PROGRESS REPORT
NORFOLK, VIRGINIA, FEDERAL FLOOD RISK MANAGEMENT STUDY

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1. Introduction

The City of Norfolk and Norfolk District, U.S. Army Corps of Engineers (USACE), are partnering to conduct a Flood Risk Management Study (FRMS) to determine the Federal interest and feasibility of alternatives to mitigate coastal flooding risk in the City. The FRMS is in the Feasibility Study (FS) phase in which alternatives are proposed and developed to conceptual/preliminary design level, benefit/cost analyses are conducted, and environmental studies are completed to comply with the National Environmental Policy Act (NEPA). The magnitude of the feasibility study will require an Environmental Impact Statement (EIS).

A component of the FS/EIS is the analysis of expected impacts of certain proposed alternatives on tidal circulation and water quality in four water bodies within the City, which include Broad Creek, Hague (Smith Creek), the Lafayette River, and Pretty Lake. The purpose of the modeling is to support the determination of whether the proposed alternatives will have significant impacts on circulation and water quality, and if so, to what degree and what potential mitigation actions may be applied/required.
This progress report documents the modeling scenarios, and preliminary model results for the scenarios. The document only provides a brief description of the model results. Dissolved oxygen (DO) levels are compared during spring and summer period at 9 selected stations. The time series comparison for phytoplankton, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (PO_4), and DO are presented at four selected stations. Detailed analysis and discussions will be presented in the final report.

Because the model grid has been changed, the water quality model is recalibrated due to the change of the dynamic field. Although the change of dynamic field is in terms of current and salinity, this can affect the water quality model as well. The current water quality calibration is not the same as the previous model used for the channel deepening study. We are currently evaluating the model results and refining model calibration to improve the model skill.

2. Approach

1.1 Model description

The EFDC model was selected for the model simulation. The modeling system is illustrated in Figure 2-1-1. The model tool includes a three-dimensional hydrodynamic model and a eutrophication sub-model. The hydrodynamics model is forced by tide, salinity, and temperature at the mouth, solar radiation, wind, and atmospheric pressure at the surface, freshwater discharge at the fall-line of the James River, and lateral runoff from adjacent watersheds (Figure 2-1-2). The open boundary conditions of tide, salinity, and temperature are obtained from the Chesapeake Bay large-domain model simulated by the SCHISM model (Zhang et al. (2017)). A three-year simulation from 2011-2013 was conducted. The model starts one year earlier to ensure that the initial condition has no impact for this three-year simulation period.

The water quality model is coupled with the hydrodynamic model and simulates the eutrophication processes. The daily flow and nutrient loadings, including organic and inorganic nitrogen and phosphorus, are obtained from the DEQ watershed model developed by TetraTech (Shen et al., 2017). The water column eutrophication model is coupled with a sediment process model with twenty-seven state variables (DiToro and Fitzpatrick, 1993). The sediment process model, upon receiving the particulate organic matter deposited from the overlying water column, simulates their diagenesis and the resulting fluxes of inorganic substances (ammonium, nitrate, phosphate, and silica) and sediment oxygen demand back to the water column. The coupling of the sediment process model enables the model to simulate the long-term changes in water quality conditions in response to changes in nutrient loadings. The initial condition for bottom sediment model was obtained by repeating the model simulation from 2010-2013 until the bottom deposition reached dynamic equilibrium. The model simulation shows the the sediment flux of nutrients and DO does not show a very large interannual variaion. Detailed eutrophication model kinetics will be presented in the final report.

In order to simulate the flood barrier in the Lafayette River accurately, the existing James and Elizabeth River model grid has been revised to increase model grid resolution in the Lafayette and Elizabeth River. The model grids for the James River and the Lafayette River are shown in Figures 2-1-3 and 2-1-4, respectively. Because of the high exchange between the Lafayette River and Elizabeth River, and between the Elizabeth River and the James River, one must simulate the entire James River together with the Elizabeth and Lafayette Rivers. Therefore it is not feasible to construct the model grid with very high resolution. The grid size of the floodgate is used as the guideline for the grid refinement to ensure that the fluxes through each floodgate are correctly simulated.

Both model calibrations for hydrodynamic and water quality models were conducted. Any slight change of either the dynamics field or the residence time will affect the water quality model results. The current model calibration results do not exactly match those results of the recent channel deepening study. The model calibration results are presented in Appendix A.

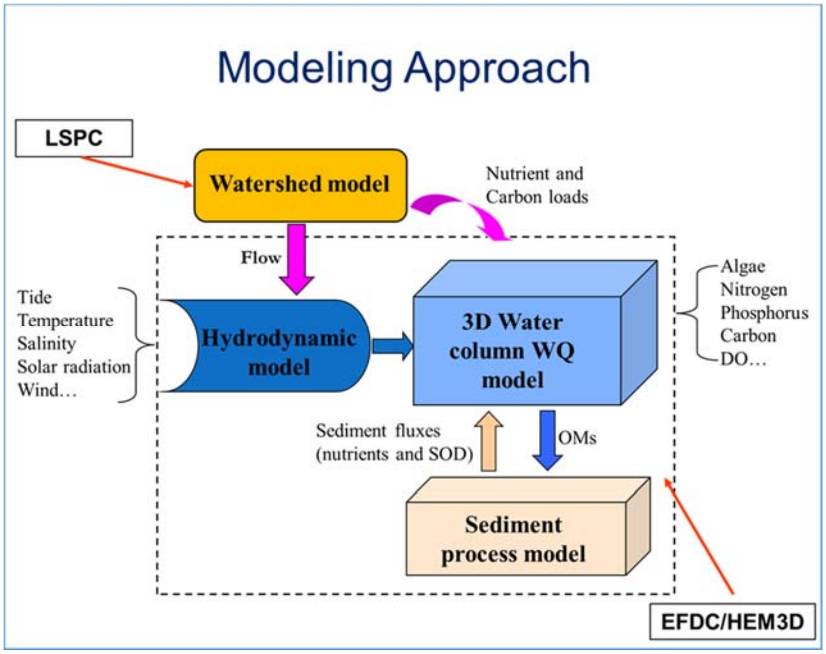


Figure 2-1-1: A Diagram of the Modeling Approach for the James River.

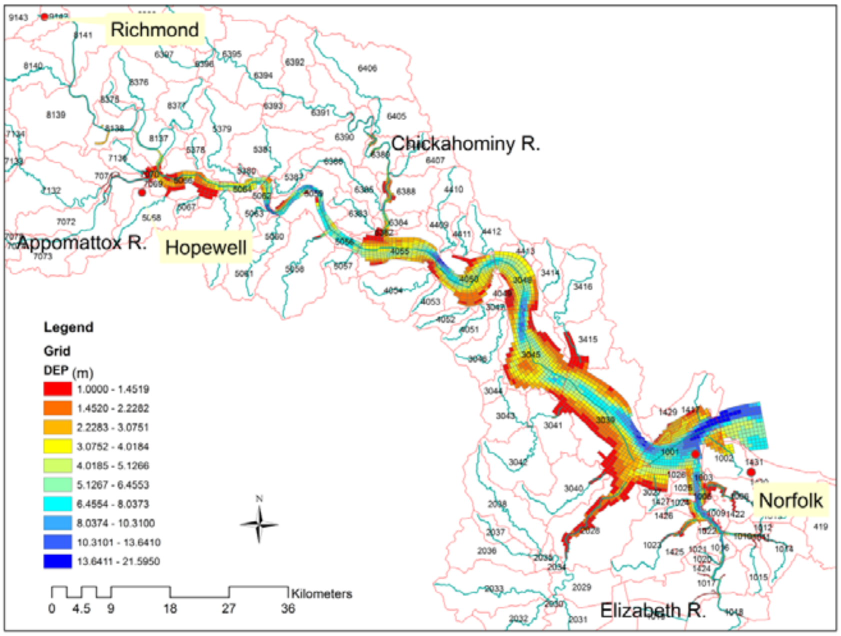


Figure 2-1-2: A Map Showing the Linkage of the Watershed and James River Models.

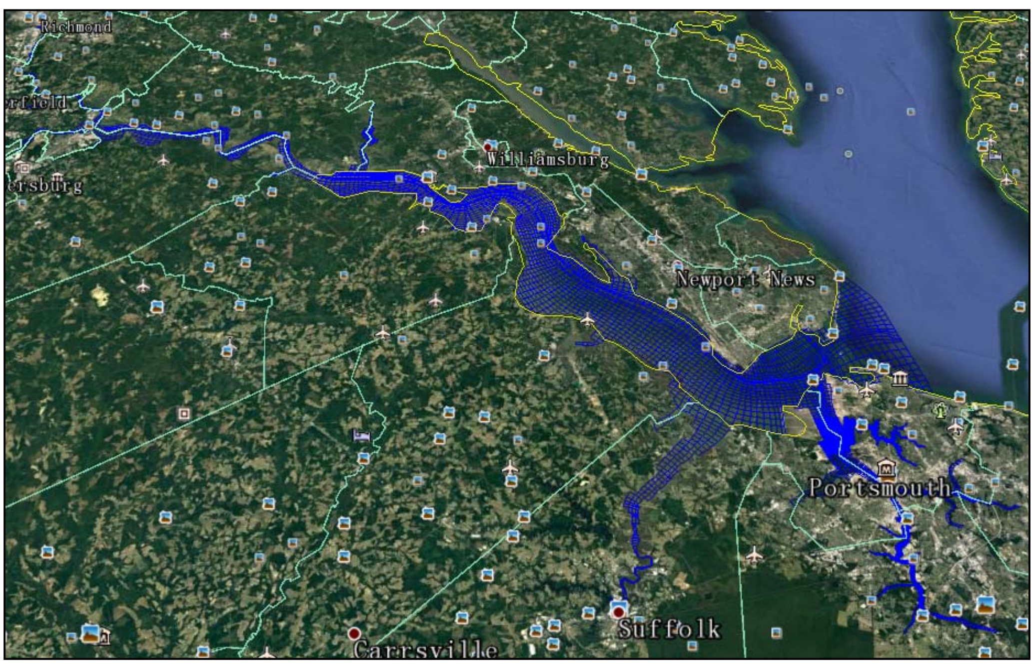


Figure 2-1-3: The EFDC Model Grid for the James River.

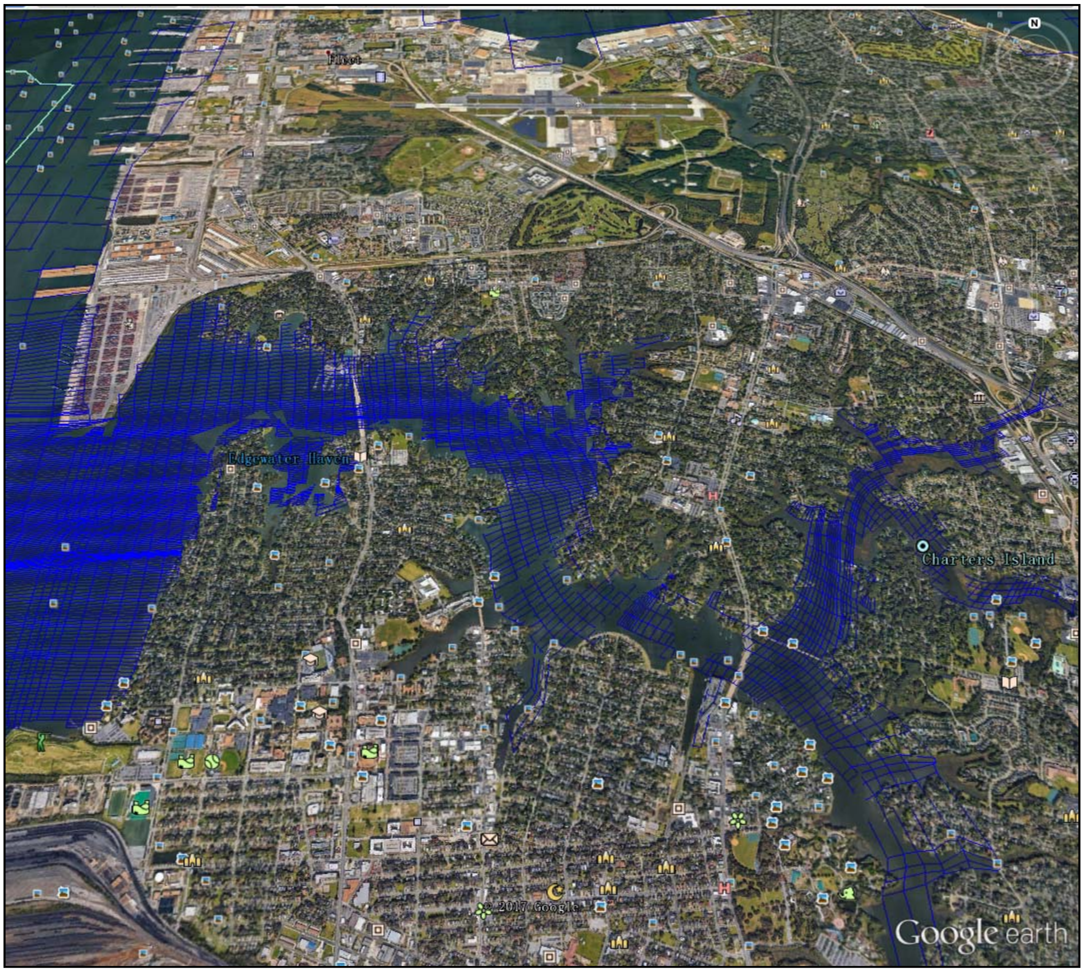


Figure 2-1-4: The Revised EFDC Model Grid for the Lafayette River

1.2 Model Scenarios

Eight model simulations were conducted to assess the impact of the installation of floodgates on water quality conditions. Two floodgate configurations are proposed: 1) a "large-barrier" configuration with 19 floodgates located near the mouth of the Lafayette River. The length of the the large barrier is about 2 km. 2) a "small-barrier" configuration with 5 floodgates located in the middle of the Lafayette River. The length of this smaller barrier is about 0.5 km. We tested scenarios of opening all designed floodgates and half-designed floodgates for both large and small barriers. In addition, the impact of the installation of floodgates on the water quality condition under the sea level rise (SLR) of 1.0 m was conducted. A description of each scenario is listed in Table 2-2-1. The model grids for large and small barriers are shown in Figures 2-2-1 and 2-2-2, respectively.

To evaluate the impact of the installation of floodgates on water quality, nine stations were selected for comparing between the simulation with project and without project and with and without project under further SLR condition. The locations of the selected stations are shown in Figure 2-2-3. Two stations are located outside of the Lafayette River but inside the Elizabeth River, and 7 stations are located inside the Lafayette River.

Table 2-2-1. Descriptions of Scenarios

Scenario	Description
Baseline (S00)	Current condition without project
S01	Simulation of large-barrier configuration with all designed gates open (total of 19 gates)
S02	Simulation of small-barrier configuration with all designed gates open (total of 5 gates)
S03	Simulation of large-barrier configuration with approximately half the gates closed (total of 9 gates are closed)
S04	Simulation of small-barrier configuration with approximately half the gates closed (total of 3 gates are closed)
Future Baseline (S05)	Future baseline condition without project with a sea-level rise of 1.0 m
S06	Future condition simulation of large-barrier configuration with all designed gates open (total of 19 gates) with a sea-level rise of 1.0 m
S07	Future condition simulation of small-barrier configuration with all designed gates open (total of 5 gates) with a sea-level rise of 1.0 m
S08	Future condition simulation of large-barrier configuration with approximately half the gates closed (total of 9 gates are closed) with a sea-level rise of 1.0 m

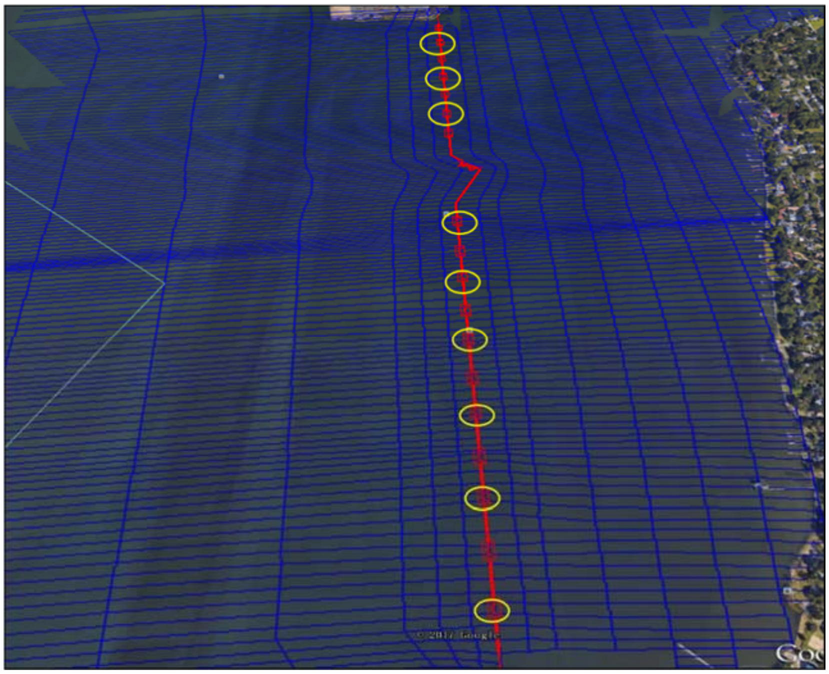


Figure 2-2-1. The Proposed Large-Barrier Configuration with 19 Floodgates (yellow circles designate floodgates that will be closed for scenario simulations of S03 and S08).

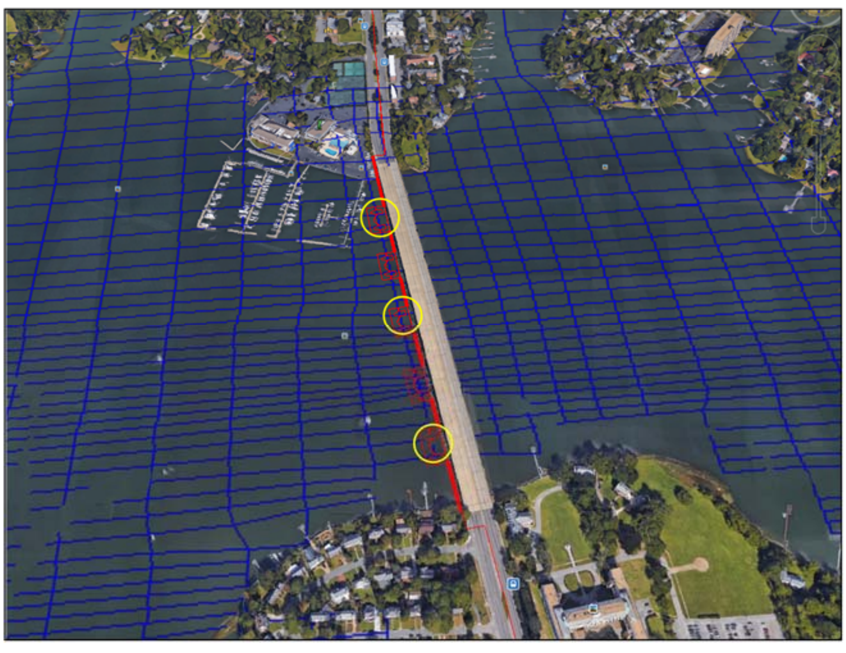


Figure 2-2-2. The Proposed Small-Barrier Configuration with 5 Floodgates (yellow circles designate floodgates that will be closed for scenario simulation of S04).

