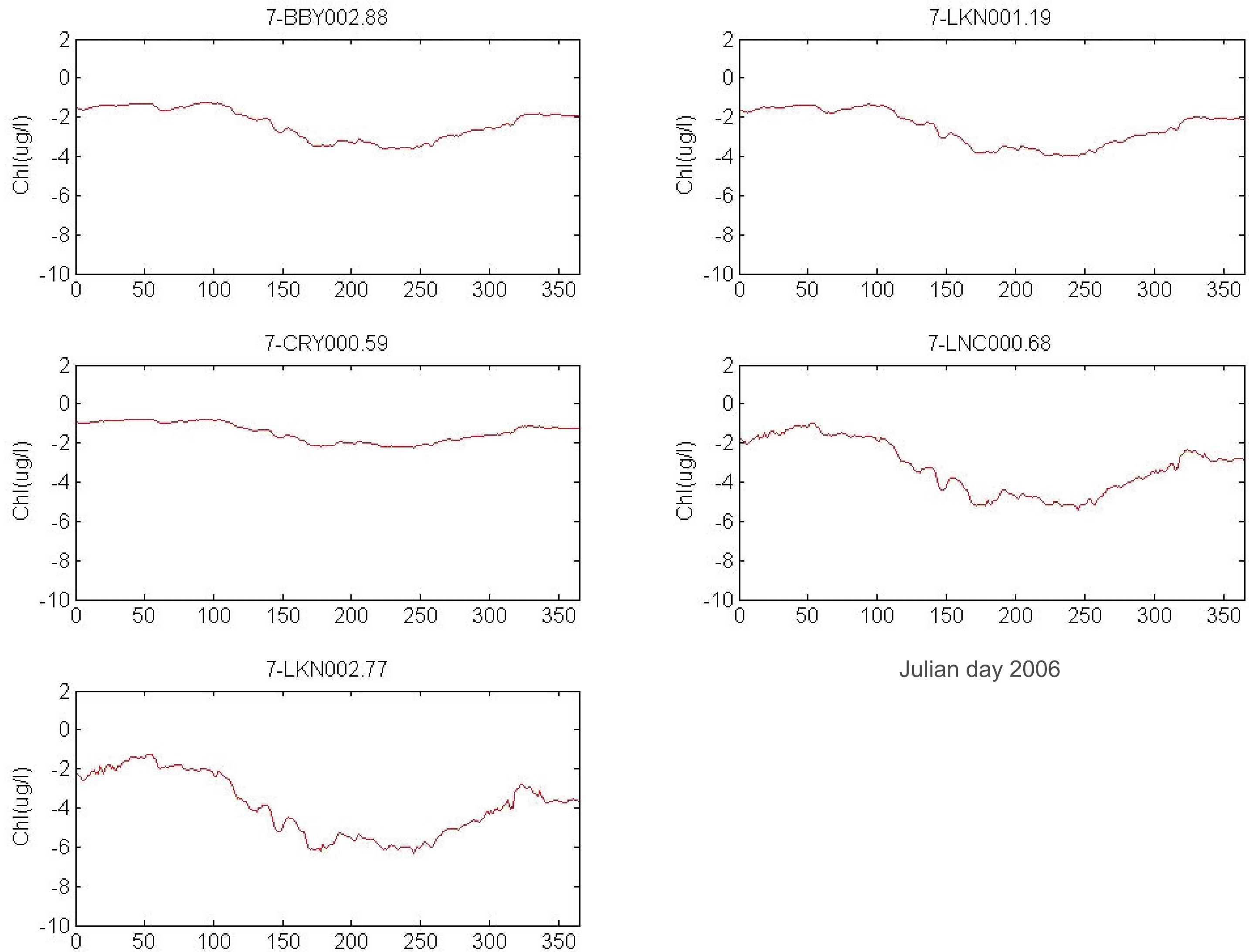

Figure 17. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

Table 10. The average chlorophyll reduction at Lynnhaven River Western Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case Chlorophyll (μg/l)	Chlorophyll Reduction (μg/l)	Percentage of Reduction
7-LYN000.03	7.7	1.8 (BC*)	24%
7-WES000.62	7.3	2.2	30%
7-WES001.68	9.8	2.5	25%
7-WES002.58	12.3	2.5	20%
7-THA000.76	15.0	4.0	27%

