Prepared in cooperation with the National Park Service

Simulation of Hydrodynamics, Water Quality, and Lake Sturgeon Habitat Volumes in Lake St. Croix, Wisconsin and Minnesota, 2013

Scientific Investigations Report 2017–5157

U.S. Department of the Interior
U.S. Geological Survey

Cover. Background photograph: Lake St. Croix Pool 4 looking upstream (north) at Kinnickinnic River delta. Photograph by Jeff Ziegeweid, U.S. Geological Survey (USGS).
Front cover photographs left to right: USGS hydrologist collecting sample at Lake St. Croix, September 2013; Lake St. Croix Pool 3, October 4, 2011; and USGS hydrologist collecting sample at Lake St. Croix Pool 1 near Bayport, Minesota, September 2013. Photographs by Sarah Elliott, USGS.

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U.S. Department of the Interior
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Transmissivity	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

LOADEST	load estimator [computer program]
MAE	mean absolute error
MCES	Metropolitan Council Environmental Services
MPCA	Minnesota Pollution Control Agency
NPS	National Park Service
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
RMSE	root mean square error
SWAT	Soil and Water Assessment Tool
TMDL	total maximum daily load
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

Lake St. Croix is a naturally impounded, riverine lake that makes up the last 40 kilometers of the St. Croix River. Substantial land-use changes during the past 150 years, including increased agriculture and urban development, have reduced Lake St. Croix water-quality and increased nutrient loads delivered to Lake St. Croix. A recent (2012–13) total maximum daily load phosphorus-reduction plan set the goal to reduce total phosphorus loads to Lake St. Croix by 20 percent by 2020 and reduce Lake St. Croix algal bloom frequencies. The U.S. Geological Survey, in cooperation with the National Park Service, developed a two-dimensional, carbon-based, laterally averaged, hydrodynamic and water-quality model, CE–QUAL–W2, that addresses the interaction between nutrient cycling, primary production, and trophic dynamics to predict responses in the distribution of water temperature, oxygen, and chlorophyll *a*. Distribution is evaluated in the context of habitat for lake sturgeon, including a combination of temperature and dissolved oxygen conditions termed oxythermal habitat.

The Lake St. Croix CE–QUAL–W2 model successfully reproduced temperature and dissolved oxygen in the lake longitudinally (from upstream to downstream), vertically, and temporally over the seasons. The simulated water temperature profiles closely matched the measured water temperature profiles throughout the year, including the prediction of thermocline transition depths (often within 1 meter), the absolute temperature of the thermocline transitions (often within 1.0 degree Celsius), and profiles without a strong thermocline transition. Simulated dissolved oxygen profiles matched the trajectories of the measured dissolved oxygen concentrations at multiple depths over time, and the simulated concentrations matched the depth and slope of the measured concentrations.

Additionally, trends in the measured water-quality data were captured by the model simulation, gaining some potential insights into the underlying mechanisms of critical Lake St. Croix metabolic processes. The CE–QUAL–W2 model tracked nitrate plus nitrite, total nitrogen, and total phosphorus throughout the year. Inflow nutrient contributions (loads), largely dominated by upstream St. Croix River loads, were the most important controls on Lake St. Croix water quality. Close to 60 percent of total phosphorus to the lake was from phosphorus derived from organic matter, and about 89 percent of phosphorus to Lake St. Croix was delivered by St. Croix River inflows. The Lake St. Croix CE–QUAL–W2 model offered potential mechanisms for the effect of external and internal loadings on the biotic response regarding the modeled algal community types of diatoms, green algae, and blue-green algae. The model also suggested the seasonal dominance of blue-green algae in all four pools of the lake.

A sensitivity analysis was completed to test the total maximum daily load phosphorus-reduction scenario responses of total phosphorus and chlorophyll *a*. The modeling indicates that phosphorus reductions would result in similar Lake St. Croix reduced concentrations, although chlorophyll *a* concentrations did not decrease in the same proportional amounts as the total phosphorus concentrations had decreased. The smaller than expected reduction in algal growth rates highlighted that although inflow phosphorus loads are important, other constituents also can affect the algal response of the lake, such as changes in light penetration and the breakdown of organic matter releasing nutrients.

The available habitat suitable for lake sturgeon was evaluated using the modeling results to determine the total volume of good-growth habitat, optimal growth habitat, and lethal temperature habitat. Overall, with the calibrated model, the fish habitat volume in general contained a large proportion of good-growth habitat and a sustained period of optimal growth habitat in the summer. Only brief periods of lethal oxy-thermal habitat were present in Lake St. Croix during the model simulation.

[1]U.S. Geological Survey.

[2]Science Museum of Minnesota, St. Croix Watershed Research Station.

Introduction

River and tributary water quality is critical to maintain the diverse aquatic ecosystem of the St. Croix River, in particular the lower 40 kilometers (km) that make up Lake St. Croix (fig. 1). Lake St. Croix is a naturally impounded, riverine lake between the States of Minnesota and Wisconsin and upstream from the confluence of the Mississippi and St. Croix Rivers. Lake St. Croix is a complex ecosystem facing multiple stressors and changes. In the St. Croix Basin, land use has changed substantially since the beginning of European settlement in the 19th century (McMahon, 2002). Land use within the Lake St. Croix drainage basin has included logging, agriculture, and urban development. The population within the lower St. Croix Basin is expected to increase by 39 percent by 2020, as predicted by the 2000 census (U.S. Census Bureau, 2000). Consistent with those predictions, results from the 2010 census revealed a population increase of about 20 percent from 2000 to 2010 (U.S. Census Bureau, 2010). Land-use changes within the lower St. Croix Basin have increased nutrient loads (Magdalene, 2009) and reduced water quality because of large algae concentrations in Lake St. Croix (Davis, 2004).

Lake St. Croix contains high-quality fish habitat for species such as northern pike (*Esox lucius*), smallmouth bass (*Micropterus dolomieu*), and lake sturgeon (*Acipenser fulvescens*). Lake sturgeon increased in Lake St. Croix during 1987 to 2010 (Kampa and others, 2014), although population surveys have indicated a disproportionately small percentage of sexually mature sturgeon and a disproportionately large percentage of juveniles (Wendel and Frank, 2012). Lake St. Croix also provides habitat for a diverse assemblage of freshwater mussels (41 species), including several threatened and two federally endangered species (Hornbach, 2001): winged mapleleaf (*Quadrula fragosa*) and Higgins' eye pearly mussel (*Lampsilis higginsii*).

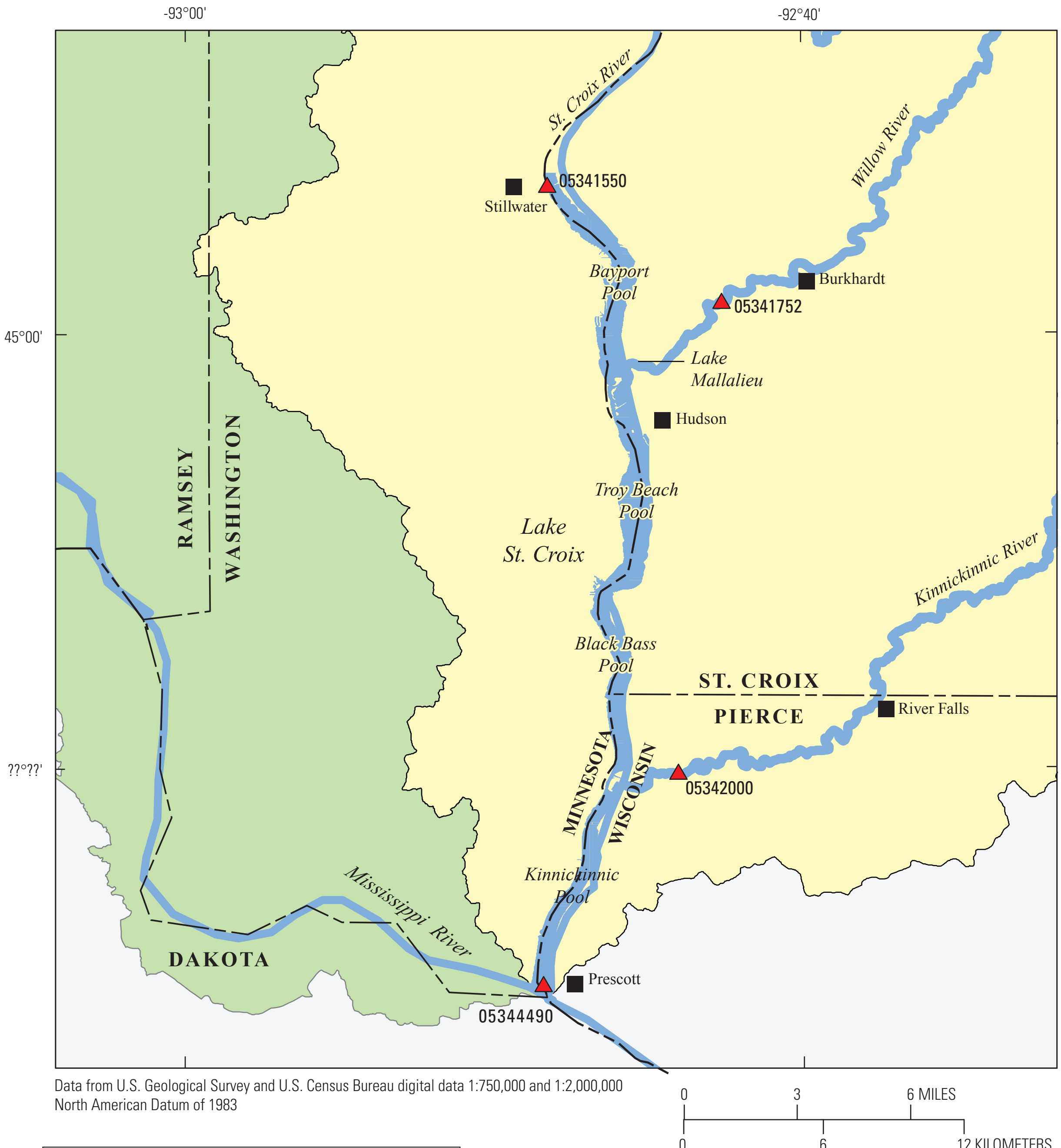
Numerous efforts were started to mitigate the effects of land-use changes, to improve water quality, and to maintain the high-quality fish and mussel habitat of Lake St. Croix (fig. 1). The St. Croix National Scenic Riverway (not shown) was designated for water quality protection as the primary natural resource management goal under the National Park Service (NPS) Centennial Strategies Initiative. Minnesota and Wisconsin have placed designations on the St. Croix River to restrict wastewater, industrial waste, and other waste discharges to the river (Holmberg and others, 1997; Payne and others, 2002). In 1994, several State and Federal agencies collaborated to form the St. Croix Basin Water Resources Planning Team with the goal of investigating water resources issues in the St. Croix Basin. In 2008, Lake St. Croix was designated as a Clean Water Act 303(d) impaired water body by Minnesota and Wisconsin for excess phosphorus. Recently (2012), the Minnesota Pollution Control Agency (MPCA) developed a total maximum daily load (TMDL) plan in conjunction with the Wisconsin Department of Natural Resources to address eutrophication in Lake St. Croix (MPCA, 2012, 2013).