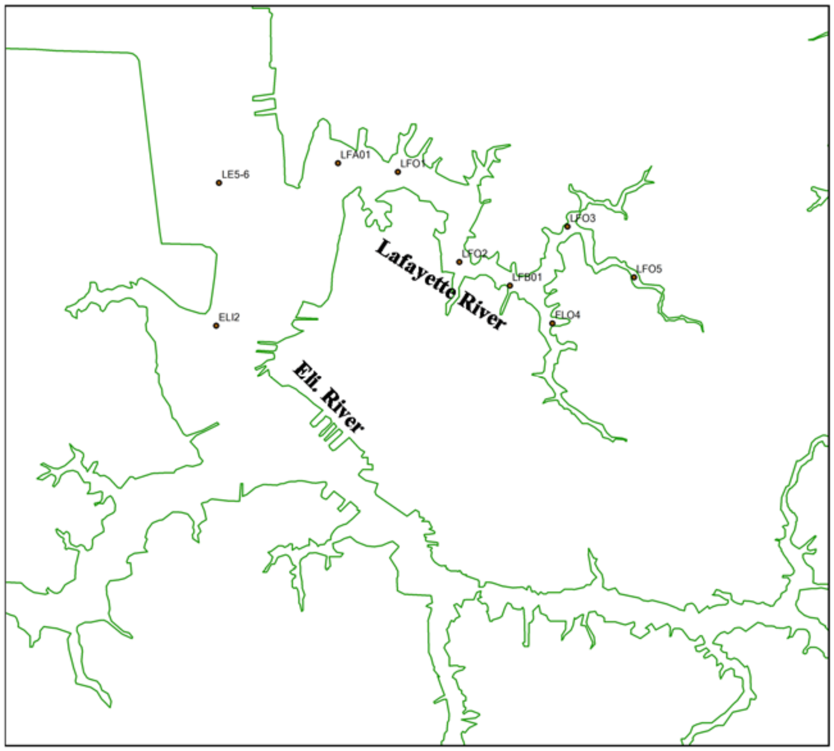


Figure 2-2-3. Locations of Stations for Water Quality Assessment for Each Scenario.

3. Model Results

Dissolved oxygen is the key water quality parameter used to assess the water quality condition in estuaries. Model simulation results are presented based on each scenario. We compare the difference between each scenario and the baseline condition. Statistics in spring (March-May) and summer (July-September) are presented for comparison. Comparisons of the model result for each scenario and baseline condition are conducted at nine selected stations (Fig. 2-2-3). As all changes of geometry are located inside the Lafayette River (LR), we therefore selected representative stations located inside the Elizabeth River (ER) near the Lafayette River mouth and inside the Lafayette River. Comparison of DO results for mean and bottom DO and the difference between scenario runs and baseline conditions or further baseline conditions (SLR by 1.0m) are listed in corresponding tables.

Time series comparisons of phytoplankton, dissolved inorganic nitrogen (DIN) and inorganic phosphorus (PO_4), and DO are presented in corresponding figures at 4 selected stations.

3.1 Comparison of Scenario S01 and Baseline Condition

This scenario simulated the large-barrier configuration with all 19 floodgates open under the current condition. The results for DO are listed in Tables 3-1-1 and 3-1-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-1-1 to 3-1-4. The remaining stations inside the Lafayette River are shown in Appendix B.

The results show that the larges differences of mean and bottom DO are -0.81 mg/L and -0.77 mg/L, respectively, during spring. The DO at ER has a slight increase, while DO has a slight decrease at the upstream stations inside the LR. The maximum differences of mean and bottom DO are -0.52 and -0.45 mg/L, respectively, during the summer. DO decreases slightly at the upstream stations inside the LR. The bottom DO difference is 5.5% at Station LFO5 during summer.

Table 3-1-1: Comparison of Scenario S01 and Baseline for DO during Spring

	Baseline		S01		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.73	6.11	6.99	6.37	0.25	0.25	3.77	4.14
ELI2	6.89	5.78	7.12	6.00	0.23	0.22	3.34	3.85
LFA01	7.38	7.34	7.60	7.59	0.23	0.25	3.10	3.42
LFB01	7.99	7.74	7.78	7.59	-0.21	-0.15	-2.62	-1.95
LFO1	7.28	7.24	7.42	7.40	0.14	0.15	1.89	2.12
LFO2	7.51	7.39	7.45	7.35	-0.06	-0.04	-0.82	-0.54
LFO3	8.48	8.38	8.06	7.97	-0.43	-0.42	-5.05	-4.95
LFO4	8.60	8.43	8.27	8.11	-0.34	-0.31	-3.90	-3.74
LFO5	9.60	9.35	8.78	8.58	-0.81	-0.77	-8.49	-8.22

Table 3-1-2: Comparison of Scenario S01 and Baseline for DO during Summer

	Baseline		S01		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.61	3.91	4.81	4.13	0.20	0.23	4.40	5.77
ELI2	4.63	3.39	4.81	3.56	0.17	0.16	3.78	4.85
LFA01	5.84	5.74	6.07	5.98	0.23	0.24	3.91	4.20
LFB01	6.84	6.55	6.78	6.55	-0.06	-0.00	-0.88	-0.01
LFO1	5.89	5.80	6.07	6.00	0.19	0.20	3.15	3.46
LFO2	6.30	6.10	6.38	6.22	0.08	0.11	1.20	1.81
LFO3	7.52	7.39	7.26	7.15	-0.26	-0.24	-3.45	-3.22
LFO4	7.40	7.08	7.27	7.01	-0.13	-0.08	-1.79	-1.07
LFO5	8.40	8.18	7.88	7.73	-0.52	-0.45	-6.17	-5.52

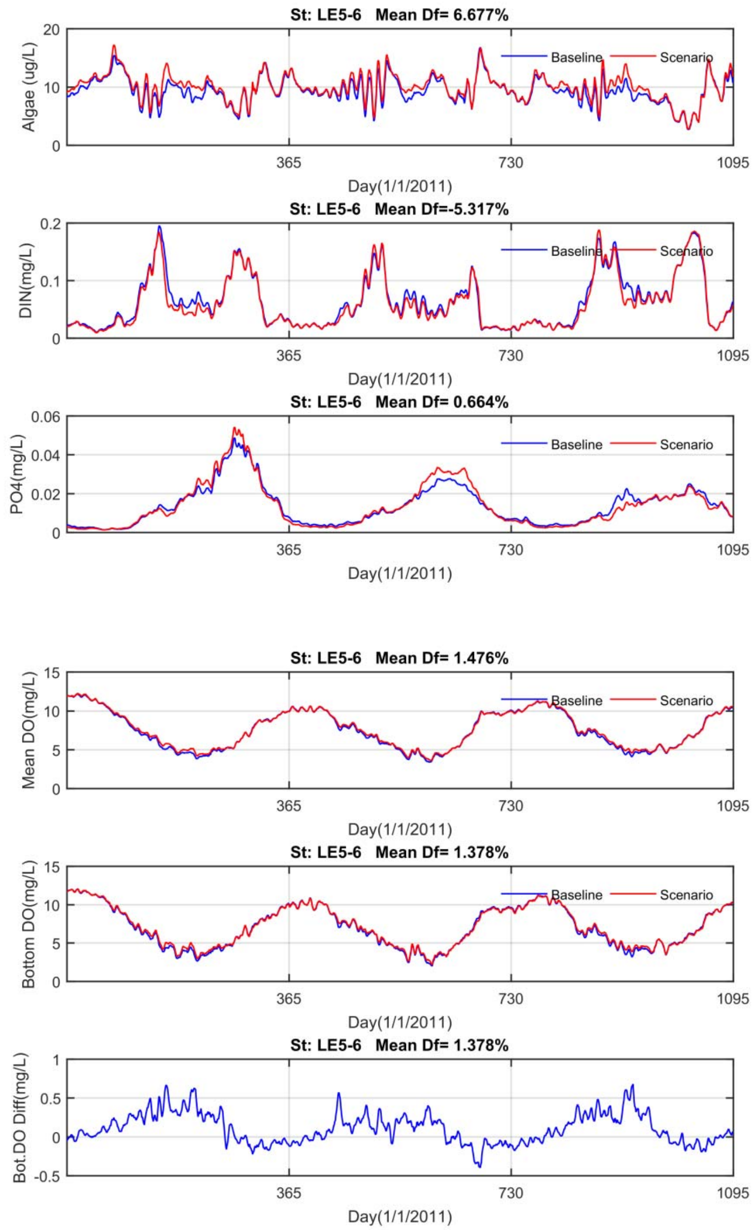


Figure 3-1-1: Comparison of Baseline and S01 Results at Station LE5-6

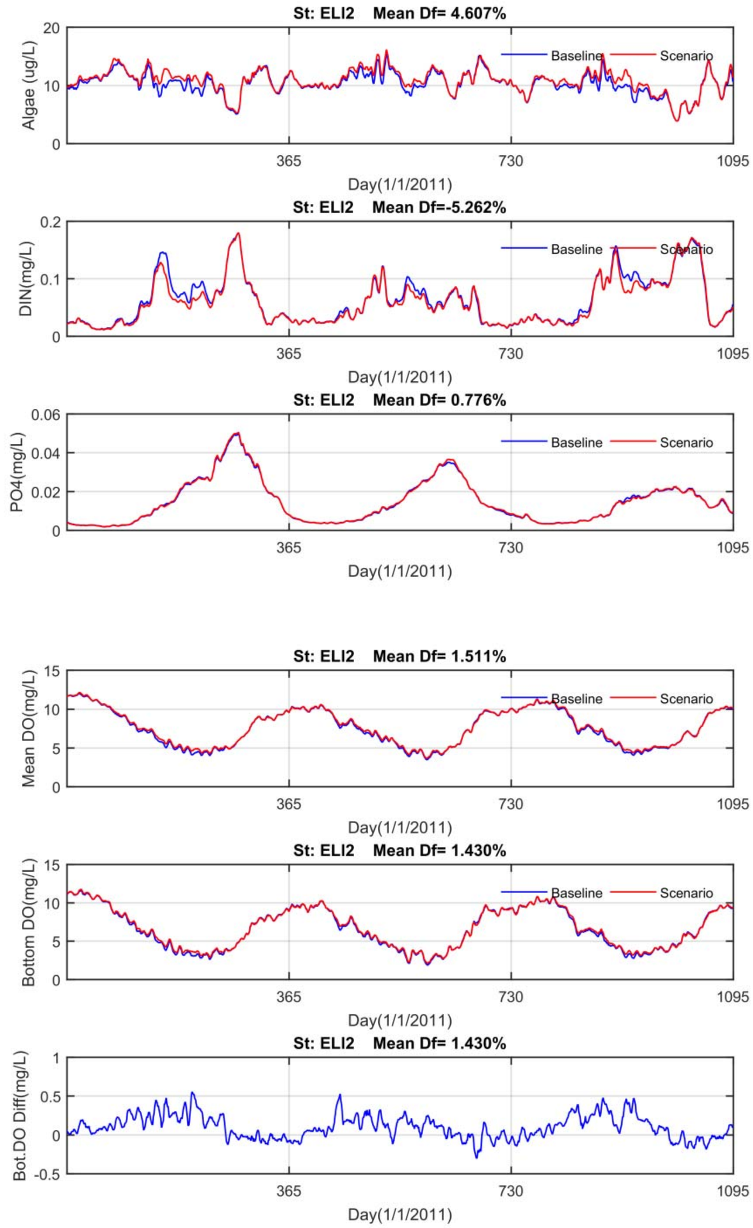


Figure 3-1-2: Comparison of Baseline and S01 Results at Station ELI2

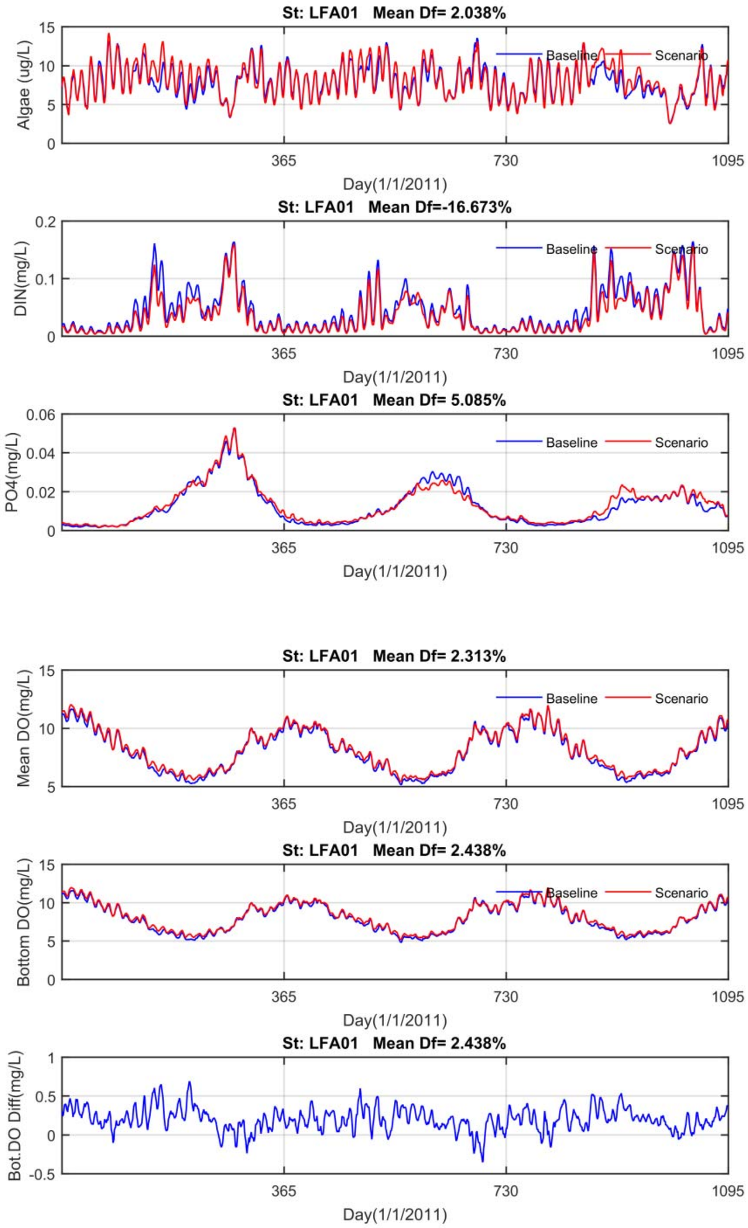


Figure 3-1-3: Comparison of Baseline and S01 Results at Station LFA01

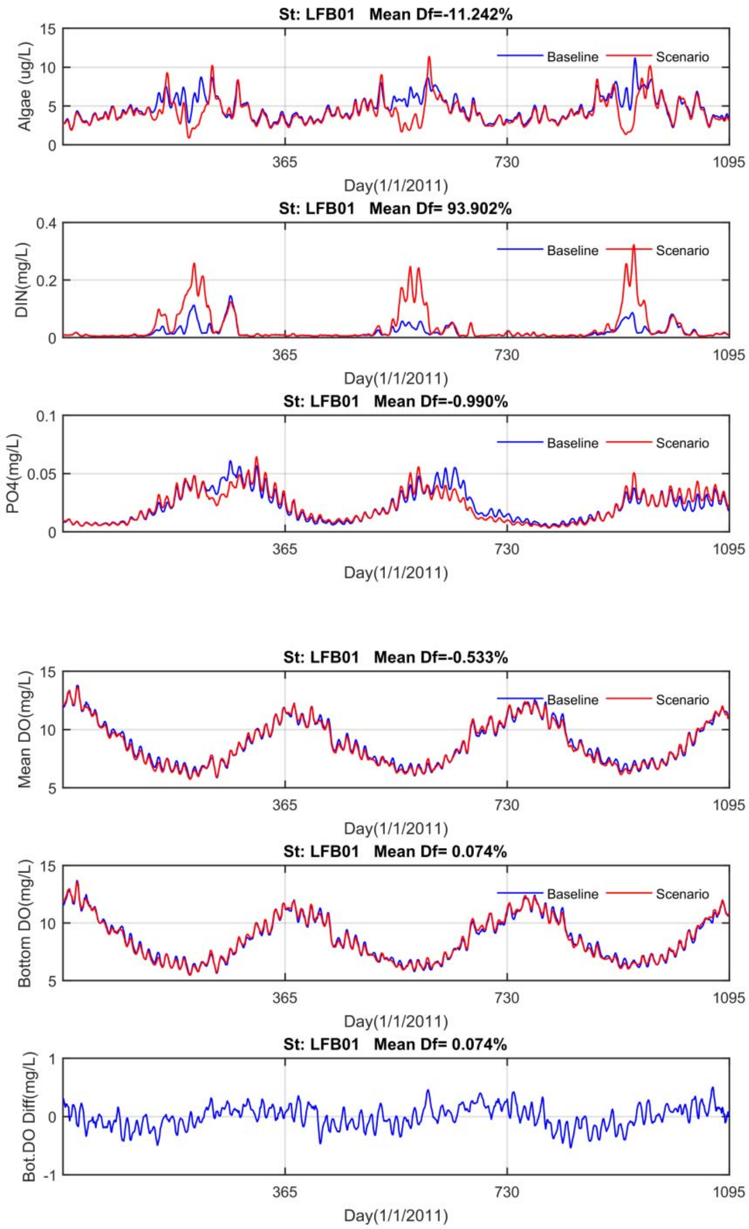


Figure 3-1-4: Comparison of Baseline and S01 Results at Station LFB01

3.2 Comparison of Scenario S02 and Baseline Condition

This scenario simulated the existing condition with the small-barrier configuration with all 5 floodgates open. The results for DO are listed in Tables 3-2-1 and 3-2-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-2-1 to 3-2-4.

