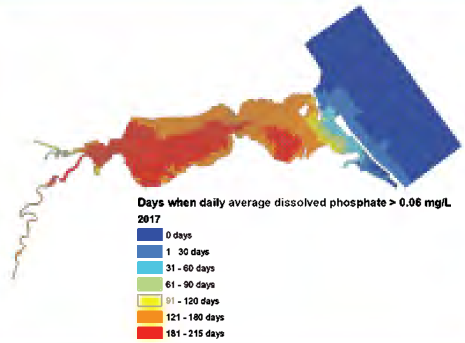
Application of the Sandusky Bay Hydrodynamic and Water Quality Model

June 30, 2019



Prepared for: Ohio Department of Natural Resources, Office of Coastal Management | Prepared by: Tetra Tech, Inc.

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Draft Report
June 30, 2019

PRESENTED TO

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EXECUTIVE SUMMARY

Sandusky Bay is a shallow, freshwater embayment in northern Ohio along the coast of Lake Erie that is impacted by harmful algal blooms (HABs). Elevated nutrient loads from the Sandusky River watershed contribute to HABs in Sandusky Bay as well as hypoxia in Lake Erie. The purpose of this report is to present the key findings from the application of a hydrodynamic and water quality model to Sandusky Bay. The modeling effort is one of many ongoing initiatives to improve and restore the water quality of the bay and Lake Erie. Key findings from this project include the following:

- The primary sources of nitrogen and phosphorus to Sandusky Bay are the Sandusky River, internal loading within the Bay, and discharges from the smaller tributaries that empty directly into Sandusky Bay (Table ES-1).

Table ES-1. Relative load contribution to Sandusky Bay (average of the three-year modeled period)

Nutrient Load	Sandusky River	Internal Loading	Small Tributaries	Point sources
Total Phosphorus	53%	34%	11%	2%
Total Nitrogen	49%	28%	18%	5%

Note: Due to averaging, relative loads do not sum to 100 percent.

- During the dry year of 2016, internal loading was the largest source of total phosphorus (TP) and contributed nearly the same load of total nitrogen (TN) as did the Sandusky River. Internal loading is most significant in Upper[1] Sandusky Bay, closely followed by Lower Sandusky Bay.
- Table ES-2 presents the estimated TP loadings from each of the small tributaries to Sandusky Bay based on the results of Soil and Water Assessment Tool (SWAT) modeling for the period 2001 to 2017. The largest loads originate from Muddy Creek, Raccoon Creek, and Pickerel Creek.

[1] This report refers to Upper Sandusky Bay and Lower Sandusky Bay. Other studies have either used the terms Western Sandusky Bay and Eastern Sandusky Bay, or Outer Sandusky Bay and Inner Sandusky Bay, respectively.

Table ES-2. Average loading of TP (metric tons/yr) from the various tributaries into Sandusky Bay

Waterbody	HUC	Drains to	TP	Soluble Phos.	Organic Phos.
Plum Brook	01 02	East Sandusky Bay	2.2	0.7	1.5
Pipe Creek		East Sandusky Bay	5.9	1.5	4.4
Mills Creek	01 03	East Sandusky Bay	6.6	2.3	4.3
Cold Creek	02 01	Lower Sandusky Bay	2.2	0.7	1.5
Unnamed Tributary		Lower and Upper Sandusky Bay	2.2	0.7	1.5
Little Pickerel Creek		Upper Sandusky Bay	2.2	0.7	1.5
Unnamed Tributary		Upper Sandusky Bay	2.2	0.7	1.5
Pickerel Creek	02 03	Upper Sandusky Bay	6.1	2.9	3.3
Raccoon Creek	02 04	Upper Sandusky Bay	6.7	1.9	4.9
South Creek	02 05	Muddy Creek Bay	3.9	1.3	2.6
Little Muddy Creek	14 03	Lower Muddy Creek (lacustuary)	4.5	1.6	2.9
Muddy Creek	14 04	Lower Muddy Creek (lacustuary)	12.9	5.1	7.7
Unnamed Tributaries	14 05	Muddy Creek Bay, Upper Sandusky Bay, and Lower Sandusky Bay	4.3	0.9	3.4

- There are significant fluctuations in water and nutrient loads that occur between Sandusky Bay and Lake Erie. During some periods, the net loading of nutrients is from the bay into the lake and during other periods the net loading is from the lake into the bay. Table ES-3 indicates that the net loading to Lake Erie was half of the load from the Sandusky River into Sandusky Bay in 2015 and 2017, whereas the bay exported more phosphorus to Lake Erie than it received from the Sandusky River in 2016. This likely resulted from the release of soluble TP from phosphorus-laden sediment deposited in the bay and loads from the smaller tributaries (i.e., other than the Sandusky River).

Table ES-3. Net loading of TP (metric tons/yr) from the Sandusky River to Sandusky Bay and from Sandusky Bay to Lake Erie

Year	Sandusky River to Sandusky Bay	Sandusky Bay to to Lake Erie
2015	459	244
2016	297	338
2017	709	488

- Other observations regarding the movement of water and nutrients within Sandusky Bay include the following:
    - Most pulses of water with high concentrations of nutrients from the Sandusky River that enter Sandusky Bay never migrate entirely through Upper Sandusky Bay. Most plumes are stopped either just after entering Upper Sandusky Bay or about half way through Upper Sandusky Bay. Very few plumes even migrate to the constriction between Upper Sandusky Bay and Lower Sandusky Bay (refer to Section 3.2 for more details).

  - With a couple of exceptions, the few plumes that extended into Lower Sandusky Bay were typically the result of several storm pulses from the Sandusky River.
  - Pulses from Pipe Creek sometimes form plumes in Castaway Bay of East Sandusky. With a few exceptions, nutrient concentrations of such plumes are considerably smaller than plumes derived from the Sandusky River.
  - Only a few storm pulses from the Sandusky River migrated intact to Lake Erie. Such pulses took weeks to traverse Sandusky Bay.
  - Seiches often migrate into Sandusky Bay. The low nutrient concentrations due to dilution caused by Lake Erie water migrating into Lower Sandusky Bay were frequently apparent during the three-year modeling period.
  - Elevated concentrations of nutrients in Sandusky Bay are typically sustained through the summer despite reduced flow and loading from the Sandusky River. This is likely due to internal loading within the bay. For example, in July and August 2015, during periods without any pulses from the Sandusky River, TP concentrations in Muddy Creek Bay ranged from 0.04 to 0.16 mg/L and concentrations in Upper Sandusky Bay and Lower Sandusky Bay ranged from 0.12 to 0.24 mg/L. Similarly, in July and August 2016, without any pulses from the Sandusky River, TP concentrations in Muddy Creek Bay, Upper Sandusky Bay, and Lower Sandusky Bay steadily increase over time until they stabilize at 0.20 to 0.24 mg/L.
  - Elevated summer and early fall nutrient concentration begin to decrease in October and continue decreasing into November and December. Small plumes from the minor tributaries are readily apparent during this timeframe, since they discharge at considerably larger concentrations.
- Simulation of several management options suggests that significant improvements in water quality would result from reducing loads of nutrients and sediments from the Sandusky River as well as from the small tributaries that discharge to the bay.
- Two scenarios with new islands located at the most upstream end of Sandusky Bay suggest that modest reductions in nutrient concentrations might occur due to the altered hydrodynamics. A modified version of one of the island scenarios suggests that additional nutrient reductions occur when new attached plants are simulated as growing in the shallower water around the islands. The model may not be fully accounting for the potential impacts of the islands because it does not account for one of their intended key features, attenuation of wave energy.
- Potential enhancements and future uses of the Sandusky Bay water quality modeling include the following:
  - Incorporate results of wave modeling to better assess the potential benefits of the proposed islands and other efforts to attenuate wave energy;
  - Evaluate conditions within the bay during years with different lake levels;
  - Continue to improve the model by incorporating results of ongoing research regarding algal dynamics, sediment/water column interactions, and the benefits of different types of restoration projects.

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
EFDC	Environmental Fluid Dynamics Code
HAB	harmful algal bloom
NOAA	National Oceanic and Atmospheric Administration (U.S. Department of Commerce)
ODNR	Ohio Department of Natural Resources
Ohio EPA	Ohio Environmental Protection Agency
SWAT	Soil and Water Assessment Tool
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
U.S. EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey (U.S. Department of the Interior)

Unit of measure	Definition
mg/L	milligram per liter
MTA	metric ton per annum (i.e., 1,000 kilograms per year)
NTU	nephelometric turbidity unit
µg/L	microgram per liter

1.0 INTRODUCTION

Sandusky Bay is a shallow, freshwater embayment along the coast of Lake Erie in northern Ohio that is impacted by HABs. Elevated nutrient loads from the Sandusky River watershed contribute to HABs in Sandusky Bay as well as to problems of hypoxia (reduced oxygen levels) in Lake Erie caused by the decay of algal biomass. *Planktothrix* is the dominant HAB-forming species and the main producer of microcystin in Sandusky Bay. *Planktothrix* may proliferate in Sandusky Bay due to its tolerance to a broad temperature range and acclimation to growth at low light intensity (Hampel et. al, 2019).

The Ohio Department of Natural Resources (ODNR) Office of Coastal Management partnered with the U.S. Environmental Protection Agency (U.S. EPA) and the Ohio Environmental Protection Agency (Ohio EPA) to develop a hydrodynamic and water quality model to better understand how nutrients are transported through the Sandusky Bay system and how they impact water quality conditions, especially the formation of HABs. A better understanding of these issues will help to guide management decisions related to the bay, such as how to best control tributary loadings, how to assess the importance of internal loading, and how to select and design optimal restoration projects.

U.S. EPA provided the original contract resources to have Tetra Tech, Inc. prepare an Environmental Fluid Dynamics Code (EFDC) hydrodynamic and water quality model of Sandusky Bay (Tetra Tech, 2018). The model was set up and calibrated under the U.S. EPA contract and then ODNR Office of Coastal Management provided additional contract resources from a National Oceanic and Atmospheric Administration (NOAA) grant to update the model and simulate a series of management scenarios.

EFDC is a state-of-the-art model that can be used to simulate aquatic systems in one, two, and three dimensions. Configuration of the Sandusky Bay EFDC model is summarized in the following bullets and additional details are provided in the original U.S.EPA contract report entitled *Development of the Sandusky Bay Hydrodynamics and Water Quality Model* (Tetra Tech 2018):

- **Domain:** The model domain is Sandusky Bay, and the model domain includes lacustrine segments of the Sandusky River and other tributaries and the portion of Lake Erie near the outlet of Lower Sandusky Bay (Figure 1).
- **Simulation period:** The EFDC model simulates (and was calibrated for) calendar years 2015, 2016, and 2017.
- **Grid:** The model includes 1,717 grid cells with a longitudinal range of 78- to 1,190 meters and a lateral range of 130- to 1,238-meters. Each cell is composed of two vertical layers and bathymetry is based on data obtained from ODNR.
- **Boundary conditions:** Lake Erie is simulated as an open boundary condition using water level and water temperature data from NOAA and water quality data collected by Bowling Green State University. Boundary conditions for the Sandusky River are based on U.S. Geological Survey (USGS) flow data and water quality data collected by the National Center for Water Quality Research at Heidelberg University. Boundary conditions for the small tributaries to the bay were developed using Soil and Water Assessment Tool (SWAT) model flow and water quality results (Tetra Tech, 2018). Loads from the Sandusky Water Pollution Control wastewater treatment facility and the Danbury Township wastewater treatment plant were simulated using discharge monitoring report data provided by Ohio EPA.
- **Calibration Data:** Water chemistry data collected by Bowling Green State University (at ODNR monitoring sites), Ohio EPA, and Environment Canada were used to calibrate the EFDC model. Calibration data included continuous monitoring data from several buoys deployed in 2017.

Tetra Tech set up and calibrated the EFDC model to the available sampling data, and output from the model was then used to better understand water and nutrient loading with the bay. The model was also used to evaluate a series of potential management options to assess the degree to which those would improve water quality within the bay. The purpose of this report is to present the key findings both in terms of water and nutrient movement as well as the benefits of the various management options. The updates to the original model are also briefly discussed.

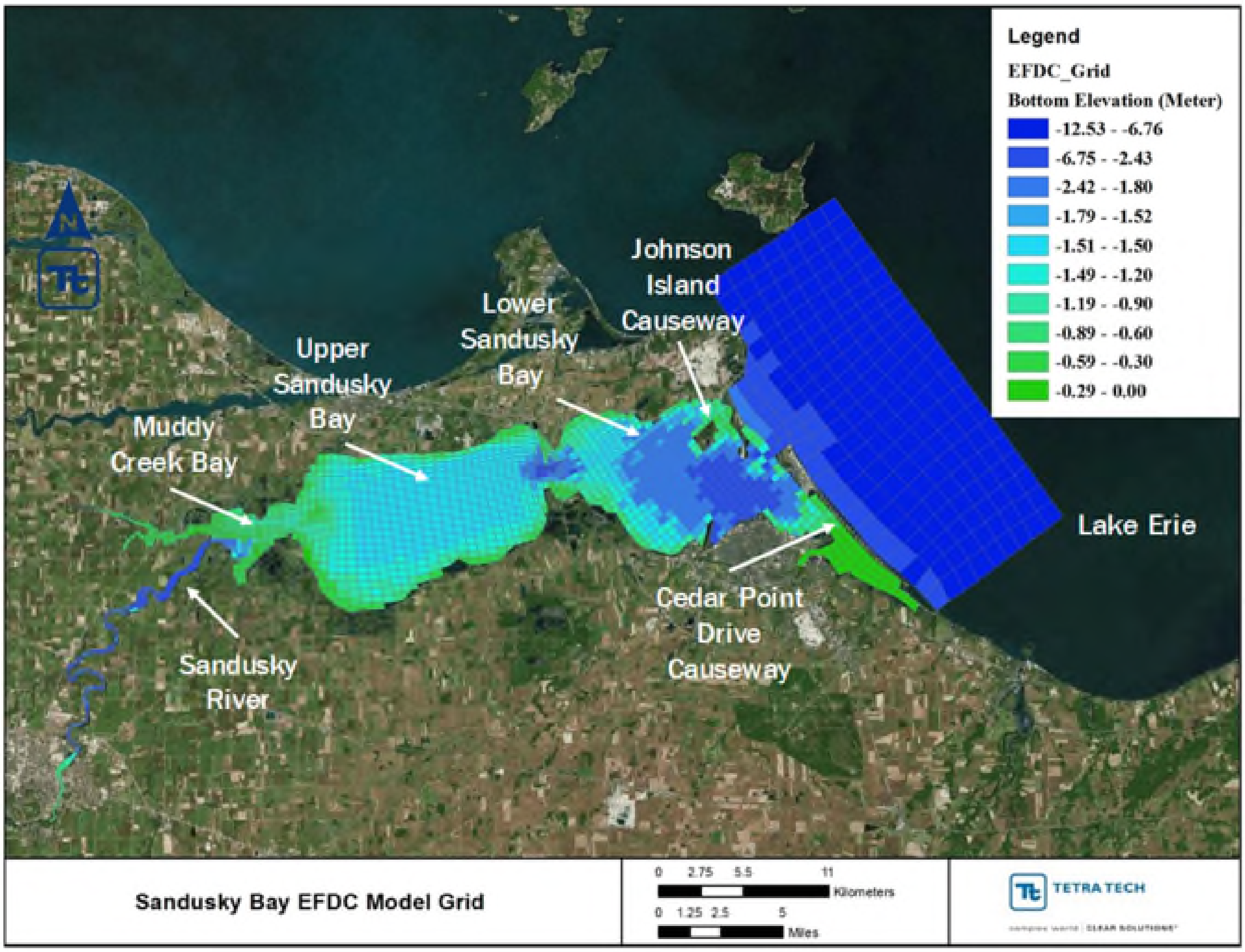


Figure 1. Sandusky Bay EFDC model grid along with associated bathymetry.