The TMDL plan objectives were to understand mechanisms of internal and external loading better, to improve nutrient mass-balance estimates, to identify the limiting nutrient, and to assess the ecological health of Lake St. Croix. The phosphorus-reduction goal, part of the TMDL plan, was to reduce total phosphorus loads by 20 percent by 2020. The TMDL plan assumes that reducing phosphorus loads should decrease chlorophyll *a* concentrations and reduce the frequency of algal blooms in Lake St. Croix. Also, this assumption was supported by BATHTUB (a water-quality model) simulations of reduced phosphorus loading (Robertson and Lenz, 2002); however, no ecosystem-based framework has existed up to this point (2017) to assess how Lake St. Croix is responding to nutrient load reductions in connection to nutrient-trophic dynamics.

This study developed a predictive water-quality model to assess water quality and habitat dynamics of Lake St. Croix under 2013 meteorological conditions. The chosen modeling framework for this study, CE–QUAL–W2 (Cole and Wells, 2015), is a two-dimensional, carbon-based, laterally averaged, hydrodynamic and water-quality model. The model originally was developed by the U.S. Army Corps of Engineers (USACE) and currently is supported by Portland State University (Cole and Wells, 2015). The CE–QUAL–W2 model addresses the interactions between nutrient cycling, primary production, and trophic dynamics to predict responses in the distribution of water temperature, oxygen, and chlorophyll *a*, thus fulfilling a primary goal of this study. The importance of this work is that it documents the best available tool for predicting the chemical, physical, and biological response of Lake St. Croix to shifting input loads that can be further exacerbated by climate change (Palmer and others, 2009) and hydrologic alteration (Novotny and Stefan, 2007).

Purpose and Scope

The purpose of this report is to outline the development and calibration of a mechanistic, biophysical water-quality model (CE–QUAL–W2) for Lake St. Croix (fig. 1). The Lake St. Croix CE–QUAL–W2 model was simulated and calibrated using data collected from April through November 2013. The complete CE-QUAL-W2 model archive is available on USGS ScienceBase (Smith, 2018). Loads developed for the model were based on water-quality data collected by various agencies, including the U.S. Geological Survey (USGS). A sensitivity analysis was done to better understand model response for total phosphorus and chlorophyll *a* to changes in nutrient loads, sediment release rates of phosphorus, sediment oxygen demand, and light extinction coefficients. Because CE–QUAL–W2 addresses trophic dynamics, the calibrated model also was used to evaluate good- and optimal-growth habitat availability for lake sturgeon using coldwater fish oxygen and thermal requirements.



Data from U.S. Geological Survey and U.S. Census Bureau digital data 1:750,000 and 1:2,000,000
North American Datum of 1983

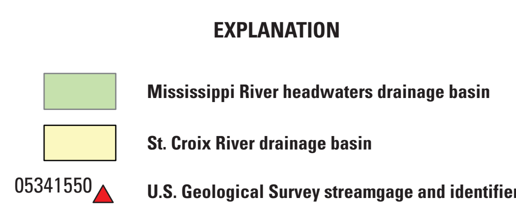


Figure 1. Map showing St. Croix River drainage basin, including Lake St. Croix, Minnesota and Wisconsin.

Study Area

The St. Croix River is a sixth-order stream that forms much of the boundary between Minnesota and Wisconsin (fig. 1). In 1968, the St. Croix National Scenic Riverway was established as one of the original eight rivers under the Wild and Scenic Rivers Act (Hanson, 2008). The St. Croix drainage basin is 20,098 square kilometers of three ecoregions: Northern Lakes and Forests, Central Hardwoods Forests, and Western Corn Belt (Holmberg and others, 1997). Land use and land cover in the St. Croix River Basin changes progressively downstream from predominantly forest to a mixture of forest, agricultural, and urban settings. The lower 40 km of the St. Croix River make up Lake St. Croix, a naturally impounded, riverine lake that was created by deposited sediments from the Mississippi River (Payne and others, 2002). Lake St. Croix is classified as eutrophic and has a surface area of about 35 square kilometers, for a ratio of basin to lake area of 574:1. The climate in the basin is subhumid continental and is characterized by long winters, substantial snow cover, and short, cool summers (Holmberg and others, 1997). Precipitation in the area averages between 0.71 and 0.81 meters per year (Stark and others, 2000).

Lake St. Croix begins at Stillwater, Minnesota, and ends at the confluence with the Mississippi River at Prescott, Wisconsin (fig. 1). Five tributaries flow directly into Lake St. Croix, including Browns Creek (not shown), Valley Creek, and Trout Brook along the western bank (Minnesota), and the Willow River (through Lake Mallalieu; fig. 1) and Kinnickinnic River on the eastern bank (Wisconsin) (fig. 2). Browns Creek is above the gaged site at Stillwater, Minn. (USGS station 05341550; fig. 1), so it was not included as part of the study area or model domain. Lake St. Croix (fig. 1) consists of four successive pools (upstream to downstream): Bayport Pool (pool 1), Troy Beach Pool (pool 2), Black Bass Pool (pool 3), and Kinnickinnic Pool (pool 4). Overall, Lake St. Croix has a mean depth of 9.7 meters (m), a water residence time of 15 to 50 days (MPCA, 2012), and a maximum depth of about 28 m. Stratification within the deep pools, along with the flow regime, give Lake St. Croix characteristics of both a lake and a river. The water balance of the drainage basin typically is controlled by a spring snowmelt in late March or early April, followed by periodic, large rainstorms in the summer. Primary inflow to Lake St. Croix is from upstream at St. Croix River at Stillwater, Minn. A smaller part of the water balance is from the Wisconsin tributaries (average between 5 and 6 percent of total water balance), and an even smaller part of the water balance is from the Minnesota tributaries (average less than 1 percent of total water balance). The outlet of Lake St. Croix is at St. Croix River at Prescott, Wisc. (USGS station 05344490; fig. 1).

Previous Studies

Several watershed-modeling projects have been started in the basin. As part of the Centennial Strategies Initiative, the NPS funded the development of a Soil and Water Assessment Tool (SWAT) model to predict nutrient and sediment loading in the St. Croix River Basin (fig. 1) (Almendinger and others, 2014). The SWAT model was used to assess watershed-based scenarios for reducing phosphorus loading to the St. Croix National Scenic Riverway and concluded that widespread use of cover crops in corn and soybean fields would help achieve the goal of a 20-percent reduction by 2020 (Almendinger, 2016). Earlier SWAT models of several St. Croix tributaries, including the Willow and Sunrise Rivers (not shown), likewise concluded that agricultural best-management practices could effectively reduce phosphorus loads (Almendinger and Murphy, 2007; Almendinger and Ulrich, 2012). Other work has included detailed studies on the watershed hydrology of Valley Creek and Browns Creek (Almendinger, 2003), two tributaries of Lake St. Croix.

Total phosphorus concentrations, as inferred from paleoecological diatom studies, increased from about 25 to 30 micrograms per liter (μg/L) around 1910 to 58 to 72 μg/L during the 1990s (Edlund and others, 2009). Diatom communities shifted during this period from benthic- to planktonic-dominated species (Edlund and others, 2009), and the hypolimnion dominance of chironomid species postsettlement (about 1850s) indicated smaller dissolved oxygen concentrations (Stewart, 2009). A seasonal Kendall analysis of total phosphorus concentrations exhibited an average decline of 0.2 μg/L per year during 1976–2004; however, 1993–2003 did not exhibit a declining trend (Lafrancois and others, 2009). Chlorophyll *a* concentrations exhibited no substantial trend during 1976–2004 and an increasing trend during 1993–2003 (Lafrancois and others, 2009). These indicators point to previous major changes in lake-ecosystem metabolism and suggest a complex trophic-level response to changes in state variables like nutrient supply.

Currently (2017), little is known about the relation among nutrient loading, hydrodynamics, lake metabolism, and temperature and oxygen (oxy-thermal) dependent fish habitat in Lake St. Croix (fig. 1). Major efforts to collect nutrient and suspended sediment data on major tributaries to the St. Croix River were summarized in Lenz and others (2001). Regression equations to calculate revised estimates of historical streamflows for Stillwater (1910–2007) and Prescott (1910–2011) were developed by Ziegeweid and Magdalene (2014), ending when index-velocity streamgages were installed (Levesque and Oberg, 2012). Coordinated monitoring efforts include tracking dissolved oxygen depletion and algal bloom formation in the pools of Lake St. Croix, such as the Metropolitan Council volunteer monitoring data. Near-anoxic conditions in all the deep pools of the lake coupled with large concentrations of algal biomass, including blue-green algal blooms, indicate that serious water quality problems are present in the lake on a regular basis.