The results show that the largest differences of mean and bottom DO are -0.75 and -0.69 mg/L, respectively, during spring. The DO with ER has a slight increase, while DO has a slight decrease at upstream stations inside the LR. The maximum differences of mean and bottom are -0.44 and -0.37 mg/L, respectively, during the summer. DO decreases slightly at the upstream stations inside the LR. The bottom DO difference is 4.5% at Station LFO5 during summer. It can be seen that, overall, changes are on the same order of magnitude as those resulting from the S01 being compared to the baseline condition.

Table 3-2-1: Comparison of Scenario S02 and Baseline for DO during Spring

	Baseline		S02		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.73	6.11	6.96	6.35	0.22	0.23	3.30	3.84
ELI2	6.89	5.78	7.06	5.97	0.17	0.19	2.43	3.31
LFA01	7.38	7.34	7.54	7.51	0.16	0.17	2.19	2.36
LFB01	7.99	7.74	7.81	7.63	-0.18	-0.11	-2.24	-1.46
LFO1	7.28	7.24	7.40	7.37	0.12	0.13	1.67	1.77
LFO2	7.51	7.39	7.51	7.40	-0.00	0.01	-0.05	0.20
LFO3	8.48	8.38	8.10	8.00	-0.39	-0.38	-4.58	-4.56
LFO4	8.60	8.43	8.26	8.12	-0.34	-0.31	-4.01	-3.67
LFO5	9.60	9.35	8.85	8.65	-0.75	-0.69	-7.77	-7.43

Table 3-2-2: Comparison of Scenario S02 and Baseline for DO during Summer

	Baseline		S02		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.61	3.91	4.79	4.12	0.18	0.21	4.01	5.47
ELI2	4.63	3.39	4.76	3.54	0.13	0.14	2.72	4.19
LFA01	5.84	5.74	6.00	5.92	0.16	0.18	2.74	3.14
LFB01	6.84	6.55	6.80	6.56	-0.04	0.02	-0.60	0.24
LFO1	5.89	5.80	6.09	5.99	0.20	0.19	3.39	3.35
LFO2	6.30	6.10	6.40	6.24	0.10	0.13	1.64	2.18
LFO3	7.52	7.39	7.31	7.20	-0.21	-0.19	-2.77	-2.56
LFO4	7.40	7.08	7.25	7.00	-0.15	-0.08	-2.01	-1.13
LFO5	8.40	8.18	7.96	7.81	-0.44	-0.37	-5.29	-4.51

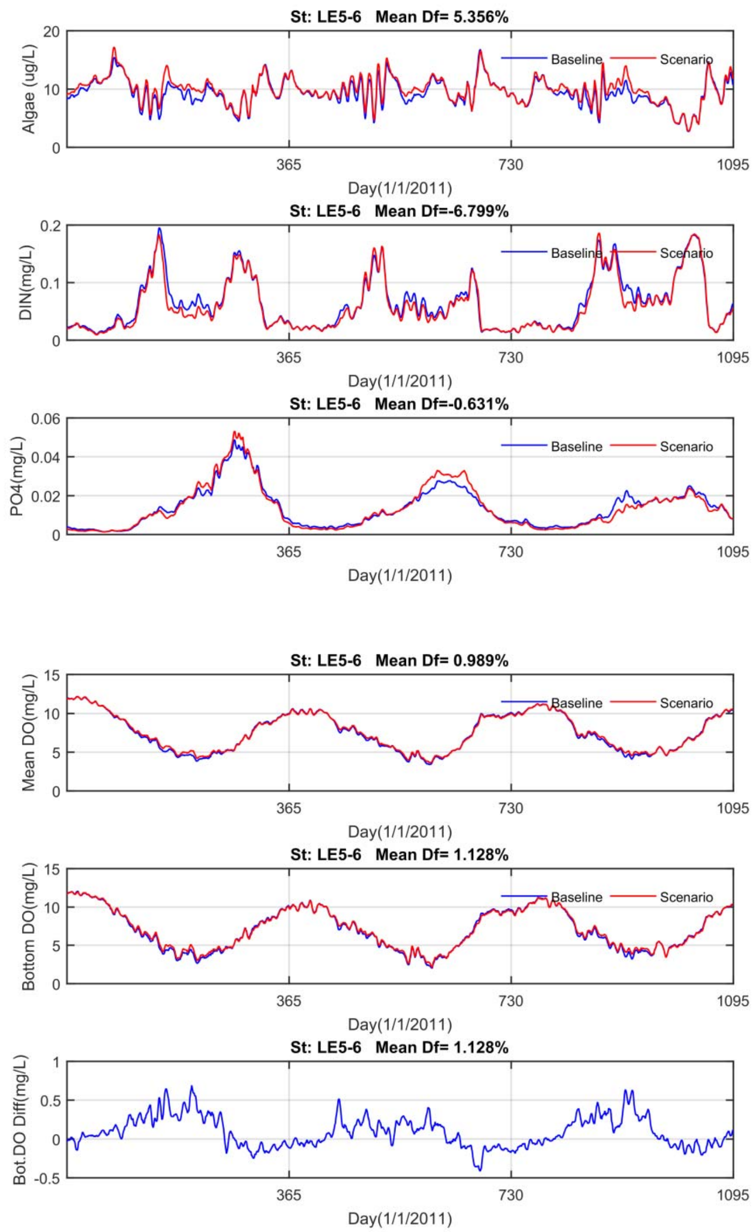


Figure 3-2-1: Comparison of Baseline and S02 Results at Station LE5-6

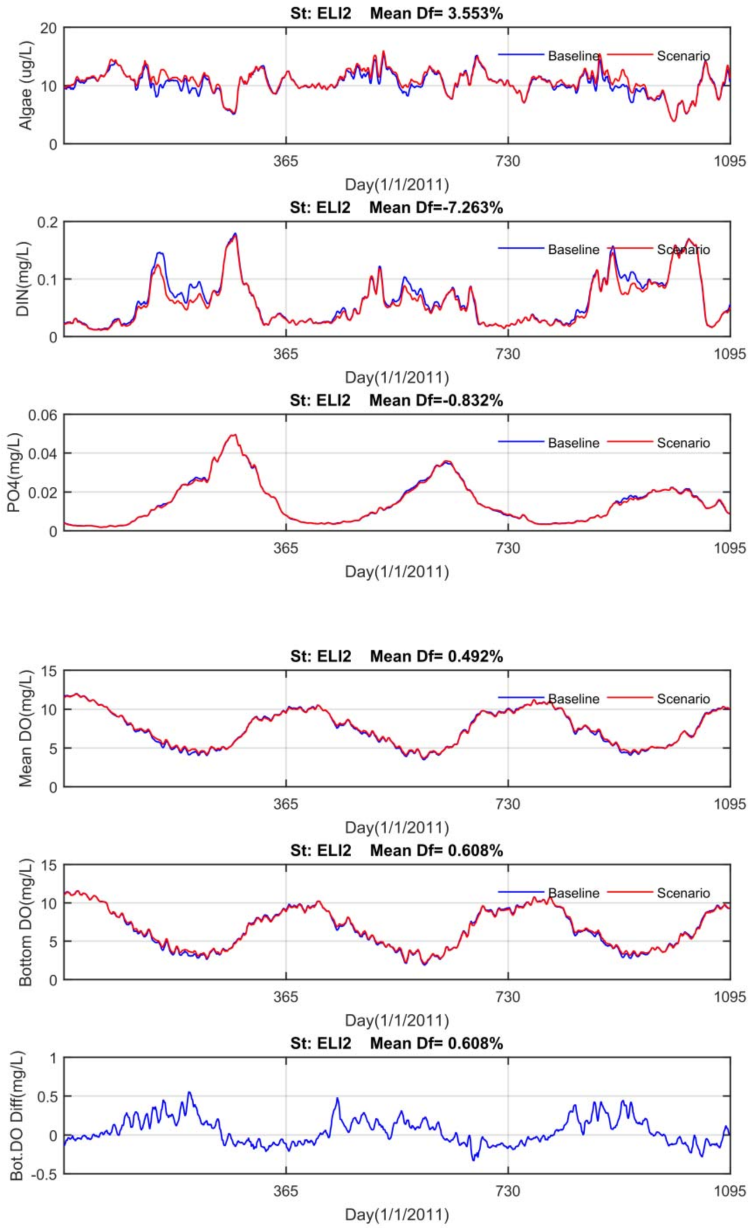


Figure 3-2-3: Comparison of Baseline and S02 Results at Station ELI2

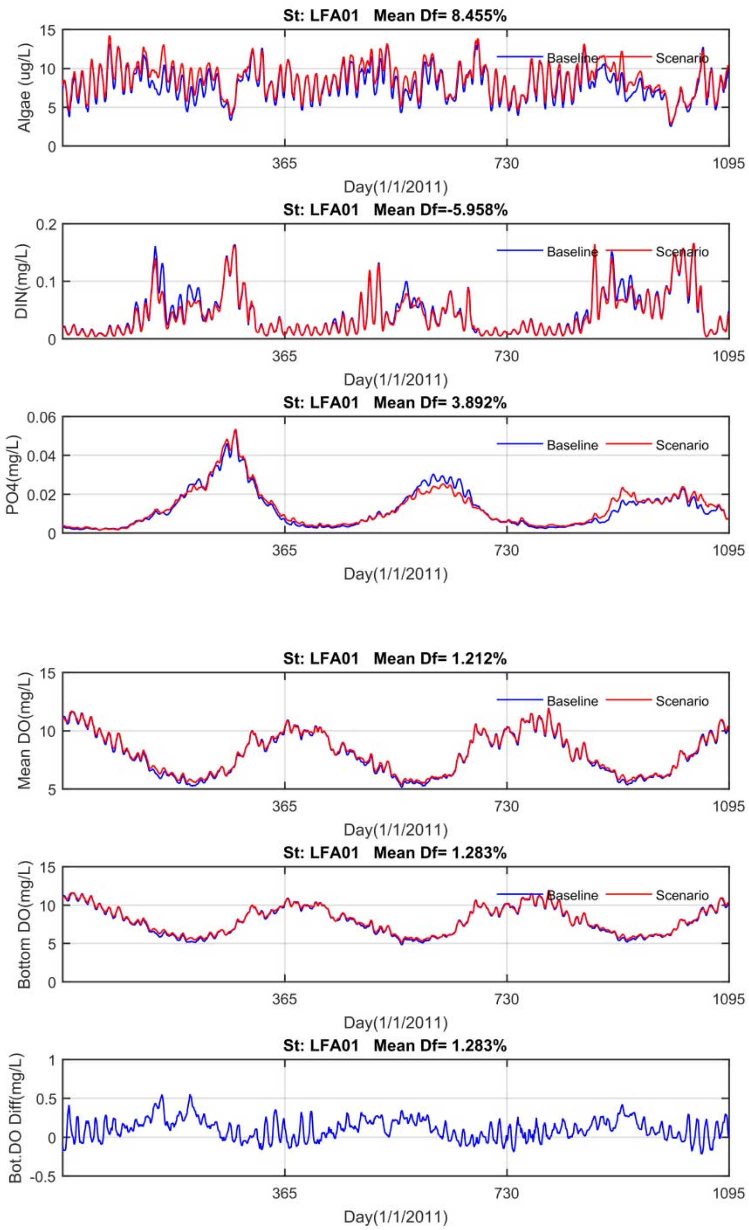


Figure 3-2-3: Comparison of Baseline and S02 Results at Station LFA01

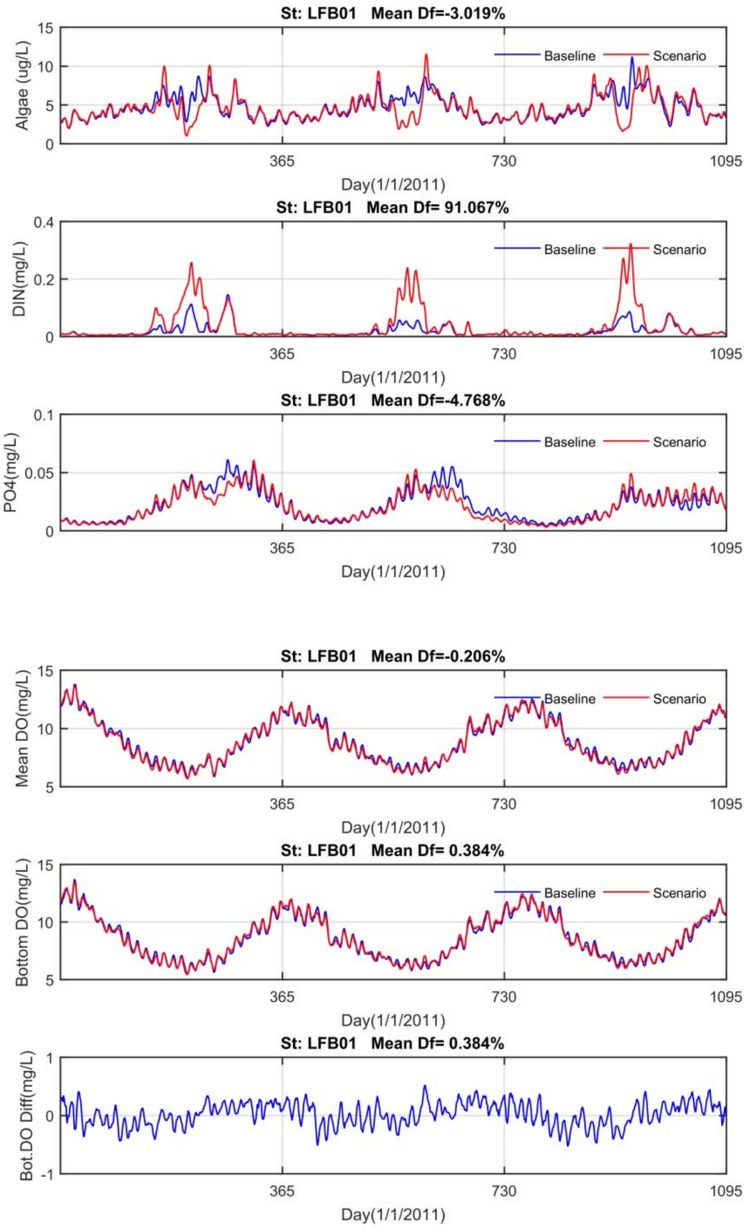


Figure 3-2-4: Comparison of Baseline and S02 Results at Station LFB01

3.3 Comparison of Scenario S03 and baseline condition

This scenario simulated the existing condition with the large-barrier configuration. The simulation is the same as that of S01, but with only half the number of designed floodgates (10 gates) being open. The results for DO are listed in Tables 3-3-1 and 3-3-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-3-1 to 3-3-4.

The results show that the larget differences of mean and bottom DO are -1.12 and -1.14 mg/L, respectively, during spring. The DO at ER has a slight increase, while DO decreases at upstream stations inside the LR. The maximum differences of mean and bottom DO are -0.84 and -0.75 mg/L, respectively, during the summer. DO decreases at the upstream stations inside the LR. The bottom DO difference is -9.2% at Station LFO5 during summer. It can be seen that DO decreases more when less floodgates were open. Comparisons of DO for S03 and S01 are listed in Tables 3-3-3 and 3-3-4, respectively, for spring and summer. Because fewer floodgates were open, tidal energy propagating to the upstream of the LR was reduced resulting in a decrease of DO.

Table 3-3-1: Comparison of Scenario S03 and Baseline for DO during Spring

	Baseline		S03		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.73	6.11	7.02	6.37	0.29	0.25	4.24	4.16
ELI2	6.89	5.78	7.17	6.03	0.28	0.25	4.03	4.40
LFA01	7.38	7.34	7.81	7.80	0.43	0.46	5.85	6.27
LFB01	7.99	7.74	7.81	7.67	-0.18	-0.07	-2.31	-0.95
LFO1	7.28	7.24	7.62	7.61	0.34	0.36	4.70	5.02
LFO2	7.51	7.39	7.57	7.48	0.06	0.10	0.83	1.29
LFO3	8.48	8.38	7.98	7.90	-0.51	-0.48	-6.00	-5.72
LFO4	8.60	8.43	8.23	8.07	-0.37	-0.35	-4.29	-4.20
LFO5	9.60	9.35	8.48	8.31	-1.12	-1.04	-11.65	-11.10

Table 3-3-2: Comparison of Scenario S03 and Baseline for DO during Summer

	Baseline		S03		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.61	3.91	4.83	4.13	0.22	0.22	4.74	5.71
ELI2	4.63	3.39	4.84	3.57	0.21	0.18	4.51	5.30
LFA01	5.84	5.74	6.24	6.15	0.40	0.41	6.77	7.14
LFB01	6.84	6.55	6.82	6.63	-0.02	0.09	-0.27	1.34
LFO1	5.89	5.80	6.26	6.18	0.37	0.38	6.26	6.62
LFO2	6.30	6.10	6.52	6.38	0.22	0.27	3.42	4.45
LFO3	7.52	7.39	7.15	7.06	-0.37	-0.33	-4.91	-4.49
LFO4	7.40	7.08	7.27	7.01	-0.13	-0.07	-1.82	-0.99
LFO5	8.40	8.18	7.56	7.43	-0.84	-0.75	-10.02	-9.20

Table 3-3-3: Comparison of Scenario S03 and Baseline for DO during Spring

	S01		S03		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.99	6.37	7.02	6.37	0.03	0	0.43	0.00
ELI2	7.12	6	7.17	6.03	0.05	0.03	0.70	0.50
LFA01	7.6	7.59	7.81	7.8	0.21	0.21	2.76	2.77
LFB01	7.78	7.59	7.81	7.67	0.03	0.08	0.39	1.05
LFO1	7.42	7.4	7.62	7.61	0.2	0.21	2.70	2.84
LFO2	7.45	7.35	7.57	7.48	0.12	0.13	1.61	1.77
LFO3	8.06	7.97	7.98	7.9	-0.08	-0.07	-0.99	-0.88
LFO4	8.27	8.11	8.23	8.07	-0.04	-0.04	-0.48	-0.49
LFO5	8.78	8.58	8.48	8.31	-0.3	-0.27	-3.42	-3.15

Table 3-3-4: Comparison of Scenario S03 and Baseline for DO during Summer

	S01		S03		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.81	4.13	4.83	4.13	0.02	0	0.42	0.00
ELI2	4.81	3.56	4.84	3.57	0.03	0.01	0.62	0.28
LFA01	6.07	5.98	6.24	6.15	0.17	0.17	2.80	2.84
LFB01	6.78	6.55	6.82	6.63	0.04	0.08	0.59	1.22
LFO1	6.07	6.00	6.26	6.18	0.19	0.18	3.13	3.00
LFO2	6.38	6.22	6.52	6.38	0.14	0.16	2.19	2.57
LFO3	7.26	7.15	7.15	7.06	-0.11	-0.09	-1.52	-1.26
LFO4	7.27	7.01	7.27	7.01	0	0	0.00	0.00
LFO5	7.88	7.73	7.56	7.43	-0.32	-0.3	-4.06	-3.88

