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Numerical Modeling Scenario Runs to Assess TSS and Chlorophyll Reductions Caused by Ecosystem Restoration, Lynnhaven River

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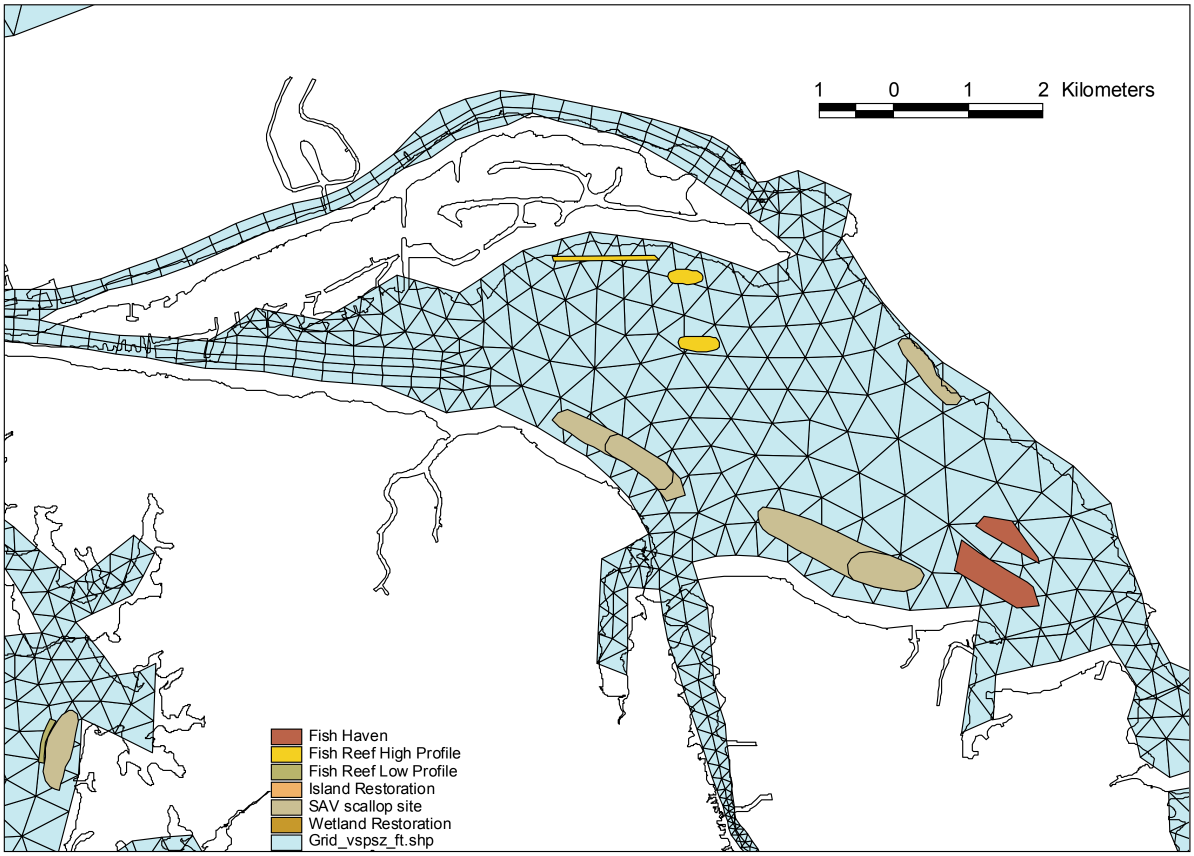

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I. Background and Introduction

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.

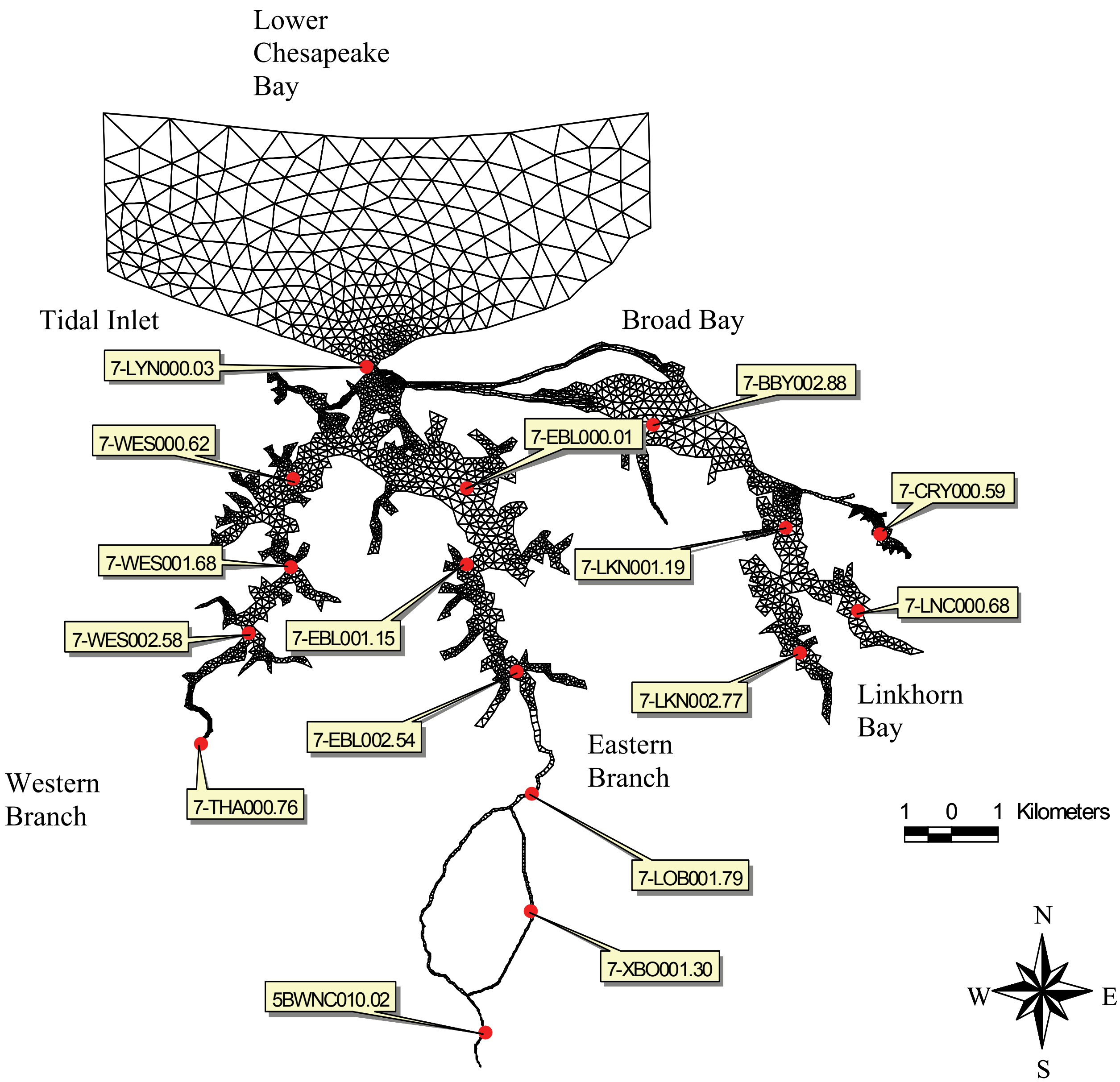

Figure 1. The unstructured grid for Lynnhaven River System and the locations of the 16 Lynnhaven stations monitored by the Virginia Department of Environmental Quality.

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

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

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.

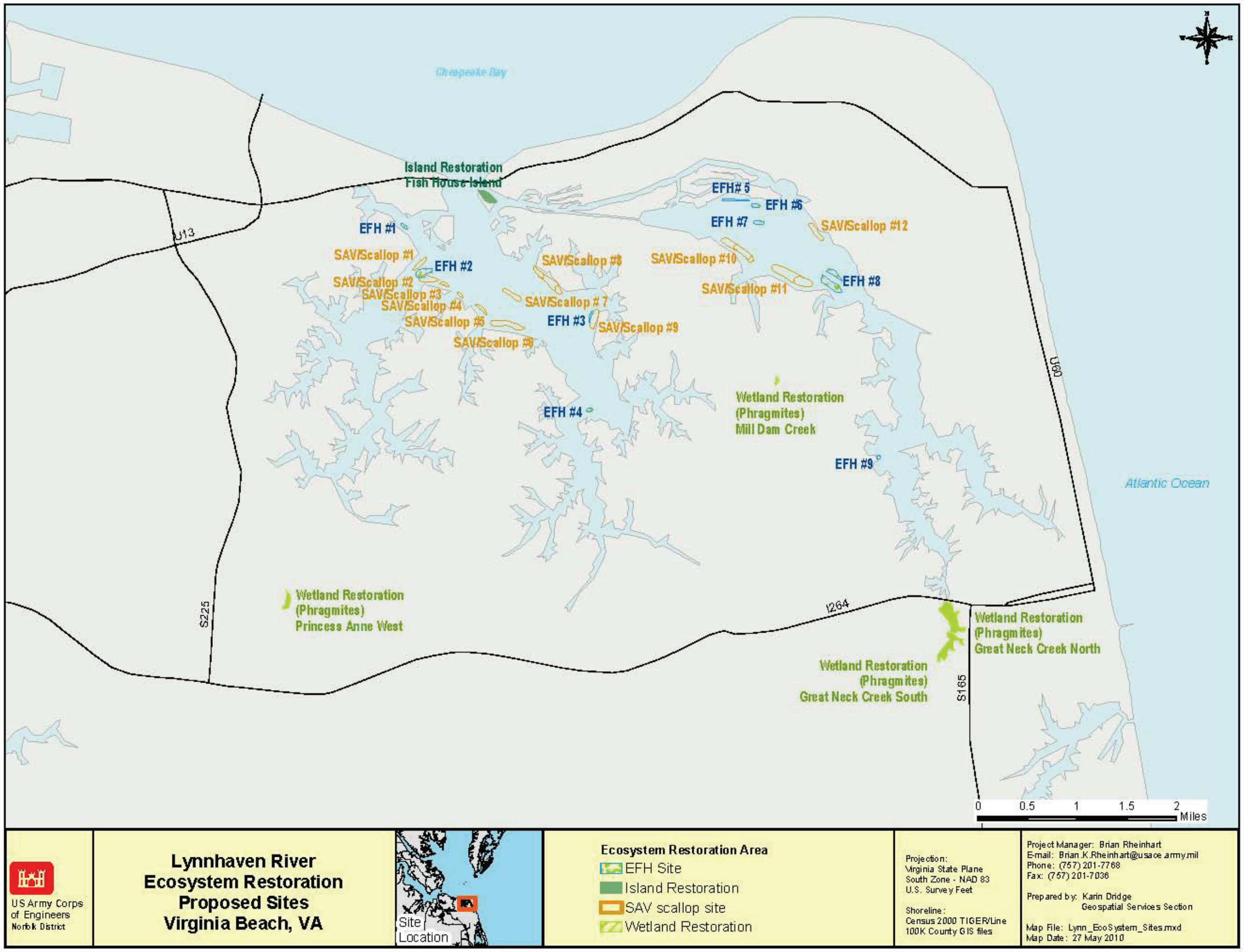

Figure 2. Lynnhaven River Ecosystem Restoration Proposed Sites (Courtesy, Norfolk District COE)

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.