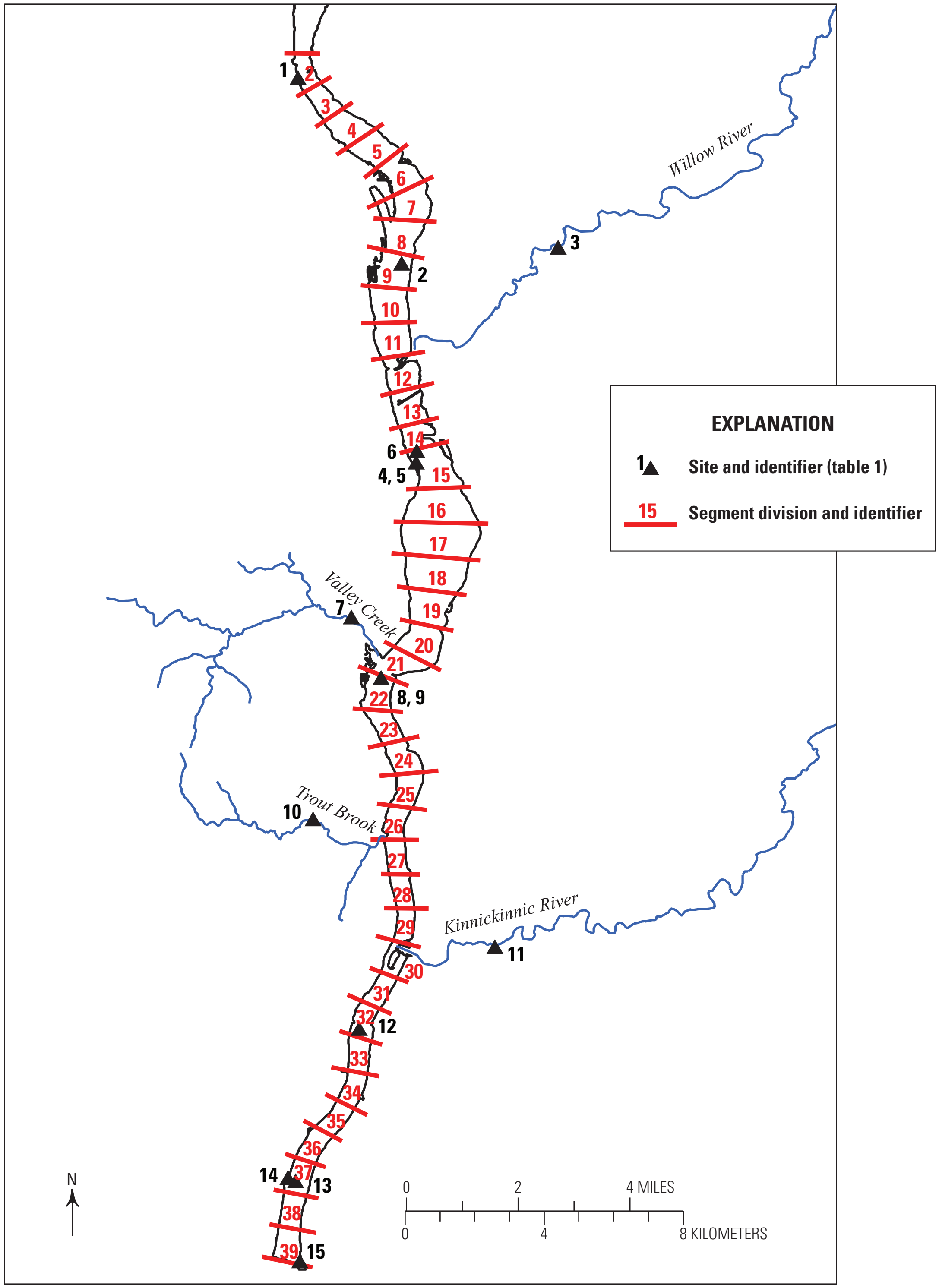


Figure 2. Map showing lLocation of water-quality sampling sites of Lake St. Croix, Minnesota and Wisconsin.

Simulation of Hydrodynamics, Water Quality, and Lake Sturgeon Fish Habitat Volumes in Lake St. Croix

The Lake St. Croix (fig. 1) model was constructed using CE–QUAL–W2, version 4.0 (Cole and Wells, 2015). The CE–QUAL–W2 model calculates water-surface elevation, velocities, and temperature and can simulate 28 water-quality variables. An advantage of CE–QUAL–W2 over similar models is that the hydrodynamic and water-quality modules are coupled through an equation of state for density that depends on temperature, suspended solids, and dissolved solids. Because CE–QUAL–W2 is laterally averaged, it is best suited for long, narrow water bodies with a nearly homogenous cross section, such as reservoirs, rivers, and estuaries. Vertical variations captured with CE–QUAL–W2 are important for distinguishing temporal variations in the lake epilimnion and hypolimnion. Initial calibration included a water balance based on water-surface elevation. Further important calibration targets included water temperature and dissolved oxygen depth profiles, in addition to discrete measurements of ammonia, nitrate plus nitrite, total nitrogen, total phosphorus, orthophosphate, and chlorophyll *a*.

The Lake St. Croix model was developed in several phases. First, data were aggregated to determine the hydrological, thermal, and water-quality boundary conditions for the calibration year (2013). A summary of the discrete and continuous constituents collected, further split by sampling location, is provided in table 1. Selection of the calibration year was chosen using the most extensive datasets available, specifically for outflow discharge, water-surface elevation, and water temperature data, because these datasets were critical for driving the model hydrodynamics. All other data were combined to best define the initial boundary conditions. These data also were used later in the calibration process. Next, the model grid was constructed on the basis of available lake bathymetry data. Before initial water-balance calibration, input parameters were selected, mainly on the basis of default values prepopulated either within CE–QUAL–W2 (Cole and Wells, 2015) itself or within previous USGS CE–QUAL–W2 modeling efforts (Galloway and Green, 2006; Galloway and others, 2008; Smith and others, 2014, 2017).

Water Balance and Calibration Framework

The Lake St. Croix water balance was calibrated for April 20–November 15, 2013, by comparing measured water levels to simulated water levels at Prescott, Wisc., the main surface-water outflow for Lake St. Croix (fig. 1; table 1). Continuous discharge into the CE–QUAL–W2 model was derived from the St. Croix River at Stillwater, Minn. (USGS station 05341550), and four gaged inflow tributaries (sites 3, 7, 10, and 11; figs. 1, 2; table 1). The common names used in this report for the main inflow and four tributaries, in order from north to south, were St. Croix River at Stillwater, Minn. (hereafter referred to as “St. Croix River”), Willow River, Valley Creek, Trout Brook, and Kinnickinnic River, respectively. Refined calibration focused on the vertical profiles of temperature and dissolved oxygen for the four Lake St. Croix pools. Additionally, refined calibration included the water-quality data highlighted previously (ammonia, nitrate plus nitrite, total nitrogen, total phosphorus, orthophosphate, and chlorophyll *a*).

Bathymetric Data and Computational Grid

Information from a 1-m light detection and ranging digital elevation model (Minnesota Geospatial Information Office, 2015) was merged with a 10-m digital elevation model (USGS, 2015) to characterize land surface topography. Topography data and USACE bathymetric data (USACE, 2010) were combined to produce a gridded, three-dimensional model of Lake St. Croix. A geographic information system layer was obtained for the drainage basin to define the maximum outer boundary of the model domain. All model grid cells represented in each 1-m slice through the water column were identified and converted to a geographic information system polygon dataset. Lake St. Croix was then segmented into lateral segments (fig. 2) along its longitudinal axis. Within each lateral segment, 1-m layers were drawn from the bottom of the lake up to 2 m above the lake’s most recent highest water level reached in 2007 at Stillwater, Minn. (fig. 1).

Distance along the longitudinal axis for individual CE–QUAL–W2 lateral segments varied; the average lateral segment was about 1-km long. Considerations for the number of lateral segments included a balance between a full-scale representation of the real structure of the lake and a segment structure that maintained numerical stability during model runs. Segments were grouped together into a single branch, representing the computational grid of the water body. Despite the ability to use different branches to represent separate bays or embayments, such as the different pools of Lake St. Croix, these pools were simulated as a single water branch for the sake of model simplicity. Delineation lines for the 38 CE–QUAL–W2 computational segments on Lake St. Croix are shown on figure 2.

Boundary and Initial Conditions

Model success largely depended on a high density of data for chemical and physical lake characteristics from which lake parameters could be calculated and calibrated. Several continuous flow and water-quality monitoring systems were used to calculate the initial and boundary conditions for the models and to provide a robust calibration dataset. Water-quality data used for model input and calibration were reviewed before the modeling efforts for considerations of appropriate usage.

Table 1. Continuous or discrete measurements used in the Lake St. Croix model development or calibration of discharge, water stage level, water temperature, dissolved oxygen, and water-quality constituents.

[All continuous measurements included regular monthly visits to download and calibrate pressure transducers, water-quality sondes, and themistors. USGS, U.S. Geological Survey; MCES, Metropolitan Council Environmental Services; NPS, National Park Service; NAD 83, North American Datum of 1983; Minn., Minnesota; --, not applicable; °, degree; ′, minute; ″, second; Q, discharge/flow; T, water temperature; DO, dissolved oxygen; TDS, total dissolved solids; MI, major inorganics; N, nutrients; I, input; MB, main branch; Alk, alkalinity; C, calibration; WQ, water quality (including discrete sampling for constituents); Wisc., Wisconsin; T, tributary; Chl-a, chlorophyll *a*; O, outflow; S, water stage level]

Site name	USGS station number	MCES station name	NPS station number	Site number (fig. 2)	Latitude/ longitude (NAD 83)	Continuous sampling	Discrete sampling	Use	Model segment (fig. 2)	Pool
St. Croix River at Stillwater, Minn.	05341550	St. Croix River at Stillwater, River Mile 23.3	--	1	45° 03′ 22″ -92° 48′ 14″	Q, T	T, DO, TDS, MI, N	I	2 (MB)	Bayport
Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	--	--	2	45° 00′ 28″ -92° 45′ 58″	--	T, DO, MI, N, Alk	I, T (C), DO (C), WQ (C)	9	Bayport
Willow River at Willow River State Park near Burkhardt, Wisc.	05341752	--	--	3	45° 00′ 42″ -92° 42′ 30″	Q	DO, MI, N, Alk	I	11 (T)	Bayport
Lake St. Croix below Hwy I-94 at Lakeland, Minn.	450028092455801	--	--	4	44° 57′ 25″ -92° 45′ 37″	--	T, DO, N	T (C), DO (C), WQ (C)	15	Troy Beach
Lake St. Croix at Pool 2	--	Lake St. Croix, Site 4	--	5	44° 57′ 26″ -92° 45′ 30″	--	T, DO	T (C), DO (C)	15	Troy Beach
Lake St. Croix at Pool 2	--	--	SACN09	6	44° 57′ 33″ -92° 45′ 37″	--	T, DO, N, Chl-a	T (C), DO (C), WQ (C)	15	Troy Beach
Valley Creek at Putnam Boulevard South[1]	--	--	--	7	44° 54′ 57″ -92° 47′ 09″	Q, T	T, DO, TDS, MI, N	I	21 (T)	Troy Beach
Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	--	--	8	44° 54′ 00″ -92° 46′ 24″	--	T, DO, N	T (C), DO (C), WQ (C)	22	Black Bass
Lake St. Croix at Pool 3	--	Lake St. Croix, Site 6	--	9	44° 54′ 03″ -92° 46′ 34″	--	T, DO, Chl-a	T (C), DO (C)	22	Black Bass
Trout Brook at St. Croix Trail South[2]	--	--	--	10	44° 51′ 49″ -92° 48′ 05″	Q, T	T, DO, MI, N	I	26 (T)	Black Bass
Kinnickinnic River near River Falls, Wisc.	05342000	--	--	11	44° 49′ 51″ -92° 43′ 59″	Q, T	T, DO, MI, N	I	30 (T)	Kinnickinnic
Lake St. Croix below Kinnickinnic R above Prescott, Wisc.	444834092465401	--	--	12	44° 48′ 35″ -92° 46′ 54″	--	T, DO, MI, N	I, T (C), DO (C), WQ (C)	32	Kinnickinnic

Table 1. Continuous or discrete measurements used in the Lake St. Croix model development or calibration of discharge, water stage level, water temperature, dissolved oxygen, and water-quality constituents.—Continued

[All continuous measurements included regular monthly visits to download and calibrate continuous pressure transducers, water-quality sondes, and themistors. USGS, U.S. Geological Survey; MCES, Metropolitan Council Environmental Services; NPS, National Park Service; NAD 83, North American Datum of 1983; Minn., Minnesota; --, not applicable; °, degree; ′, minute; ″, second; Q, discharge/flow; T, water temperature; DO, dissolved oxygen; TDS, total dissolved solids; MI, major inorganics; N, nutrients; I, input; MB, main branch; Alk, alkalinity; C, calibration; WQ, water quality (including discrete constituents); Wisc., Wisconsin; T, tributary; Chl-a, chlorophyll *a*; O, outflow; S, water stage level]

Site name	USGS station number	MCES station name	NPS station number	Site number (fig. 2)	Latitude/ longitude (NAD 83)	Continuous sampling	Discrete sampling	Use	Model segment (fig. 2)	Pool
Lake St. Croix at Pool 4	--	--	SACN11	13	44° 46′ 11″ -92° 48′ 18″	--	T, DO, N, Chl-a	T (C), DO (C), WQ (C)	37	Kinnickinnic
Lake St. Croix below at Pool 4	--	Lake St. Croix, Site 7	--	14	44° 46′ 07″ -92° 48′ 32″	--	T, DO	T (C), DO (C)	37	Kinnickinnic
St. Croix River at Prescott, Wisc.	05344490	St. Croix River at Prescott, River Mile 0.3	--	15	44° 44′ 57″ -92° 48′ 16″	S, Q, T	T	S (C), T (C)	39 (O)	Kinnickinnic

[1]Site maintained and sampled by Valley Branch Watershed District.