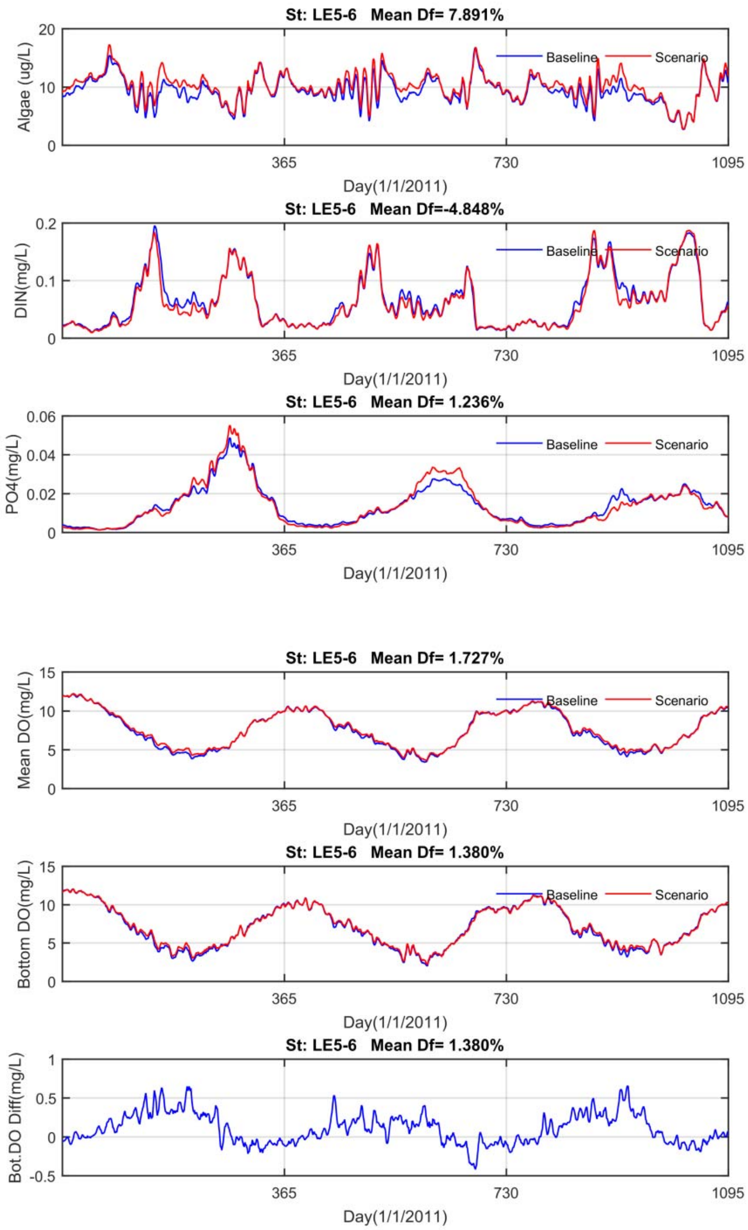


Figure 3-3-1: Comparison of Baseline and S03 Results at Station LE5-6

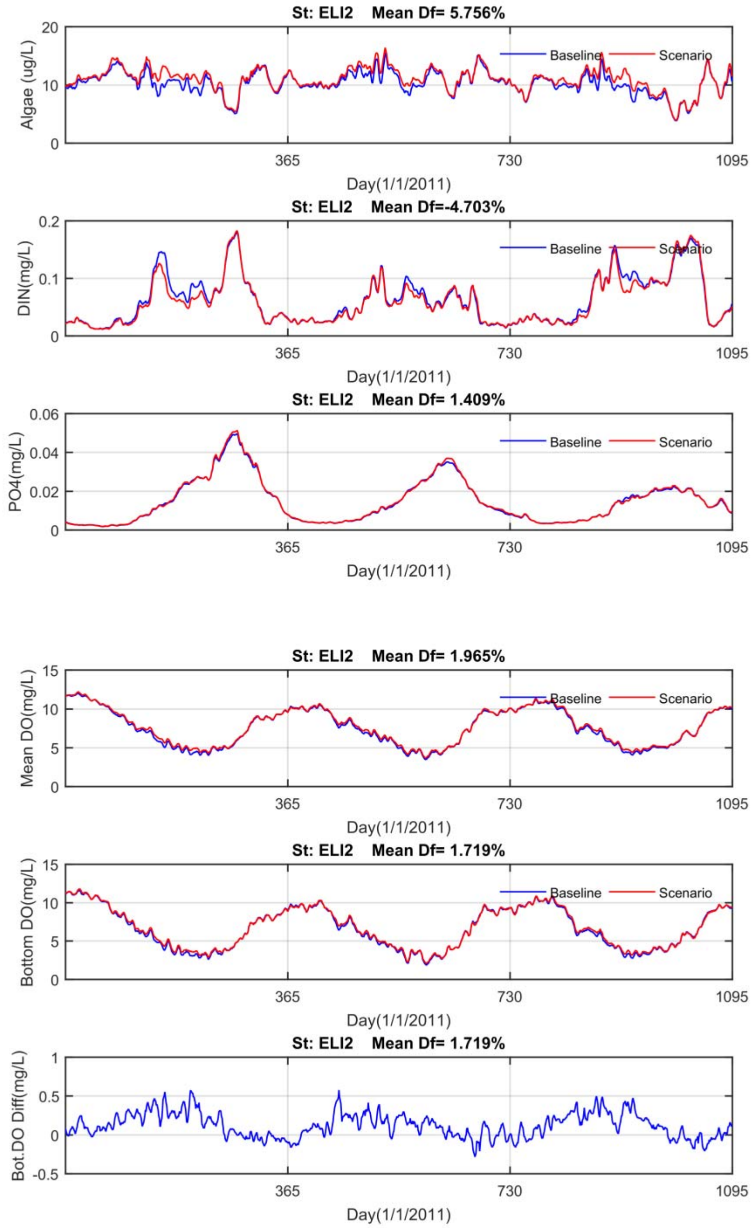


Figure 3-3-2: Comparison of Baseline and S03 Results at Station ELI2

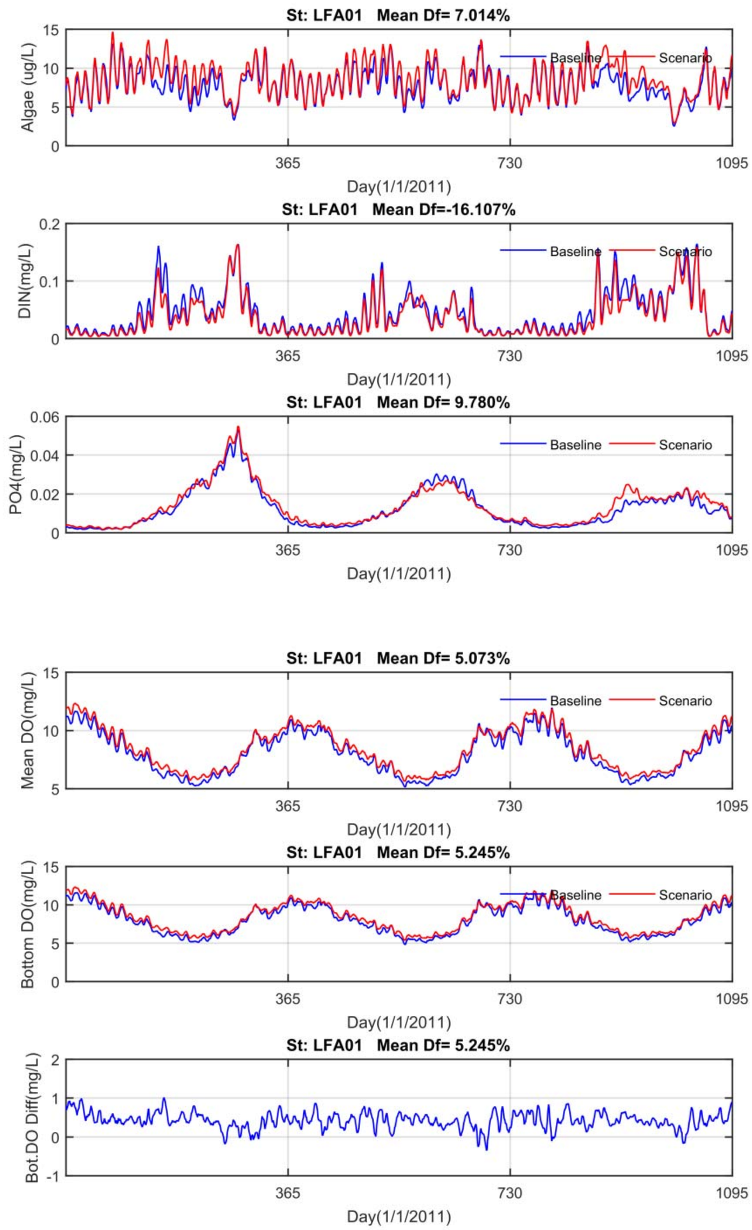
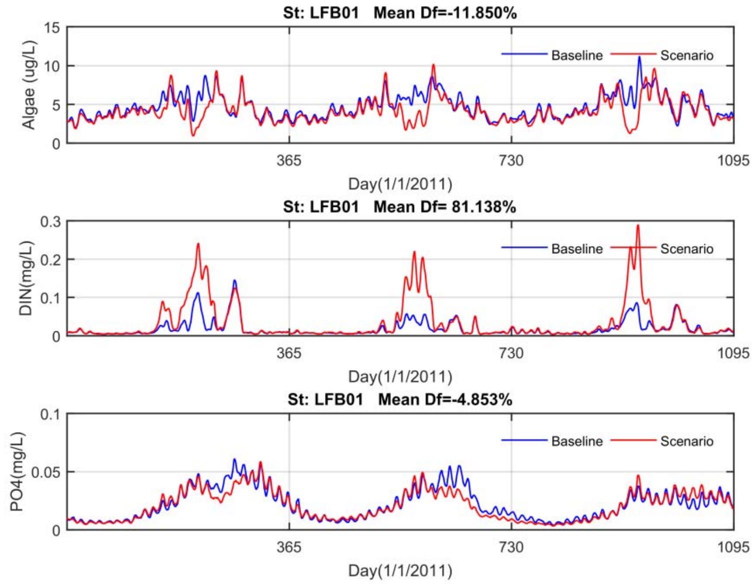


Figure 3-3-3: Comparison of Baseline and S03 Results at Station LFA01



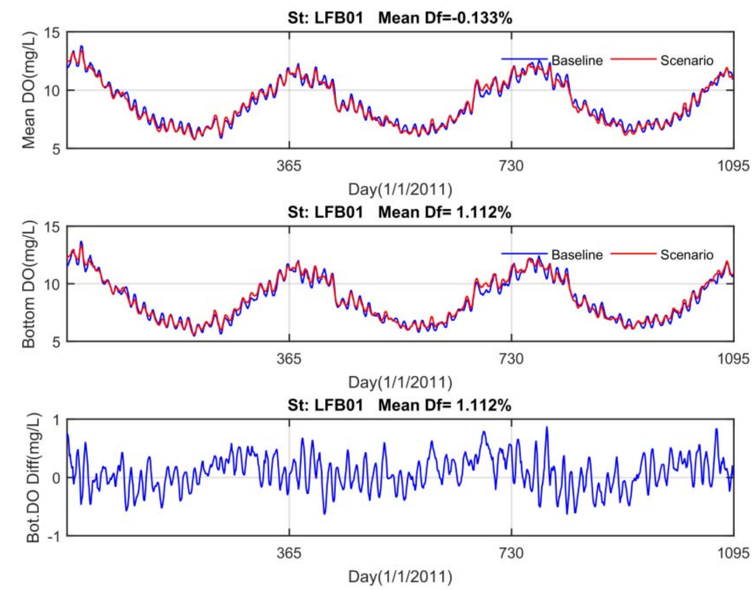


Figure 3-3-4: Comparison of Baseline and S03 Results at Station LFB01

3.4 Comparison of Scenario S04 and Baseline Condition

This scenario simulated the existing condition with the small-barrier configuration. The simulation is the same as that of S02, but only a partial amount of the designed floodgates (3 gates) are open. The results for DO are listed in Tables 3-4-1 and 3-4-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-4-1 to 3-4-4.

The results show that the largest differences of mean and bottom DO are -1.85 and -2.12 mg/L, respectively, during spring. The DO at ER has a slight increase, while DO levels decrease at upstream stations inside the LR. The maximum differences of mean and bottom DOare -2.02 and -2.28 mg/L, respectively, during the summer. DO decreases at the upstream stations inside the LR. The bottom DO difference is -9.2% at Station LF04 during summer. It can be seen that DO decreases more when fewer floodgates are open. Comparisons of DO for S03 and S01 are listed in Tables 3-3-3 and 3-3-4, respectively, for spring and summer. Because fewer floodgates were open, tidal energy propagating to the upstream of the LR was reduced resulting in a decrease of DO. Comparing model results of S02 with 5 floodgates open and S04 with 3 floodgate open, DO decreases more inside the LR. The reduced flux has more impact on the DO upstream inside the LR. It appears that reducing the number of floodgates for the small-barrier configuration has more impact on upstream in LR than reducing the opening of the large-barrier configuration in LR. The cause of this needs further analysis.

Table 3-4-1: Comparison of Scenario S04 and Baseline for DO during Spring

	Baseline		S04		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.73	6.11	6.94	6.37	0.20	0.26	3.02	4.20
ELI2	6.89	5.78	7.03	5.98	0.14	0.20	1.99	3.48
LFA01	7.38	7.34	7.57	7.35	0.19	0.02	2.63	0.26
LFB01	7.99	7.74	6.91	6.51	-1.09	-1.24	-13.58	-15.97
LFO1	7.28	7.24	7.35	7.29	0.07	0.05	0.99	0.70
LFO2	7.51	7.39	6.97	6.76	-0.54	-0.63	-7.18	-8.46
LFO3	8.48	8.38	7.82	7.69	-0.67	-0.69	-7.87	-8.27
LFO4	8.60	8.43	6.75	6.31	-1.85	-2.12	-21.54	-25.15
LFO5	9.60	9.35	9.22	8.96	-0.38	-0.39	-3.94	-4.13

Table 3-4-2: Comparison of Scenario S04 and Baseline for DO during Summer

	Baseline		S04		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.61	3.91	4.79	4.15	0.18	0.24	3.89	6.22
ELI2	4.63	3.39	4.75	3.55	0.12	0.16	2.56	4.69
LFA01	5.84	5.74	5.82	5.39	-0.02	-0.35	-0.35	-6.11
LFB01	6.84	6.55	5.43	4.91	-1.41	-1.64	-20.56	-25.02
LFO1	5.89	5.80	5.77	5.59	-0.11	-0.22	-1.93	-3.71
LFO2	6.30	6.10	5.56	5.21	-0.74	-0.89	-11.76	-14.63
LFO3	7.52	7.39	6.75	6.55	-0.77	-0.84	-10.23	-11.34
LFO4	7.40	7.08	5.39	4.80	-2.02	-2.28	-27.23	-32.20
LFO5	8.40	8.18	8.11	7.86	-0.29	-0.32	-3.43	-3.87

Table 3-4-3: Comparison of Scenario S04 and Baseline for DO during Spring

	S02		S04		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.96	6.35	6.94	6.37	-0.02	0.02	-0.29	0.31
ELI2	7.06	5.97	7.03	5.98	-0.03	0.01	-0.42	0.17
LFA01	7.54	7.51	7.57	7.35	0.03	-0.16	0.40	-2.13
LFB01	7.81	7.63	6.91	6.51	-0.9	-1.12	-11.52	-14.68
LFO1	7.40	7.37	7.35	7.29	-0.05	-0.08	-0.68	-1.09
LFO2	7.51	7.40	6.97	6.76	-0.54	-0.64	-7.19	-8.65
LFO3	8.10	8.00	7.82	7.69	-0.28	-0.31	-3.46	-3.88
LFO4	8.26	8.12	6.75	6.31	-1.51	-1.81	-18.28	-22.29
LFO5	8.85	8.65	9.22	8.96	0.37	0.31	4.18	3.58

Table 3-4-4: Comparison of Scenario S04 and Baseline for DO during Summer

	S02		S04		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.79	4.12	4.79	4.15	0	0.03	0.00	0.73
ELI2	4.76	3.54	4.75	3.55	-0.01	0.01	-0.21	0.28
LFA01	6.00	5.92	5.82	5.39	-0.18	-0.53	-3.00	-8.95
LFB01	6.80	6.56	5.43	4.91	-1.37	-1.65	-20.15	-25.15
LFO1	6.09	5.99	5.77	5.59	-0.32	-0.4	-5.25	-6.68
LFO2	6.40	6.24	5.56	5.21	-0.84	-1.03	-13.13	-16.51
LFO3	7.31	7.20	6.75	6.55	-0.56	-0.65	-7.66	-9.03
LFO4	7.25	7.00	5.39	4.80	-1.86	-2.2	-25.66	-31.43
LFO5	7.96	7.81	8.11	7.86	0.15	0.05	1.88	0.64