BC* - Suspected impact from fixed boundary condition in the Bay

Table 11. The average chlorophyll reduction at Lynnhaven River Eastern Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case Chlorophyll (μg/l)	Chlorophyll Reduction (μg/l)	Percentage of Reduction
7-EBL000.01	9.1	2.0	22%
7-EBL001.15	10.3	2.0	19%
7-EBL002.54	11.9	1.9	16%
7-LOB001.79	12.3	2.2	18%
7-XBO001.30	14.2	1.9	14%
5BWNC010.02	11.9	2.0	17%

Table 12. The average chlorophyll reduction at Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations in 2006 resulting from the Plan A restoration.

Station	Avg. Predicted Base Case Chlorophyll (µg/l)	Chlorophyll Reduction (µg/l)	Percentage of Reduction
7-BBY002.88	9.6	2.3	24%
7-LKN001.19	10.3	2.6	25%
7-CRY000.59	12.9	1.4	12%
7-LNC000.68	13.6	3.2	24%
7-LKN002.77	14.6	3.9	27%

III-2-2. Chlorophyll removal resulting from "Plan B" habitat restoration – Scenario 4

The CE-QUAL-ICM water quality model was used to simulate Scenario 4 for calendar year 2006 for comparison to the base case, as was done earlier for Scenario 3. The impact of "Plan B" is the difference (Plan B minus base case) for the VA-DEQ Lynnhaven stations grouped branch-by-branch (Figures 18 through 20). This difference, in effect, represents the removal of chlorophyll due to the habitat restoration modeled for "Plan B". One way to assess the chlorophyll removal is to compare the average of this difference over the entire year for each Lynnhaven VA-DEQ station with the average predicted base case value for that station, as shown in Tables 13 through 15.

Tables 13, 14, and 15 display the average predicted base case chlorophyll concentrations at VA-DEQ stations, respectively, in the Western, Eastern, and Broad Bay/Linkhorn Bay Branches of the Lynnhaven and it can be seen that these range from 7.7 to 15.0 µg/l for calendar year 2006. The removal of chlorophyll resulting from the Plan B restoration ranges from 1.1 to 3.8 µg/l at stations in these 3 branches, and the percentage of chlorophyll removal ranges from 8% to 25% over these 3 branches.

Compared with the results of the chlorophyll reductions resulting from the Scenario 3 (Plan A) assessment shown in Section III-2-1, the chlorophyll reductions in the results of Scenario 4 (Plan B) were slightly less in each branch. For Scenario 4, the averages of the percentages of reduction shown in Tables 13 through 15 at the DEQ stations in the Western, Eastern, and Broad Bay/Linkhorn Bay Branches, respectively, are 21.0%, 14.3%, and 19.8%, less than the 25.2%, 17.7%, and 22.4% shown earlier for Scenario 3 (Plan A impact).