[2]Site maintained and sampled by South Washington Watershed District. Full data available at the South Washington Watershed District website, http://wq.swwdmn.org/.

Hydraulic and Thermal Boundary Conditions

Lake-inflow discharge data used in the Lake St. Croix CE–QUAL–W2 model development are available from the USGS National Water Information System (NWIS) database (USGS, 2017a) for the following USGS streamgages (figs. 1, 2; table 1): St. Croix River at Stillwater, Minn. (station 05341550); Willow River at Willow River State Park near Burkhardt, Wisc. (station 05341752); Kinnickinnic River near River Falls, Wisc. (station 05342000); and St. Croix River at Prescott, Wisc. (station 05344490). Willow River does not directly discharge into Lake St. Croix; instead, the Willow River discharges into Lake Mallalieu. Six Lake Mallalieu discharge measurements (from 2012 and 2013) into Lake St. Croix were related linearly to the Willow River discharge record to establish flow out of Lake Mallalieu; this linear relation had a coefficient of determination of 0.94. Trout Brook (Trout Brook at St. Croix Trail South) discharge, maintained and sampled by South Washington Watershed District, is available at the South Washington Watershed District website (South Washington Watershed District, 2017). Valley Creek (Valley Creek at Putnam Boulevard South), maintained and sampled by Valley Branch Watershed District, is available as part of the CE–QUAL–W2 model archive (Smith, 2018).

Additional water inflows to Lake St. Croix also were assumed from ungaged locations in the lake and from groundwater flow, known as distributed tributary flow. The distributed tributary flow also compensates for errors in the other water balance components. Distributed tributary flow was input into the model in daily time steps and distributed evenly across all the model segments. Because direct water temperature measurements were not possible for distributed tributary flow, the Trout Brook water temperature record was used as a surrogate temperature record because this was the closest available streamflow record with a large base flow (groundwater) component.

Continuous water temperature data for the St. Croix River at Stillwater, Minn., are available at the USACE river gages website (USACE, 2017). For the Kinnickinnic River, continuous water temperature measurements were collected at a variable interval of every 5 to 15 minutes from ice off to ice on in 2013 near the USGS station on the Kinnickinnic River near River Falls, Wisc. These continuous water temperature measurements were collected by Trout Unlimited and are available as part of the CE–QUAL–W2 model archive (Smith, 2018). For Trout Brook, continuous water temperature measurements were collected by the Minnesota Department of Natural Resources every 15 minutes from early February to November 10, 2013, at the same location as discharge (South Washington Watershed District, 2017). For Valley Creek, continuous water temperature measurements were collected every 60 minutes for all of 2013 at the same location as discharge and are available as part of the CE–QUAL–W2 model archive (Smith, 2018). Temperature measurements were not available for the Willow River; instead, a linear relation between the Kinnickinnic River temperature record and a weekly Willow River temperature reading was established to create a synthetic temperature record for the Willow River tributary. The approximate relation established the Willow River temperature as 2.1 degrees Celsius (°C) cooler than the Kinnickinnic River record. Continuous water temperature data for the St. Croix River at Prescott, Minn., are available through the USGS NWIS database (USGS, 2017a).

Required meteorological data included air temperature, dew point temperature, wind speed, wind direction, and cloud cover. All unit conversions from the meteorological data to the required units for the model were straightforward except for cloud cover. The qualitative sky cover parameter (that is, clear, scattered, broken, and overcast) was converted to an integer value ranging from 0 to 10: clear is 0, scattered (1/8 to 1/2 cloud coverage) is 3, broken (5/8 to 7/8 cloud coverage) is 7, and overcast is 10. All the required data were available at hourly intervals for the Lake Elmo Municipal Airport (U.S. Air Force station identification number 720583), less than 10 km west of Lake St. Croix, from the Climate Data Online portal (National Climatic Data Center, 2017). Lake surface evaporation was estimated internally by CE–QUAL–W2 using the latitude and longitude of the lake and the required meteorological inputs.

Water-Quality Data Collection, Vertical Profiles, and Laboratory Analyses

Limnological characteristics, including properties that could affect trophic state, were examined at nine sites with coverage across all four pools (fig. 2; table 1): Lake St. Croix below Lakeside Park at Bayport, Minn. (site 2; Bayport Pool), Lake St. Croix below Highway I–94 at Lakeland, Minn. (site 4; Troy Beach Pool), two separate Lake St. Croix at Pool 2 sites (sites 5 and 6; Troy Beach Pool), Lake St. Croix below Catfish Bar near Afton, Minn. (site 8; Black Bass Pool), Lake St. Croix at Pool 3 (site 9; Black Bass Pool), Lake St. Croix below Kinnickinnic River above Prescott, Wisc. (site 12; Kinnickinnic Pool), and two separate Lake St. Croix at Pool 4 sites (sites 13 and 14; Kinnickinnic Pool). The sites were sampled at different schedules from late April through November 2013; all pools except the Bayport Pool had about biweekly profiles for temperature and dissolved oxygen. Water-quality samples were collected near the surface (1 to 2 m below surface) and at depth (2 m above the bottom) for the four sites with USGS stations that represented all four pools: site 2 (Bayport Pool), site 4 (Troy Beach Pool), site 8 (Black Bass Pool), and site 12 (Kinnickinnic Pool).

Samples were collected using a Kemmerer sampler (Wildco no. 1200E; Wildlife Supply Co., Yulee, Florida) and were analyzed to determine concentrations of alkalinity, nutrients, major ions, and chlorophyll *a*. Water samples were filtered and preserved as required. Alkalinity was determined by incremental titration at the field laboratory (Wilde, 2006). Vertical profiles (1-m intervals) of temperature, dissolved oxygen concentration, pH, and specific conductance were measured with a multiparameter YSI sonde (YSI model 6920) at each lake site in conjunction with the water samples, following the methods for field measurements in still water presented in Gibs and others (2012). Sampling also was completed by the USGS at two of the four tributaries within the Lake St. Croix model domain: Willow River at Willow River State Park (USGS station 05341752; site 3) and Kinnickinnic River near River Falls (USGS station 05342000; site 11) (fig. 2; table 1). The same constituents and methodologies as the limnological sites were followed for these sites. Sampling frequency for the inflows and outflows varied between the two tributaries.

Water samples collected by the USGS at the lake and inflow sites were analyzed by the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. Method information and NWQL long-term method detection limits for constituents analyzed for Lake St. Croix are given in table 2. Dissolved concentrations are those analyzed for a 0.45-micron filtered sample, whereas total concentrations were determined for an unfiltered water sample. All the samples analyzed by NWQL had been previously reviewed and published and are available online through the NWIS water-quality portal by searching for the station number in table 1 (USGS, 2017b). The quality-assurance plan for this study followed USGS guidelines (Brunett and others, 1997). Field instruments were maintained according to manufacturer's guidelines, calibration standards were properly stored, calibration for portable field instruments was done at the start of each day (Gibs and others, 2012), and all field sampling equipment was cleaned before use according to the National Field Manual guidelines (Wilde, 2004). Additional quality assurance specific to NWQL is available online (USGS, 2017c).

Monthly water samples were collected by the NPS (through the Great Lakes Inventory and Monitoring Network) at two sites: Lake St. Croix at Pool 2 (SACN09; site 6) and Lake St. Croix at Pool 4 (SACN11; site 13) (fig. 2; table 1). All samples were processed and handled according to standard operating procedures (Magdalene and others, 2008) and as detailed in the 2007 annual water-quality report (VanderMeulen and Elias, 2008). NPS water-quality data were used specifically for calibration purposes only, rather than for model input development, and are available with the CE–QUAL–W2 model archive (Smith, 2018). Water samples were collected, analyzed, reviewed, and published online for Trout Brook at St. Croix Trail South (site 10; fig. 2; table 1) by the South Washington Watershed District (South Washington Watershed District, 2017). Total dissolved solids concentrations were based on multiplying the measured specific conductance by 0.55, an estimate based on the recommended lower end of the correlation factor range published in Atekwana and others (2004). Water samples were collected and analyzed for Valley Creek at Putnam Boulevard South (site 7; fig. 2; table 1) by the Valley Creek Watershed District, with full water-quality data quality assurance provided in Almendinger and others (2014). All water-quality data collected by the Metropolitan

Table 2. Water-quality methods for constituents analyzed in water samples by the U.S. Geological Survey from Lake St. Croix, 2013.

[mg/L, milligram per meter; µg/L, microgram per liter]

Constituent	Method	Long-term method detection limit[1]
Dissolved nitrite as nitrogen	Colorimetry (Fishman, 1993)	0.0010 mg/L
Dissolved nitrite plus nitrate nitrogen	Colorimetry, enzyme reduction-diazotization (Patton and Kryskalla, 2011)	0.01 mg/L
Dissolved ammonia as nitrogen	Colorimetry, salicylate-hypochlorate (Fishman, 1993)	0.010 mg/L
Total Kjeldahl as nitrogen	Colorimetry, micro-Kjeldahl digestion (Patton and Truit, 2000)	0.07 mg/L
Dissolved ammonia plus organic nitrogen as nitrogen	Colorimetry, micro-Kjeldahl digestion (Patton and Truitt, 2000)	0.07 mg/L
Total phosphorus	EPA 365.1 (U.S. Environmental Protection Agency, 1993)	0.004 mg/L
Dissolved phosphorus as phosphorus	EPA 365.1 (U.S. Environmental Protection Agency, 1993)	0.003 mg/L
Dissolved orthophosphate as phosphorus	Colorimetry, phosphomolybdate (Fishman, 1993)	0.004 mg/L
Chlorophyll *a*	Fluorometric (Arar, 1997)	0.1 µg/L
Total dissolved solids	Residue on evaporation (Fishman and Friedman, 1989)	20 mg/L
Total silica, as silicon dioxide	Inductively coupled plasma atomic emission spectroscopy (Fishman, 1993)	0.018 mg/L
Total alkalinity	Inflection point titration (Wilde, 2006)	1 mg/L
Dissolved iron	Inductively coupled plasma atomic emission spectroscopy (Fishman, 1993)	0.0010 mg/L

[1]The long-term method detection level is derived by determining the standard deviation of a minimum of 24 method detection limit spike sample measurements for an extended time (Childress and others, 1999).