2.0 UPDATES TO EFDC MODEL

The original model simulation period under the U.S. EPA contract was for a period of two years (calendar years 2015 and 2016). The model was extended through calendar year 2017 under the ODNR contract. Important updates to the model made under the ODNR contract are listed below:

- Revision of the model grid to represent causeway openings (Figure 1). The previous model did not include the Cedar Point Drive, Cedar Point Road, or Johnson Island causeways so those were added. Two-way control structures were used to represent causeway openings via a hypothetical weir between the two sides of the openings; flows depend on the elevation differences between the two sides.
- Replacement of the Sandusky River boundary condition from the U.S. EPA contract model (i.e., SWAT model simulation) with a new boundary condition developed from daily and sub-daily water chemistry data provided by the National Center for Water Quality Research for the Sandusky River at Fremont. The new boundary condition included corresponding flow data from the co-located USGS gage.
- Extension of the SWAT model through calendar year 2017. Boundary conditions for the small tributaries were developed using the SWAT results.
- Extension of boundary condition of the Sandusky Water Pollution Control Plant through calendar year 2017.
- Addition of boundary condition loads for the Danbury Township wastewater treatment plant.
- Extension of the weather data, Lake Erie elevation data, and Lake Erie water quality boundary conditions through calendar year 2017.
- Simulation of two groups rather than one group of phytoplankton. The added group was parameterized to mimic the behavior of the cyanobacterium (blue-green algae) genus *Planktothrix* (e.g., ability to grow well under light-limited conditions).
- Addition of suspended sediment to the model to represent the impact of fine sediments on water quality (note that full sediment transport is not currently modeled).
- Re-calibration of the model to obtain the best possible fit for the years 2015, 2016, and 2017 for water elevation, velocity, and water quality data.

Turbidity is an important measure of water quality within Sandusky Bay because the low light conditions are believed to be a key factor in the dominance of *Planktothrix.* Turbidity is not a parameter that is simulated by EFDC, however. Paired samples of chlorophyll-*a*, total suspended solids (TSS), and turbidity from Ohio EPA's sampling site off Johnson's Island (site 300900) were therefore used to develop an equation to predict turbidity as a function of TSS and chlorophyll-a. The individual regressions of these parameters are shown in Figure 2 and the equation derived from multiple regression ($r^2 = 0.79$) is:

$$\text{Turbidity} = (0.057 * \text{chlorophyll-a}) + (0.542 * \text{TSS}) + 2.724$$

for turbidity in nephelometric turbidity units (NTU), chlorophyll-a in µg/L, and TSS in mg/L.

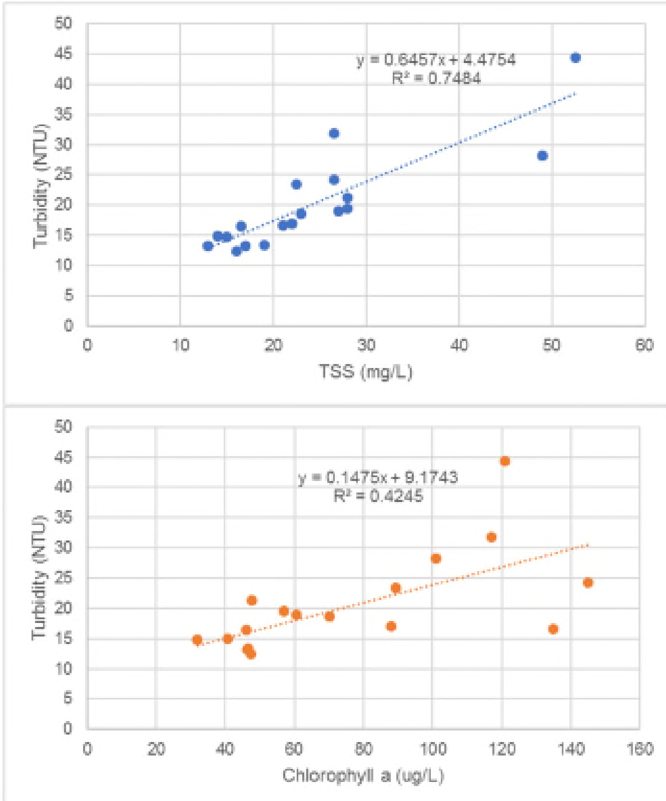


Figure 2. Regressions between TSS and turbidity (top) and chlorophyll-*a* and turbidity (bottom).

A comparison of the updated model results to the observed sampling data revealed the following;

- The model simulates hydrodynamics well, with a good match of predicted water elevations, flow velocities, and temperature to the observed data.
- Phosphate and TP are simulated reasonably well, with the model matching the seasonal pattern in concentrations although sometimes overpredicting peak values.
- The model does not perform as well for the various nitrogen species (ammonium, total Kjeldahl nitrogen, and TN), usually overpredicting the observed concentrations. This is especially true for the sampling stations in Upper Sandusky Bay and could be due to an overprediction of the internal loading of nitrogen or an underprediction of denitrification losses.
- The model simulates chlorophyll-*a* fairly well, with a good match of predicted concentrations to observed data at some locations and a fair match at other locations.

The Sandusky Bay model simulates most of the important processes that affect water quality within the bay and is therefore a powerful tool to aid in better understanding the existing system, how it functions, and how it might be better managed. Several of these key processes include:

- Hydrodynamic circulation patterns governed by river flows, winds, lake levels, and bay bathymetry;
- The seiche effect of Lake Erie with water moving upstream into the bay and river during significant periods of the year;
- Internal loading of phosphorus and nitrogen due to sediment release during anoxic conditions;
- Complex interactions of nutrient concentrations, temperature, light availability, and other variables on growth of phytoplankton.

It should be noted, though, that some aspects of these processes are not fully addressed by the model. Perhaps most significantly, the model does not currently incorporate the impact of waves on sediment and nutrient re-suspension. Since EFDC is not a wave model, it is not explicitly accounting for the fact that Sandusky Bay frequently experiences large wave events that increase turbidity and can contribute to internal loading of nutrients. The movement and deposition of coarse materials are also not tracked because the full sediment transport component of EFDC is not being used. Since nutrient particles primarily absorb to fine sediments, the lack of full sediment transport modeling likely does not affect the simulation of nutrients but could contribute to an underprediction of TSS and turbidity. Finally, research suggests that internal, "cryptic[2]" nutrient cycling represents an important knowledge gap in our understanding of HABs in Lake Erie and elsewhere that is not fully accounted for in the EFDC model.

USEPA (2009) defines a model as "a simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system." Models are based on simplifying assumptions and cannot completely replicate the complexity inherent in environmental systems. Despite these limitations, models are essential for a variety of purposes in the environmental field under two general categories: (1) Diagnosis (i.e., assessment of what happened and examination of causes of events that have taken place), and (2) Forecasting the probable outcomes of future events (i.e., what will happen). The Sandusky Bay EFDC model is considered a useful tool for better understanding key aspects of this complex system and how bay water quality might change to various management activities. However, the model is not an exact representation of reality, and output from the model should be used within a weight-of-evidence context along with all other ongoing scientific efforts to guide management of the bay.

3.0 SOURCES OF NUTRIENTS AND PATTERNS IN WATER AND NUTRIENT MOVEMENT

This section of the report presents the key findings from the application of the updated Sandusky Bay hydrodynamic and water quality model.

3.1 SOURCES OF NUTRIENT LOADING

The EFDC model was used to assess the primary sources of phosphorus and nitrogen to Sandusky Bay. The results are shown in Figure 3. The sources of nitrogen and phosphorus to Sandusky Bay are the Sandusky River, internal loading, the smaller tributaries that discharge directly to Sandusky Bay, and the two wastewater treatment plants (or point sources) that discharge into the bay. Internal loading as represented in the EFDC model is primarily due to the release of nutrients during hypoxic (low oxygen) conditions within the bay. The internal loading estimates do not include any load that may be associated with wave-driven sediment resuspension, although that is likely an additional source of internal loads.

On average for the three-year period, these sources contributed the following relative loads:

- **Sandusky River**: 53 percent of the TP load and 48 percent of the TN load
- **Internal loading**: 34 percent of the TP load and 29 percent of the TN load
- **Smaller tributaries**: 11 percent of the TP load and 18 percent of the TN load

[2] Cryptic nutrient cycling refers to the fact that zooplankton typically excrete nitrogen and phosphorus, which can influence the production and composition of primary producers. As a result, the benthic consumer community can contribute substantially to water column nitrogen and phosphorus supply (Conroy et al. 2005, Zhang et al. 2011).

- **Point sources**: 2 percent of the TP load and 5 percent of the TN load.

Results differ across the three major segments of Sandusky Bay (refer to Figure 1). Significantly less internal loading occurs in Muddy Creek Bay (Figure 4), which was expected due to its size relative to Upper Sandusky Bay and Lower Sandusky Bay. The largest internal loading (across all three bays) occurred in 2016, which was the year with the lowest flow from the Sandusky River. More internal loading occurred during the non-spring (August 1st through February 28th) in 2015 and 2016 than in the Annex 4 spring (March 1st through July 31st).

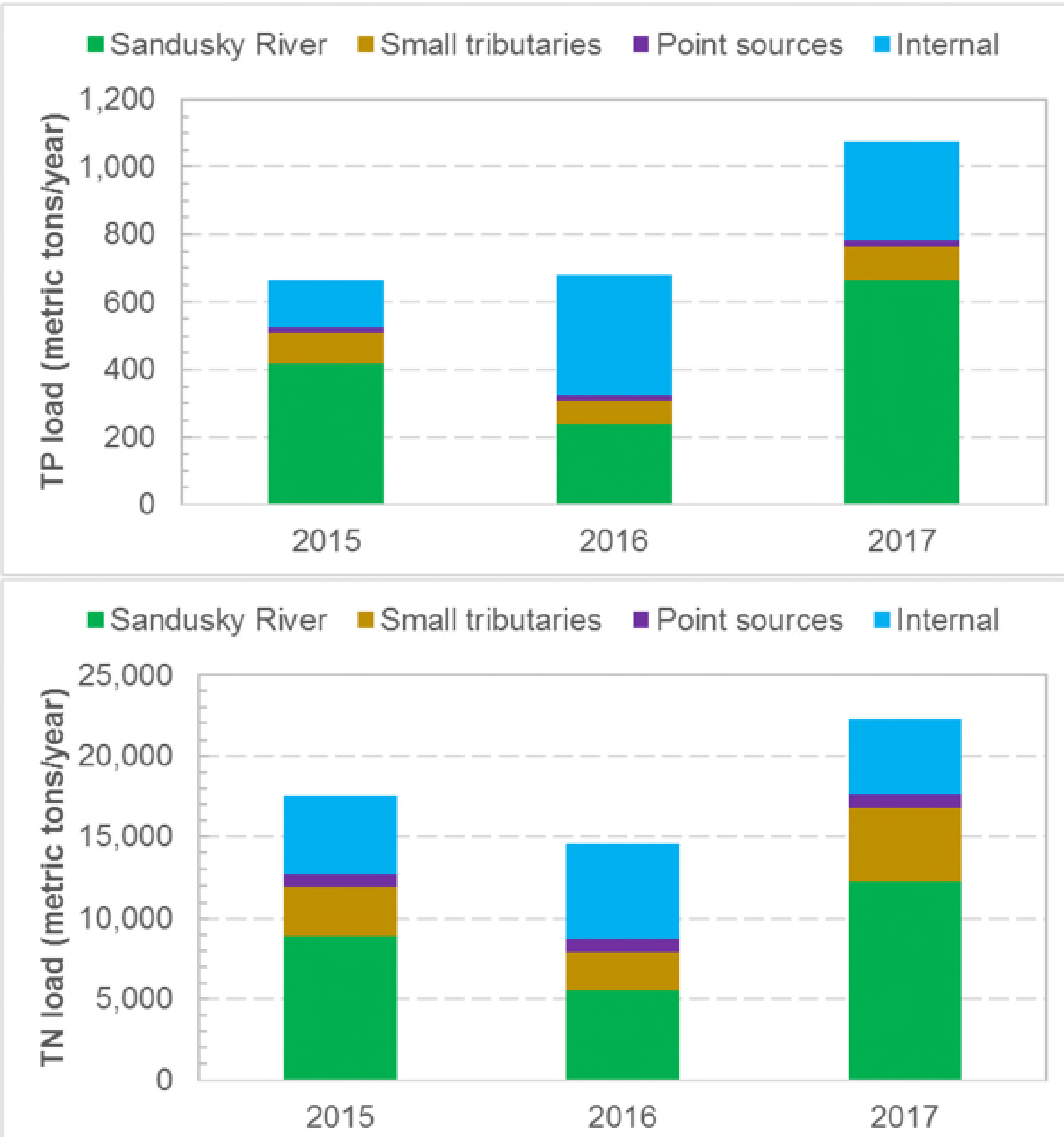


Figure 3. Sources of TP (top) and TN (bottom) loads to Sandusky Bay.