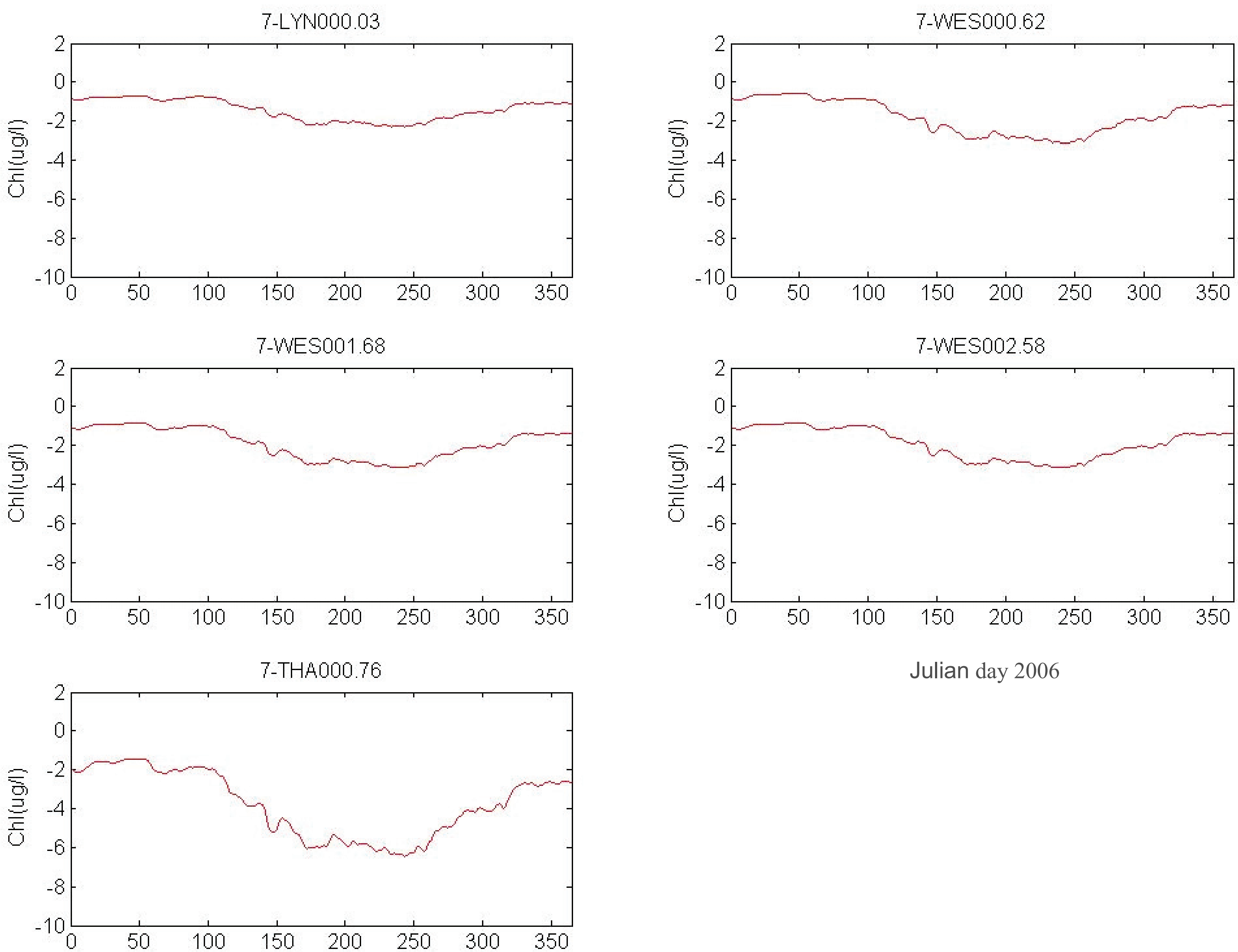

Figure 18. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

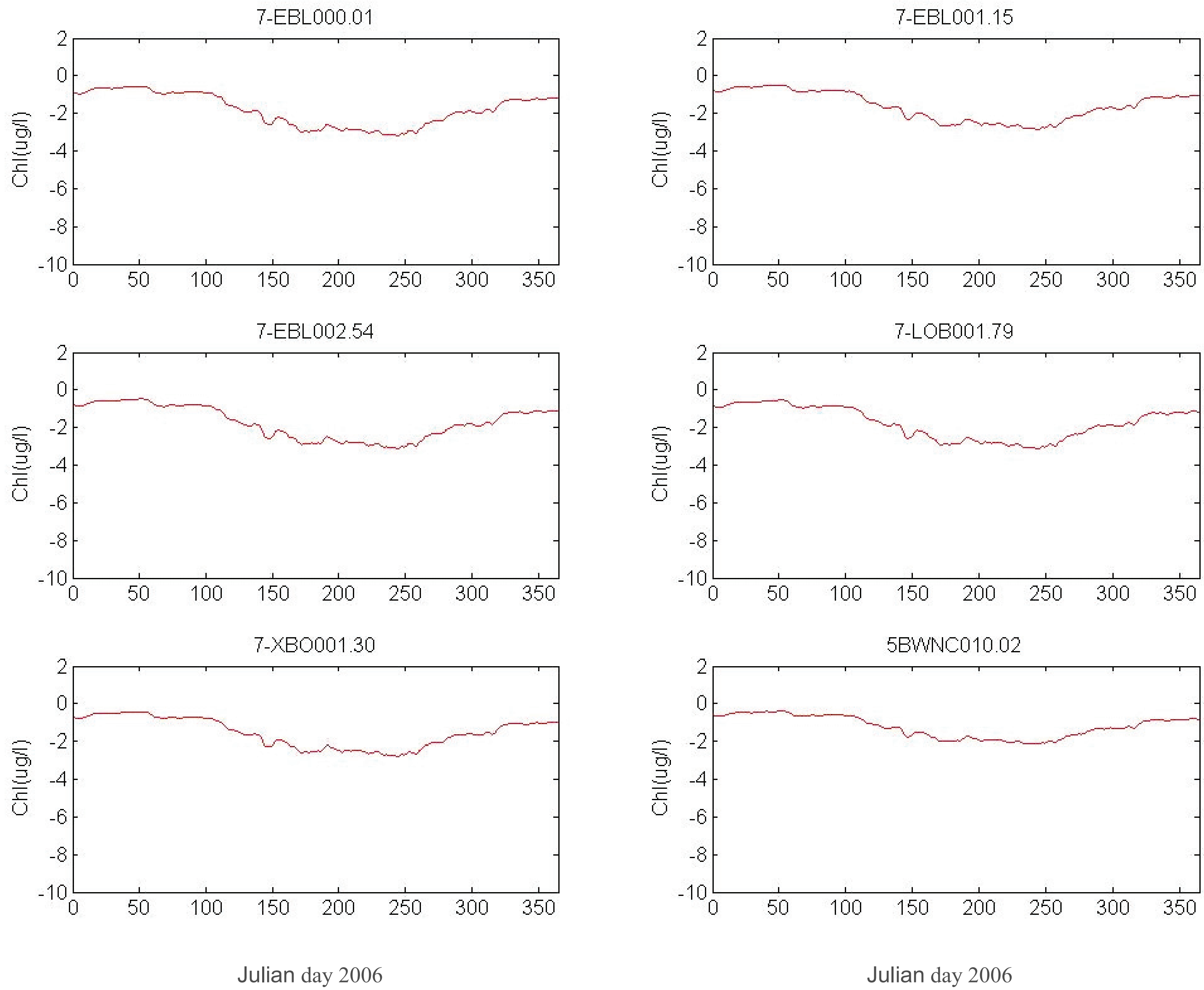

Figure 19. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

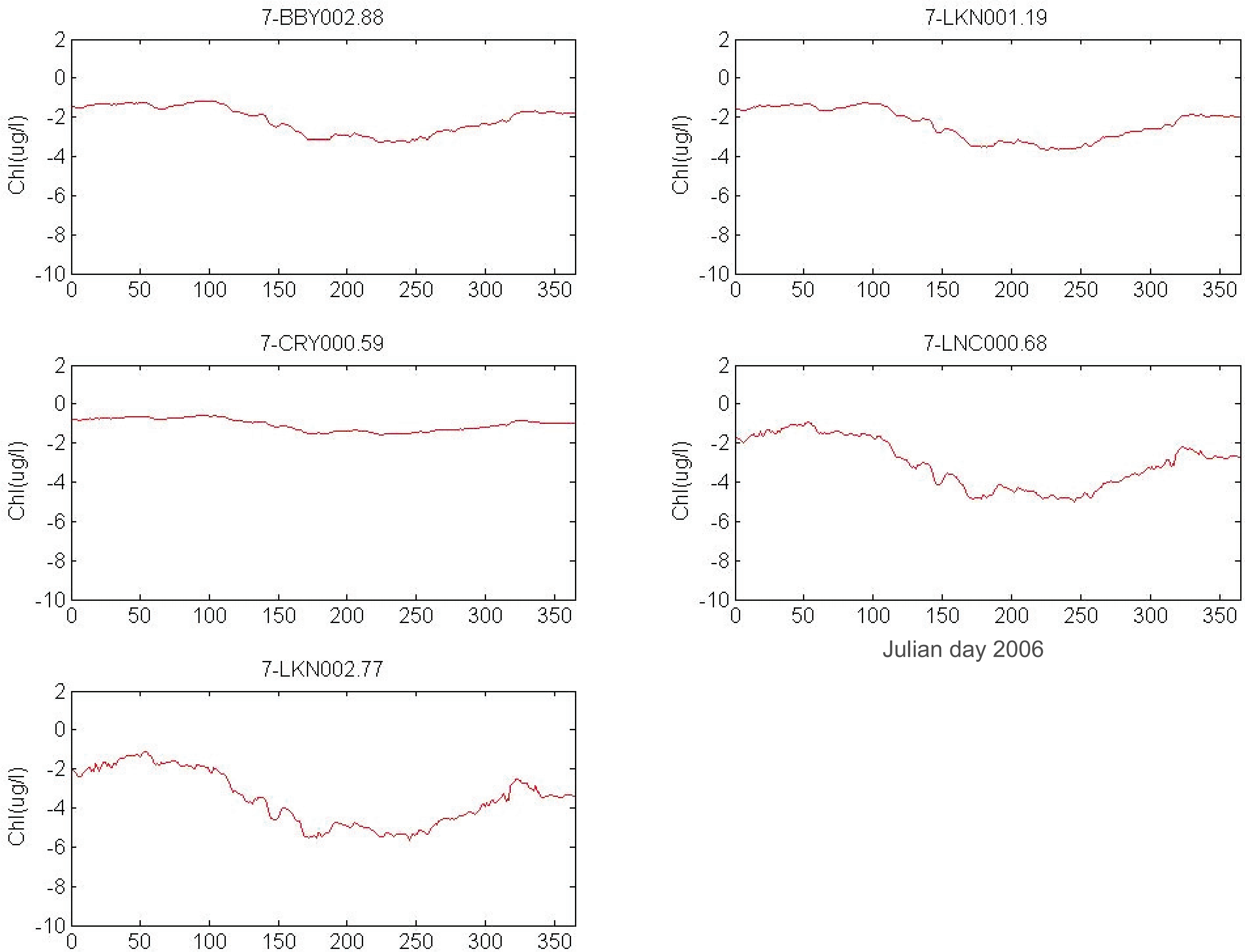

Figure 20. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

Table 13. The average chlorophyll reduction at Lynnhaven River Western Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case Chlorophyll (μg/l)	Chlorophyll Reduction (μg/l)	Percentage of Reduction
7-LYN000.03	7.7	1.4 (BC*)	19%
7-WES000.62	7.3	1.8	25%
7-WES001.68	9.8	1.9	20%
7-WES002.58	12.3	1.9	16%
7-THA000.76	15.0	3.8	25%

BC* - Suspected impact from fixed boundary condition in the Bay

Table 14. The average chlorophyll reduction at Lynnhaven River Eastern Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case Chlorophyll (μg/l)	Chlorophyll Reduction (μg/l)	Percentage of Reduction
7-EBL000.01	9.1	1.8	20%
7-EBL001.15	10.3	1.6	16%
7-EBL002.54	11.9	1.7	15%
7-LOB001.79	12.3	1.8	14%
7-XBO001.30	14.2	1.5	11%
5BWNC010.02	11.9	1.2	10%

Table 15. The average chlorophyll reduction at Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations in 2006 resulting from the Plan B restoration.