Council (table 1) were collected, analyzed, reviewed, and published online through the Metropolitan Council Environmental Services (MCES) water-quality advanced search portal by searching for the MCES station name in table 1 (MCES, 2017).

Initial Conditions

Each simulated constituent (including temperature) in a CE–QUAL–W2 model starts with an initial, single concentration for the entire model domain or a grid-wide initial vertical profile of concentrations at the start of each model run. Because the Lake St. Croix (fig. 1) model started after ice out, the lake was assumed to be isothermal and well-mixed. Initial conditions for each water-quality constituent are shown in table 3. Initial water-surface elevation and water temperature were set to measured values at the simulation start.

Table 3. Initial constituent concentrations for the Lake St. Croix model.

[m NGVD 29; meters above National Geodetic Vertical Datum of 1929; mg/L, milligram per liter; °C, degrees Celsius]

Constituent	Value
Initial water-surface elevation, m NGVD 29	206.49
Total dissolved solids, mg/L	125.22
Dissolved orthophosphate as phosphorus, mg/L	0.0224
Dissolved ammonia as nitrogen, mg/L	0.0429
Dissolved nitrate plus nitrite as nitrogen, mg/L	0.3405
Dissolved silica, mg/L	9.9744
Particulate silica, mg/L	1.00
Total iron, mg/L	0.6307
Labile dissolved organic matter, mg/L	1.9021
Refractory dissolved organic matter, mg/L	4.4382
Labile particulate organic matter, mg/L	0.4586
Refractory particulate organic matter, mg/L	1.0701
Diatoms, mg/L	0.05
Green algae, mg/L	0.20
Blue-green algae, mg/L	0.10
Dissolved oxygen, mg/L	12.3
Inorganic carbon, mg/L	70.47
Zooplankton, mg/L	1.00
Alkalinity, mg/L	57.96
Initial temperature, °C	2.1
Sediment temperature, °C	7.95

Chemical Boundary Conditions

Each simulated water-quality constituent, including total dissolved solids, dissolved orthophosphate, ammonia, nitrate plus nitrite, silica, iron, organic matter, and inorganic carbon, must have a daily concentration value for all inflow tributaries (including distributed tributary flow). Depending on the discrete water-quality sampling frequency, the input constituent concentrations were either transformed into daily load estimates, a daily concentration value was linearly interpolated between discrete samples, or a mean concentration was applied for the entire model run. In a few cases, a substitution from another source was made or an estimate was calculated from another constituent based on a relation developed from a literature source. For the daily load estimates, the load estimates were transformed back into daily constituent concentrations based on the daily average discharge. CE–QUAL–W2 automatically calculates the load internally in cases only a linearly interpolated daily concentration or a mean concentration was applied for the entire model run. All constituents had sufficient data for daily load estimates for the main inflow (St. Croix River), except for organic matter subcomponents.

The load estimator (LOADEST) computer program (Runkel and others, 2004) was used to estimate daily loads for the calibration period if (1) sufficient water-quality samples were available, (2) continuous discharge records existed, and (3) the LOADEST model run converged. With LOADEST, constituent concentration for discrete samples were transformed into load estimates through a relation to discharge using one of several different regression equations, as shown in table 4. LOADEST uses the adjusted maximum likelihood estimator to account for censored data; in cases where the results were not normally distributed, the least absolute deviation results were used in lieu of the adjusted maximum likelihood estimator because least absolute deviation results do not depend on the data being normally distributed.

Load estimates were available for the main inflow (St. Croix River) for the following constituents: total dissolved solids, orthophosphate, total phosphorus, ammonia, nitrate plus nitrite, dissolved silica, total iron, total Kjeldahl nitrogen and organic matter pools, inorganic carbon, chlorophyll *a*, and alkalinity (table 4). Concentrations for the main inflow for the following constituents were applied from Lake St. Croix below Lakeside Park (site 2; as a surrogate site for the main inflow): iron, inorganic carbon, and alkalinity. Organic matter loads were back-calculated from the total Kjeldahl nitrogen load minus the dissolved ammonia load, with an additional calculation based on a linear relation between streamflow and the particulate organic nitrogen to total organic nitrogen ratio (Smith and others, 2017). Organic matter concentrations were then further divided into four separate pools: labile dissolved, refractory dissolved, labile particulate, and refractory particulate, with dissolved and particulate pools separated into labile and refractory at 30 and 70 percent, respectively.

Table 4. Methods for calculating the daily water-quality constituent concentrations for the main inflow (St. Croix River) and the four tributaries: Willow River, Valley Creek, Trout Brook, and Kinnickinnic River.

[Each constituent was calculated based on LOADEST, a linear interpolation (noted as linear), substitution from another source (noted as substitution, with source in parentheses), an estimate from another constituent, or a mean. Also in parentheses with LOADEST is the regression model number, as shown in table 7 of Runkel and others (2004). --, not applicable]

Constituent	St. Croix River/ main inflow	Willow River	Valley Creek	Trout Brook	Kinnickinnic River
Total dissolved solids	LOADEST (8)	Linear	LOADEST (9)1	LOADEST (1)[1]	LOADEST (1)
Orthophosphate	LOADEST (9)	Linear	LOADEST (6)	LOADEST (1)	LOADEST (1)
Total phosphorus	LOADEST (9)	--	--	--	--
Ammonia	LOADEST (9)	Linear	LOADEST (9)	LOADEST (3)	Linear
Nitrate plus nitrite	LOADEST (9)	Linear	LOADEST (7)	LOADEST (5)	LOADEST (1)
Dissolved silica	LOADEST (4)	Linear	--	Substitution (from St. Croix River/ main inflow)	Linear
Total iron	LOADEST (9)	Linear	--	Substitution (from St. Croix River/ main inflow)	Linear
Total Kjeldahl nitrogen and organic matter pools	LOADEST (9)	Linear	LOADEST (9)	LOADEST (3)	Linear
Inorganic carbon	LOADEST (4)	Linear	--	Substitution (from St. Croix River/ main inflow)	LOADEST (4)
Chlorophyll *a*	LOADEST (9)	--	--	--	--
Alkalinity	LOADEST (4)	Linear	--	Substitution (from St. Croix River/ main inflow)	LOADEST (4)

[1]Total dissolved solids derived by multiplying specific conductance measurements by 0.55, based upon recommended correlation factor (lower limit of 0.55 to 0.80 range) from Atekwana and others (2004).

For the tributaries, load estimates were not available for every constituent, either because LOADEST did not converge or there was not enough data available. Methods for either constructing a constituent load independently or a linear interpolation for an internal CE–QUAL–W2 load calculation are summarized in table 4. For Trout Brook (site 10), measurements of dissolved silica, inorganic carbon, or alkalinity were not available, so substitution from the St. Croix River (site 1) was used. For total dissolved solids, only specific conductance was available for Valley Creek and Trout Brook. Based on Atekwana and others (2004), the specific conductance was multiplied by 0.55 to estimate total dissolved solids concentrations, and loads were calculated on the estimated total dissolved solids concentrations. Organic matter calculations and divisions into four separate pools were calculated with the same method as the main inflow. For Trout Brook and Valley Creek, load estimates were available, but linear interpolation was used for the Willow and Kinnickinnic Rivers (sites 3 and 11). For the Willow River, linear interpolations were done for all constituents because there was not enough discharge data to complete independent daily load estimates. Finally, as with the temperature record, the Trout Brook concentrations were used for the distributed tributary inflow constituents because direct measurements were not available.

Model Parameters

Numerous CE–QUAL–W2 studies have determined that the default hydraulic parameters in the model are robust across different hydrologic settings and are relatively insensitive to variations (Cole and Wells, 2015). The default hydraulic parameters that control the hydrodynamics and heat exchange provided within CE–QUAL–W2 or the accompanying manual were followed. The density control for all inflows in the model allowed for the water inflows to match up with the layers within the lake that corresponded to the inflow density.

For the water-quality algorithms, more than 160 parameters control the constituent kinetics (table 5). An advantage of CE–QUAL–W2 is the modular design that allows for control of the water-quality constituents by adding specific subroutines. Several of these parameters were optional depending on the inclusion of groups such as epiphyton, zooplankton, macrophytes, and algae. Only the parameters required for the selected modules were included in table 5. As with the hydraulic and heat exchange parameters that control the hydrodynamics, all parameters were time and space invariant. The option existed to vary some parameters, such as the light extinction coefficient of water; however, not enough data were collected to justify dynamic control of any parameters.

Several of the parameters in table 5 were left as the default values (88 parameters), whereas the remaining parameters (74 parameters) were adjusted during the calibration process. Guidance for adjusting selected parameters came from other USGS CE–QUAL–W2 model applications (Green and others, 2003; Sullivan and Rounds, 2004; Galloway and Green, 2006; Galloway and others, 2008; Sullivan and others, 2011; Smith and others, 2014, 2017; Cole and Wells, 2015).

Table 5. Model parameters used in the water-quality algorithm for Lake St. Croix.