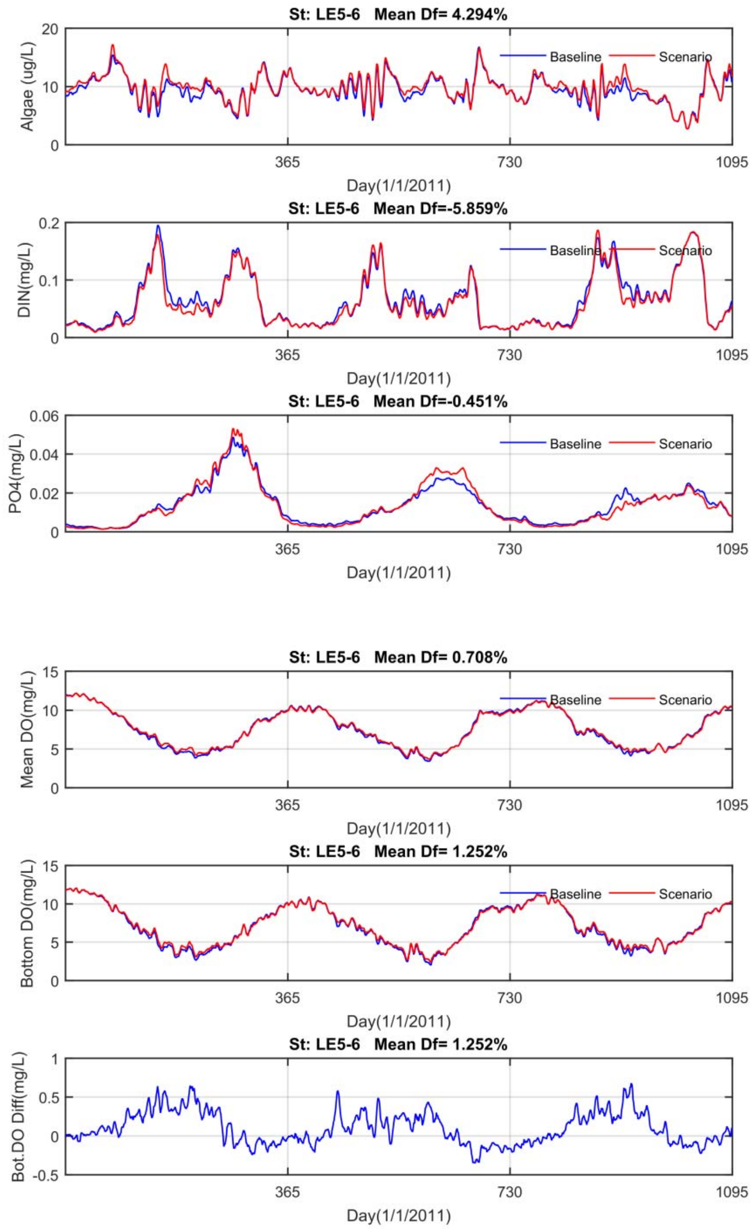


Figure 3-4-1: Comparison of Baseline and S04 Results at Station LE5-6

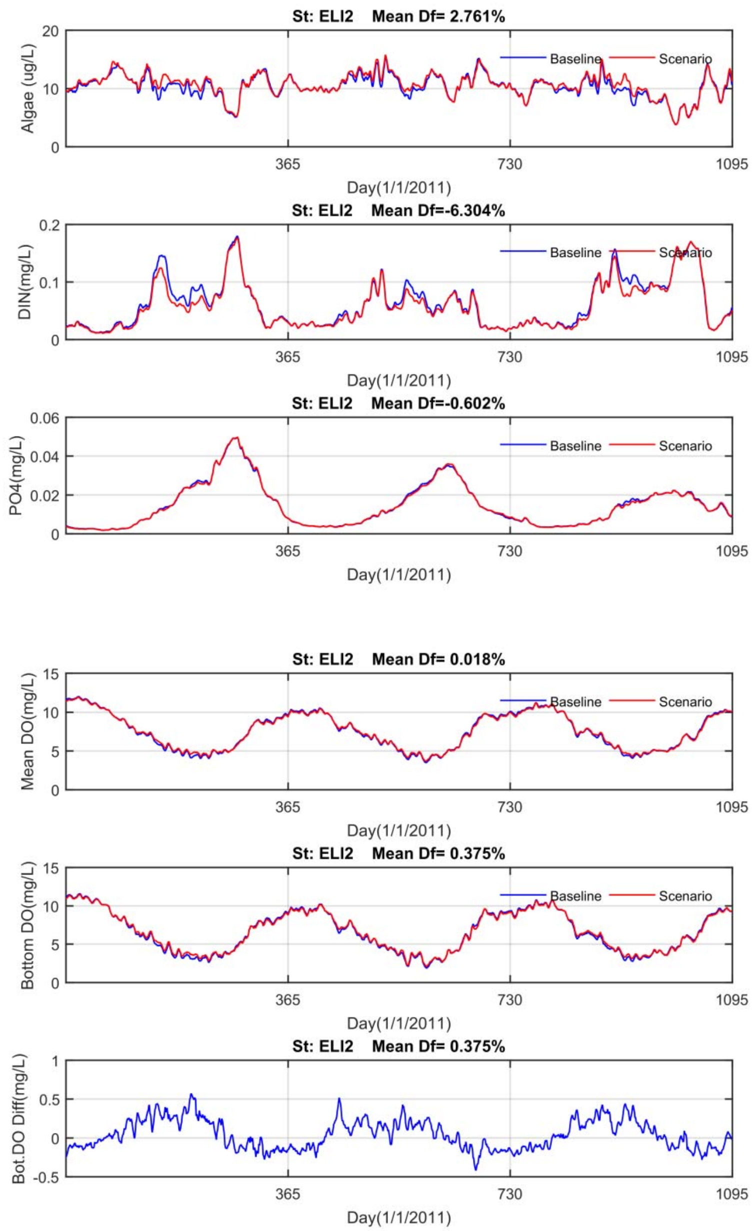


Figure 3-4-2: Comparison of Baseline and S04 Results at Station ELI2

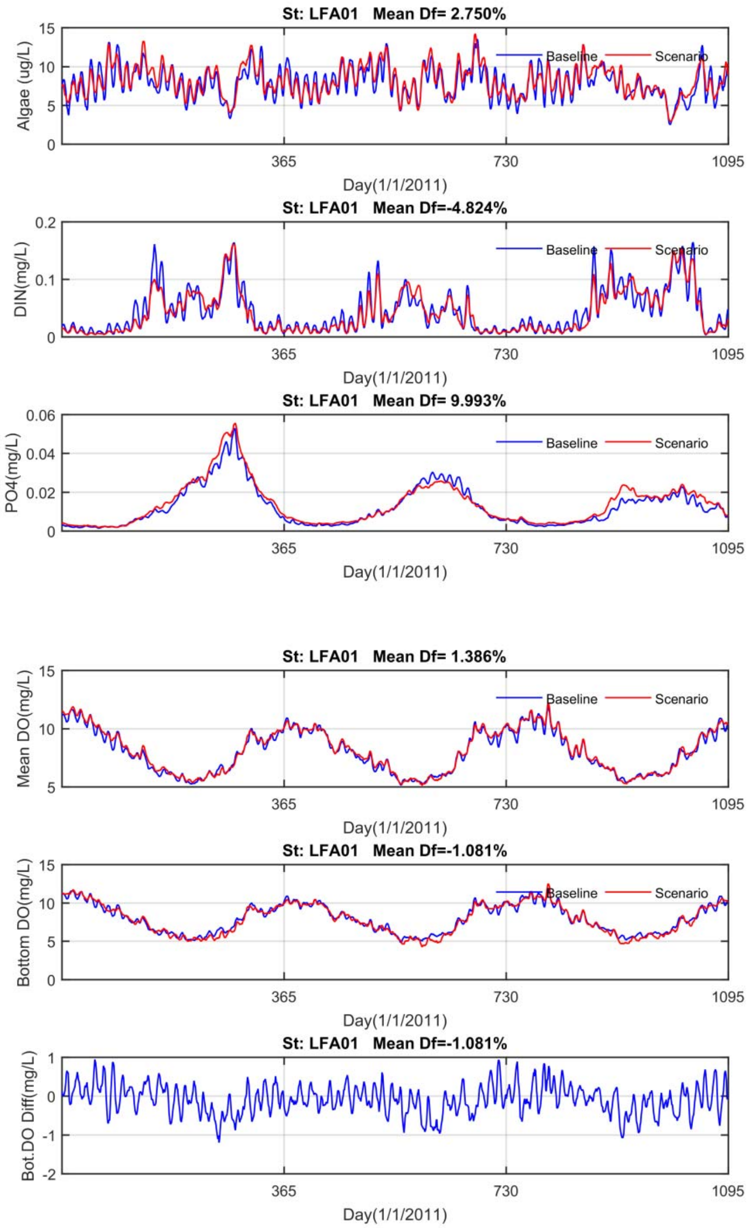


Figure 3-4-3: Comparison of Baseline and S04 Results at Station LFA01

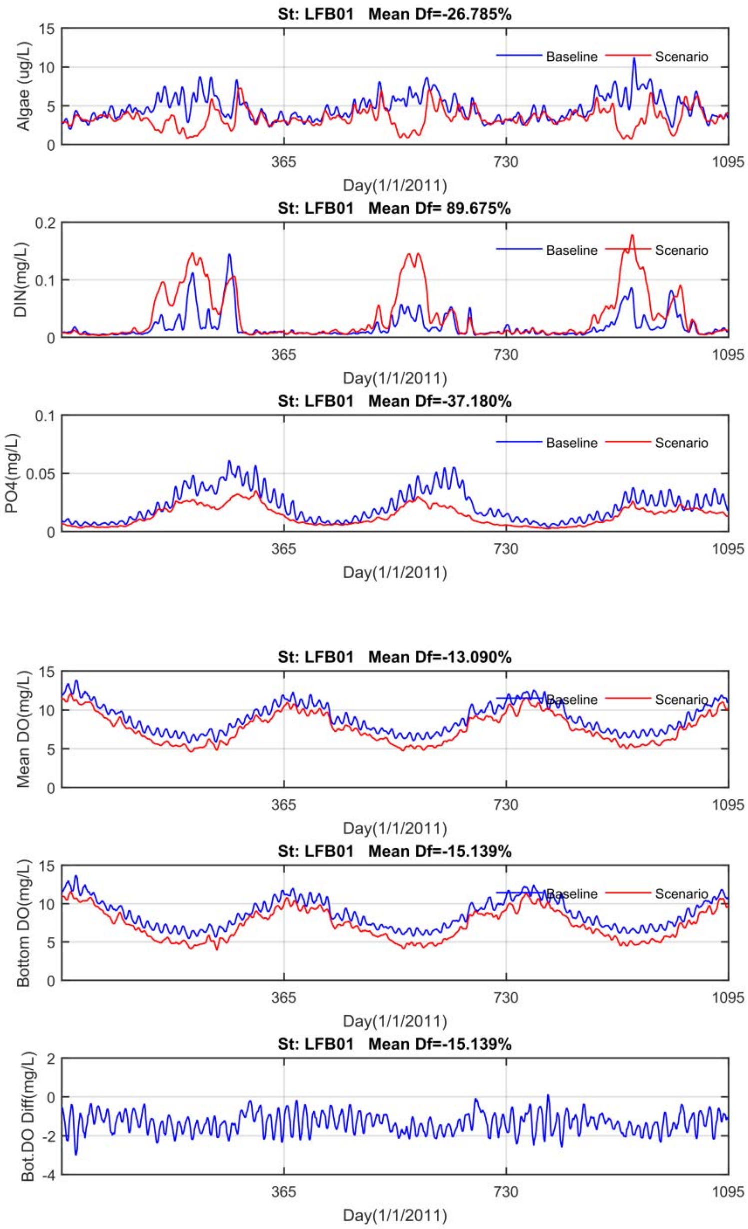


Figure 3-4-4: Comparison of Baseline and S04 Results at Station LFB01

3.5 Comparison of Future Condition with SLR and Baseline Condition

This scenario simulated the future condition with SLR by 1.0 m without project. The model configuration was the same as the baseline condition (S00). The boundary conditions of tide and salinity were output from a large-domain Chesapeake Bay model used for the channel deepening project (Zhang et al. (2017)). The results for DO are listed in Tables 3-5-1 and 3-5-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-5-1 to 3-5-4.

The results show that DO increases slightly as SLR in the ER and LR near the LR mouth, but DO levels decrease in the two upstream small tributaries during the spring. Same change of DO occurred in summer, except the bottom DO in the ER decreases. The decrease of DO in the tributary due to SLR ranges from 1-3 mg/L, which is significant. It is noted that phytoplankton concentration increases near the mouth of LR (Station LFA01, Fig. 3-5-1). It is not clear if more algal is to be transported into the LR or if there is an increase of nutrient input. The increase phytoplankton concentration is one of the reasons for the increase of DO at this station.

Our recent study of an ideal estuary suggests that the change of tidal range due to SLR is related to the length of the estuary. For an estuary having a length shorter than a quarter length of the tidal wave, the tidal range will decrease with SLR. It is not clear if the tidal mixing is the cause of decrease of DO in the upstream small tributary. Additional analysis will be conducted to investigate the change of this dynamic condition.

Table 3-5-1: Comparison of SLR (S05) and Baseline (S00) for DO during Spring

	Baseline		S05		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.73	6.11	6.83	6.07	0.10	-0.05	1.47	-0.77
ELI2	6.89	5.78	7.18	5.91	0.29	0.13	4.20	2.28
LFA01	7.38	7.34	8.46	8.25	1.09	0.92	14.77	12.52
LFB01	7.99	7.74	8.16	8.52	0.17	0.77	2.10	9.99
LFO1	7.28	7.24	8.84	8.68	1.56	1.44	21.41	19.87
LFO2	7.51	7.39	8.94	9.12	1.43	1.73	19.00	23.48
LFO3	8.48	8.38	6.82	6.82	-1.67	-1.56	-19.66	-18.67
LFO4	8.60	8.43	7.40	7.31	-1.20	-1.11	-13.95	-13.22
LFO5	9.60	9.35	6.28	6.05	-3.32	-3.29	-34.54	-35.25

Table 3-5-2: Comparison of SLR (S05) and Baseline (S00) for DO during Summer

	Baseline		S05		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.61	3.91	4.56	3.74	-0.05	-0.17	-0.98	-4.33
ELI2	4.63	3.39	4.69	3.29	0.06	-0.11	1.25	-3.19
LFA01	5.84	5.74	6.34	5.95	0.50	0.21	8.49	3.69
LFB01	6.84	6.55	7.10	7.32	0.26	0.78	3.76	11.87
LFO1	5.89	5.80	6.76	6.38	0.87	0.58	14.82	9.98
LFO2	6.30	6.10	7.58	7.57	1.28	1.47	20.36	24.01
LFO3	7.52	7.39	5.89	5.93	-1.63	-1.47	-21.67	-19.82
LFO4	7.40	7.08	6.65	6.50	-0.75	-0.58	-10.16	-8.16
LFO5	8.40	8.18	5.20	5.04	-3.20	-3.15	-38.07	-38.45