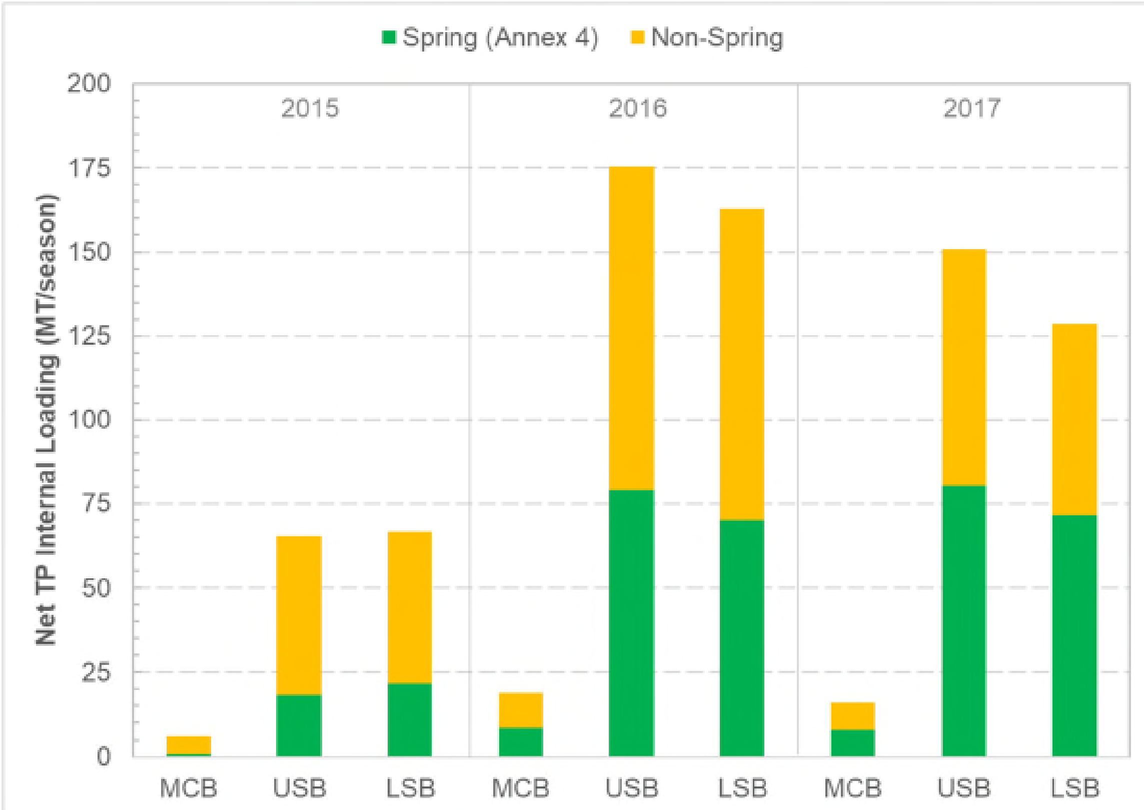


Figure 4. Internal TP loading by bay

Note: MCB = Muddy Creek Bay, USB = Upper Sandusky Bay, LSB = Lower Sandusky Bay.

3.2 EXISTING PATTERNS IN WATER AND NUTRIENT MOVEMENT

The movement of water and nutrients between the Sandusky River, the three bays of Sandusky Bay, and Lake Erie was evaluated using EFDC model results. Pollutant concentrations were spatially and temporally evaluated using animations of EFDC model results and by plotting the number of days that certain pollutant concentrations exceeded selected index concentrations. Pollutant loads were evaluated through visual analysis of charts of load flux.

3.2.1 Pollutant Concentration Animations

Animations of the EFDC model concentration results were reviewed to assess general patterns in the movement of water and nutrients from the Sandusky River into Sandusky Bay and then Lake Erie; refer to Figure 5 for an example static output of the animation. The results indicate that very few pulses of water with high nutrient concentrations migrate from the Sandusky River all the way into Lake Erie without dilution and that most pulses result in plumes that dissipate in Upper Sandusky Bay. The following general conclusions were drawn regarding these reviews:

- **Muddy Creek Bay:** No pulse from Muddy Creek, without a corresponding pulse from the Sandusky River (which generally obscures the pulse from Muddy Creek), ever migrates out of Muddy Creek Bay.
- **Upper Sandusky Bay:** Most nutrient pulses from the Sandusky River that enter Upper Sandusky Bay never migrate entirely through Upper Sandusky Bay (Figure 6). Most high concentration plumes dissipate either just after entering Upper Sandusky Bay or about half way through Upper Sandusky Bay.

  Very few plumes even migrate to the constriction between Upper Sandusky Bay and Lower Sandusky Bay. The influence of this constriction is clear in Figure 7, beginning on March 25th.
- **Lower Sandusky Bay:** With a couple of exceptions, the few high concentration plumes that extended into Lower Sandusky Bay were typically the result of several pulses from the Sandusky River.

  Pulses from Mills Creek form plumes in Lower Sandusky Bay that do not migrate very far (Figure 5) and are often dissipated quickly.
- **East Sandusky Bay:** Plumes entering Lower Sandusky Bay from Upper Sandusky Bay do not usually migrate east beyond the Cedar Point Causeway.

  Pulses from Pipe Creek sometimes form plumes in Castaway Bay of East Sandusky Bay (Figure 5; Figure 6 and Figure 7 also). With a few exceptions, concentrations of such plumes are considerably smaller than plumes derived from the Sandusky River.
- **Lake Erie:** Only a couple of pulses from the Sandusky River migrated to Lake Erie without dissipating. Such pulses took weeks to traverse Sandusky Bay (Figure 7).

  Seiches often migrate into Sandusky Bay. The low TP concentrations due to dilution caused by Lake Erie water migrating into Lower Sandusky Bay are clear in Figure 6 from May 5th through May 11.

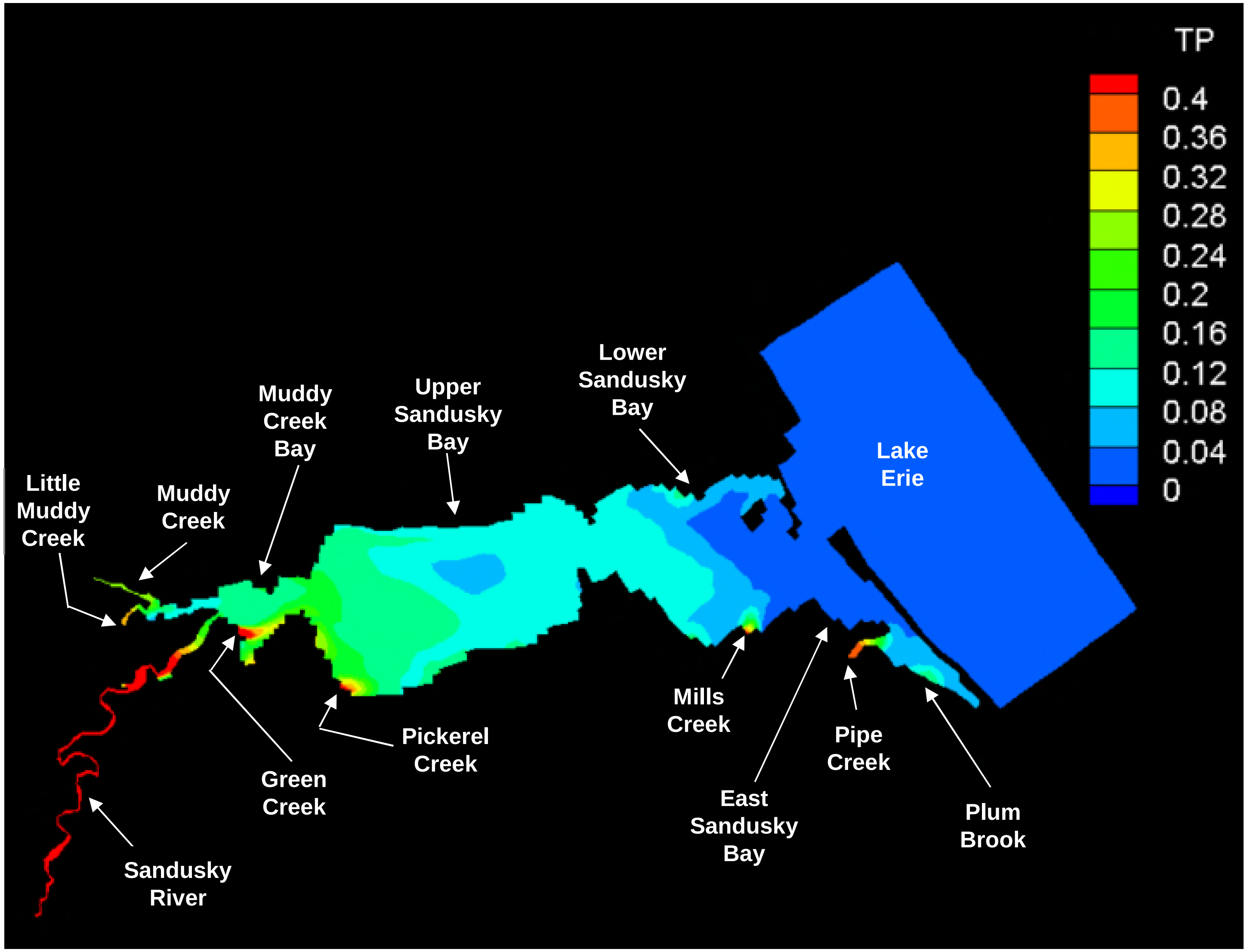


Figure 5. Visual representation of EFDC model results on February 25, 2016.

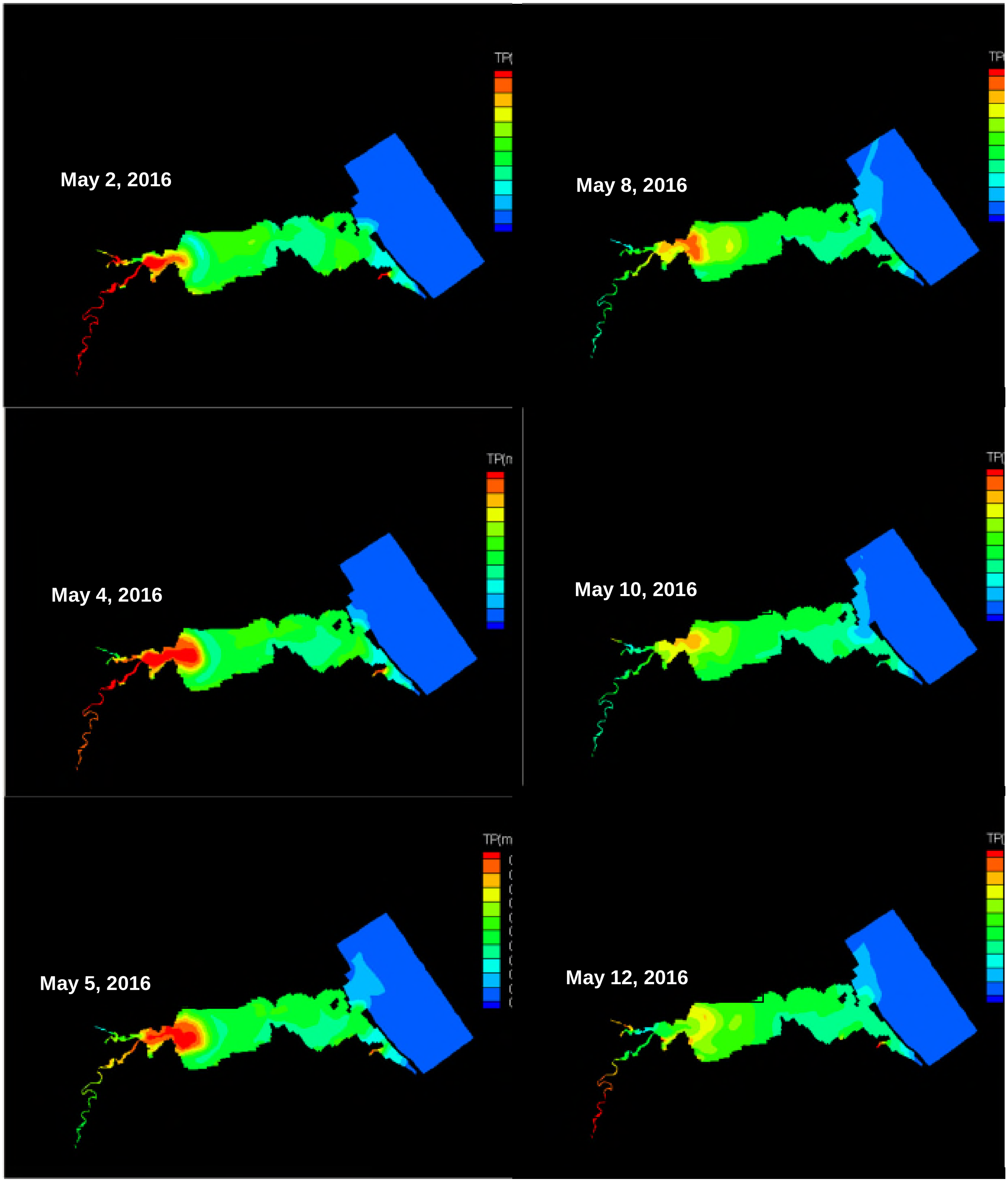


Figure 6. Visual representation of EFDC model results for a storm pulse in May 2016.