[Bold text indicates parameters adjusted from default value; m^2/s, square meter per second; $W/(m^2 \times °C)$, watt per square meter times degree Celsius; $m/(g \times m^3)$, meter per gram times cubic meter; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, watt per square meter; °C, degree Celsius; m/s, meter per second; $g/m^2/d$, gram per square meter per day]

Parameter	Description	Parameter value
AX	Horizontal eddy coefficient, in m^2/s	1.00
DX	Vertical eddy coefficient, in m^2/s	1.00
CBHE	Sediment heat exchange coefficient, in $W/(m^2 \times °C)$	**0.5**
FI	Inferfacial friction factor	0.015
TSEDF	Heat lost to sediments that is added back to water column	**0.75**
AZC	Vertical turbulence closure algorithm	TKE
EXH2O	Light extinction for pure water, in meters	0.25
EXSS	Light extinction because of inorganic suspended solids, in meters	**0.01**
EXOM	Light extinction because of organic suspended solids, in meters	**0.01**
BETA	Fraction of incident solar radiation absorbed at water surface	0.45
EXA1	Light extinction because of algae (diatoms), in $m/(g \times m^3)$	**0.1**
EXA2	Light extinction because of algae (green), in $m/(g \times m^3)$	**0.1**
EXA3	Light extinction because of algae (blue-green), in $m/(g \times m^3)$	**0.13**
EXZ1	Light extinction because of zooplankton, in $m/(g \times m^3)$	**0.02**
AG	Maximum algal growth rate (diatoms), per day	**1.05**
AG	Maximum algal growth rate (green), per day	**1.86**
AG	Maximum algal growth rate (blue-green), per day	**1.51**
AR	Maximum algal respiration rate (diatoms), per day	0.04
AR	Maximum algal respiration rate (green), per day	0.04
AR	Maximum algal respiration rate (blue-green), per day	0.04
AE	Maximum algal excretion rate (diatoms), per day	0.04
AE	Maximum algal excretion rate (green), per day	0.04
AE	Maximum algal excretion rate (blue-green), per day	0.04
AM	Maximum algal mortality rate (diatoms), per day	0.10
AM	Maximum algal mortality rate (green), per day	**0.04**
AM	Maximum algal mortality rate (blue-green), per day	**0.04**
AS	Algal settling rate (diatoms), in m/d	**0.2**
AS	Algal settling rate (green), in m/d	**0.07**
AS	Algal settling rate (blue-green), in m/d	**0**
AHSP	Algal half-saturation for phosphorus limited growth (diatoms), in g/m^3	**0.002**

Table 5. Model parameters used in the water-quality algorithm for Lake St. Croix.—Continued

[Bold text indicates parameters adjusted from default value; m^2/s, square meter per second; $W/(m^2{\times}°C)$, watt per square meter times degree Celsius; $m/(g{\times}m^3)$, meter per gram times cubic meter; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, watt per square meter; °C, degree Celsius; m/s, meter per second; $g/m^2/d$, gram per square meter per day]

Parameter	Description	Parameter value
AHSP	Algal half-saturation for phosphorus limited growth (green), in g/m^3	**0.002**
AHSP	Algal half-saturation for phosphorus limited growth (blue-green), in g/m^3	**0.002**
AHSN	Algal half-saturation for nitrogen limited growth (diatoms), in g/m^3	0.014
AHSN	Algal half-saturation for nitrogen limited growth (green), in g/m^3	0.014
AHSN	Algal half-saturation for nitrogen limited growth (blue-green), in g/m^3	**0.001**
AHSSI	Algal half-saturation for silica limited growth (diatoms), in g/m^3	0
AHSSI	Algal half-saturation for silica limited growth (green), in g/m^3	0
AHSSI	Algal half-saturation for silica limited growth (blue-green), in g/m^3	0
ASAT	Light saturation intensity at maximum photosynthetic rate (diatoms), in W/m^2	**105**
ASAT	Light saturation intensity at maximum photosynthetic rate (green), in W/m^2	**52**
ASAT	Light saturation intensity at maximum photosynthetic rate (blue-green), in W/m^2	**25**
AT1	Lower temperature for algal growth (diatoms), in °C	5
AT1	Lower temperature for algal growth (green), in °C	**10**
AT1	Lower temperature for algal growth (blue-green), in °C	**12**
AT2	Lower temperature for maximum algal growth (diatoms), in °C	**7**
AT2	Lower temperature for maximum algal growth (green), in °C	**13**
AT2	Lower temperature for maximum algal growth (blue-green), in °C	**20**
AT3	Upper temperature for maximum algal growth (diatoms), in °C	**18**
AT3	Upper temperature for maximum algal growth (green), in °C	**25**
AT3	Upper temperature for maximum algal growth (blue-green), in °C	**27**
AT4	Upper temperature for algal growth (diatoms), in °C	**25**
AT4	Upper temperature for algal growth (green), in °C	**30**
AT4	Upper temperature for algal growth (blue-green), in °C	**32**
AK1	Fraction of algal growth rate at AT1 (diatoms)	0.1
AK1	Fraction of algal growth rate at AT1 (green)	0.1
AK1	Fraction of algal growth rate at AT1 (blue-green)	0.1
AK2	Fraction of maximum algal growth rate at AT2 (diatoms)	0.99
AK2	Fraction of maximum algal growth rate at AT2 (green)	0.99
AK2	Fraction of maximum algal growth rate at AT2 (blue-green)	0.99
AK3	Fraction of maximum algal growth rate at AT3 (diatoms)	0.99
AK3	Fraction of maximum algal growth rate at AT3 (green)	0.99
AK3	Fraction of maximum algal growth rate at AT3 (blue-green)	0.99
AK4	Fraction of algal growth rate at AT4 (diatoms)	0.1
AK4	Fraction of algal growth rate at AT4 (green)	0.1
AK4	Fraction of algal growth rate at AT4 (blue-green)	0.1
ALGP	Stoichiometric equivalent between algal biomass and phosphorus (diatoms)	**0.012**
ALGP	Stoichiometric equivalent between algal biomass and phosphorus (green)	**0.0045**

Table 5. Model parameters used in the water-quality algorithm for Lake St. Croix.—Continued

[Bold text indicates parameters adjusted from default value; m^2/s, square meter per second; W/(m^2×°C), watt per square meter times degree Celsius; m/(g×m^3), meter per gram times cubic meter; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, watt per square meter; °C, degree Celsius; m/s, meter per second; $g/m^2/d$, gram per square meter per day]

Parameter	Description	Parameter value
ALGP	Stoichiometric equivalent between algal biomass and phosphorus (blue-green)	**0.0075**
ALGN	Stoichiometric equivalent between algal biomass and nitrogen (diatoms)	**0.075**
ALGN	Stoichiometric equivalent between algal biomass and nitrogen (green)	**0.091**
ALGN	Stoichiometric equivalent between algal biomass and nitrogen (blue-green)	0.08
ALGC	Stoichiometric equivalent between algal biomass and carbon (diatoms)	0.45
ALGC	Stoichiometric equivalent between algal biomass and carbon (green)	0.45
ALGC	Stoichiometric equivalent between algal biomass and carbon (blue-green)	0.45
ALGSI	Stoichiometric equivalent between algal biomass and silica (diatoms)	**0.2**
ALGSI	Stoichiometric equivalent between algal biomass and silica (green)	**0.1**
ALGSI	Stoichiometric equivalent between algal biomass and silica (blue-green)	**0.08**
ACHLA	Ratio between algal biomass and chlorophyll *a* in terms of milligrams of algae to micrograms of chlorphyll a (diatoms)	**0.04**
ACHLA	Ratio between algal biomass and chlorophyll *a* in terms of milligrams of algae to micrograms of chlorphyll *a* (green)	0.05
ACHLA	Ratio between algal biomass and chlorophyll *a* in terms of milligrams of algae to micrograms of chlorphyll a (blue-green)	**0.066**
ALPOM	Fraction of algal biomass that is converted to particulate organic matter when algae die (diatoms)	**0.75**
ALPOM	Fraction of algal biomass that is converted to particulate organic matter when algae die (green)	**0.75**
ALPOM	Fraction of algal biomass that is converted to particulate organic matter when algae die (blue-green)	**0.75**
ANEQN	Equation number for algal ammonium preference (diatoms)	**0.9**
ANEQN	Equation number for algal ammonium preference (green)	**0.7**
ANEQN	Equation number for algal ammonium preference (blue-green)	0.8
ANPR	Algal half saturation constant for ammonium preference (diatoms)	0.001
ANPR	Algal half saturation constant for ammonium preference (green)	0.001
ANPR	Algal half saturation constant for ammonium preference (blue-green)	0.001
O2AR	Oxygen stoichiometry for algal respiration (diatoms)	1.1
O2AR	Oxygen stoichiometry for algal respiration (green)	1.1
O2AR	Oxygen stoichiometry for algal respiration (blue-green)	1.1
O2AG	Oxygen stoichiometry for algal primary production (diatoms)	**1.1**
O2AG	Oxygen stoichiometry for algal primary production (green)	1.4
O2AG	Oxygen stoichiometry for algal primary production (blue-green)	1.4
ZG	Maximum algal growth rate, per day	**1.6**
ZR	Maximum algal respiration rate, per day	0.1
ZM	Maximum algal mortality rate, per day	0.01
ZEFF	Zooplankton assimilation efficiency	0.5
PREFP	Preference factor of zooplankton for detrius or labile particulate organic matter	**0.7**

Table 5. Model parameters used in the water-quality algorithm for Lake St. Croix.—Continued

[Bold text indicates parameters adjusted from default value; m^2/s, square meter per second; $W/(m^2 \times °C)$, watt per square meter times degree Celsius; $m/(g \times m^3)$, meter per gram times cubic meter; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, watt per square meter; °C, degree Celsius; m/s, meter per second; $g/m^2/d$, gram per square meter per day]

Parameter	Description	Parameter value
ZOOMIN	Threshold food concentration at which zooplankton feeding begins, in g/m^3	**0.35**
ZS2P	Zooplankton half-saturation constant for food saturation, in g/m^3	0.3
ZT1	Lower temperature for zooplankton growth, in °C	5
ZT2	Lower temperature for maximum zooplankton growth, in °C	**8**
ZT3	Upper temperature for maximum zooplankton growth, in °C	**24**
ZT4	Upper temperature for zooplankton growth, in °C	**35**
ZK1	Fraction of zooplankton growth rate at AT1	0.1
ZK2	Fraction of maximum zooplankton growth rate at AT2	0.99
ZK3	Fraction of maximum zooplankton growth rate at AT3	0.99
ZK4	Fraction of zooplankton growth rate at AT4	0.1
ZP	Stoichiometric equivalent between zooplankton biomass and phosphorus	0.005
ZN	Stoichiometric equivalent between zooplankton biomass and nitrogen	0.08
ZC	Stoichiometric equivalent between zooplankton biomass and carbon	0.45
OSZR	Oxygen stoichiometry for zooplankton respiration	1.1
PREFA1	Preference factor of zooplankton for algae (diatoms)	**1.0**
PREFA2	Preference factor of zooplankton for algae (green)	**0.3**
PREFA3	Preference factor of zooplankton for algae (blue-green)	**0.15**
LDOMDK	Labile dissolved organic matter decay rate, per day	**0.09**
RDOMDK	Refractory dissolved organic matter decay rate, per day	0.001
LRDDK	Labile-to-refractory dissolved organic matter decay rate, per day	**0.025**
LPOMDK	Labile particulate organic matter decay rate, per day	**0.08**
RPOMDK	Refractory particulate organic matter decay rate, per day	0.001
LRPDK	Labile-to-refractory particulate organic matter decay rate, per day	0.01
POMS	Particulate organic matter settling rate, in m/d	**0.2**
ORGP	Stoichiometric equivalent between organic matter and phosphorus	**0.0032**
ORGN	Stoichiometric equivalent between organic matter and nitrogen	0.08
ORGC	Stoichiometric equivalent between organic matter and carbon	0.45
ORGSI	Stoichiometric equivalent between organic matter and silica	**0.15**
OMT1	Lower temperature for organic matter decay, in °C	4
OMT2	Upper temperature for organic matter decay, in °C	**30**
OMK1	Fraction of organic matter decay at OMT1	0.1
OMK2	Fraction of organic matter decay at OMT2	0.99

Table 5. Model parameters used in the water-quality algorithm for Lake St. Croix.—Continued