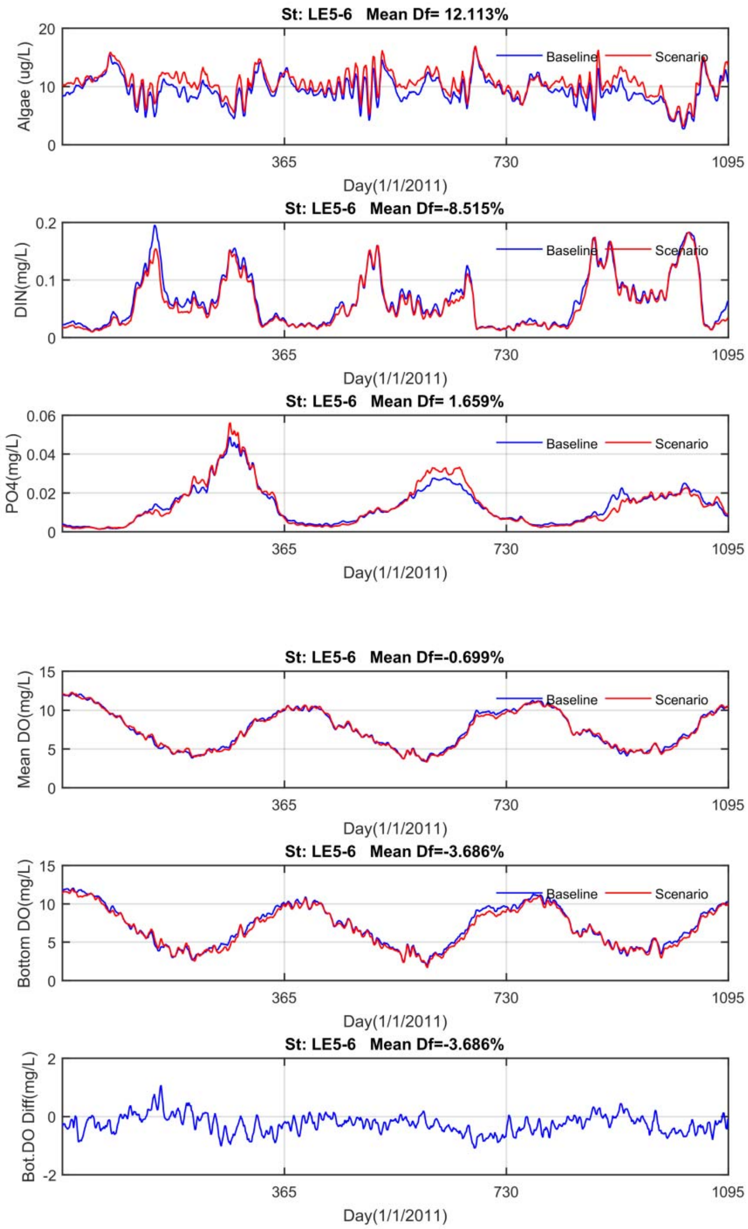


Figure 3-5-1: Comparison of Results of Baseline and SLR (S05) at Station LE5-6

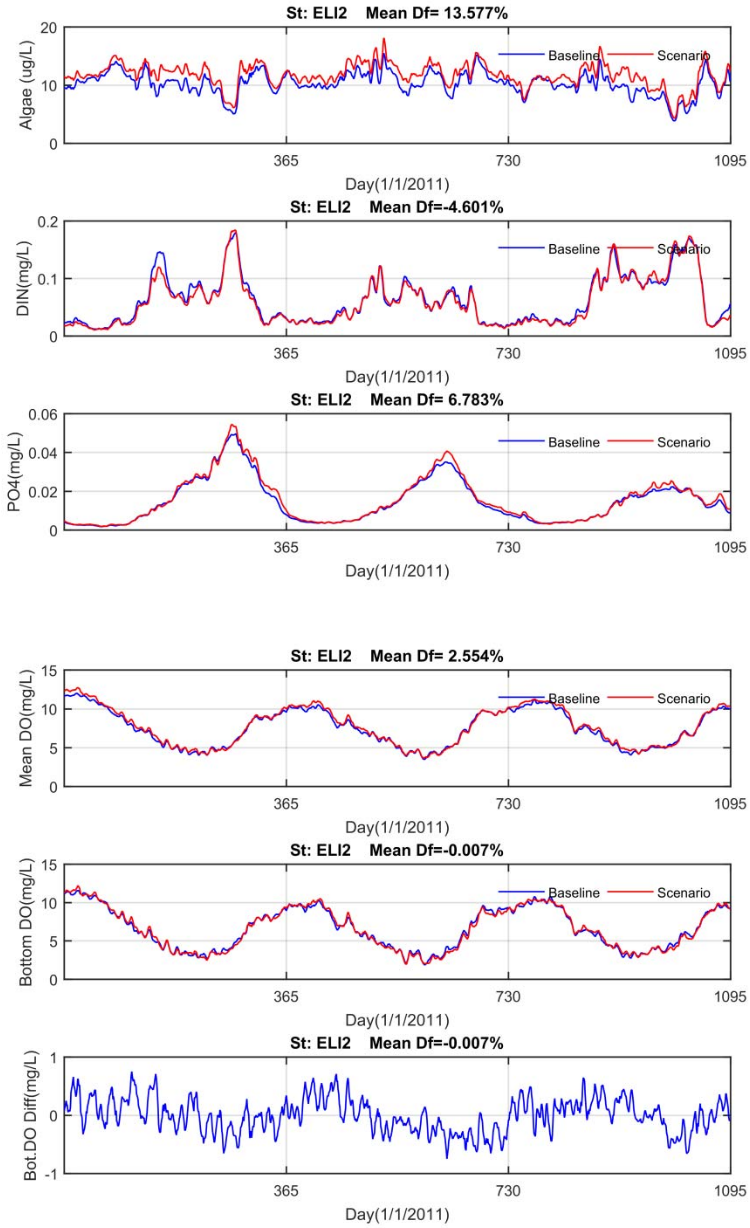


Figure 3-5-2: Comparison of Results of Baseline and SLR (S05) Station ELI2

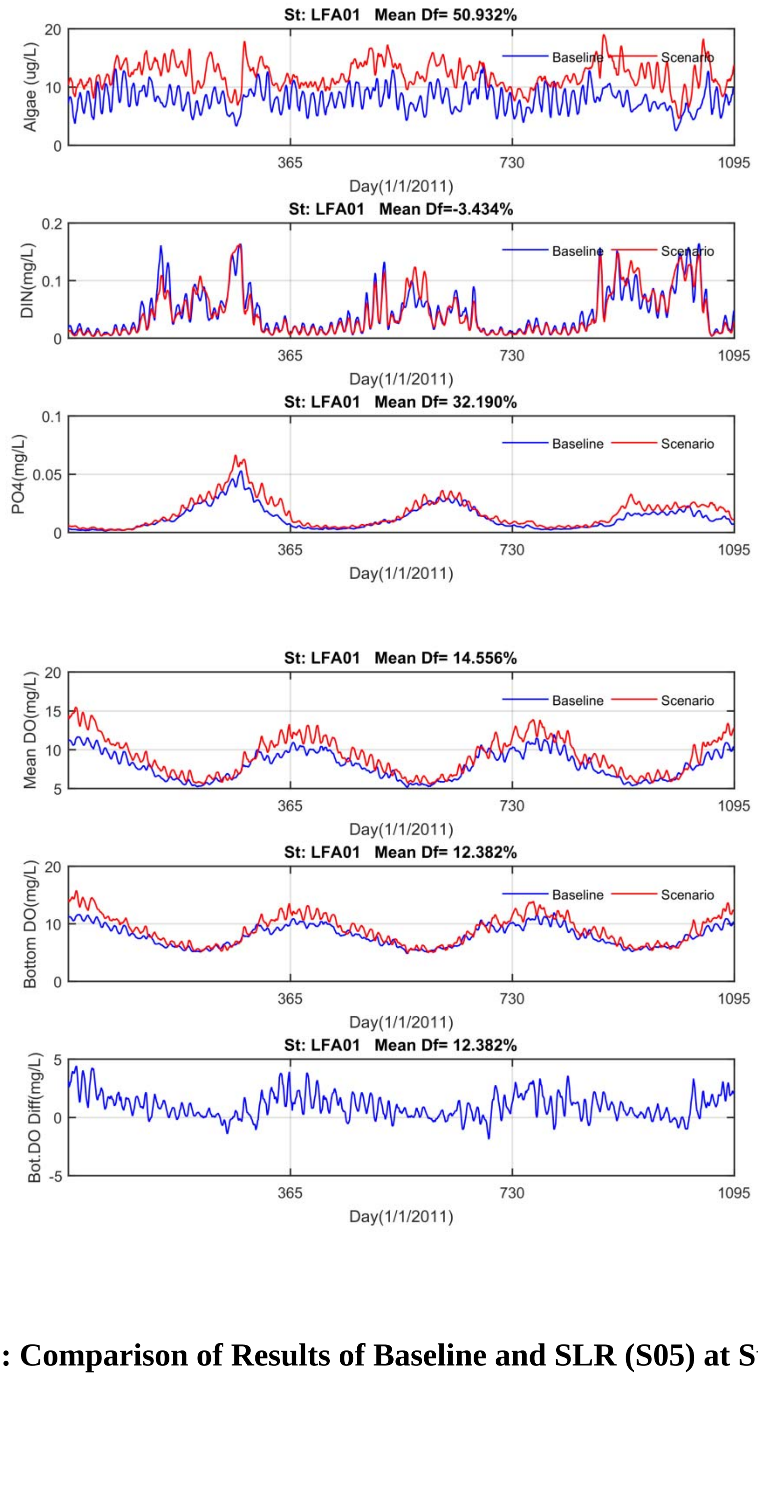


Figure 3-5-3: Comparison of Results of Baseline and SLR (S05) at Station LFA01

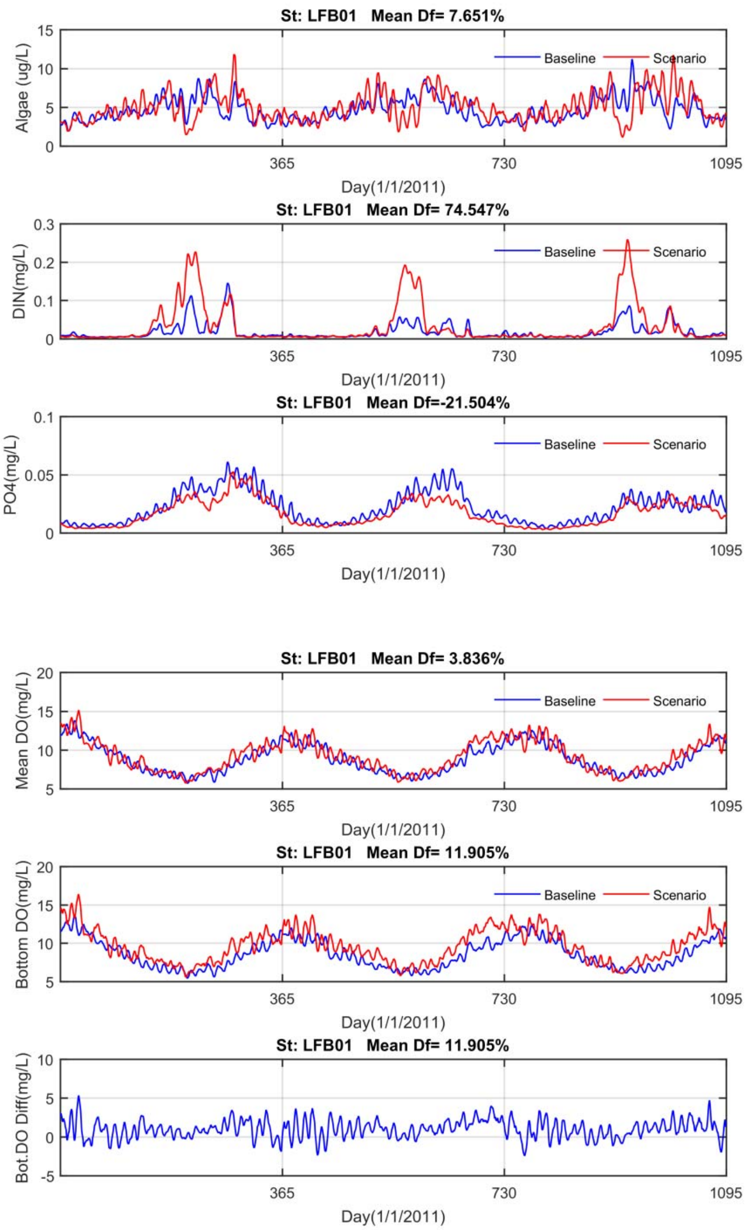


Figure 3-5-4: Comparison of Results of Baseline and SLR (S05) at Station LFB01

3.6 Comparison of Scenario S06 and Future Baseline Condition

This scenario simulated the SLR with installation of the large floodgate. The SLR by 1.0 m is treated as the future condition. The large barrier with 19 floodgates was open during the simulation period. The results for DO are listed in Tables 3-6-1 and 3-6-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-6-1 to 3-6-4.

Compared to the future baseline condition (with SLR), the results with the large storm surge barrier show that the largest differences of mean and bottom DO are 0.53 and 0.56 mg/L, respectively, during spring. The DO in the ER shows a slight decrease, while a DO decrease occurs inside the LR. The maximum differences of mean and bottom DO are 0.45 and 0.48 mg/L, respectively, during the summer. It is interesting that the DO increases slightly at the upstream of a small tributary with the floodgates. One reason for that is because the large barrier changed the tidal reflection. More analysis is needed to understand the change.

Table 3-6-1: Comparison of S06 and Future Baseline (S05) for DO during Spring

	S05		S06		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.83	6.07	6.82	6.06	-0.02	-0.01	-0.22	-0.10
ELI2	7.18	5.91	7.15	5.86	-0.03	-0.05	-0.39	-0.86
LFA01	8.46	8.25	8.52	8.36	0.05	0.10	0.63	1.27
LFB01	8.16	8.52	7.92	8.15	-0.24	-0.37	-2.93	-4.35
LFO1	8.84	8.68	8.71	8.61	-0.13	-0.07	-1.50	-0.79
LFO2	8.94	9.12	8.51	8.64	-0.43	-0.49	-4.82	-5.34
LFO3	6.82	6.82	7.08	7.03	0.26	0.22	3.88	3.18
LFO4	7.40	7.31	7.36	7.24	-0.04	-0.07	-0.58	-1.00
LFO5	6.28	6.05	6.82	6.61	0.53	0.56	8.46	9.26

Table 3-6-2: Comparison of S06 and Future Baseline (S05) for DO during Summer

	S05		S06		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.56	3.74	4.53	3.71	-0.03	-0.02	-0.75	-0.57
ELI2	4.69	3.29	4.65	3.24	-0.04	-0.05	-0.83	-1.56
LFA01	6.34	5.95	6.51	6.14	0.17	0.20	2.65	3.28
LFB01	7.10	7.32	6.89	7.01	-0.21	-0.31	-2.92	-4.29
LFO1	6.76	6.38	6.85	6.55	0.09	0.17	1.36	2.72
LFO2	7.58	7.57	7.30	7.27	-0.28	-0.30	-3.74	-3.97
LFO3	5.89	5.93	6.11	6.09	0.22	0.16	3.76	2.68
LFO4	6.65	6.50	6.57	6.39	-0.08	-0.12	-1.23	-1.80
LFO5	5.20	5.04	5.66	5.51	0.45	0.48	8.69	9.51

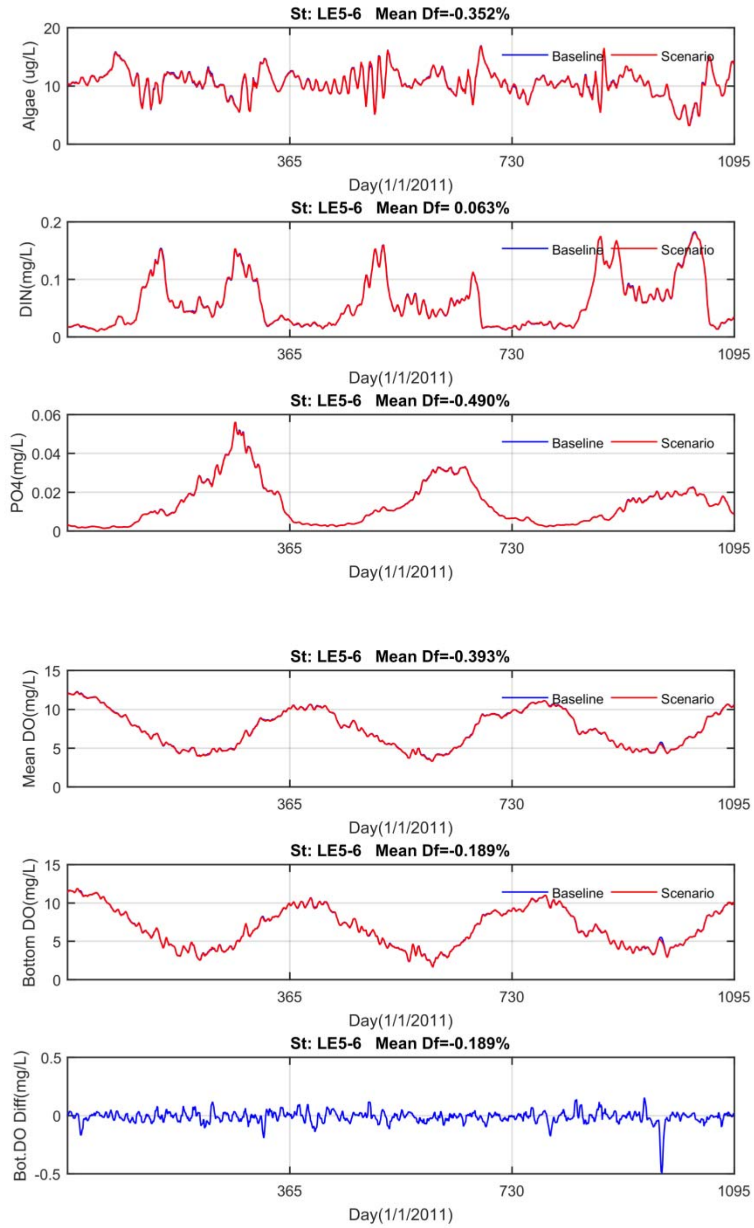


Figure 3-6-1: Comparison of S06 and Future Baseline Results (S05) at Station LE5-6

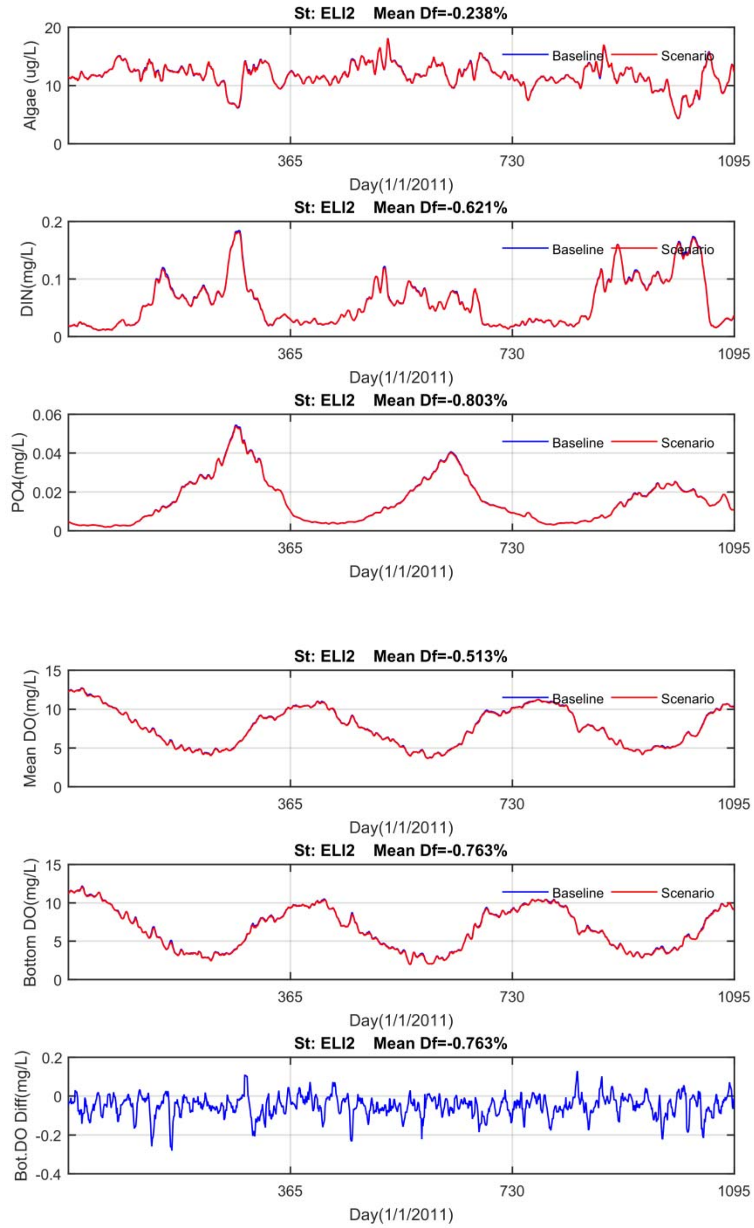


Figure 3-6-2: Comparison of S06 and Future Baseline Results (S05) at Station ELI2

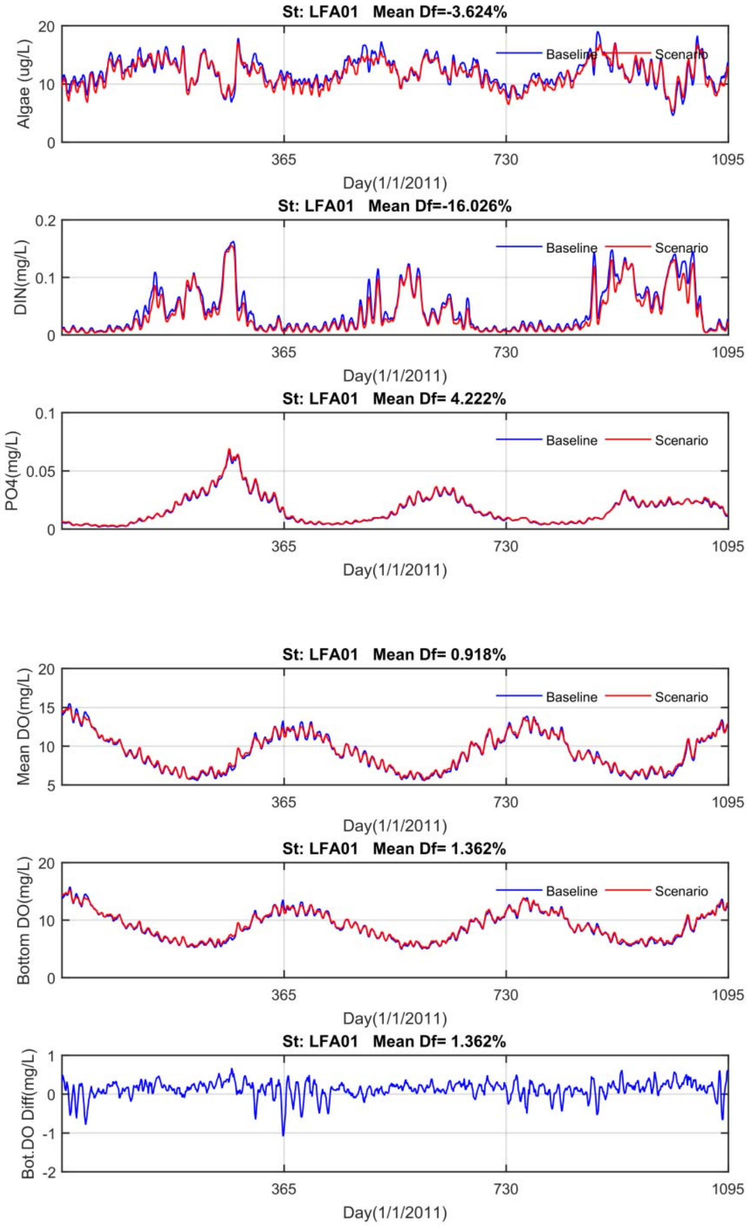


Figure 3-6-3: Comparison of S06 and Future Baseline Results (S05) at Station LFA01