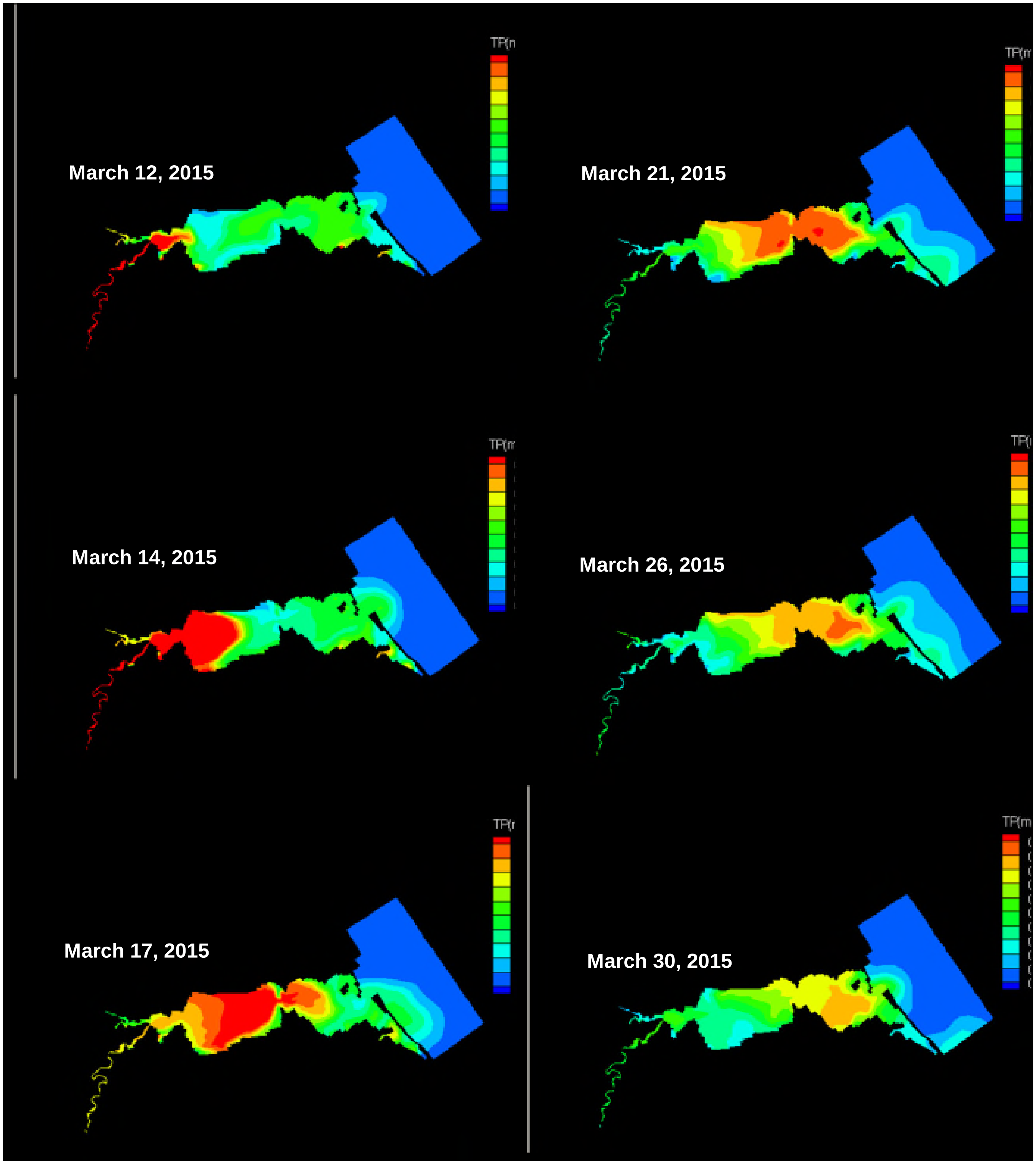


Figure 7. Visual representation of EFDC model results for TP for a large storm event in the spring of 2015.

Elevated nutrient concentrations in Sandusky Bay are typically sustained through the summer despite the lack of TP pulses from the Sandusky River (Figure 8). In July and August 2015, during periods without any pulses from the Sandusky River, Predicted TP concentrations in Muddy Creek Bay ranged from 0.04 to 0.16 mg/L and concentrations in Upper Sandusky Bay and Lower Sandusky Bay ranged from 0.12 to 0.24 mg/L. Similarly, in July and August 2016, without any pulses from the Sandusky River, TP concentrations in Muddy Creek Bay, Upper Sandusky Bay, and Lower Sandusky Bay steadily increase over time until they stabilize at 0.20 to 0.24 mg/L. Sometimes concentrations in East Sandusky Bay are larger than in Lower Sandusky Bay. The same patterns that exist for TP generally hold true for TN and dissolved P.

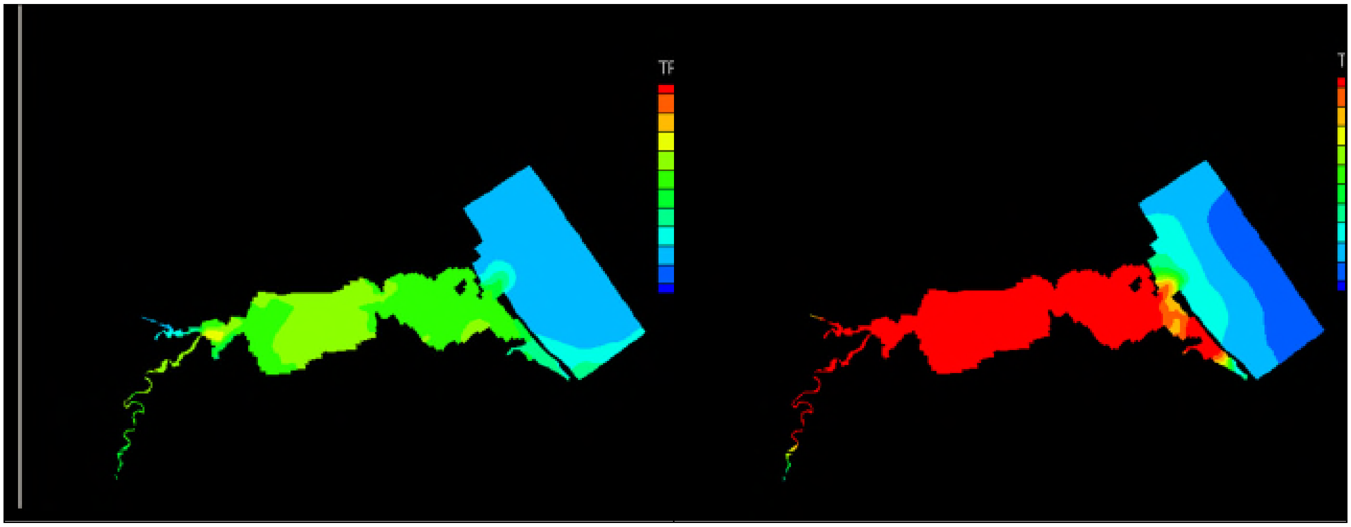


Figure 8. Visual representation of EFDC model results on July 6, 2015 (left) and August 9, 2016 (right).

Elevated summer and early fall TP concentrations begin to decrease in October. Concentrations in November and December are lower (Figure 9), typically below 0.08 mg/L, but often still greater than the *Sandusky Basin Shoreline* TP concentration target of 0.03 mg/L (Ohio EPA 2014a, Table I5-4, p. I-36). Small plumes from the minor tributaries are obvious during this timeframe, since they discharge at considerably higher concentrations (0.08 to 0.16 mg/L).

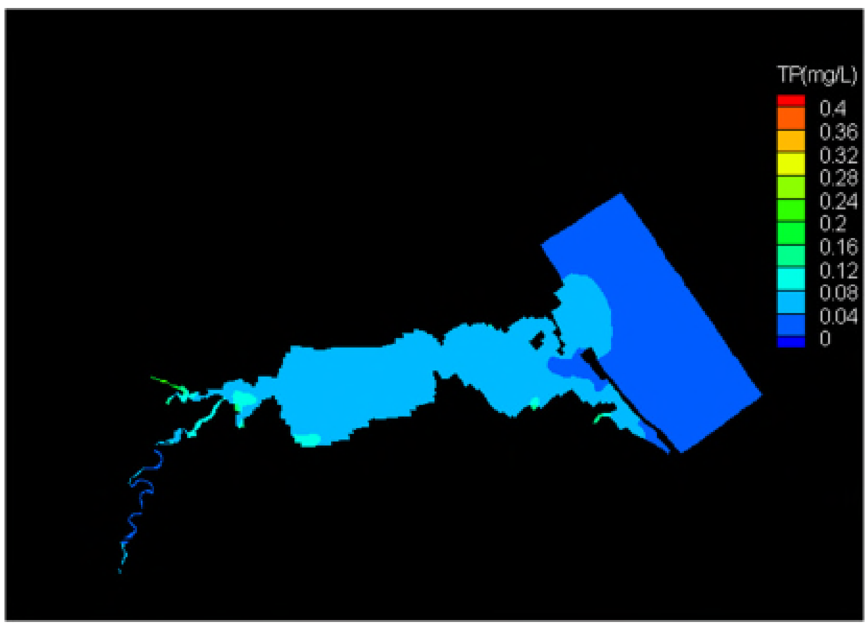


Figure 9. Visual representation of EFDC model results on November 28, 2015.

3.2.2 Pollutant Concentration Frequency Visualization

EFDC model results were post-processed to yield daily average pollutant concentrations by model grid cell. These data were evaluated against arbitrary index levels[3] (see the bulleted list below) to visualize the location and number of days per year and per Annex 4 spring (March 1st through July 31st) that elevated pollutant concentration occur:

- **Total phosphorus**: 0.24 mg/L
- **Dissolved phosphate as P**: 0.06 mg/L
- **Chlorophyll-*a***: 80 µg/L
- **Total suspended solids**: 50 mg/L

"Heat maps" were developed for each pollutant for each year and each Annex 4 spring; these maps are presented in Appendix A. Generally, concentrations above the index levels were most frequent in 2017 and no concentrations exceeding these index levels were simulated in the open waters of Lake Erie adjacent to Sandusky Bay.

Evaluation of TP results indicate that TP concentrations were most often elevated in 2017 and least often in 2015, both on an annual basis and for the Annex 4 spring (Figure A - 1). More frequent high concentrations tended to occur in the northern, and especially northwestern, portion of Upper Sandusky Bay. The Sandusky River tended to exhibit concentrations greater than the index levels more often than Muddy Creek.

Dissolved phosphate results were similar to TP results. However, on an annual basis, higher dissolved phosphate concentrations tended to occur through the middle of Upper Sandusky Bay. Also, western Upper Sandusky Bay and Muddy Creek Bay had more frequent concentrations exceeding index levels in 2015 than in 2016.

No patterns are visually apparent with simulated chlorophyll-*a* results. Elevated concentrations were much more frequent on an annual basis then when evaluating only the Annex 4 spring. The spatial distributions of concentrations exceeding index levels are similar between the annual analysis and that of the Annex 4 spring for both 2016 and 2017. Results seem to indicate that during certain timeframes, high concentrations are more frequent closer to the constriction between Upper and Lower Sandusky Bay.

Days with elevated TSS were more frequent in 2017 and less frequent in 2015. On an annual basis, elevated concentrations tended to occur more frequently in eastern Upper Sandusky Bay, the constriction, and western Lower Sandusky Bay. High concentrations were more frequent in Upper and Lower Sandusky Bay than Muddy Creek Bay, the Sandusky River, Muddy Creek, and East Sandusky Bay. Annex 4 spring results indicate that TSS ubiquitously exceeds the target in Upper and Lower Sandusky Bay throughout the spring.

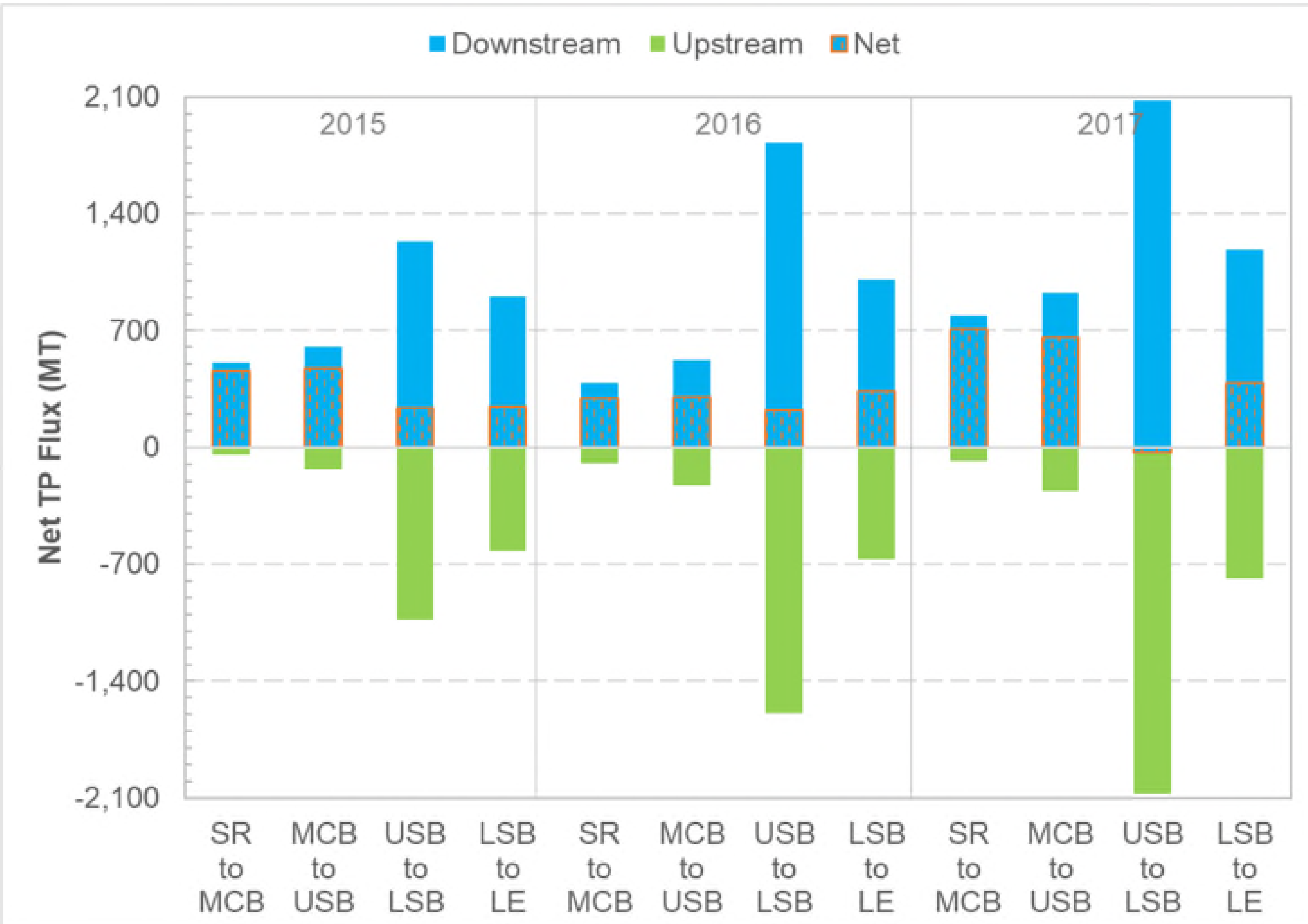
[3] The selected index levels were chosen primarily to illustrate patterns in the data and are not based on any thresholds of water quality conditions.