[Bold text indicates parameters adjusted from default value; m^2/s, square meter per second; $W/(m^2\times°C)$, watt per square meter times degree Celsius; $m/(g\times m^3)$, meter per gram times cubic meter; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, watt per square meter; °C, degree Celsius; m/s, meter per second; $g/m^2/d$, gram per square meter per day]

Parameter	Description	Parameter value
PO4R	Sediment release rate of phosphorus, fraction of sediment oxygen demand	**0.003**
PARTP	Phosphorus partitioning coefficient for suspended solids	0
NH4R	Sediment release rate of ammonium, fraction of sediment oxygen demand	0.001
NH4DK	Ammonium decay rate, per day	0.12
NH4T1	Lower temperature for ammonia decay, in °C	5
NH4T2	Lower temperature for maximum ammonia decay, in °C	**30**
NH4K1	Fraction of nitrification rate at NH4T1	0.1
NH4K2	Fraction of nitrification rate at NH4T2	0.99
NO3DK	Nitrate decay rate, per day	**0.14**
NO3S	Denitrification rate from sediments, in m/d	0.001
FNO3SED	Fraction of nitrate-nitrogen diffused into the sediments that become part of organic nitrogen in the sediments	0
NO3T1	Lower temperature for nitrate decay, in °C	**4**
NO3T2	Lower temperature for maximum nitrate decay, in °C	**30**
NO3K1	Fraction of denitrification rate at NO3T1	0.1
NO3K2	Fraction of denitrification rate at NO3T2	0.99
DSIR	Dissolved silica sediment release rate, fraction of sediment oxygen demand	0.1
PSIS	Particulate biogenic settling rate, in m/s	1
PSIDK	Particulate biogenic silica decay rate, per day	**0.3**
PARTSI	Dissolved silica partitioning coefficient	0
SEDS	Sediment settling or focusing velocity, in m/d	0.1
SEDK	Sediment decay rate, per day	0.1
SOD	Zero-order sediment oxygen demand, in $g/m^2/d$	**3.45 (pool 1, 4)** **0.4383 (pool 2)** **1.27052 (pool 3, 4)**
O2LIM	Dissolved oxygen half-saturation constant or concentration at which aerobic processes are at 50 percent of their maximum, in g/m^3	0.1
FER	Iron sediment release rate, fraction of sediment oxygen demand	**0.3**
FES	Iron settling velocity, in m/d	2
CO2R	Sediment carbon dioxide release rate, fraction of sediment oxygen demand	1.2
O2NH4	Oxygen stoichiometry for nitrification	4.57
O2OM	Oxygen stoichiometry for organic matter decay	1.4
TYPE	Type of waterbody	LAKE
EQN#	Equation number used for determining reaeration	**3**

Model Calibration

The CE–QUAL–W2 model successfully reproduced temperature and dissolved oxygen in the lake longitudinally (from upstream to downstream), vertically, and temporally over the seasons. Additionally, trends in measured water-quality data were captured by the model simulation, indicating that the model should be sufficiently accurate.

Model calibration was based on two goodness of fit measures: mean absolute error (MAE) and the root mean square error (RMSE). The MAE, computed using equation 1 (for example, see usage in Smith and others, 2017), is a measure of the average difference between the simulated value and the measured value:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |\, simulated\ value - measured\ value \,| \quad (1)$$

where

n is the number of observations.

For example, an MAE of 1.0 milligram per liter (mg/L) for dissolved oxygen means that the absolute difference between the simulated model value and measured concentration was on average 1.0 mg/L. The RMSE, as computed by equation 2, is a relative term that gives a measure of the variability between the simulated and measured value:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (simulated - measured\ value)^2} \quad (2)$$

For example, 95 percent of the prediction errors will fall within two standard deviations of the mean error; therefore, if the RMSE for dissolved oxygen was 1 mg/L, 95 percent of the predictions errors will be less than ±2 mg/L.

The degree of fit between the simulated and measured water-surface elevation and outlet water temperature was only considered during the initial calibration. By calibrating to water-surface elevation and outlet water temperature first, the subsequent water-quality calibration was easier because changes in the amount of flow in and out of the lake, wind stress, inflow water temperature, and meteorological effects had already been considered. The water-quality calibration for dissolved oxygen, nutrients, water temperature, and algae followed, using the MAE and RMSE metrics.

Water Balance

The first step in the calibration process was to evaluate water balance. The water balance was considered complete when the MAE and RMSE values were less than 0.03 m for the simulated water-surface elevation. The initial attempt to achieve a water balance for Lake St. Croix used the main inflow (St. Croix River) and the four tributaries (table 1) as the sole inflows for the simulation/calibration period of April 20 to November 15, 2013; however, the simulated water-surface elevation was below the measured water-surface elevation, indicating additional sources of water to the lake, such as ungaged tributaries and groundwater. To represent unaccounted inflow in the model better, a distributed tributary flow was added to all segments equally. This distributed tributary flow can be positive or negative and includes a summation of measurement errors from all water sources. A comparison between the final simulated and measured water-surface elevations for Lake St. Croix is shown in figure 3.

Temperature

Temperature calibration is critical because temperature affects water density and thus affects interlayer exchange of constituents. Water temperature was a key metric to determine the accuracy of the Lake St. Croix model's calibration. Measured vertical temperature profiles did not exhibit uniform behavior across the four different pools of Lake St. Croix (fig. 1). Despite the lack of uniformity, the simulated temperature profiles closely matched the measured profiles throughout the year, including the prediction of thermocline transition depths (often within 1 m), the absolute temperature of the thermocline transitions (often within 1.0 °C), and profiles without a strong thermocline transition. The final aggregate of the four different pools was 0.74 and 1.10 °C for the MAE and RMSE values, respectively (table 6). The MAE and RMSE values for most dates were much less than 1.0 °C, providing confidence in the model's ability to predict water temperature.

Boundary conditions that affect water temperature include sediment temperature, initial lake-water temperature, and inflow water temperature. Meteorological effects include air temperature, wind velocity, wind direction, and solar radiation. Because solar radiation data were not directly available, an internal calculation within the model was made based on the amount of cloud cover and the latitude/longitude. Wind effects can be further augmented by the wind sheltering coefficient, controlled through a separate input file, which considers the effects of boundary factors such as topography and shoreline tree cover on wind mixing. Several hydraulic parameters also affect water temperature; for example, the TSEDF parameter is the amount of reradiated heat back to the water column from solar radiation that penetrates the entire water column. Another set of critical parameters are the light extinction coefficients for water (EXH2O), suspended inorganic (EXSS) and organic solids (EXOM), algae (EXA1, EXA2, and EXA3), and zooplankton (EXZ1) (table 5).

The temperature profiles for each of the four pools (Bayport [fig. 4], Troy Beach [fig. 5], Black Bass [fig. 6], Kinnickinnic [figs. 7, 8]) (table 6) were the initial temperature calibration targets based on collected vertical temperature profiles. The three different Troy Beach locations are shown together in figure 5, and the two Black Bass sites are shown together in figure 6 because sites were close enough to show in a single figure; however, sites in the Kinnickinnic Pool where too far apart to accurately depict the locations in a single figure.

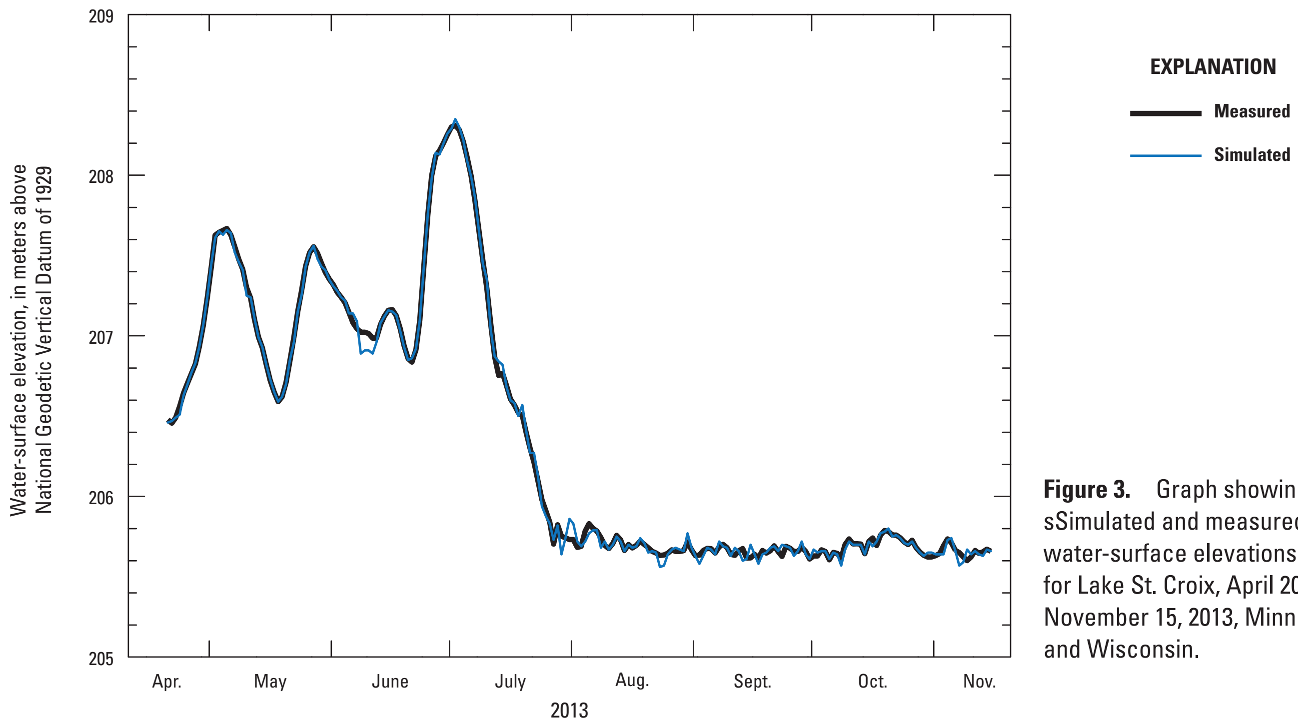


Figure 3. Graph showing sSimulated and measured water-surface elevations for Lake St. Croix, April 20 to November 15, 2013, Minnesota and Wisconsin.

Lake St. Croix below Kinnickinnic River (USGS station 444834092465401), therefore, is shown in figure 7, and the other two Kinnickinnic pool sites are shown in figure 8. The most difficult aspect of the model temperature calibration was optimizing the degree of fit, based on MAE and RMSE values, across all four pools of Lake St. Croix.

Four measured temperature profiles collected on different dates in 2013 are shown for Bayport Pool (pool 1) in figure 4. Mean MAE and RMSE for the Bayport pool were 0.60 and 0.81 °C, respectively (table 6). The simulated temperatures follow the measured temperatures throughout the year; however, the July simulated temperature was too warm in the hypolimnion.