$(C'*V' - C*V)/\Delta t$ = 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:

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

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.

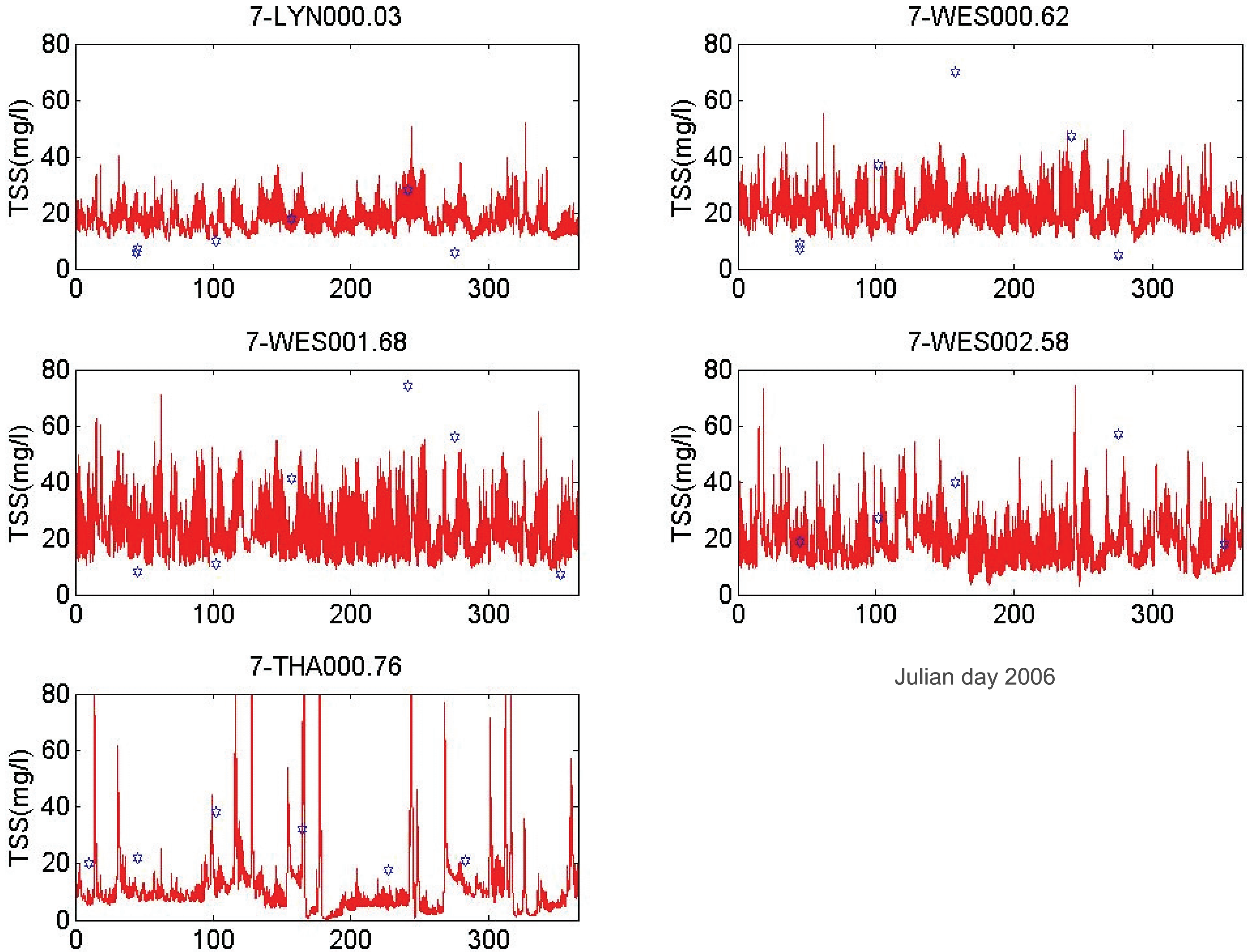

Figure 3. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Western Branch stations for 2006.

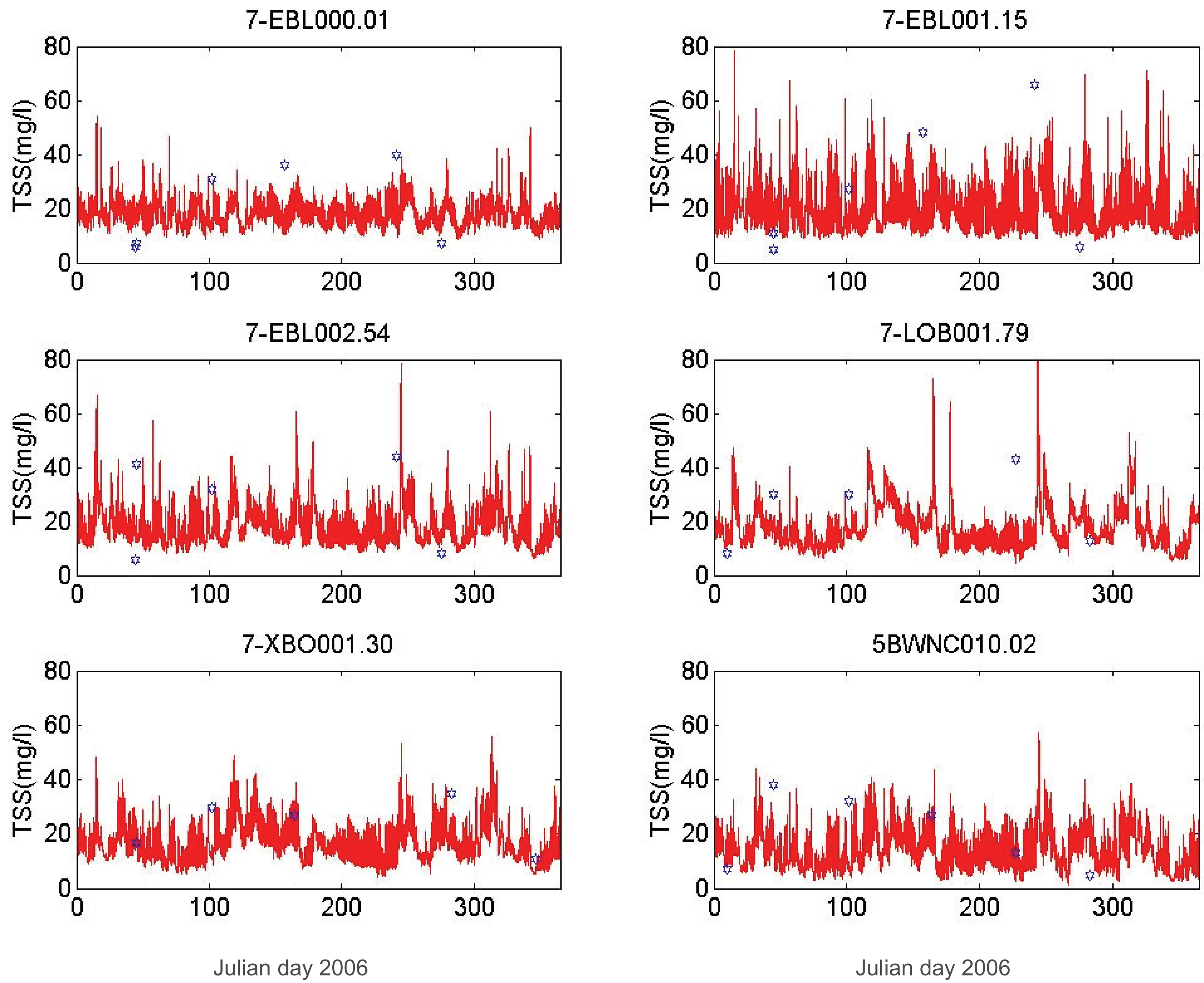

Figure 4. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Eastern Branch stations for 2006.