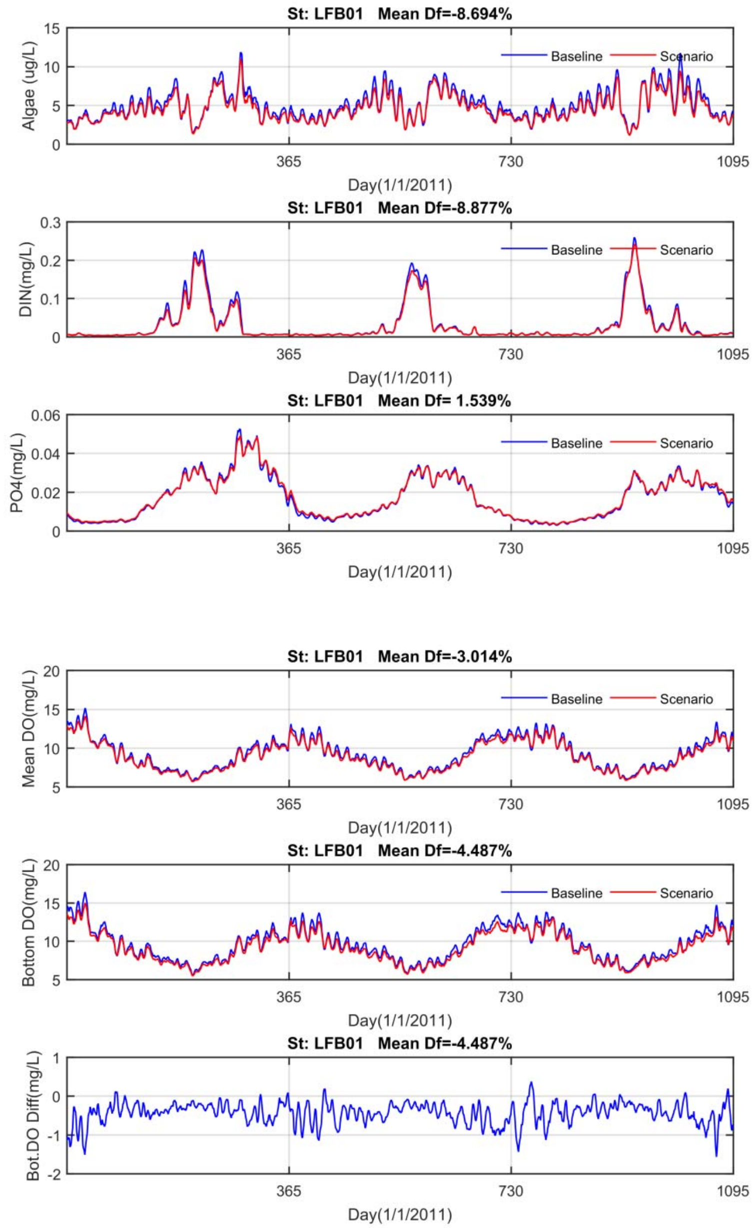


Figure 3-6-4: Comparison of S06 and Future Baseline Results (S05) at Station LFB01

3.7 Comparison of Scenario S07 and Future Baseline Condition

This scenario simulated the SLR with installation of the small floodgate. The SLR by 1.0 m is treated as the future condition. The small-barrier is assessed with 5 floodgates open during the simulation period. The results for DO are listed in Tables 3-7-1 and 3-7-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-7-1 to 3-7-4.

Compared to the future baseline condition (with SLR), the results with small storm surge show that largest differences of mean and bottom DO are -0.21 and -0.23 mg/L, respectively, during spring. The increase and decrease of DO vary with location. The maximum differences of mean and bottom DO are 0.18 and 0.27 mg/L, respectively, during the summer. It is interesting that the DO increases slightly toward the upstream small tributary with the floodgates. Compared to the results with large storm surge barrier, the changes of DO are on the same order of magnitude.

Table 3-7-1: Comparison of S07 and Future Baseline (S05) for DO during Spring

	S05		S07		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.83	6.07	6.85	6.08	0.01	0.01	0.21	0.14
ELI2	7.18	5.91	7.18	5.91	0.00	-0.00	0.02	-0.02
LFA01	8.46	8.25	8.57	8.39	0.11	0.14	1.24	1.65
LFB01	8.16	8.52	8.07	8.35	-0.09	-0.17	-1.09	-1.94
LFO1	8.84	8.68	8.92	8.80	0.08	0.12	0.95	1.41
LFO2	8.94	9.12	8.73	8.90	-0.21	-0.23	-2.31	-2.50
LFO3	6.82	6.82	6.93	6.93	0.12	0.11	1.73	1.66
LFO4	7.40	7.31	7.44	7.34	0.04	0.03	0.54	0.36
LFO5	6.28	6.05	6.44	6.24	0.16	0.18	2.56	3.05

Table 3-7-2: Comparison of S07 and Future Baseline (S05) for DO during Summer

	S05		S07		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.56	3.74	4.57	3.73	0.01	-0.00	0.12	-0.09
ELI2	4.69	3.29	4.69	3.28	-0.00	-0.01	-0.03	-0.24
LFA01	6.34	5.95	6.42	6.09	0.08	0.14	1.20	2.34
LFB01	7.10	7.32	7.01	7.17	-0.09	-0.15	-1.27	-2.07
LFO1	6.76	6.38	6.95	6.65	0.18	0.27	2.73	4.19
LFO2	7.58	7.57	7.43	7.42	-0.15	-0.15	-1.99	-2.01
LFO3	5.89	5.93	6.00	6.02	0.10	0.10	1.75	1.63
LFO4	6.65	6.50	6.66	6.51	0.01	0.00	0.22	0.03
LFO5	5.20	5.04	5.35	5.21	0.14	0.17	2.78	3.37

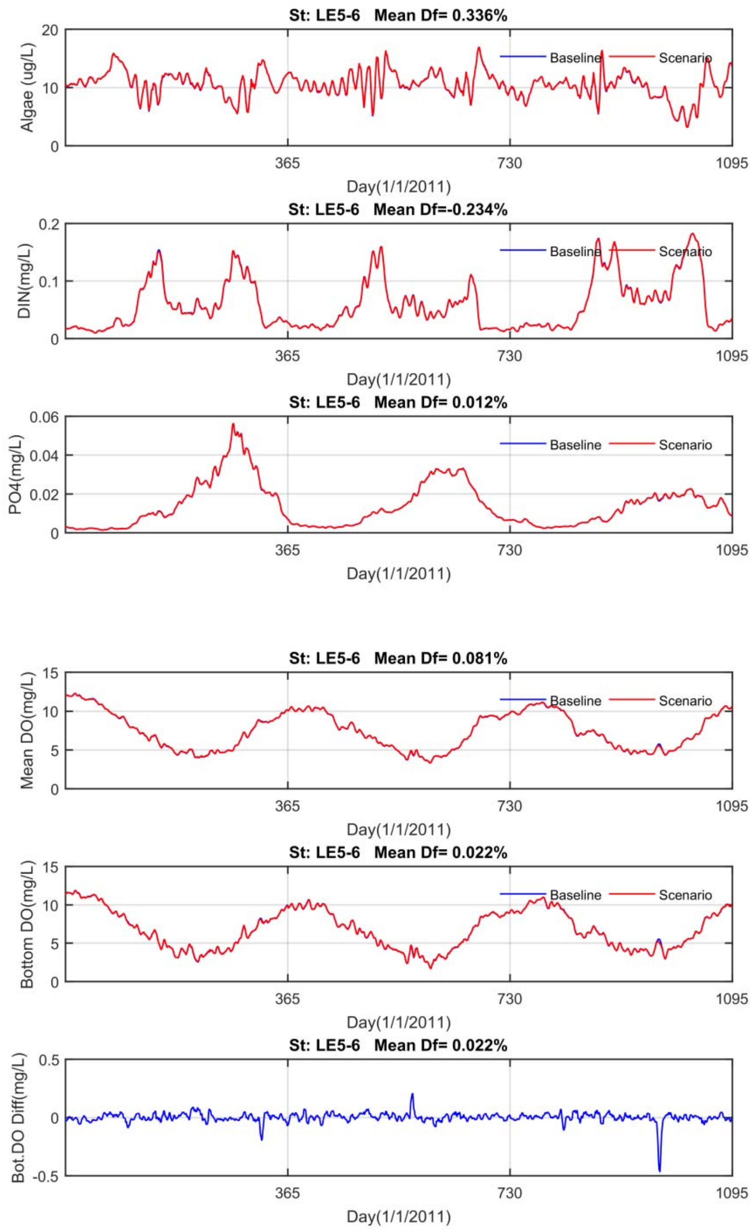


Figure 3-7-1: Comparison of S07 and Future Baseline (S05) Results at Station LE5-6

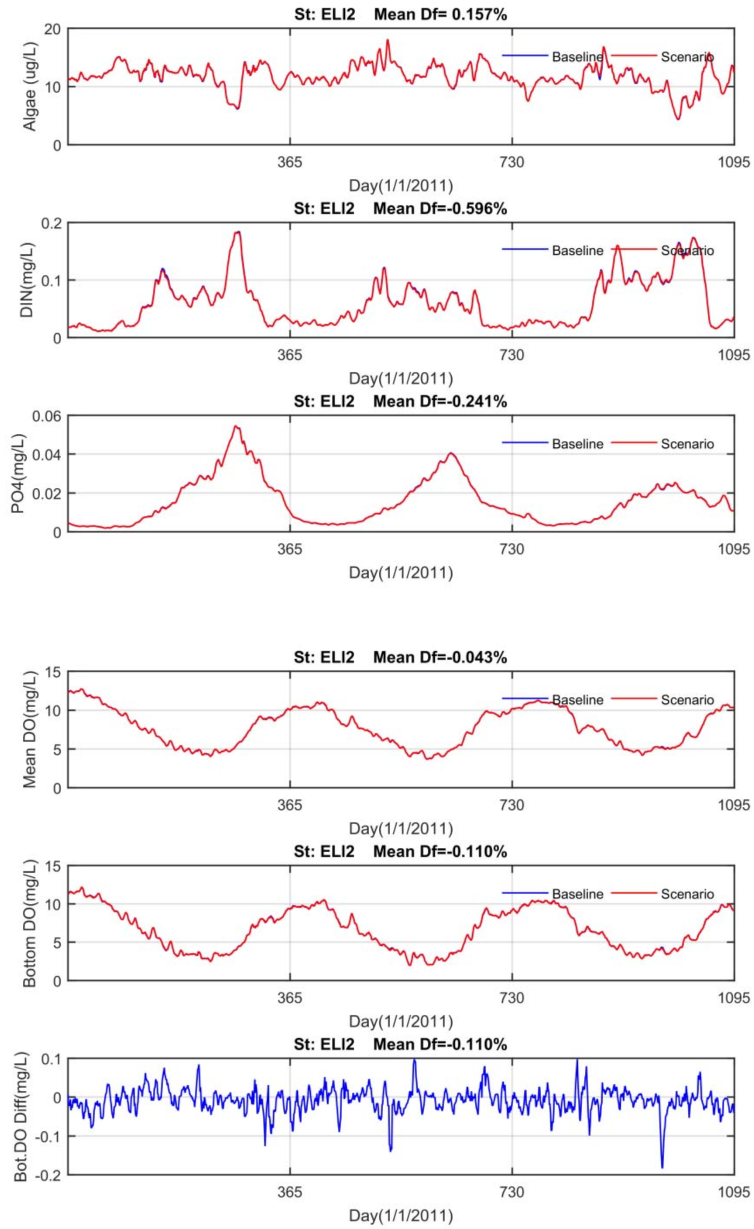


Figure 3-7-2: Comparison of S07 and Future Baseline (S05) Results at Station ELI2

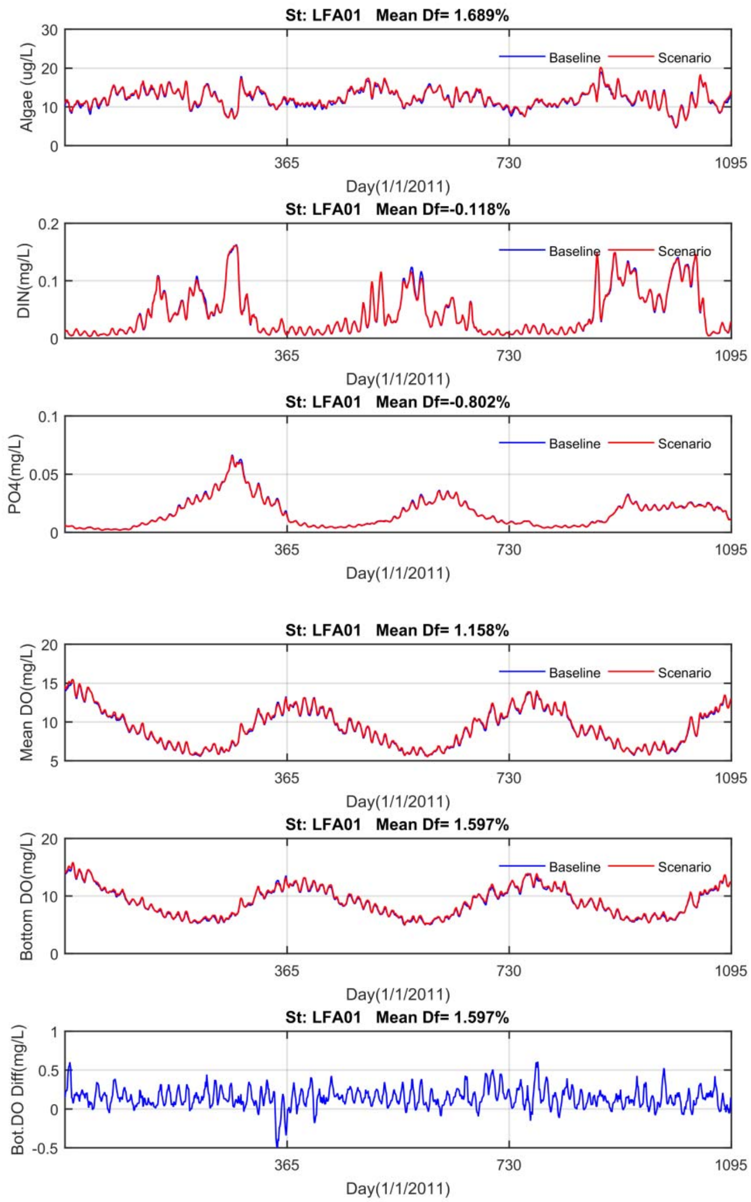


Figure 3-7-3: Comparison of S07 and Future Baseline (S05) Results at Station LFA01

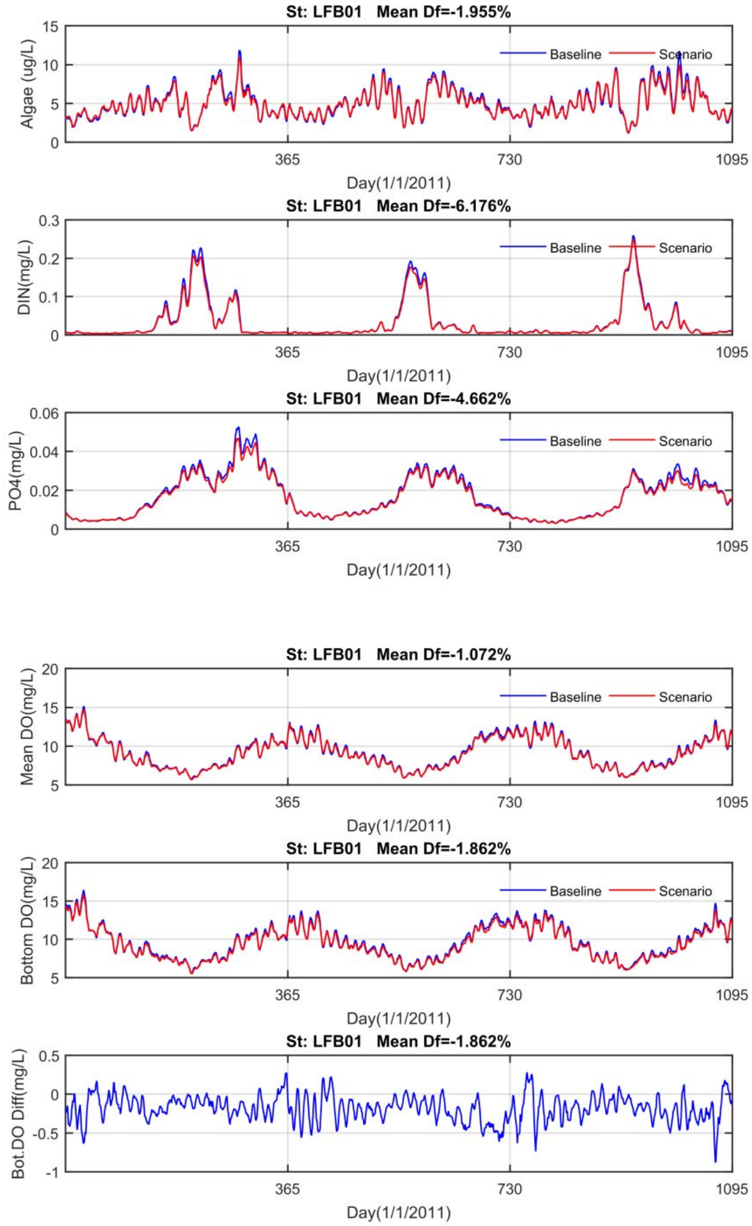


Figure 3-7-5: Comparison of S07 and Future Baseline (S05) Results at Station LFB01

3.8 Comparison of Scenario S07 and Future Baseline Condition

This scenario simulated the SLR with installation of the large floodgate. The SLR by 1.0 m is treated as the future condition. The large barrier with half-designed floodgates (total of 10) are open during the simulation period. The results for DO are listed in Tables 3-8-1 and 3-8-2 for spring and summer, respectively. Comparisons of time series plots for phytoplankton, DIN, DIP, and DO at 4 selected stations are shown in Figures 3-8-1 to 3-8-4.