Station	Avg. Predicted Base Case Chlorophyll (μg/l)	Chlorophyll Reduction (μg/l)	Percentage of Reduction
7-BBY002.88	9.6	2.1	22%
7-LKN001.19	10.3	2.4	23%
7-CRY000.59	12.9	1.1	8%
7-LNC000.68	13.6	3.0	22%
7-LKN002.77	14.6	3.5	24%

IV. Summary and Discussion

For this project, formulations have been developed that predict spatial and temporal distributions of TSS and chlorophyll reductions throughout the Lynnhaven River that are caused by site-specific habitat restorations of essential fish habitat (including oyster reefs), submerged aquatic vegetation (SAV), and scallop sites. These formulations depend on the application of hydrodynamic and water quality models calibrated respectively for TSS and chlorophyll concentrations as well as the size of the habitat restoration area. These models have been enhanced to include sink terms for TSS and chlorophyll that are activated in those portions of the numerical model domain that intersect the habitat restoration sites.

In order to examine the spatial distribution of TSS removal throughout the Lynnhaven's three branches, year-long time averages of 1) the predicted base case TSS concentrations and 2) the TSS reductions due to both habitats "Plan A" and "Plan B" were calculated at each of 16 Lynnhaven VA-DEQ stations. These averages, shown in Tables 4 through 6 for Plan A and in Tables 7 through 9 for Plan B, yield TSS reduction percentages ranging from 2.5% at Station 5BWNC010.02 (in the upper Eastern Branch) to 74% at Station 7-BBY002.88 (in Broad Bay). For both Plan A and Plan B, the average TSS reductions for the Western, Eastern, and Broad Bay/Linkhorn Bay Branches are, respectively, 28.0%, 22.4%, and 60.6%.

In order to assess the spatial distribution of chlorophyll removal throughout the Lynnhaven's three branches, year-long time averages of 1) the predicted base case chlorophyll concentrations and 2) the chlorophyll reductions due to both habitats "Plan A" and "Plan B" were calculated at each of 16 Lynnhaven VA-DEQ stations. These averages, shown in Tables 10 through 12 for Plan A and in Tables 13 through 15 for Plan B, yield chlorophyll reduction percentages ranging from 10% at Station 5BWNC010.02 (in the upper Eastern Branch) to 30% at Station 7-WES000.62 (in the Lower Western Branch). For Plan A, the average chlorophyll reductions for the Western, Eastern, and Broad Bay/Linkhorn Bay branches are, respectively, 25.2%, 17.7%, and 22.4%. For Plan B, these reductions are 21.0%, 14.3%, and 19.8%. Compared to the TSS reductions, the percentages of chlorophyll reductions are more moderate, and spatially uniform. While the secondary production of the restored habitat reduces the phytoplankton population, the reduced TSS concentration promotes the phytoplankton growth instead, thus dampening the impact of the uptake by the restored habitat.

Overall, TSS and chlorophyll reductions were indeed achieved when the ecosystem restoration were implemented, as shown above. The scenario run results for the stations in Broad Bay/Linkhorn Bay (Tables 6 and 9), where the base case TSS concentrations are low and the percentage reductions are high, should be interpreted with caution. In fact, these reduction results should be interpreted as the maximum benefits achievable. In reality, the TSS reduction rates and the secondary production should decrease as the water column concentrations of TSS and phytoplankton decrease. The specification of sink terms independent of water column concentrations will result in over-estimation of reduction effects when water column concentrations are lower than some yet-to-be-determined critical values. To be more precise, the magnitudes of sink terms in the model equations should be dependent on the water column concentrations. Furthermore, some of the TSS may get resuspended after deposition by the filter feeders. The process and magnitude of the resuspension are not yet completely understood, and not included in the current specification of the sink term. The TSS reduction can also affect the light field in the water column and, hence, affect the chlorophyll concentration in a feedback system. Much more research is required to formulate the functional relationships between the sink terms and water column concentrations, and its feedback mechanism, which is beyond the scope of this project. On the other hand, the US EPA is giving serious consideration to the inclusion of the effect of filter feeders into their formulation of the primary Bay cleanup plan, the Bay Total Maximum Daily Load (TMDL) (Chesapeake Bay Journal, June 2010). It is anticipated that more research on these issues will develop.