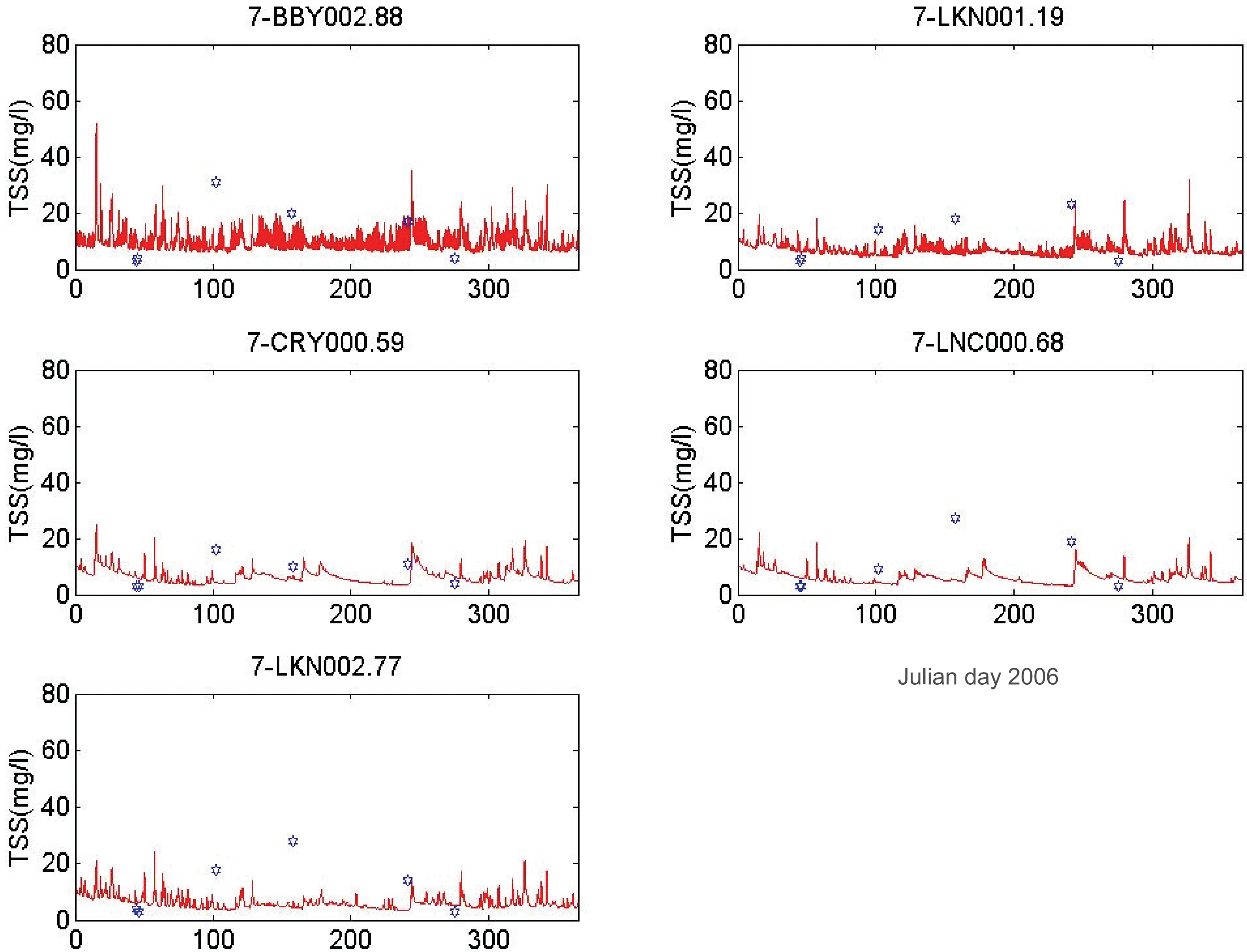

Figure 5. TSS observations (blue symbols) and TSS model predictions (red lines) shown for Lynnhaven Broad Bay/Linkhorn Bay Branch stations for 2006.