Compared to the future baseline condition (with SLR), the results with small storm surge show that the largest differences of mean and bottom DO are -0.86 and -1.1 mg/L, respectively, during spring when only 10 floodgates are open. The increase and decrease of DO vary with location. The maximum differences of mean and bottom DO are 0.98 and 1.01 mg/L, respectively, during the summer. It is interesting that the DO increases slightly moving upstream toward the small tributary with less floodgates open compared to the results with 19 floodgates open. Compared to the results with large storm surge barrier (S06, Tables 3-8-3 and 3-8-4), DO increases in the downstream of LR, but increases in the small tributary. It can be seen that the storm surge barrier may affect the tidal propagation inside the LR.

Table 3-8-1: Comparison of S08 and Future Baseline (S05) For DO during Spring

	S05		S08		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.83	6.07	6.81	6.05	-0.02	-0.02	-0.34	-0.35
ELI2	7.18	5.91	7.15	5.84	-0.03	-0.07	-0.47	-1.19
LFA01	8.46	8.25	8.31	8.20	-0.16	-0.06	-1.88	-0.69
LFB01	8.16	8.52	7.72	7.79	-0.44	-0.73	-5.33	-8.53
LFO1	8.84	8.68	8.37	8.31	-0.47	-0.37	-5.36	-4.27
LFO2	8.94	9.12	8.08	8.11	-0.86	-1.01	-9.63	-11.07
LFO3	6.82	6.82	7.39	7.29	0.58	0.47	8.46	6.93
LFO4	7.40	7.31	7.43	7.27	0.03	-0.05	0.34	-0.64
LFO5	6.28	6.05	7.39	7.20	1.10	1.15	17.56	18.93

Table 3-8-2: Comparison of S08 and Future Baseline (S05) For DO during Summer

	S05		S08		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.56	3.74	4.52	3.72	-0.04	-0.02	-0.88	-0.45
ELI2	4.69	3.29	4.64	3.23	-0.05	-0.06	-1.02	-1.75
LFA01	6.34	5.95	6.42	6.13	0.08	0.19	1.18	3.13
LFB01	7.10	7.32	6.64	6.61	-0.45	-0.72	-6.39	-9.81
LFO1	6.76	6.38	6.66	6.44	-0.10	0.06	-1.44	0.88
LFO2	7.58	7.57	6.90	6.79	-0.69	-0.78	-9.04	-10.26
LFO3	5.89	5.93	6.38	6.27	0.49	0.34	8.23	5.77
LFO4	6.65	6.50	6.55	6.31	-0.09	-0.19	-1.43	-2.98
LFO5	5.20	5.04	6.18	6.05	0.98	1.01	18.78	20.08

Table 3-8-3: Comparison of S08 and Future Baseline (S05) For DO during Spring

	S06		S08		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	6.82	6.06	6.81	6.05	-0.01	-0.01	-0.15	-0.17
ELI2	7.15	5.86	7.15	5.84	0	-0.02	0.00	-0.34
LFA01	8.52	8.36	8.31	8.20	-0.21	-0.16	-2.46	-1.91
LFB01	7.92	8.15	7.72	7.79	-0.2	-0.36	-2.53	-4.42
LFO1	8.71	8.61	8.37	8.31	-0.34	-0.3	-3.90	-3.48
LFO2	8.51	8.64	8.08	8.11	-0.43	-0.53	-5.05	-6.13
LFO3	7.08	7.03	7.39	7.29	0.31	0.26	4.38	3.70
LFO4	7.36	7.24	7.43	7.27	0.07	0.03	0.95	0.41
LFO5	6.82	6.61	7.39	7.20	0.57	0.59	8.36	8.93

Table 3-8-4: Comparison of S08 and Future Baseline (S05) For DO during Summer

	S06		S08		Difference		% Difference	
Station	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean (mg/L)	Bottom (mg/L)	Mean	Bottom
LE5-6	4.53	3.71	4.52	3.72	-0.01	0.01	-0.22	0.27
ELI2	4.65	3.24	4.64	3.23	-0.01	-0.01	-0.22	-0.31
LFA01	6.51	6.14	6.42	6.13	-0.09	-0.01	-1.38	-0.16
LFB01	6.89	7.01	6.64	6.61	-0.25	-0.4	-3.63	-5.71
LFO1	6.85	6.55	6.66	6.44	-0.19	-0.11	-2.77	-1.68
LFO2	7.30	7.27	6.90	6.79	-0.4	-0.48	-5.48	-6.60
LFO3	6.11	6.09	6.38	6.27	0.27	0.18	4.42	2.96
LFO4	6.57	6.39	6.55	6.31	-0.02	-0.08	-0.30	-1.25
LFO5	5.66	5.51	6.18	6.05	0.52	0.54	9.19	9.80

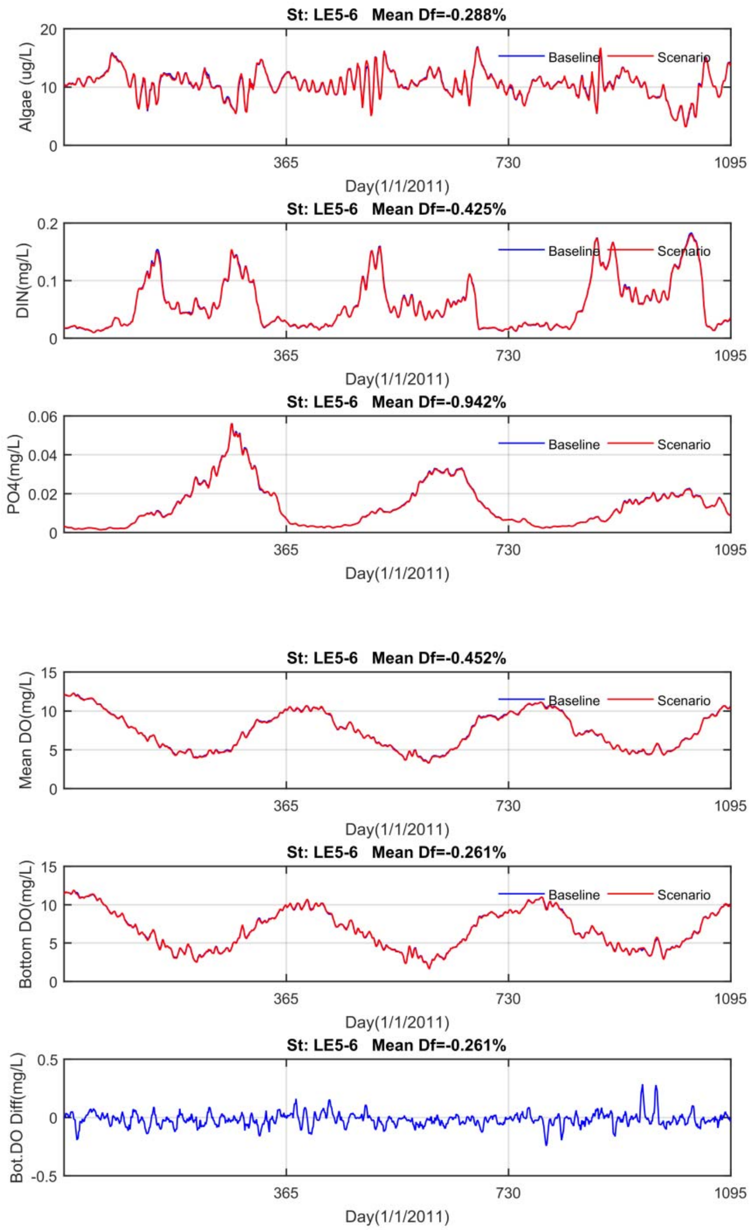


Figure 3-8-1: Comparison of S08 and Future Baseline Condition (S05) Results at Station LFB01

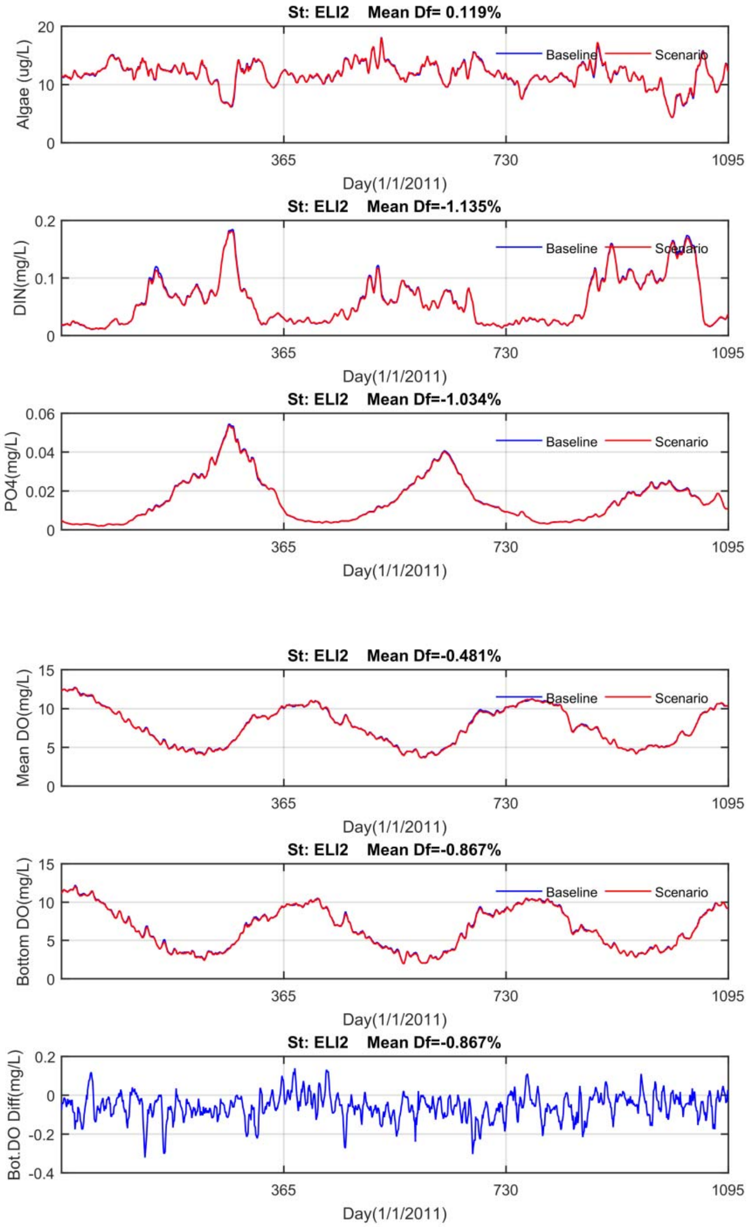


Figure 3-8-2: Comparison of S08 and Future Baseline Condition (S05) Results at Station LFB01

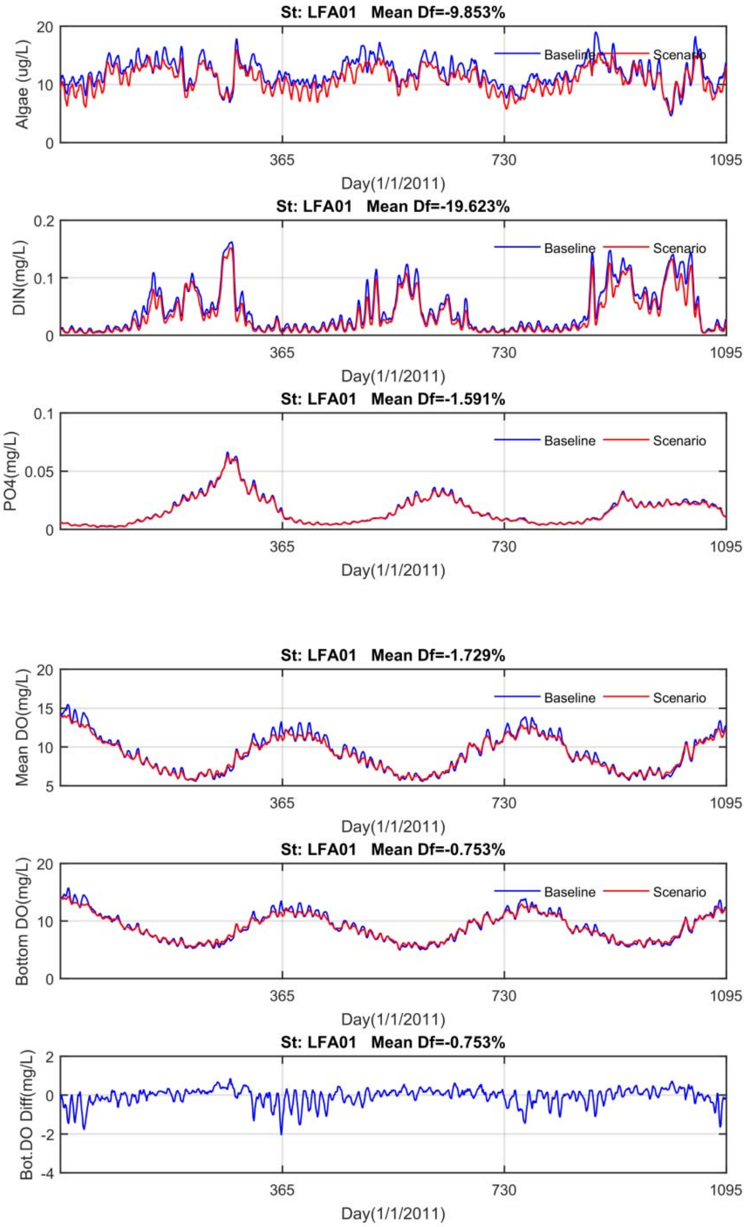


Figure 3-8-3: Comparison of S08 and Future Baseline Condition (S05) Results at Station LFA01

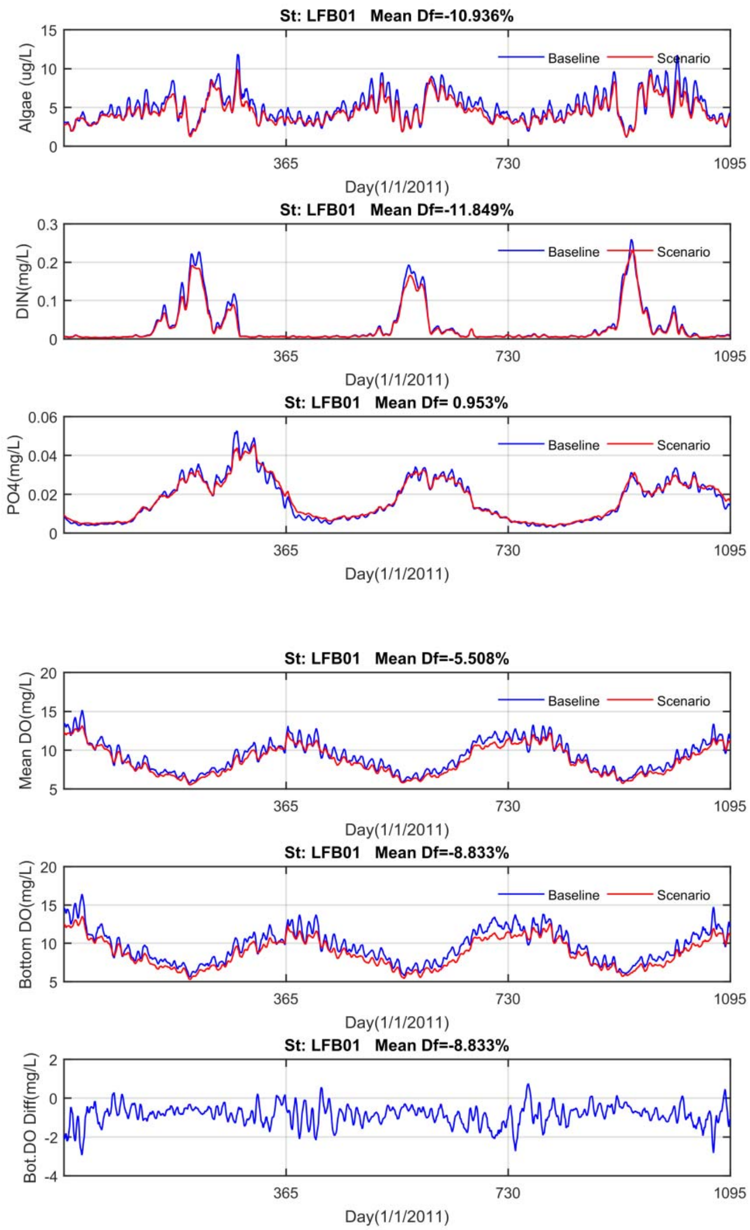


Figure 3-8-4: Comparison of S08 and Future Baseline Condition (S05) Results at Station LFB01

4. Summary

The model simulations for different configurations of storm surge barrier were studied. Four different scenarios have been tested and the results are compared to the baseline condition (existing condition). Both the large barrier (with 19 floodgates) and the small barrier (with 5 floodgates) were tested. The model results show that both barriers have minor impacts on DO levels. DO increases in the ER and near the mouth of LR, but slightly decreases in the upstream of LR due to the reduction of the tide energy propagating upstream. When only half-designed floodgate (total of 10) were open for the large barrier, the impact on DO increases, especially in the upstream of the LR. When only 3 floodgates were open for the small barrier, the impact on DO increases in the upstream of LR.

The model simulation of change of DO due to SLR was conducted. The impact of SLR on DO seems larger than the storm surge barrier. Additional scenarios of large and small barriers under the SLR were conducted. Changes of DO are not even and vary with location. The change of DO due to storm surge barriers under the SLR condition is on the same order of magnitude as the change of DO due to storm surge barriers under the current condition. If the number of floodgates reduces to 10, the change of DO increases. DO decreases in the downstream of LR, but increase in the upstream of LR.

5. References

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Zhang, J., H. Wang, F.Ye, and Z. Wang. 2017. Assessment of Hydrodynamic and Water Quality Impacts for Channel Deepening in the Thimble Shoals, Norfolk Harbor, and Elizabeth River Channels.(*Final report on the hydrodynamic modeling)*. Final Report submitted to Moffatt and Nchol and the Fort Norfolk Office of the U.S. Army Corps of Engineers. 55 pp.