3.2.3 Pollutant Load Flux

EFDC model results indicate that flux between waterbodies in the Sandusky system is complex, with considerable upstream flux during certain conditions (e.g., seiches). Flux (TP, phosphate, and TN) was in the downstream direction during most days:

- Sandusky River to Muddy Creek Bay: 66 to 68 percent of days
- Muddy Creek Bay to Upper Sandusky Bay: 59 to 63 percent of days
- Upper Sandusky Bay to Lower Sandusky Bay: 50 to 55 percent of days
- Lower Sandusky Bay to Lake Erie: 50 to 54 percent of days

Evaluation of annual and seasonal net TP flux indicated that the most flux occurred in 2017. Net spring flux exceeded net non-spring flux in 2015 and at most locations in 2016 and 2017 (Figure 10). Significant daily flux is simulated in an upstream direction (e.g., Muddy Creek Bay upstream to the Sandusky River); however, net flux is generally in the downstream direction (Figure 10).



Notes

LE = Lake Erie; LSB = Lower Sandusky Bay; MCB = Muddy Creek Bay; SR = Sandusky River; USB = Upper Sandusky Bay.

Negative daily fluxes represent loading moving in an upstream direction.

Figure 10. Daily TP flux in Sandusky Bay in 2015 through 2017.

4.0 EVALUATION OF VARIOUS MANAGEMENT ACTIONS

The updated Sandusky Bay model was used to simulate five scenarios to help inform the management of the bay. The five scenarios are compared to the baseline or calibration conditions (Scenario 0) to assess their impact.

0) **Calibration**: The model results for the calibration condition (January 1, 2015 through December 31, 2017) serve as the baseline condition against which the scenario results are compared. Except where noted, the same weather and boundary conditions were used for the calibration and scenario runs.

1) **Sandusky River Load Reduction**: Inputs of phosphorus, nitrogen, and sediment from the Sandusky River were reduced by 40 percent to reflect continued efforts to address nonpoint source loading in the Sandusky River (e.g., implementation of total maximum daily loads, ongoing efforts as part of Ohio's Domestic Action Plan). The EFDC model was then used to evaluate the resulting changes to water quality within the bay.

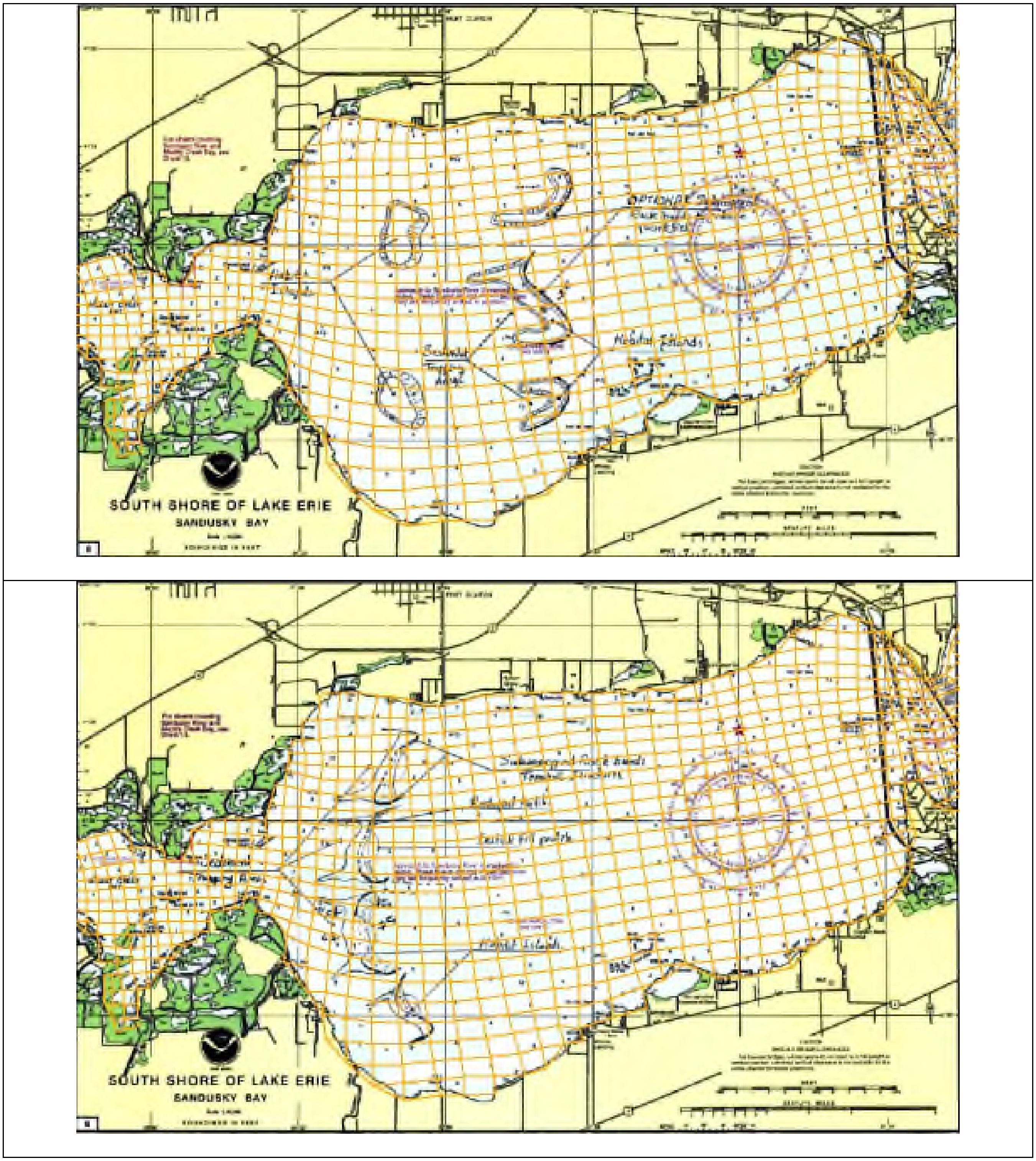
   This scenario was simulated with a lower sediment settling rate from an earlier calibration of the model that had little discernable impacts on some constituents (e.g., TP, TN) and had significant impacts upon others (e.g., TSS).

2) **Island Concept B**: Tetra Tech worked with Biohabitats, Inc. and Baird, Inc. (consultants for the Sandusky Bay Initiative) to simulate the creation of a series of islands in Upper Sandusky Bay. Biohabitats and Baird created conceptual drawings of the islands and Tetra Tech incorporated those designs into the model (Figure 11). Island Concept B includes a series of narrow outer islands with concave lee sides to promote sediment trapping (length scale = 1-mile long, 0.25-mile wide). The inner islands are aligned with the gaps between the outer islands to further reduce open fetches.

3) **Island Concept C**: A second island concept was simulated that includes the creation of habitat islands approximately 1-mile to the east of the mouth of Muddy Creek Bay.

4) **Sandusky Bay Tributary Load Reductions**: Inputs of phosphorus, nitrogen, and sediment from the small tributaries to Sandusky Bay were eliminated to reflect the potential benefits of reduced loadings (i.e., 100 percent reduction). Reduced loadings could result from projects within the tributary subwatersheds (e.g., projects to address agricultural and urban runoff) or projects at the locations where the tributaries discharge into the bay. For example, the Sandusky Bay Initiative recommends a project at the mouth of Pickerel Creek that would plug the creek drainage and allow water to flow into adjacent land, expanding wetland habitats and allowing sediment and nutrient loads to be filtered out.

5) **Revised Island Concept C**: Island Concept C was revised to include the expected change in bathymetry that should result from the accretion of sediments upstream of the islands. Plant growths were also added to the model around the islands to simulate the expected growth in submerged aquatic vegetation (SAV) that should occur with reduced wave energy and improved light conditions. A concept plan similar to Revised Island Concept C is included within the *Sandusky Bay Strategic Restoration Initiative Plan* (Biohabitats, 2019).



Source: Biohabitats and Baird.

Figure 11. Conceptual drawings of Island Concept B (top) and Concept C (bottom).

Seasonal averages of model scenario results were evaluated for each bay. Narrative summaries are presented below and tabular summaries are presented in Appendix B.

1) **Sandusky River Load Reduction**[4]: TP concentrations decreased from January through September, with the largest decreases in Muddy Creek Bay. All three bays saw the largest TP decreases in January through March. Dissolved phosphate concentration decreased in January through June. In Upper and Lower Sandusky Bays, concentrations increased in July through December.

   TN concentrations decreased considerably across the year in each bay.

   Chlorophyll-a concentrations decreased considerably across the year in each bay. Decreases were largest in Upper Sandusky Bay and decreases were smallest in Muddy Creek Bay. Decreases were also largest in July through September.

2) **Island Concept B**: TP, dissolved phosphate, TN, and chlorophyll-*a* results were very similar to the calibration. Both TSS and turbidity were similar, sometimes with a slight increase. The model may not be fully accounting for the potential impacts of the islands because it does not account for one of their key intended features, attenuation of wave energy.

3) **Island Concept C**: TP, dissolved phosphate, TN, and chlorophyll-*a* results were very similar to the calibration. Both TSS and turbidity were similar, sometimes with a slight increase.

4) **Sandusky Bay Tributary Load Reductions**: TP, dissolved phosphate, and TN concentrations decrease considerably across the year in Upper and Lower Sandusky Bay; little to no change occurred in Muddy Creek Bay.

   Similar to scenario 1, chlorophyll-*a* concentrations decreased considerably across the year in each bay. Decreases were largest in Upper Sandusky Bay and decreases were smallest in Muddy Creek Bay. Decreases were also largest in July through September.

   TSS concentrations slightly decreased in Muddy Creek Bay in January through September. Turbidity followed the same patterns as TSS.[5]

5) **Revised Island Concept C**: TP, dissolved phosphate, and TN results were very similar to the calibration. Chlorophyll-*a* concentrations decreased slightly in Muddy Creek Bay and increased in Upper and Lower Sandusky Bay.

[4]Scenario 1 was run with a lower sediment settling rate used in the initial calibration of the model. The lower sediment settling rate results in values for TSS and turbidity for this scenario that are higher than the calibration run and thus are not presented here.

[5] Anomalously large decreases in TSS concentrations in October through December (notably in 2016 and to a larger extent in Upper and Lower Sandusky Bays) are inexplicable and not presented in this report.

5.0 RECOMMENDATIONS

The following recommendations are made based on the results of this phase of the Sandusky Bay hydrodynamic and water quality modeling:

- The primary source of phosphorus and nitrogen to Sandusky Bay is the Sandusky River and the management scenario that provided the most significant improvement to water quality was the one that reduced loads from this source by 40 percent. Partners should therefore continue efforts to reduce loading from this source through a variety of activities within the 1,827-square mile Sandusky River watershed. Projects at the mouth of the Sandusky River in Muddy Creek Bay and at the far western end of Upper Sandusky Bay that trap loading from the Sandusky River should also result in water quality improvements to the rest of the bay. Several such projects are included within the *Sandusky Bay Strategic Restoration Initiative Plan* (Biohabitats, 2019).
- The second largest source of phosphorus and nitrogen to Sandusky Bay is internal loading. Continued research must be performed to better understand the various complex mechanisms that affect this source (e.g., impact of wave re-suspension, biochemical reactions, sediment characteristics) as well as the types of projects that can reduce its impact.
- The third most significant source of phosphorus and nitrogen to Sandusky Bay are the small tributaries that discharge directly to the bay (e.g., Muddy Creek, Raccoon Creek, and Pickerel Creek). The management scenario that reduced loads from this source also resulted in significant improvements to bay water quality. Partners should pursue projects that reduce loading both in the upland areas of these tributaries as well as at their confluence with Sandusky Bay. These include the living shoreline and wetland enhancement projects included within the *Sandusky Bay Strategic Restoration Initiative Plan* (Biohabitats, 2019).
- Simulation of several different island concepts in Upper Sandusky Bay led to only modest improvements to water quality, but the current configuration of the EFDC model does not account for some benefits these islands should provide in terms of reducing wave attenuation. This potentially transformative project deserves further study, including a more thorough analysis of the impact of wave attenuation on water quality as well as other potential consequences of building the islands (e.g., shift in dominant algal species due to increased light availability, decreased mixing upstream of islands which leads to increased anoxic conditions and more internal loading).
- The model scenario that included new plant growths in the shallow waters around the islands resulted in better water quality than the two island scenarios that did not include such plant growths. This reinforces the notion that increasing SAV in Sandusky Bay should help to improve water quality conditions via vegetative uptake of nutrients.
- Continued use of the model to support management of Sandusky Bay would benefit from several potential enhancements and additional analyses, including the following:
  - Incorporate results of wave modeling;
  - Add sediment transport capabilities to the model;
  - Continue to incorporate results of research findings regarding relationship between phosphorus loading, nitrogen loading, light availability, algal dynamics, cryptic nutrient cycling, HABs, etc.
  - Evaluate impacts of wet and dry years, high and low lake levels, and climate change.