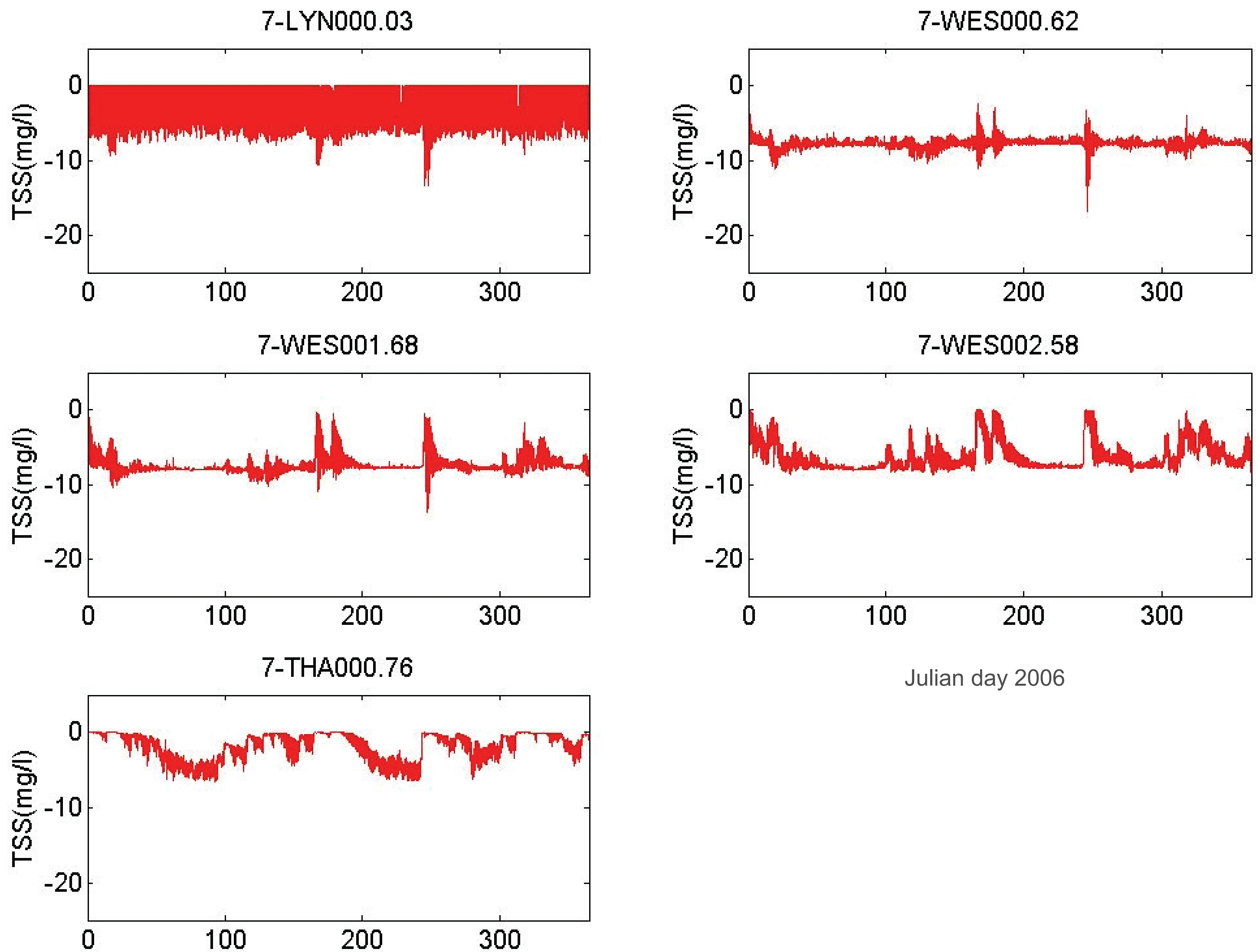

Figure 6. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

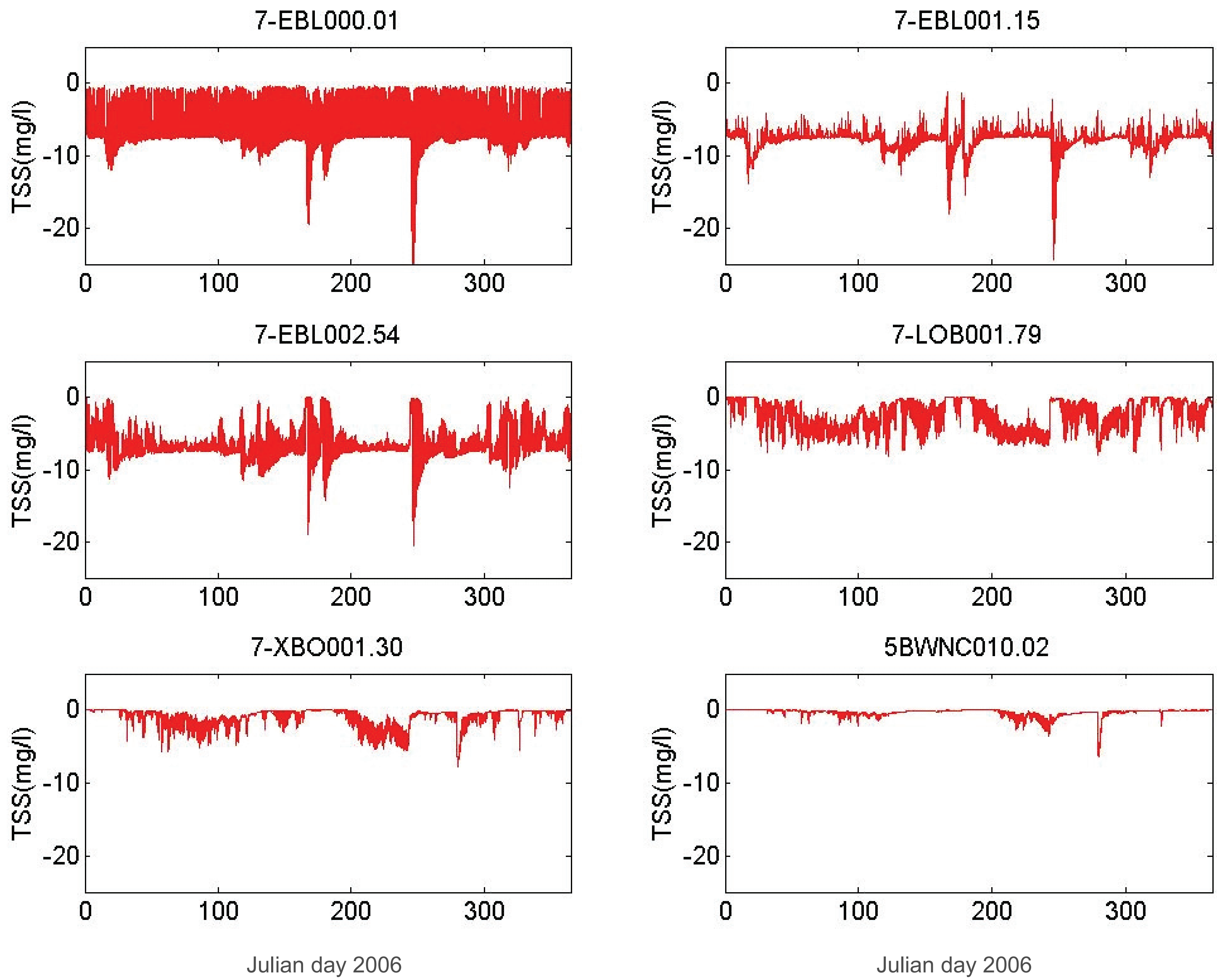

Figure 7. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

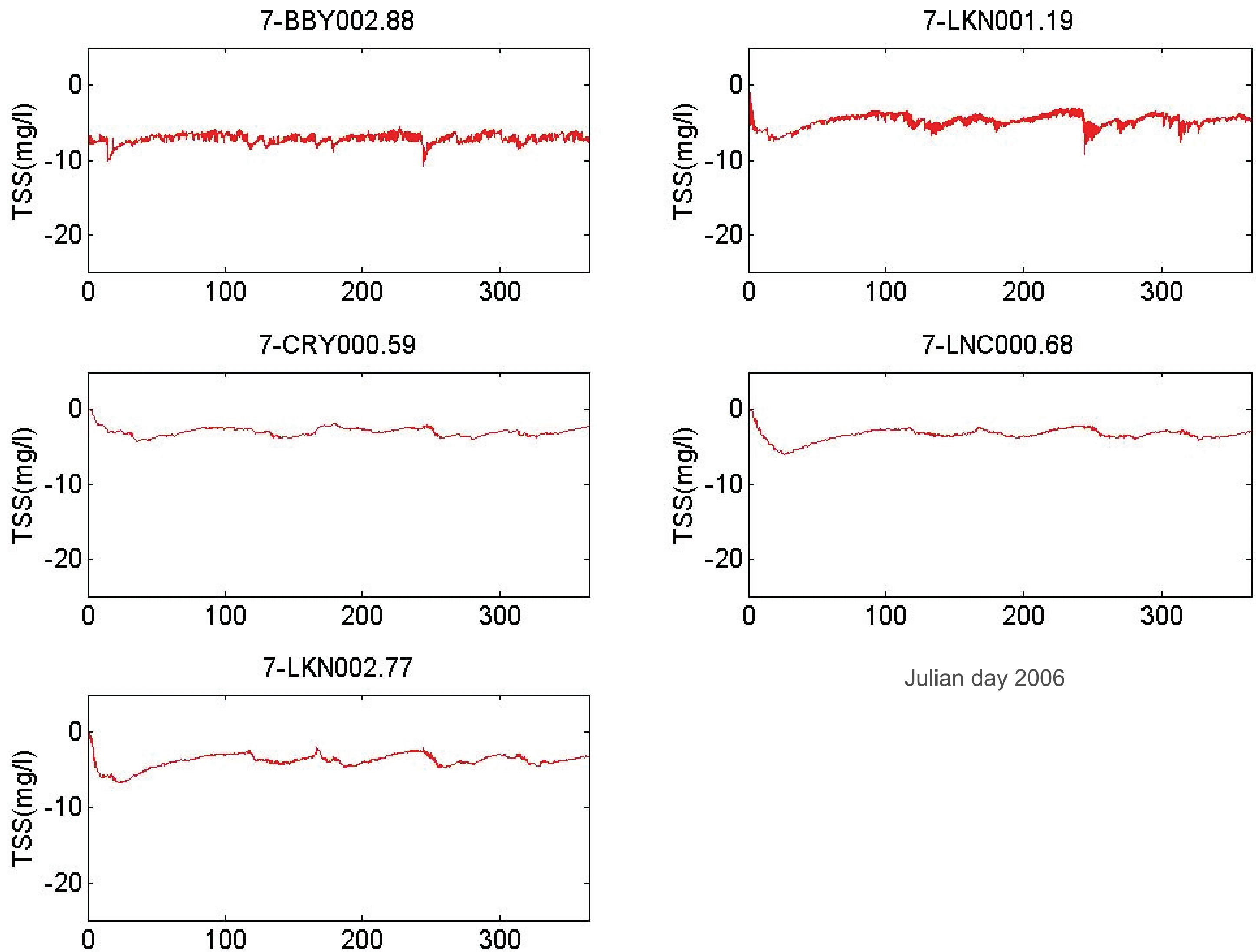

Figure 8. TSS differences (Plan A minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

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.