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Appendix A. Documentation of Unprocessed Request of Incorporation of Revised Specifications of Secondary Production Numbers

On September 20, 2010 the numerical modeling group received a request from Norfolk District personnel asking if new secondary production numbers could be incorporated into the water quality scenarios.

Due to the time constraints associated with this project, and given the information that post-simulation corrections could be made once the final numbers were obtained, the revised specifications were not incorporated into the scenarios.

These specifications are listed in Table A-1 on the next 2 pages for purposes of documentation.

Table A-1. Specification Table provided by Norfolk District Personnel showing the TSS uptake and secondary productivity numbers, with a request for revision to the secondary production numbers for scallops.

Time (months)	SAV TSS	SAV Sec Prod	Scallops TSS	Scallops Sec Prod	Wetlands TSS	Wetlands Sec Prod	Fish Reffs LRR TSS	Fish Reefs HRR TSS
1	12.14	32.76	22.09	4.57	921	4.83	223.19	353.70
2	12.14	32.76	22.09	4.57	921	4.83	223.19	353.70
3	24.28	65.51	44.19	9.14	921	9.66	446.30	707.29
4	18.21	98.26	66.28	13.71	921	14.49	669.57	1061.09
5	60.7	131.02	118.06	24.43	921	25.82	1115.96	1768.48
6	109.26	274.51	185.13	38.31	921	40.49	1870.12	2963.65
7	109.26	294.87	198.86	41.15	921	43.49	2008.72	3183.26
8	109.26	294.87	198.86	41.15	921	43.49	2008.72	3183.26
9	60.7	131.02	118.06	24.43	921	25.82	1115.96	1768.48
10	36.42	98.26	66.28	13.71	921	14.49	669.57	1061.09
11	24.48	65.51	44.19	9.14	921	9.66	446.30	774.06
12	24.48	32.76	22.09	4.57	921	4.83	223.19	353.70
	601.33	**1552.09**	**1106.18**	**228.85**	**11052**	**241.89**	**11020.79**	**17531.71**
		129.34		19.07		20.16		

Notes: All secondary production numbers are in ash free dry weight and in kilograms/acre of habitat per month
All TSS reduction numbers are in kilograms TSS removed/acre/month

From the literature, I believe a reasonable figure would be a 10% trophic level transfer from primary to secondary level and that there is 1% chlorophyll A per unit weight of plankton, for modeling purposes.
It is obvious that this type of secondary production will filter a lot of plankton.
I believe the dry weight conversion of phytoplankton often used is 10% of the wet weight.

If you have better numbers on the plankton, please let me know. I can also provide "wet weights" of the different secondary production elements if needed.

Table A-1 (con't).

Fish Reefs LRR Sec Prod	Fish Reefs HRR Sec Prod	Fish Reef Original Plan TSS (HRR)	Fish Reef Original Plan Sec Prod (HRR)	Fish Reef Original Plan TSS (LRR)	Fish Reef Original Plan Sec Prod (LRR)
35.22	57.41	552.65	89.71	446.60	72.50
35.22	57.41	552.65	89.71	446.60	72.50
71.70	114.83	1105.14	179.42	893.06	144.99
107.55	172.24	1657.95	269.13	1339.79	217.49
179.24	287.07	2763.24	448.55	2232.98	362.48
311.16	498.36	4630.70	778.69	3742.07	629.26
322.70	516.73	4973.84	807.39	4019.36	652.46
322.70	516.73	4973.84	807.39	4019.36	652.46
179.24	287.07	2763.24	448.55	2232.98	362.48
107.55	172.24	1657.95	269.13	1339.79	217.49
71.70	114.83	1209.46	179.42	977.37	144.99
35.22	57.41	552.65	89.71	446.60	72.50
1779.20	**2852.36**	**27393.30**	**4456.82**	**22136.52**	**3601.55**
	237.70				