6.0 REFERENCES

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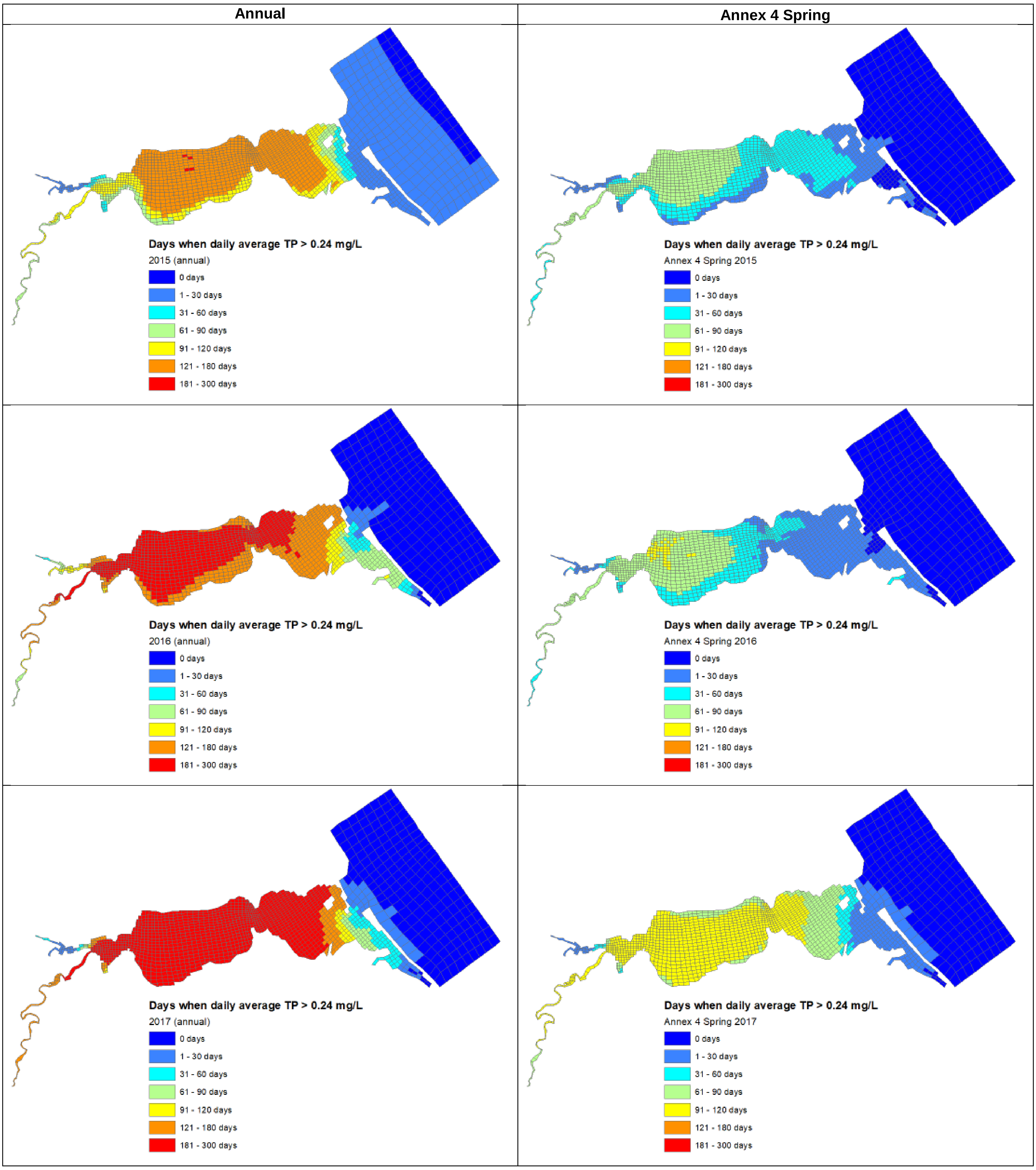
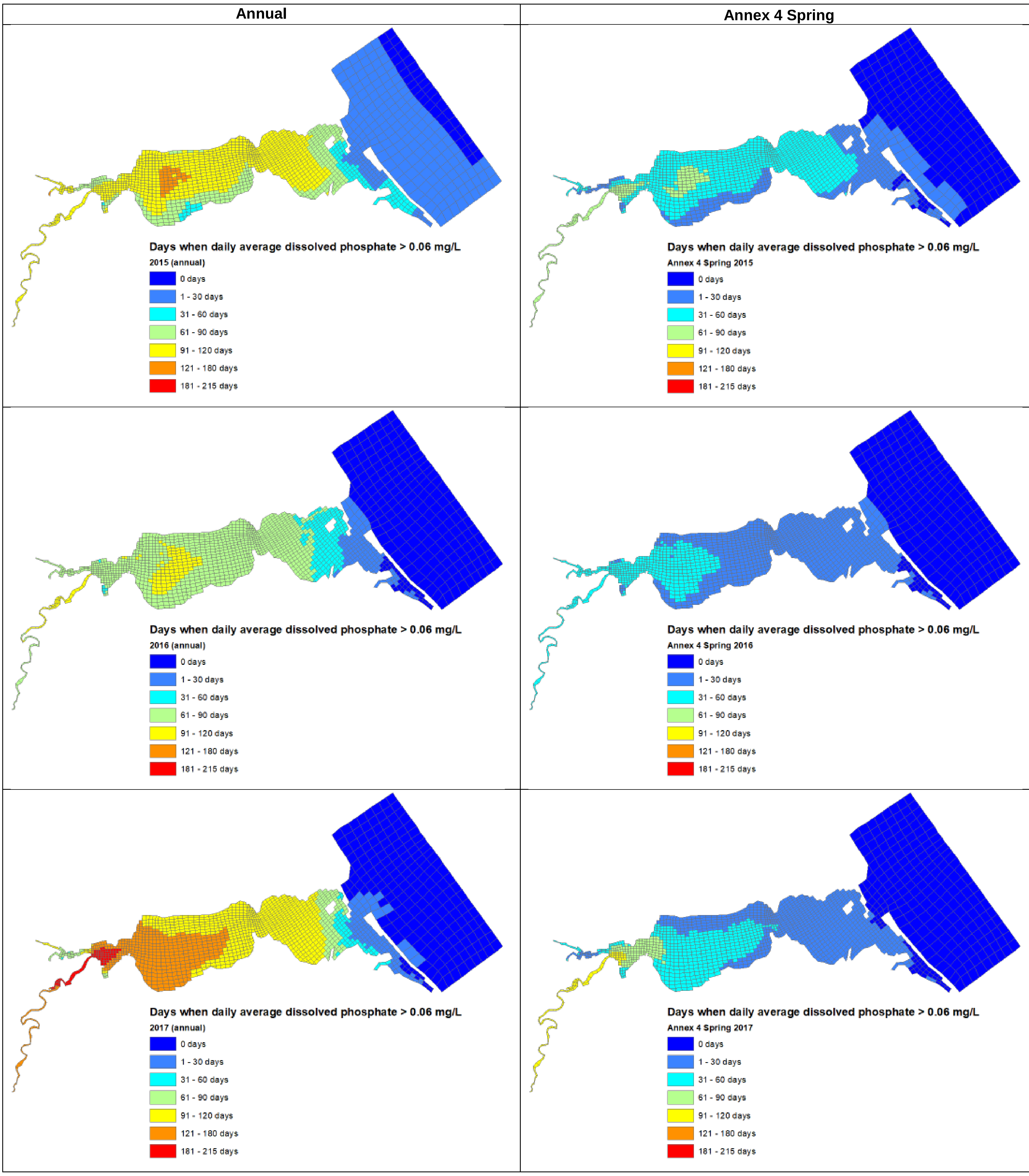
APPENDIX A. CONCENTRATION HEAT MAPS



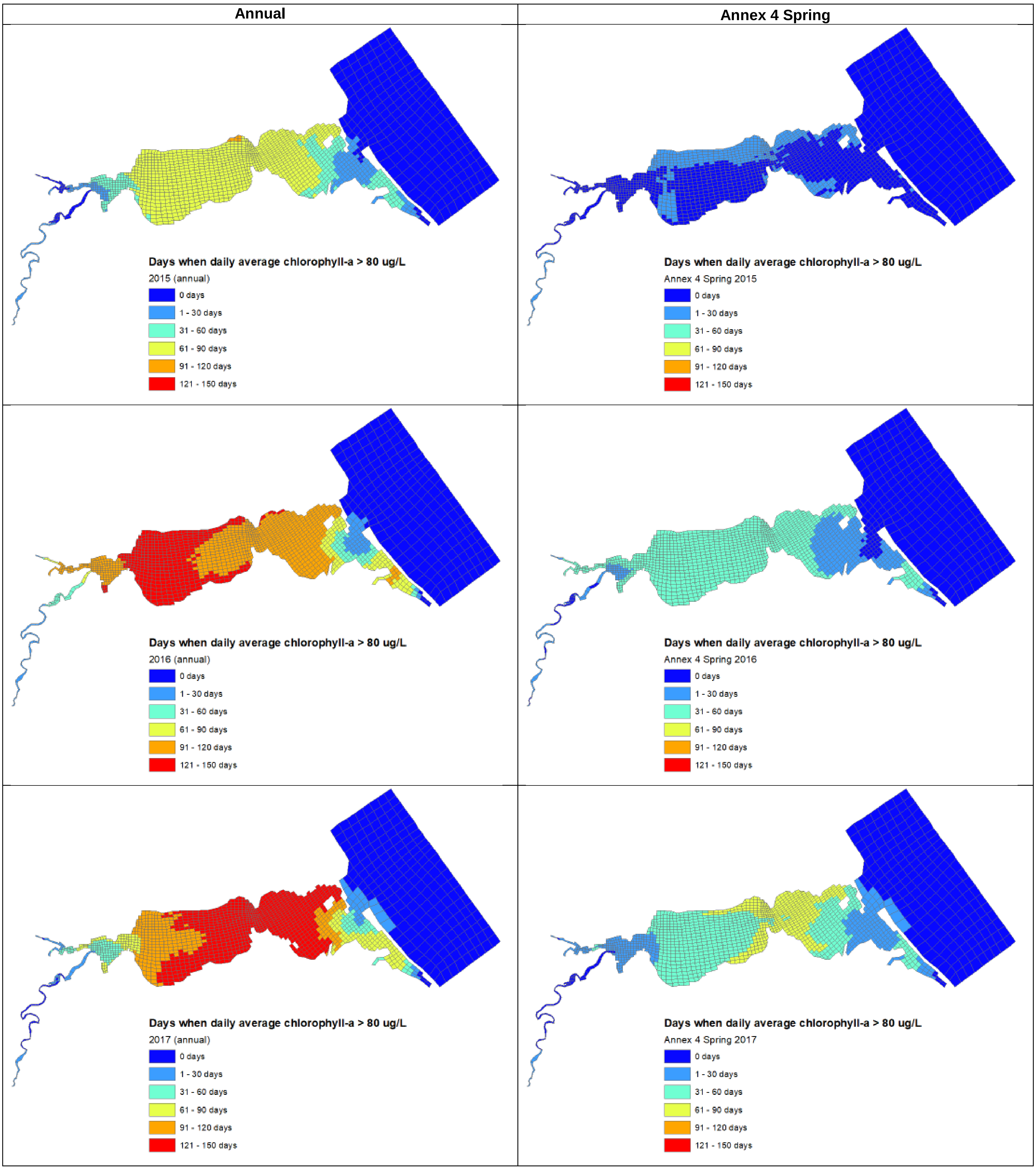
Note: The same symbology is used on all six maps. The Annex 4 spring is 153 days.

Figure A - 1. Days per year (left) or per Annex 4 spring (right) above a TP concentration of 0.24 mg/L in 2015 (top), 2016 (middle), and 2017 (bottom).



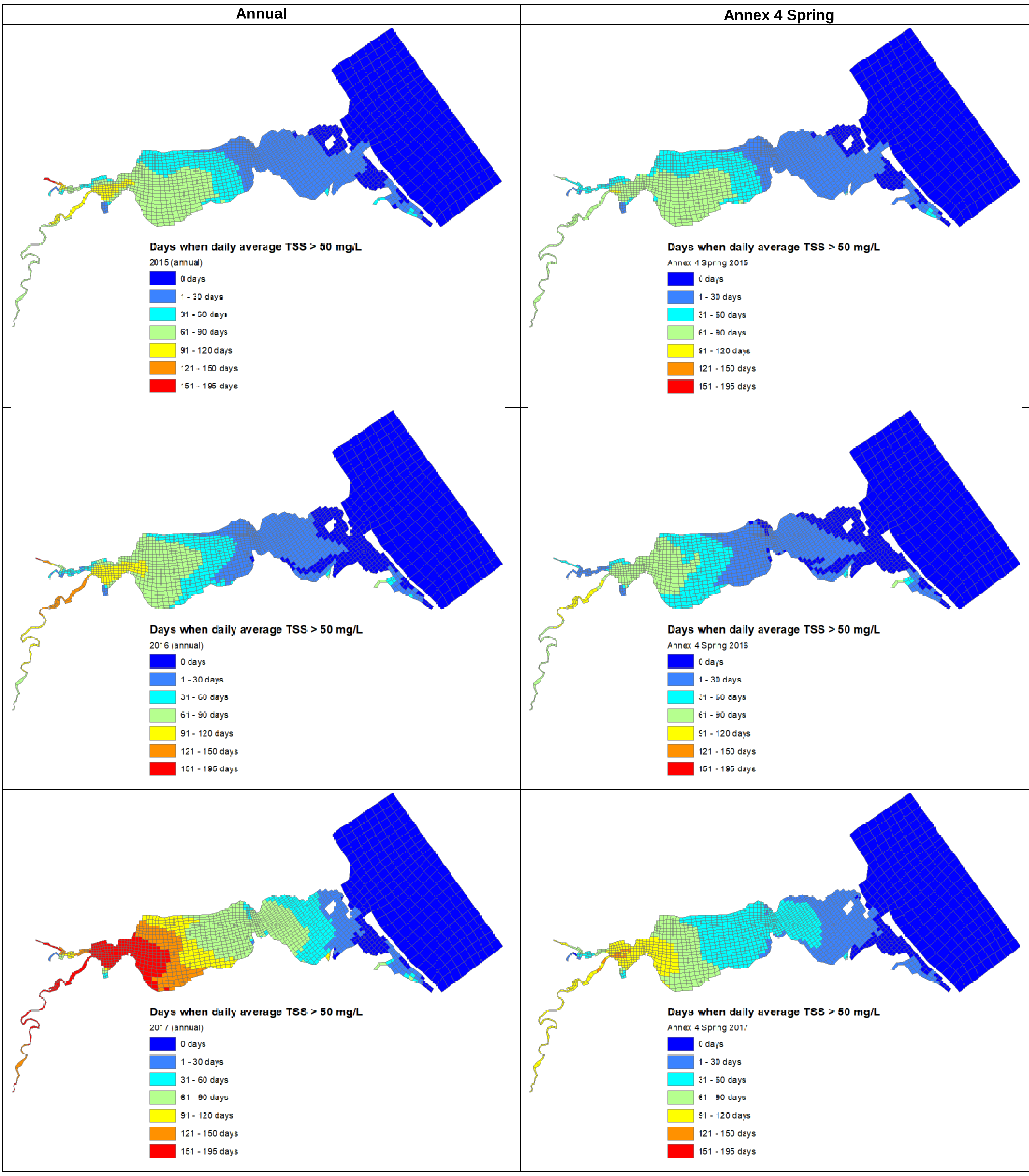
Note: The same symbology is used on all six maps. The Annex 4 spring is 153 days.

Figure A - 2. Days per year (left) or per Annex 4 spring (right) above a dissolved phosphate concentration of 0.06 mg/L in 2015 (top), 2016 (middle), and 2017 (bottom).



Note: The same symbology is used on all six maps. The Annex 4 spring is 153 days.

Figure A - 3. Days per year (left) or per Annex 4 spring (right) above a chlorophyll-*a* concentration of 80 µg/L in 2015 (top), 2016 (middle), and 2017 (bottom).