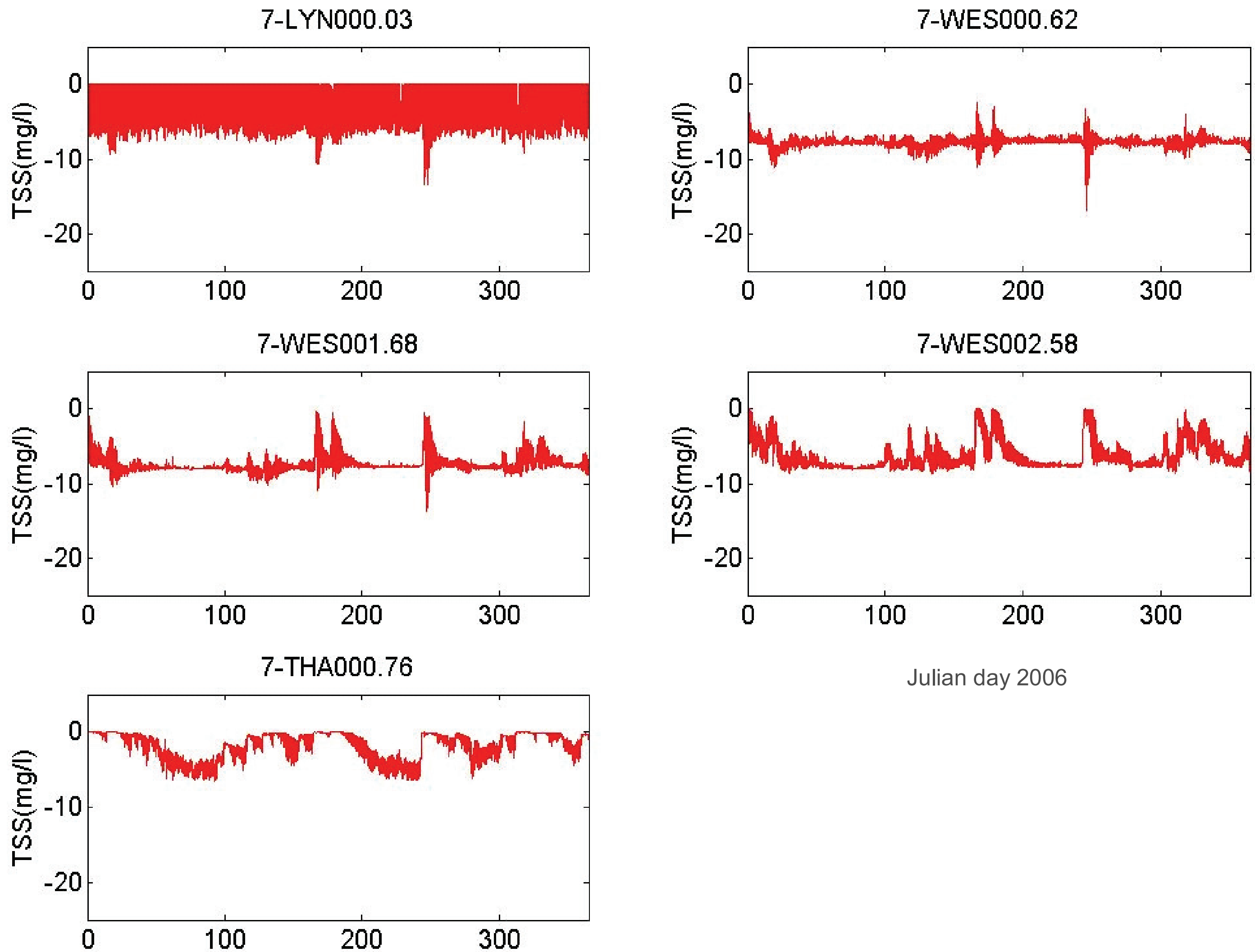

Figure 9. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

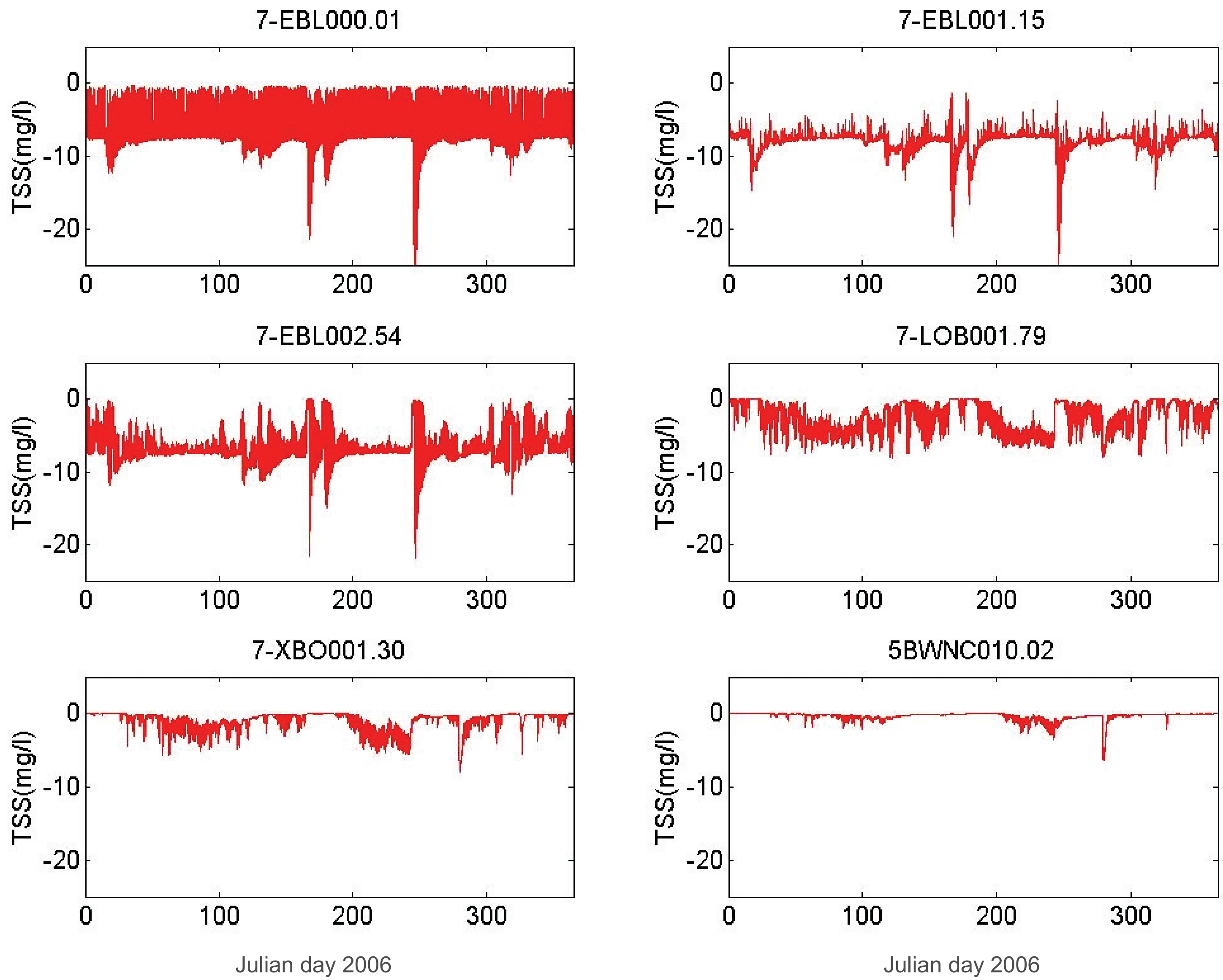

Figure 10. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

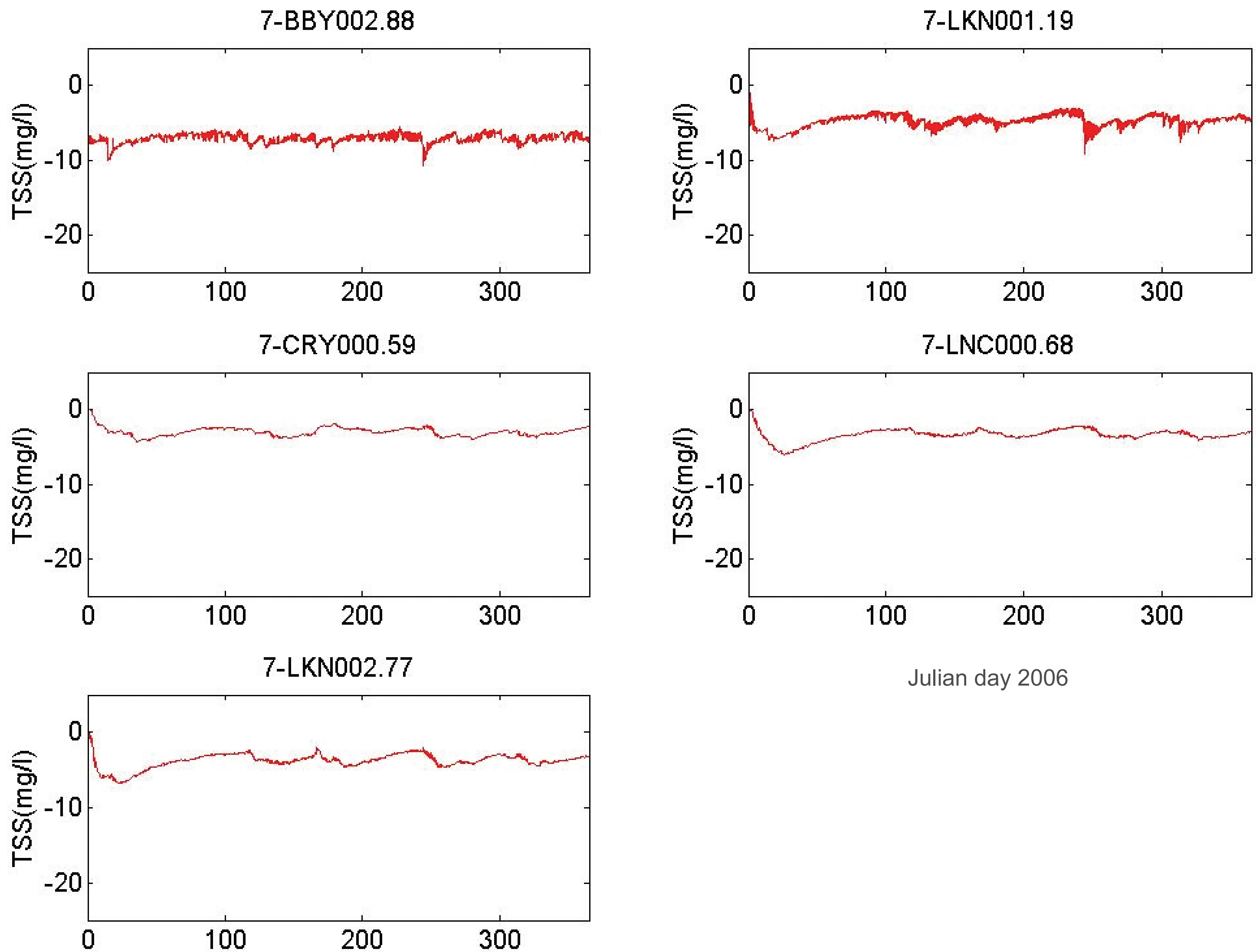

Figure 11. TSS differences (Plan B minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

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%.

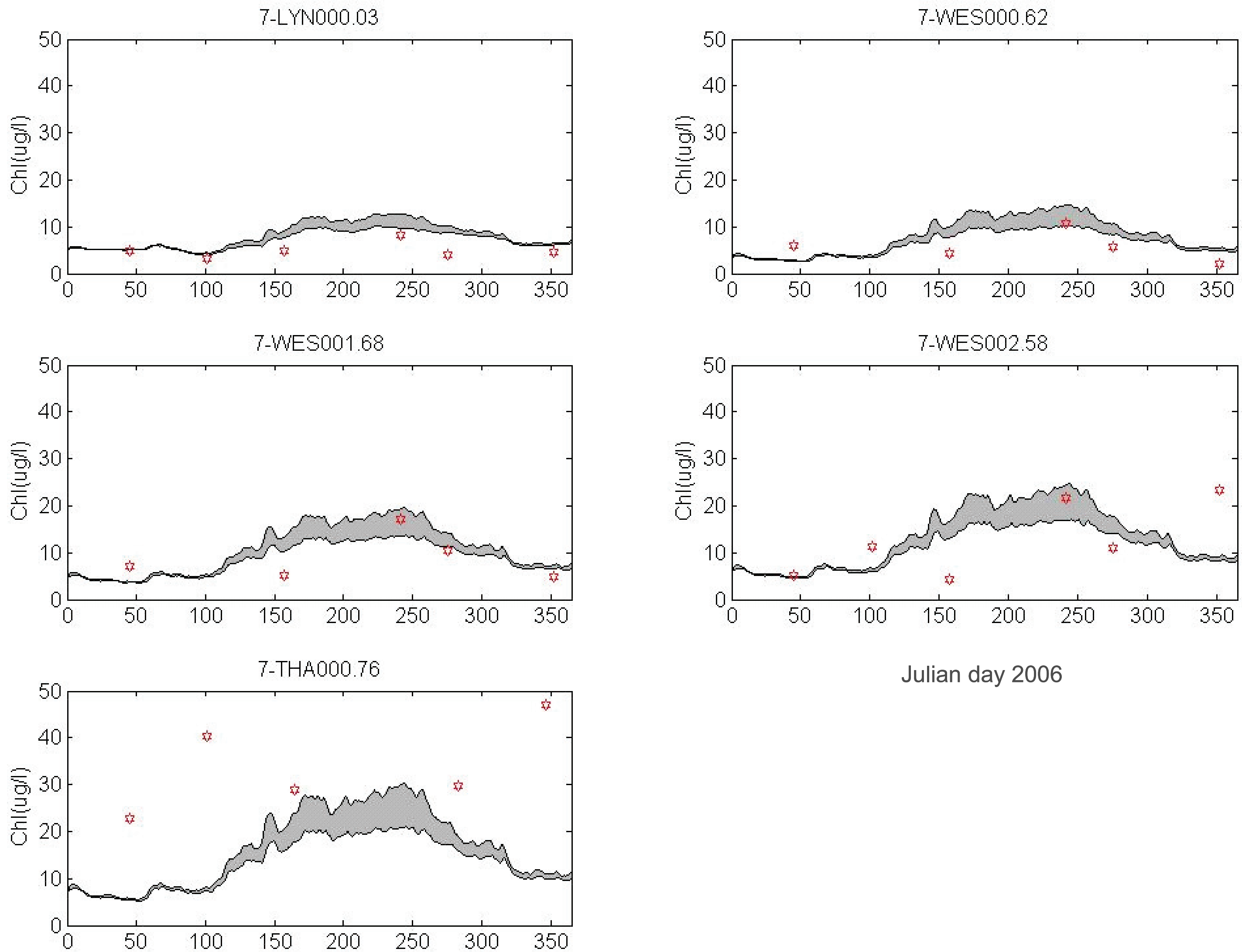

Figure 12. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Western Branch stations for 2006.

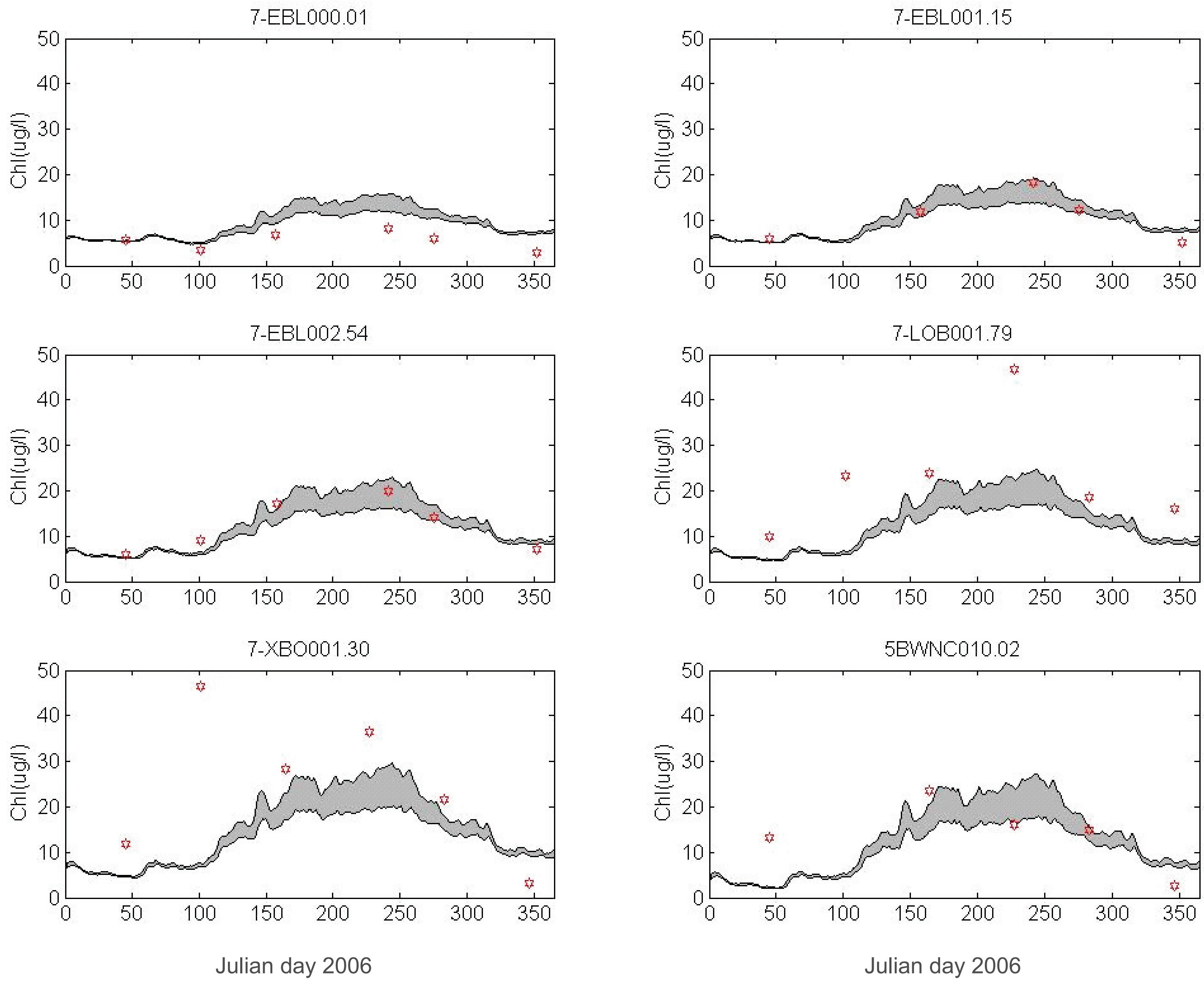

Figure 13. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Eastern Branch stations for 2006.

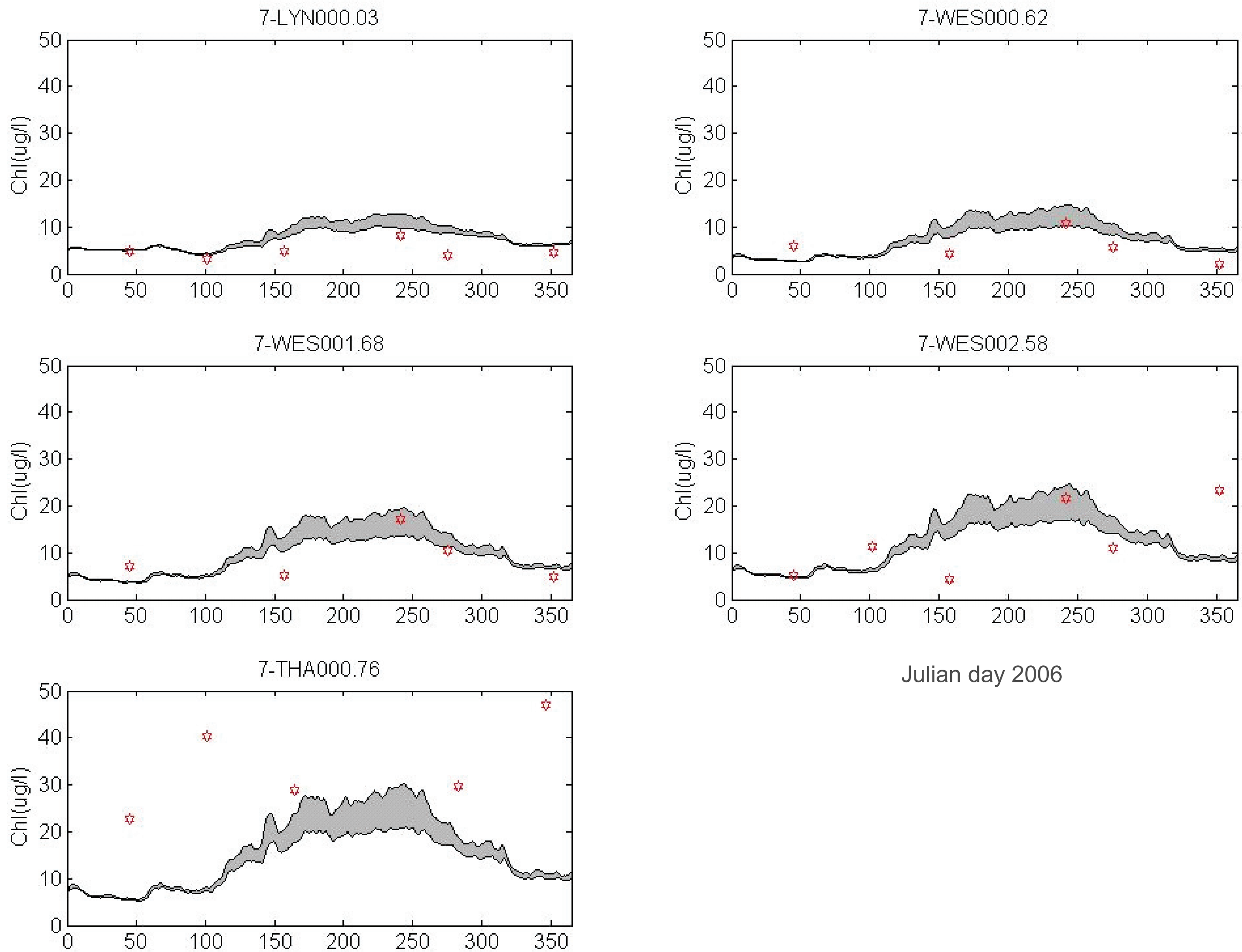

Figure 14. Chlorophyll observations (red symbols) and chlorophyll model predictions (grey areas) shown for Lynnhaven Broad Bay/Linkhorn Bay Branch stations for 2006.