Note: The same symbology is used on all six maps. The Annex 4 spring is 153 days.

Figure A - 4. Days per year (left) or per Annex 4 spring (right) above a TSS concentration of 50 mg/L in 2015 (top), 2016 (middle), and 2017 (bottom).

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APPENDIX B. COMPARISON OF SCENARIO RESULTS

Table B - 1. Average TP concentrations (mg/L) for each scenario by season and location

	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	0.25	0.27	0.21	0.28	0.23	0.15	0.31	0.39	0.35	0.17	0.25	0.18
1 [a]	0.15	0.13	0.14	0.17	0.16	0.11	0.25	0.34	0.30	0.14	0.23	0.18
2	0.25	0.27	0.21	0.28	0.24	0.15	0.31	0.39	0.35	0.17	0.25	0.19
3	0.25	0.27	0.21	0.28	0.24	0.15	0.31	0.39	0.35	0.17	0.25	0.18
4	0.22	0.19	0.15	0.26	0.18	0.13	0.30	0.22	0.20	0.17	0.09	0.08
5	0.25	0.25	0.19	0.28	0.25	0.15	0.30	0.38	0.34	0.16	0.23	0.17

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

a. This scenario was simulated with a lower sediment settling rate. Analysis of sediment settling rates during calibration indicated that TP concentrations with lower or higher sediment settling rates were nearly the same (i.e., the settling rate had minimal effect on TP concentrations).

Table B - 2. Average dissolved phosphate concentrations (mg/L) for each scenario by season and location

	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	0.071	0.086	0.070	0.049	0.020	0.006	0.027	0.024	0.020	0.027	0.036	0.020
1 [a]	0.042	0.054	0.059	0.028	0.015	0.007	0.027	0.038	0.034	0.026	0.046	0.031
2	0.071	0.085	0.071	0.049	0.021	0.006	0.027	0.024	0.020	0.027	0.037	0.022
3	0.070	0.086	0.071	0.050	0.021	0.006	0.027	0.025	0.020	0.027	0.037	0.021
4	0.059	0.066	0.054	0.047	0.011	0.005	0.028	0.015	0.008	0.028	0.003	0.002
5	0.070	0.065	0.063	0.050	0.020	0.006	0.027	0.024	0.021	0.026	0.031	0.019

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

a. This scenario was simulated with a lower sediment settling rate. Analysis of sediment settling rates during calibration indicated that dissolved phosphate concentrations increased with higher sediment settling rate and some increases were significant.

Table B - 3. Average TN concentrations (mg/L) for each scenario by season and location

	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	6.9	6.0	4.2	8.4	7.8	5.8	5.6	6.6	6.5	3.2	3.2	2.5
1 [a]	4.0	1.7	2.9	5.0	4.7	3.5	3.4	4.2	4.2	2.0	2.1	1.6
2	6.9	6.0	4.3	8.4	7.9	5.9	5.6	6.5	6.5	3.2	3.3	2.5
3	6.9	6.0	4.3	8.4	7.9	5.9	5.6	6.5	6.5	3.2	3.3	2.5
4	5.8	2.4	1.0	6.5	4.5	4.1	4.6	3.9	4.2	2.2	1.4	1.3
5	6.9	5.9	4.2	8.4	8.0	5.8	5.5	6.6	6.4	3.2	3.3	2.5

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

The model frequently overpredicts the observed concentrations of nitrogen, especially for the sampling stations in Upper Sandusky Bay. This is likely due to an overprediction of the internal loading of nitrogen.

a. This scenario was simulated with a lower sediment settling rate. Analysis of sediment settling rates during calibration indicated that TN concentrations with lower or higher sediment settling rates were nearly the same (i.e., the settling rate had minimal effect on TN concentrations).

Table B - 4. Average chlorophyll concentrations (µg/L) for each scenario by season and location

	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	3.9	5.9	7.0	34	55	45	94	110	100	35	41	36
1 [a]	3.8	2.0	4.5	30	42	36	75	85	80	22	29	26
2	3.9	5.7	6.9	34	55	46	94	110	100	34	41	36
3	3.9	5.8	6.9	34	54	46	94	109	100	34	41	36
4	3.4	1.7	2.5	29	32	44	89	78	75	25	27	26
5	3.8	4.8	6.1	33	52	45	91	106	97	33	39	35

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

a. This scenario was simulated with a lower sediment settling rate. Analysis of sediment settling rates during calibration indicated that chlorophyll concentrations increased with higher sediment settling rate and most increases were significant.

Table B - 5. Average TSS concentrations (mg/L) for each scenario by season and location

	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	53	34	16	76	44	17	23	20	16	14	9.2	4.7
2	53	35	17	76	45	18	23	20	16	14	10	5.1
3	53	35	16	76	45	18	22	20	16	14	10	4.9
4	47	12	7	74	34	15	21	--[a]	--[a]	9	--[a]	--[a]
5	56	38	19	79	51	22	25	23	19	16	11.1	6.0

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

Scenario 1 was simulated with a lower sediment settling rate and results are therefore not presented. Analysis of sediment settling rates during calibration indicated that TSS concentrations decreased significantly with higher sediment settling rate.

a. Results for July through December of Scenario 4 are anomalously low and are not presented.

Table B - 6. Average turbidity concentrations (NTU) for each scenario by season and location

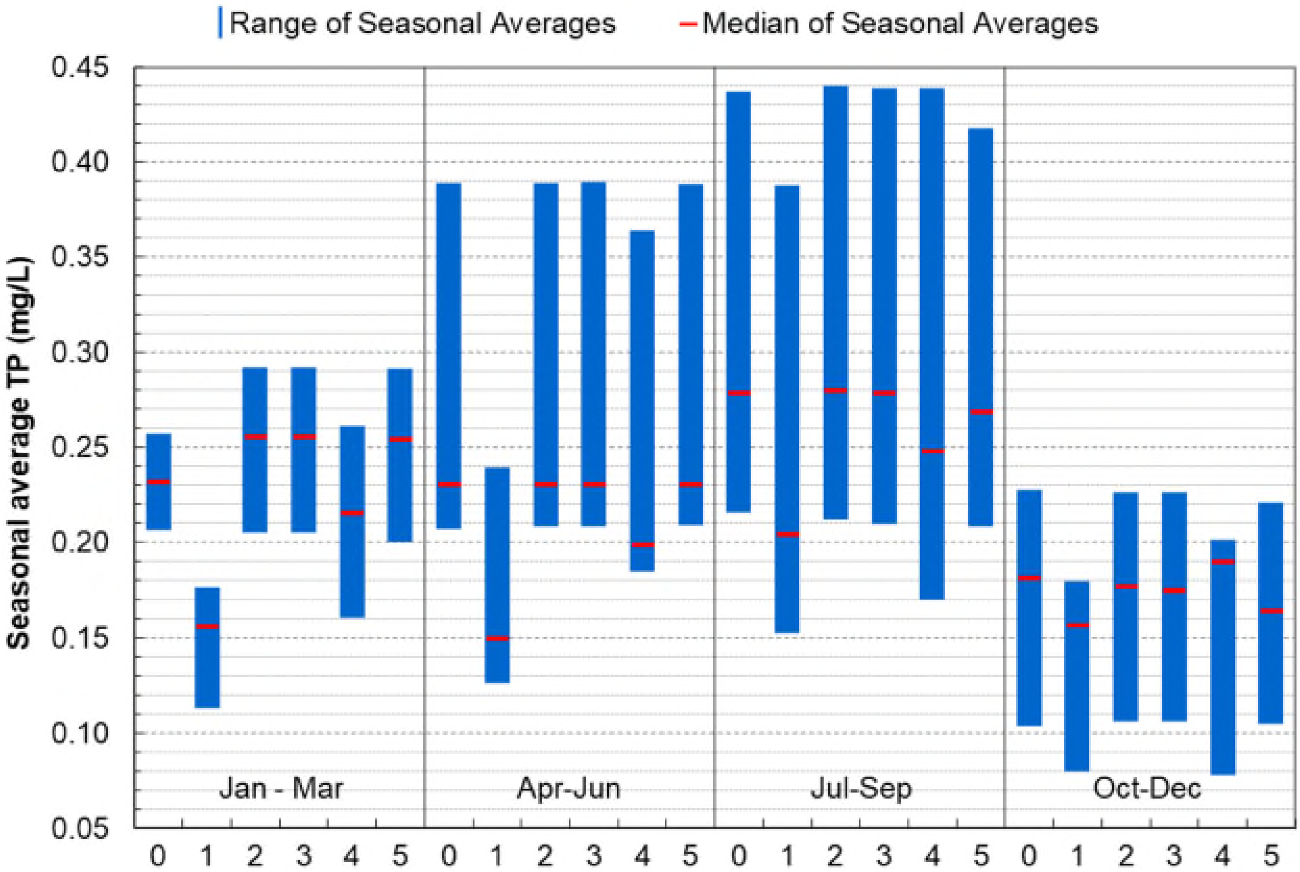
	Jan - Mar			Apr – Jun			Jul – Sep			Oct - Dec		
	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB	MCB	USB	LSB
0	32	21	12	46	29	15	21	20	17	12	10	7.4
2	32	22	12	46	30	15	21	20	17	12	10	7.5
3	32	22	12	46	30	15	21	20	17	12	10	7.4
4	28	10	7	45	24	14	19	--[a]	--[a]	9	--[a]	--[a]
5	33	24	14	48	33	17	22	21	19	13	11	8.0

Notes

0 = calibration; 1 = Sandusky River Load Reduction; 2 = Island Concept B; 3 = Island Concept C; 4 = Sandusky Bay Tributary Load Reductions; 5 = Revised Island Concept C.

Scenario 1 was simulated with a lower sediment settling rate. Analysis of sediment settling rates during calibration indicated that turbidity decreased significantly with higher sediment settling rate.

b. Results for July through December of Scenario 4 are anomalously low and are not presented.

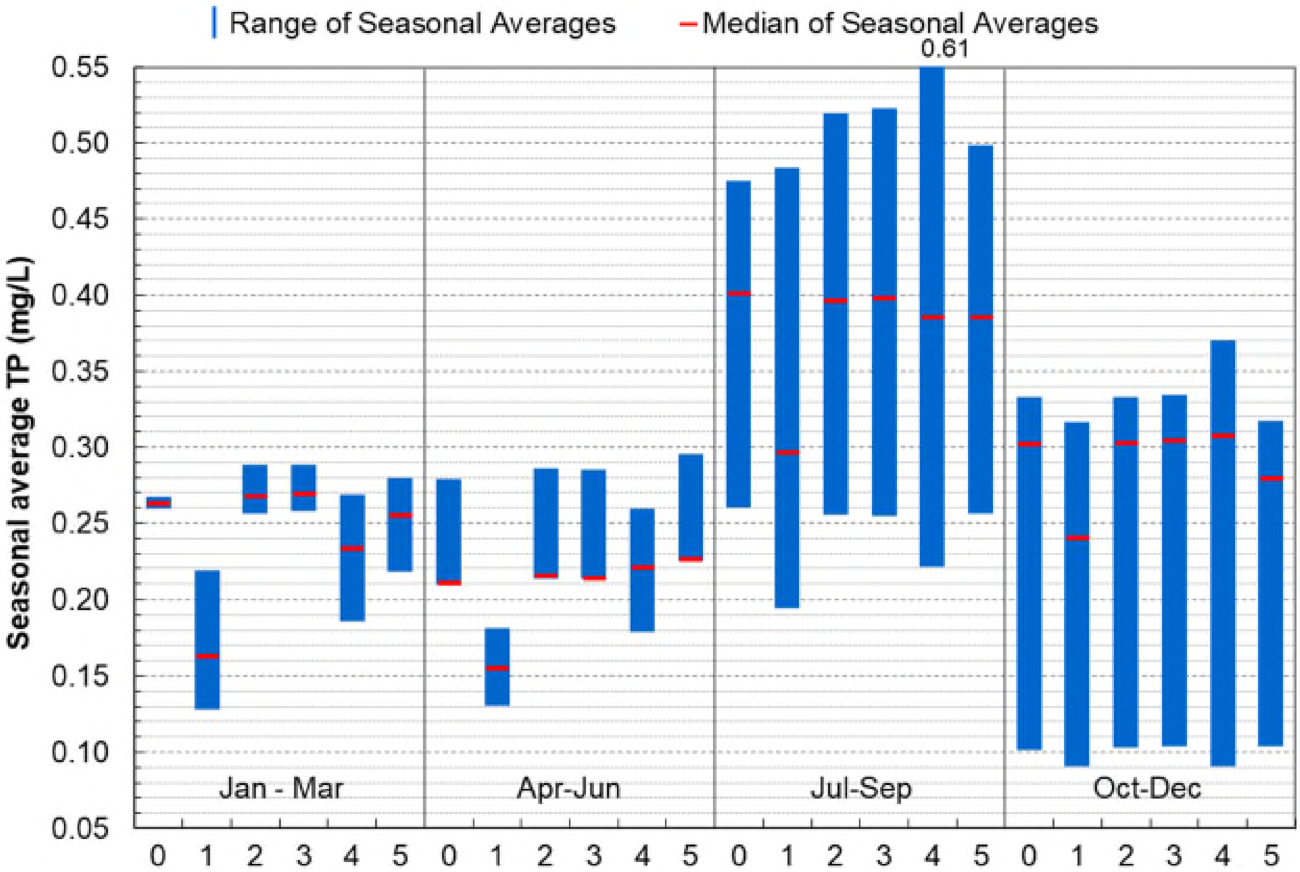


Notes

Scenarios 2, 3, and 5 involve island construction in Upper Sandusky Bay, which has little impact on seasonal average TP concentrations across Muddy Creek Bay.