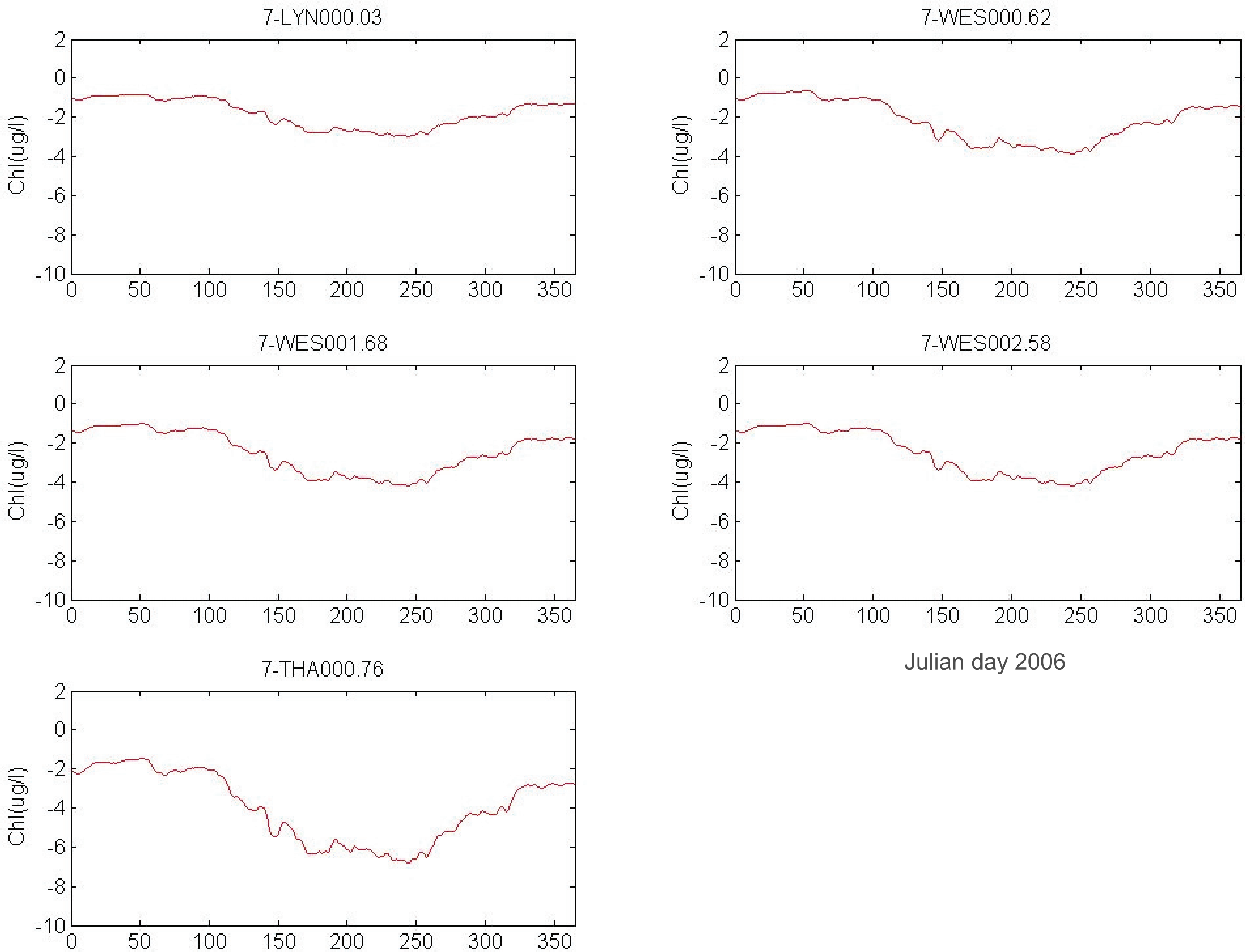

Figure 15. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

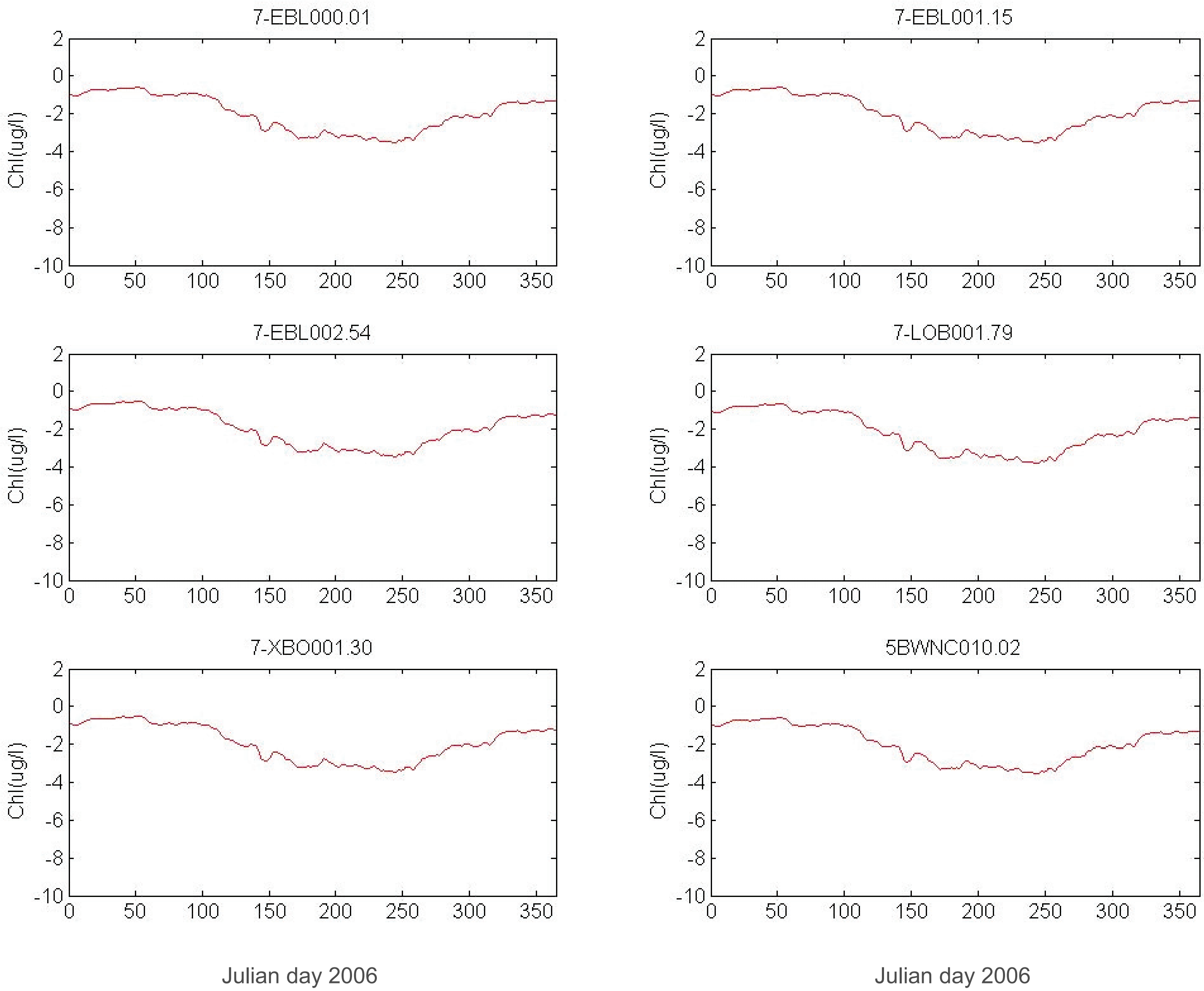

Figure 16. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

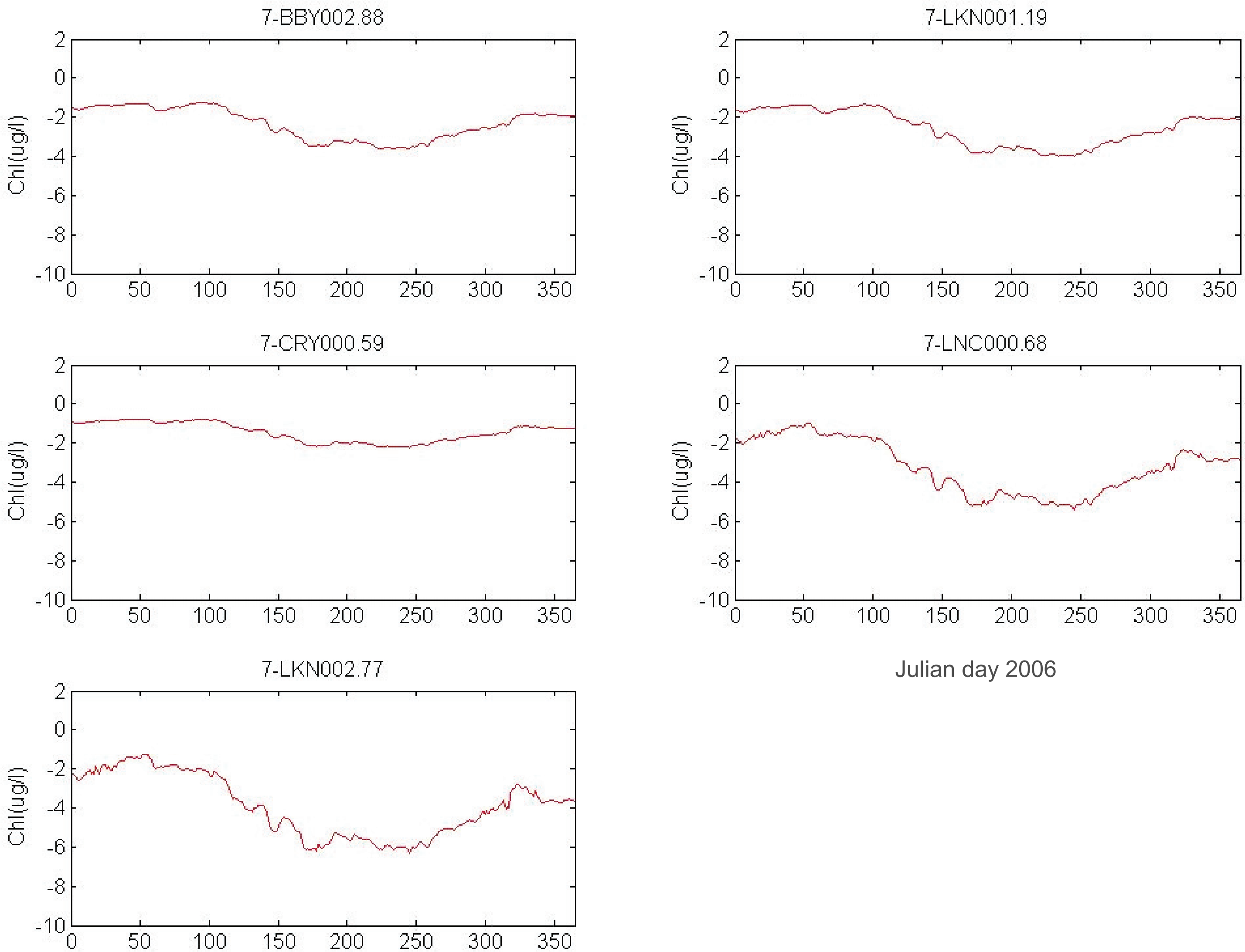

Figure 17. Chlorophyll differences (Plan A minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

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).

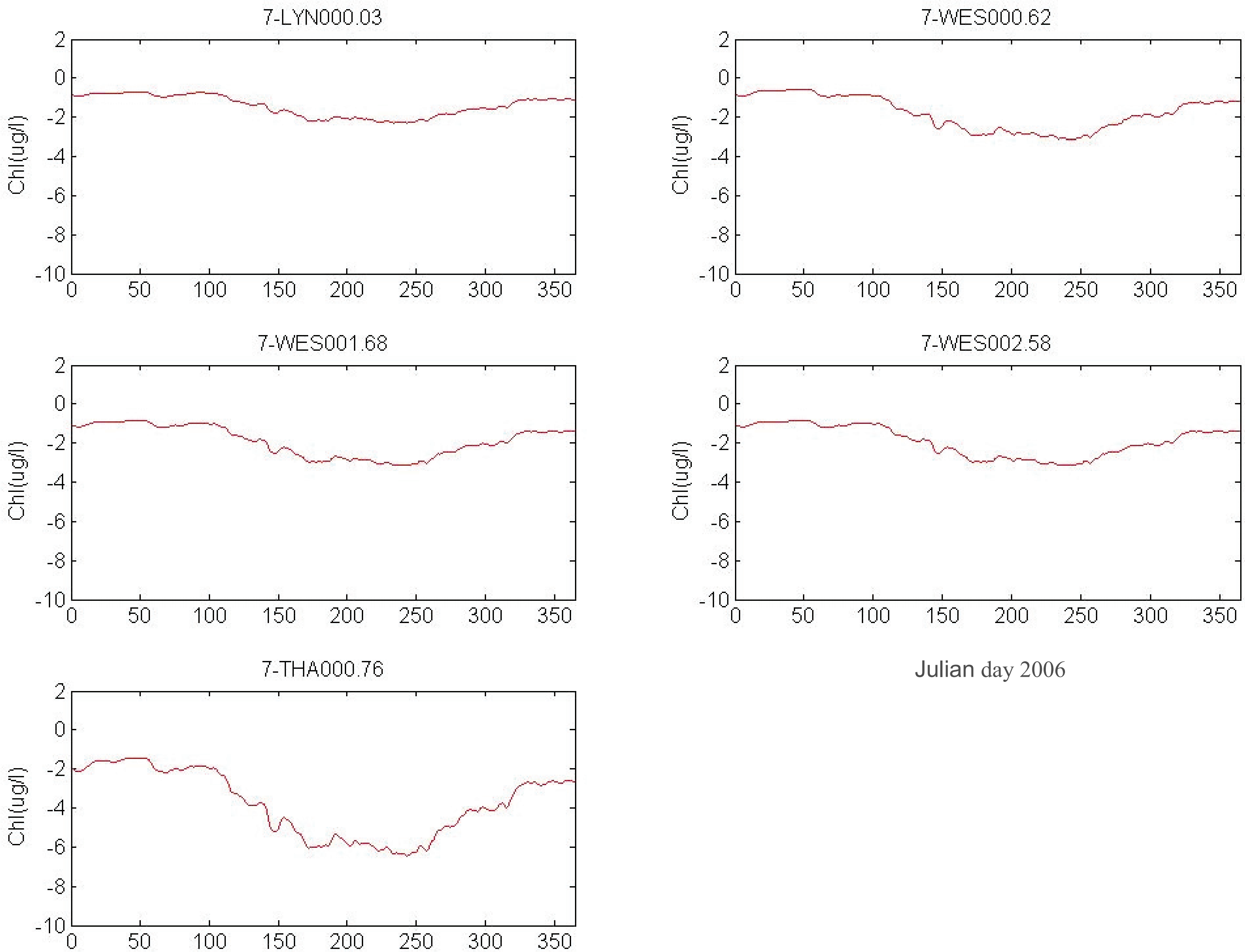

Figure 18. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Western Branch VA-DEQ stations for year 2006.

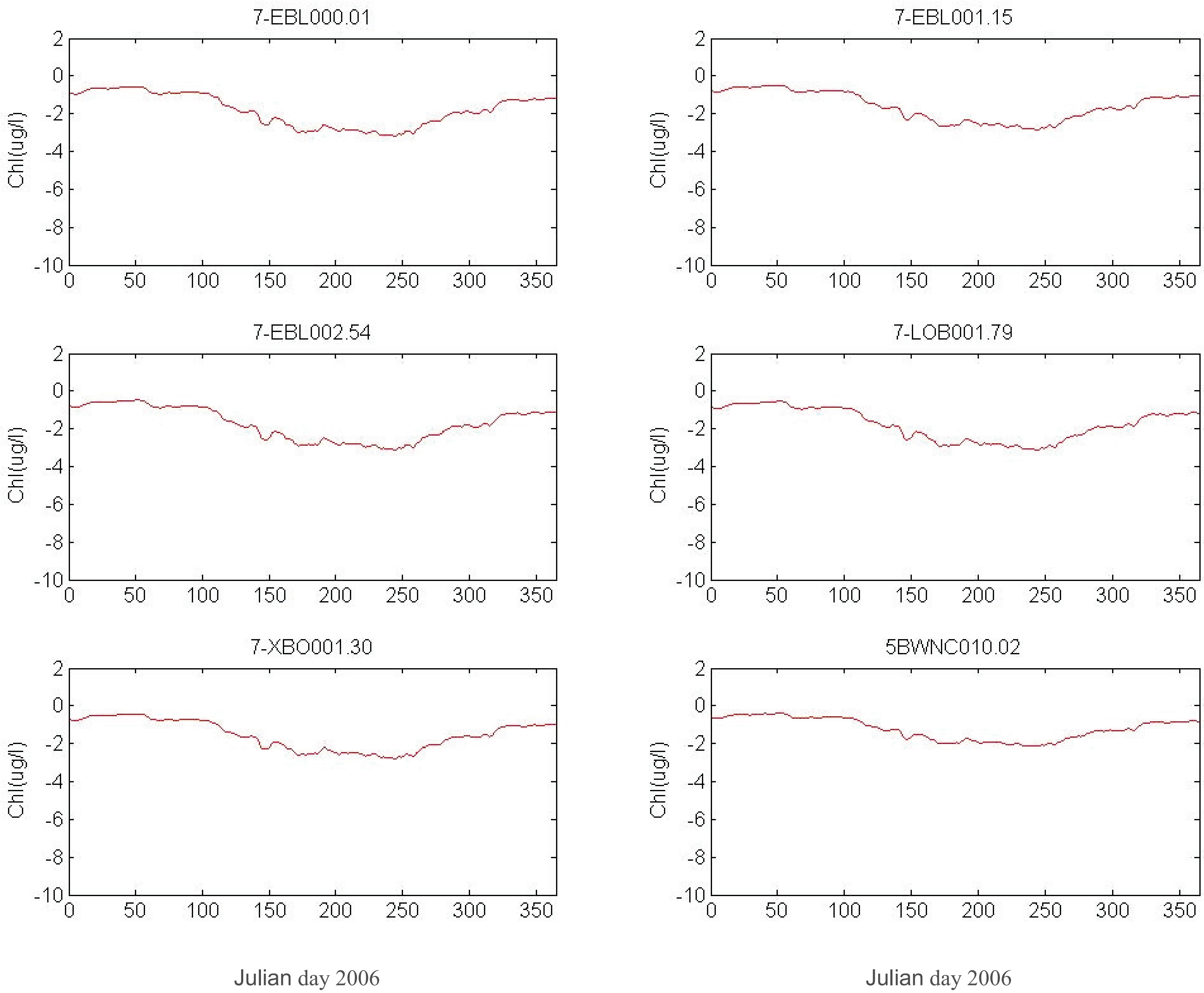

Figure 19. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Eastern Branch VA-DEQ stations for year 2006.

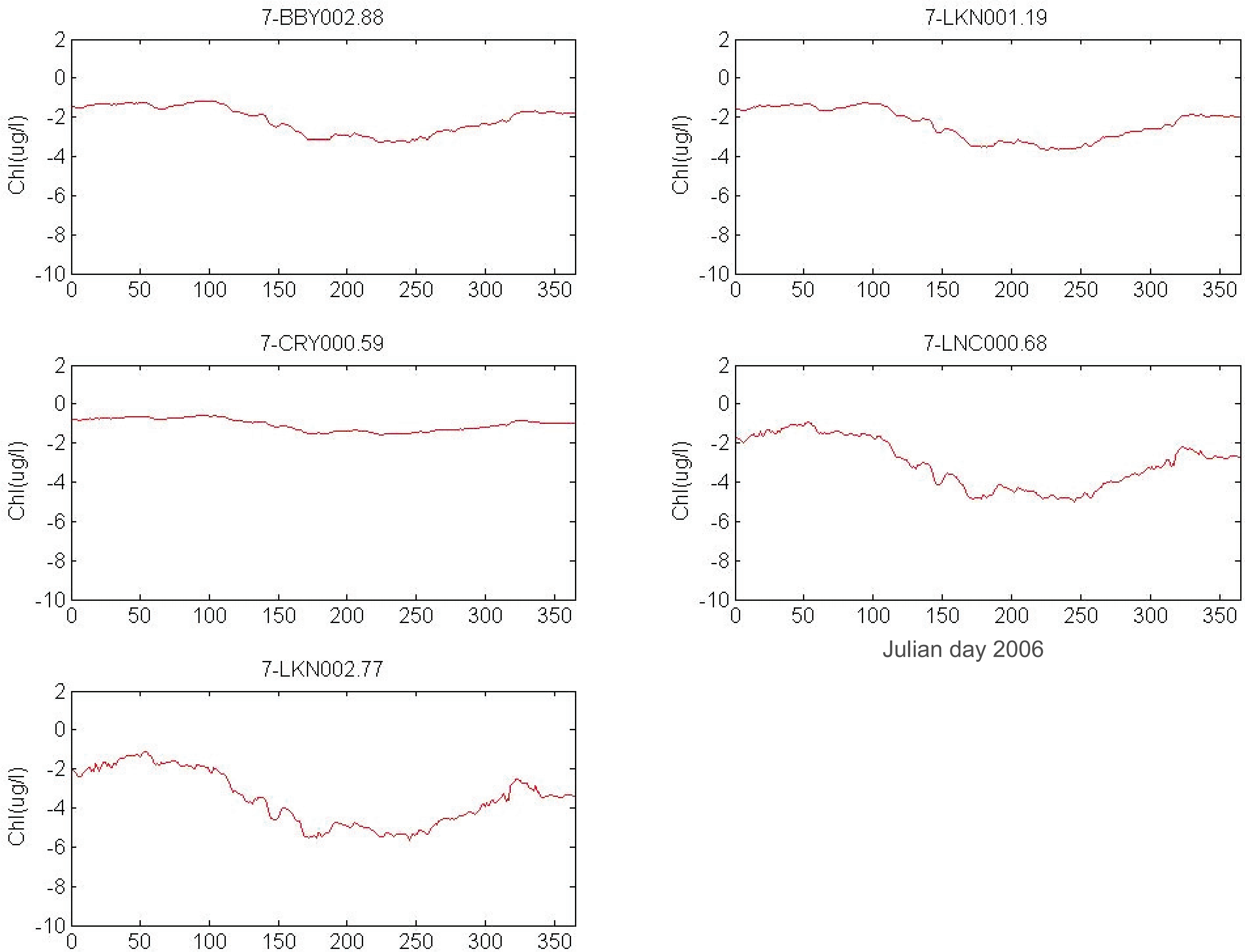

Figure 20. Chlorophyll differences (Plan B minus Base Case) shown for the Lynnhaven River Broad Bay/Linkhorn Bay Branch VA-DEQ stations for year 2006.

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				