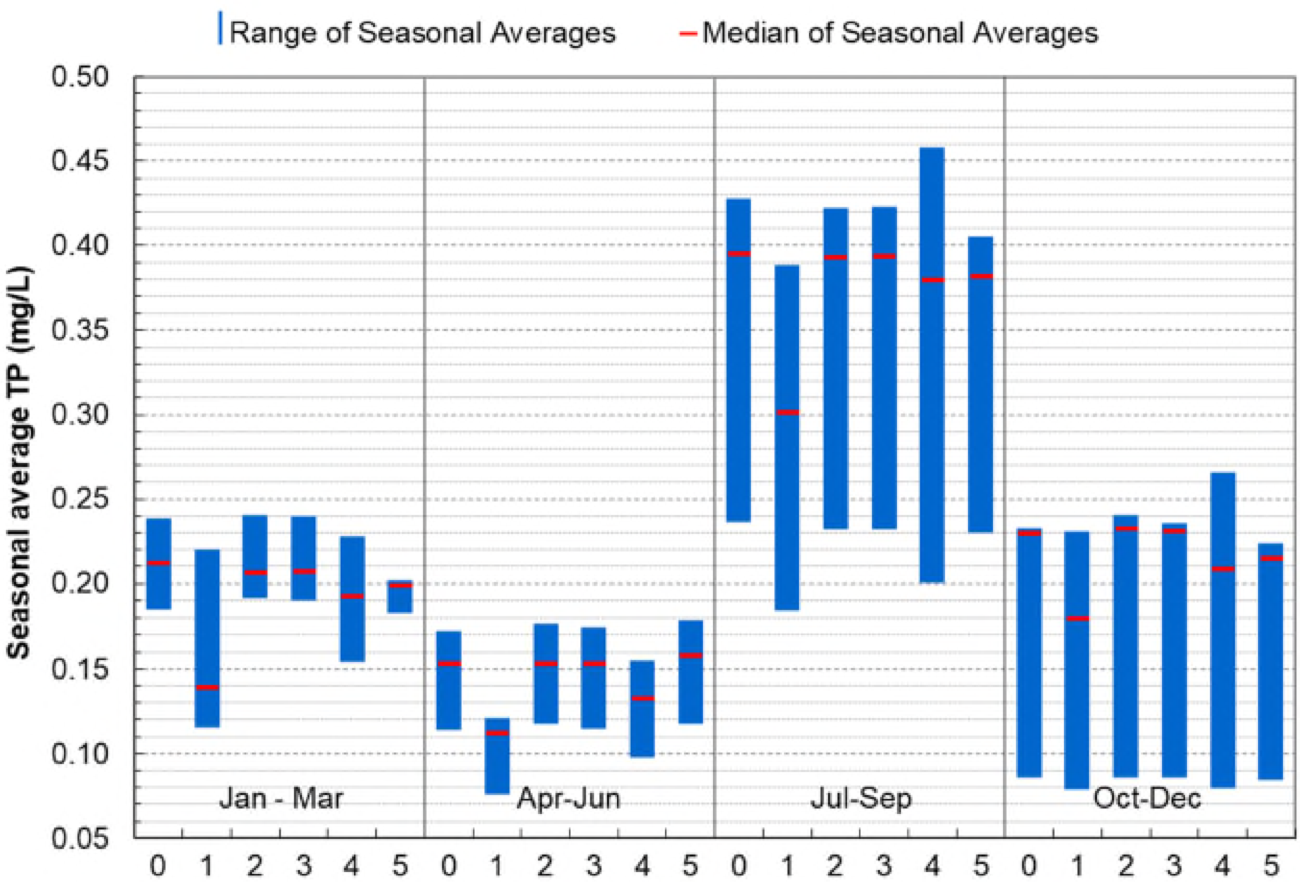
Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 1. TP scenario results for Muddy Creek Bay.



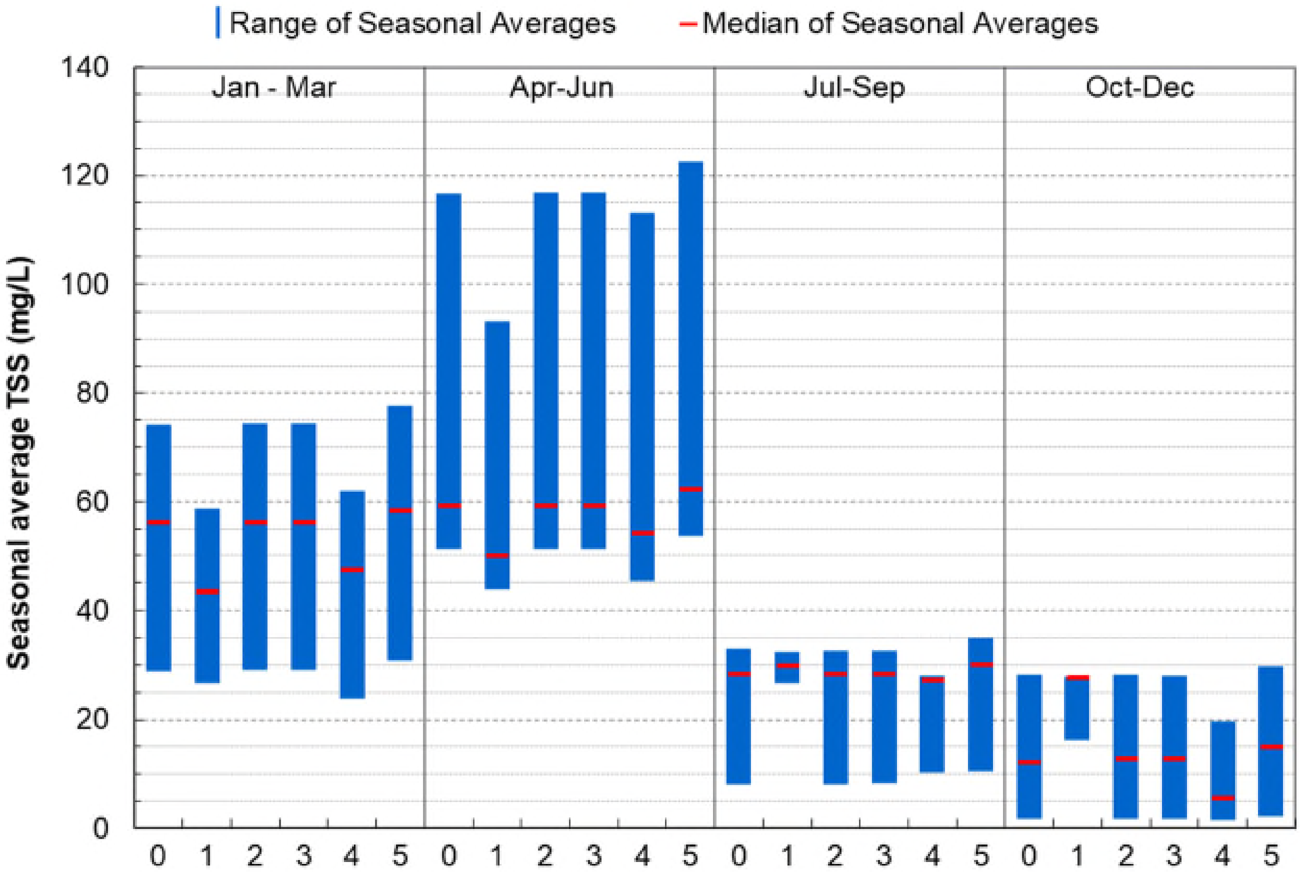
Note: Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 2. TP scenario results for Upper Sandusky Bay.



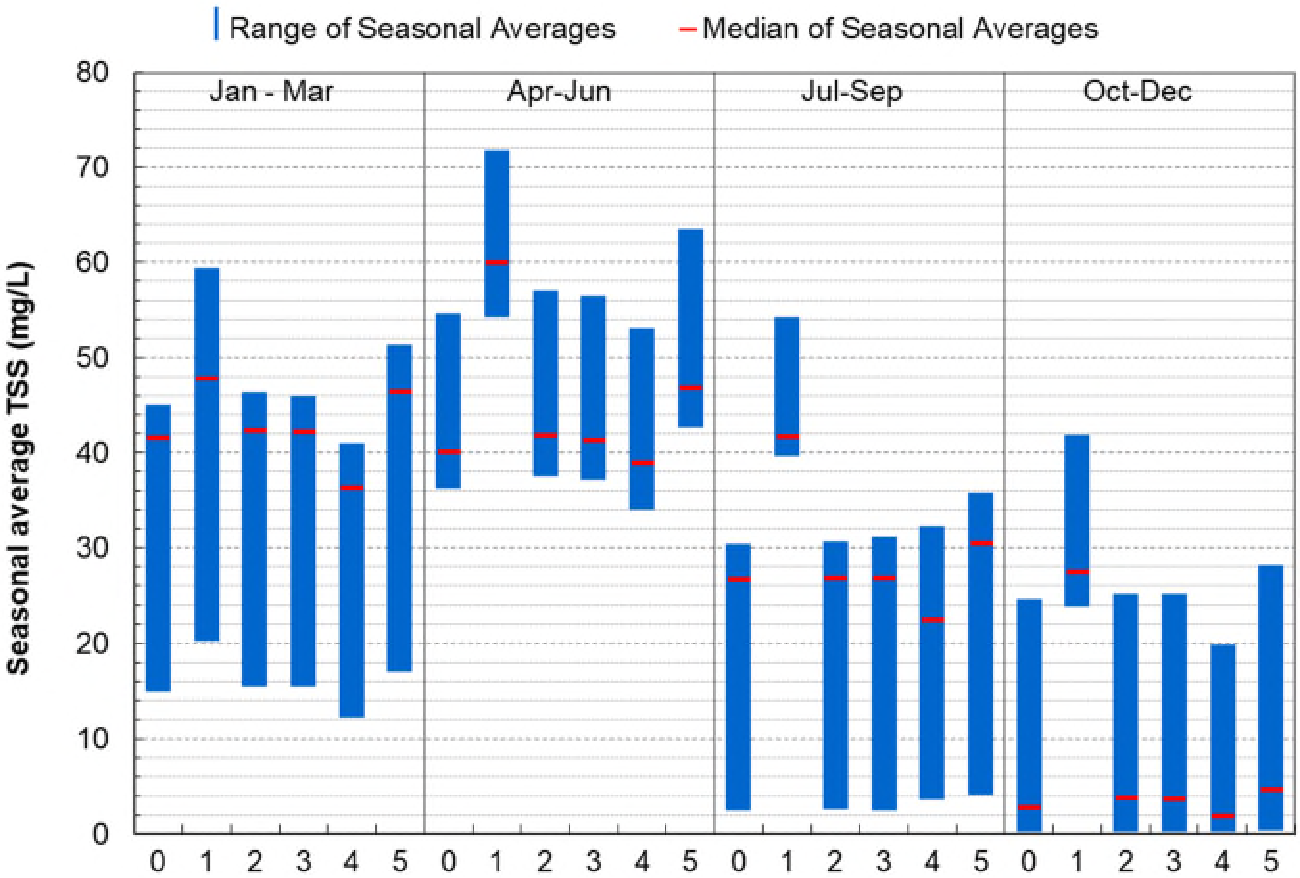
Note: Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 3. TP scenario results for Lower Sandusky Bay.



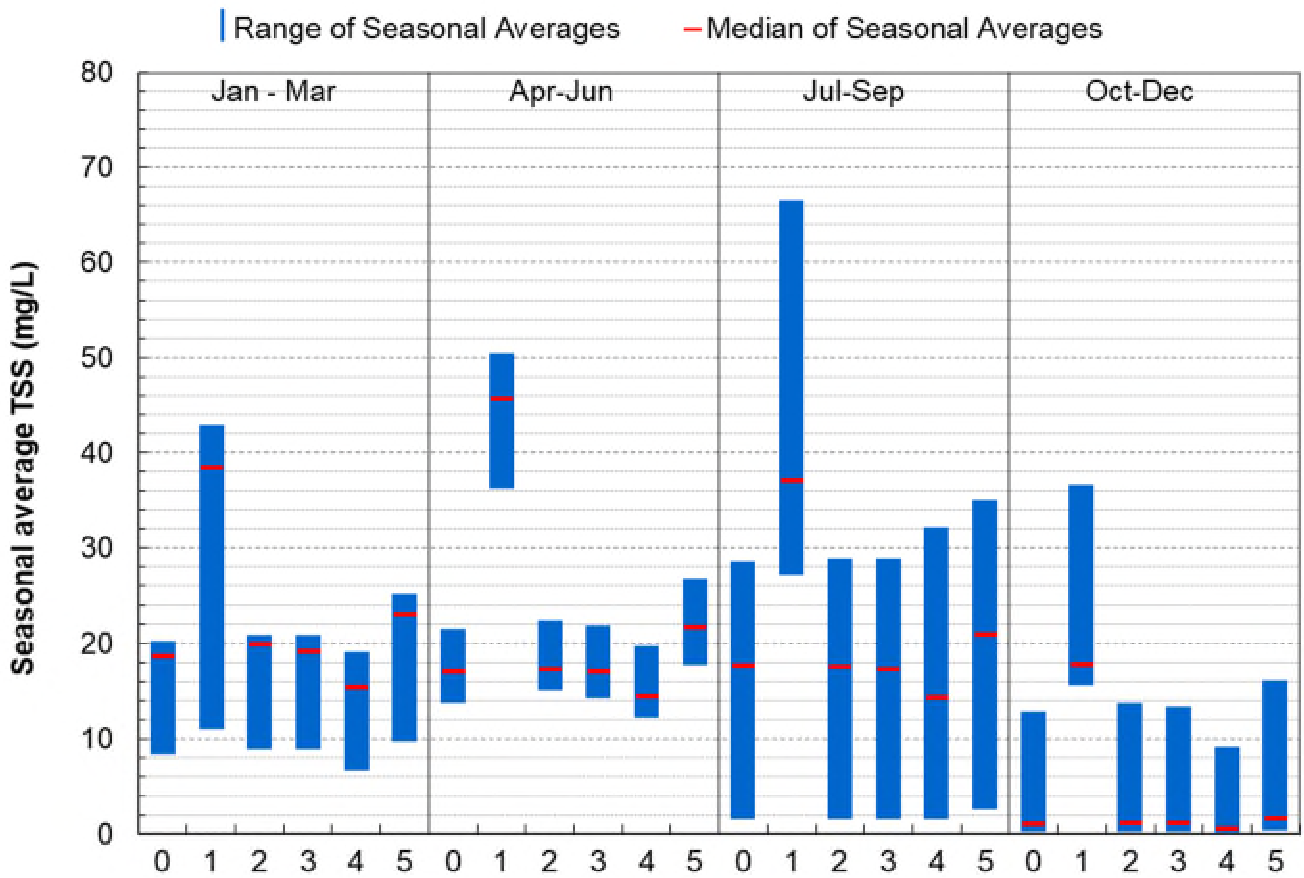
Note: Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 4. TSS scenario results for Muddy Creek Bay.



Note: Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 5. TSS scenario results for Upper Sandusky Bay.



Note: Scenarios 0, 2, 3, and 5 were simulated for 3-years, while scenarios 1 and 4 were simulated for 9-years.

Figure B - 6. TSS scenario results for Lower Sandusky Bay.