A total of 15 dates are shown for Troy Beach Pool (pool 2) in figure 5, providing measured temperature profiles almost every 2 weeks. For weak thermoclines, simulated results transitioned within 1–2 m of the correct depth. The simulated record generally was within 1–2 °C, although one considerable difference was on July 22, 2013. The primary cause of the deviation may have been a larger wind sheltering coefficient for Troy Beach Pool (80 percent) than Bayport Pool (70 percent). The wind sheltering coefficient controls the amount of wind energy transferred to the lake, with smaller coefficients caused by shifts in primary wind directions during the year and differences in terrain between the meteorological station and the lake itself. The wind sheltering coefficient was adjusted from 70 to 100 percent across the different segments and pools. Overall, the MAE and RMSE values were 0.61 and 0.89 °C, respectively, for the three different locations in Troy Beach Pool (fig. 5).

Eight measured temperature profiles are shown for Black Bass Pool (pool 3) in figure 6. Mean MAE and RMSE values were 0.93 and 1.27 °C, respectively (table 6). The simulated temperatures follow the measured temperatures throughout the year, although the simulated temperatures exceeded the measured temperatures in the hypolimnion for July through September. The simulated thermocline depth was within 1 m of measured thermocline depths for all profile dates with more developed thermoclines, except for the profile collected on May 24, 2013, which was too shallow for the simulated profile. A total of 17 measured temperature profiles are shown for the Kinnickinnic Pool (pool 4) in figures 7 and 8. Figure 7 shows profiles (4 dates) from the upper Kinnickinnic Pool (pool 4), and figure 8 shows profiles (13 dates) from the lower Kinnickinnic Pool (pool 4). With the exception of the temperature profile collected on July 22, 2013 (fig. 7), simulated temperatures follow the measured temperatures closely, including the steady transition from warm to cooler temperatures at depth. The overall MAE and RMSE values were 0.74 and 1.16 °C, respectively, for the combined pool 4 profiles.

A secondary calibration target was the outlet water temperature measured at Prescott, Wisc. (USGS station 05344490; site 15; fig. 2; table 1). The CE–QUAL–W2 model simulation followed the measured average daily temperature throughout the year, with MAE and RMSE values of 0.83 and 0.98 °C, respectively (fig. 9). Earlier in the year, simulated temperatures were slightly warmer than measured temperatures by 1 °C. Later in the year, the opposite trend happened, and simulated temperatures were slightly cooler by 1 °C (table 6; fig. 9).

Table 6. Summary of mean absolute error and root mean square error values for calibration run.

[Bold text indicates totals; MAE, mean absolute error; RMSE, root mean square error; Minn. Minnesota; Multiple, integrated vertical profile data; --, not applicable; <, less than; Wisc. Wisconsin]

Pool number	Site name	Station number	Depth, in meters	Number of compared data points	MAE	RMSE
	Water temperature, in degrees Celsius					
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	Multiple	42	0.60	0.81
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	Multiple	26	0.63	1.04
2	Lake St. Croix at Pool 2 (Harper)	SCM-4	Multiple	93	0.70	0.98
2	Lake St. Croix at Pool 2	SACN09	Multiple	64	0.47	0.65
Overall (pool 2)	--	--	--	**183**	**0.61**	**0.89**
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	Multiple	28	1.00	1.26
3	Lake St. Croix below at Pool 3 (Harper)	SCM-6	Multiple	128	0.91	1.24
Overall (pool 3)	--	--	--	**156**	**0.93**	**1.27**
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	Multiple	52	1.20	1.98
4	Lake St. Croix at Pool 4	SACN11	Multiple	88	0.46	0.57
4	Lake St. Croix below at Pool 4 (Harper)	SCM-7	Multiple	79	0.75	0.88
Overall (pool 4)	--	--	--	**219**	**0.74**	**1.16**
Overall	--	--	--	**600**	**0.74**	**1.10**
Outlet	St. Croix River at Prescott, Wisc.	05344490	1	210	0.83	0.98
	Dissolved oxygen, in milligrams per liter					
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	Multiple	42	0.58	0.71
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	Multiple	26	0.90	1.22
2	Lake St. Croix at Pool 2 (Harper)	SCM-4	Multiple	78	0.51	0.76
2	Lake St. Croix at Pool 2	SACN09	Multiple	64	0.63	0.91
Overall (pool 2)	--	--	--	**168**	**0.61**	**0.90**
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	Multiple	28	0.88	1.16
3	Lake St. Croix below at Pool 3 (Harper)	SCM-6	Multiple	108	0.86	1.18
Overall (pool 3)	--	--	--	**136**	**0.87**	**1.18**
4	Lake St. Croix below Kinnickinnic River above Prescott, Wisc.	444834092465401	Multiple	52	1.06	1.47
4	Lake St. Croix at Pool 4	SACN11	Multiple	88	0.78	0.98
4	Lake St. Croix below at Pool 4 (Harper)	SCM-7	Multiple	67	0.75	1.05
Overall (pool 4)	--	--	--	**155**	**0.84**	**1.14**
Overall	--	--	--	**553**	**0.76**	**1.06**
	Cholorophyll *a*, in milligrams per liter					
2	Lake St. Croix at Pool 2	SACN09	2	11	3	5
3	Lake St. Croix below at Pool 3 (Harper)	SCM-6	2	17	6	9
4	Lake St. Croix at Pool 4	SACN11	2	16	4	6

Table 6. Summary of mean absolute error and root mean square error values for calibration run.—Continued

[Bold text indicates totals; MAE, mean absolute error; RMSE, root mean square error; Minn. Minnesota; Multiple, integrated vertical profile data; --, not applicable; <, less than; Wisc. Wisconsin]

Pool number	Site name	Station number	Depth, in meters	Number of compared data points	MAE	RMSE
		Orthophosphate, in milligrams per liter				
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	2	4	<0.01	<0.01
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	2	11	0.02	0.02
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	2	4	<0.01	<0.01
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	2	4	<0.01	<0.01
		Ammonia, in milligrams per liter				
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	2	4	0.04	0.06
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	2	11	0.04	0.06
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	2	4	0.06	0.09
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	2	4	0.03	0.04
4	Lake St. Croix at Pool 4	SACN11	2	6	0.03	0.02
		Nitrate plus nitrite, in milligrams per liter				
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	2	4	0.07	0.07
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	2	11	0.11	0.11
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	2	4	0.10	0.13
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	2	4	0.13	0.16
4	Lake St. Croix at Pool 4	SACN11	2	7	0.24	0.22
		Total nitrogen, in milligrams per liter				
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	2	4	0.19	0.20
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	2	11	0.15	0.16
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	2	4	0.12	0.16
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	2	4	0.15	0.18
4	Lake St. Croix at Pool 4	SACN11	2	6	0.11	0.10

Table 6. Summary of mean absolute error and root mean square error values for calibration run.—Continued

[Bold text indicates totals; MAE, mean absolute error; RMSE, root mean square error; Minn. Minnesota; Multiple, integrated vertical profile data; --, not applicable; <, less than; Wisc. Wisconsin]

Pool number	Site name	Station number	Depth, in meters	Number of compared data points	MAE	RMSE
Total phosphorus, in micrograms per liter						
1	Lake St. Croix below Lakeside Park at Bayport, Minn.	450028092455801	2	4	13	15
2	Lake St. Croix below Highway Interstate 94 at Lakeland, Minn.	450028092455801	2	11	11	12
3	Lake St. Croix below Catfish Bar near Afton, Minn.	445400092462401	2	4	8	9
4	Lake St. Croix below KinnickinnicRiver above Prescott, Wisc.	444834092465401	2	4	4	5
4	Lake St. Croix at Pool 4	SACN11	2	7	17	19

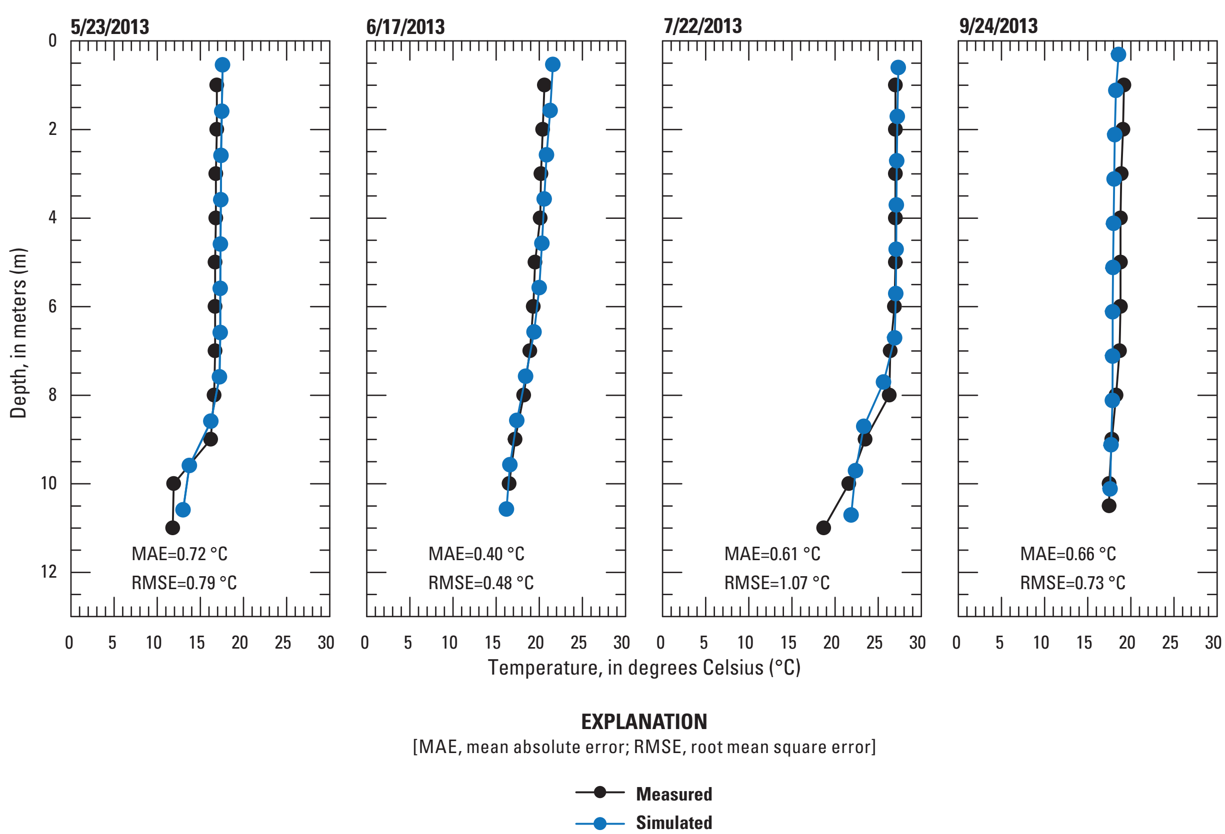


Figure 4. Graphs showing sSimulated and measured vertical water temperature profiles for Bayport Pool (pool 1) in Lake St. Croix for four dates in 2013, with corresponding mean absolute error and root mean square error values.

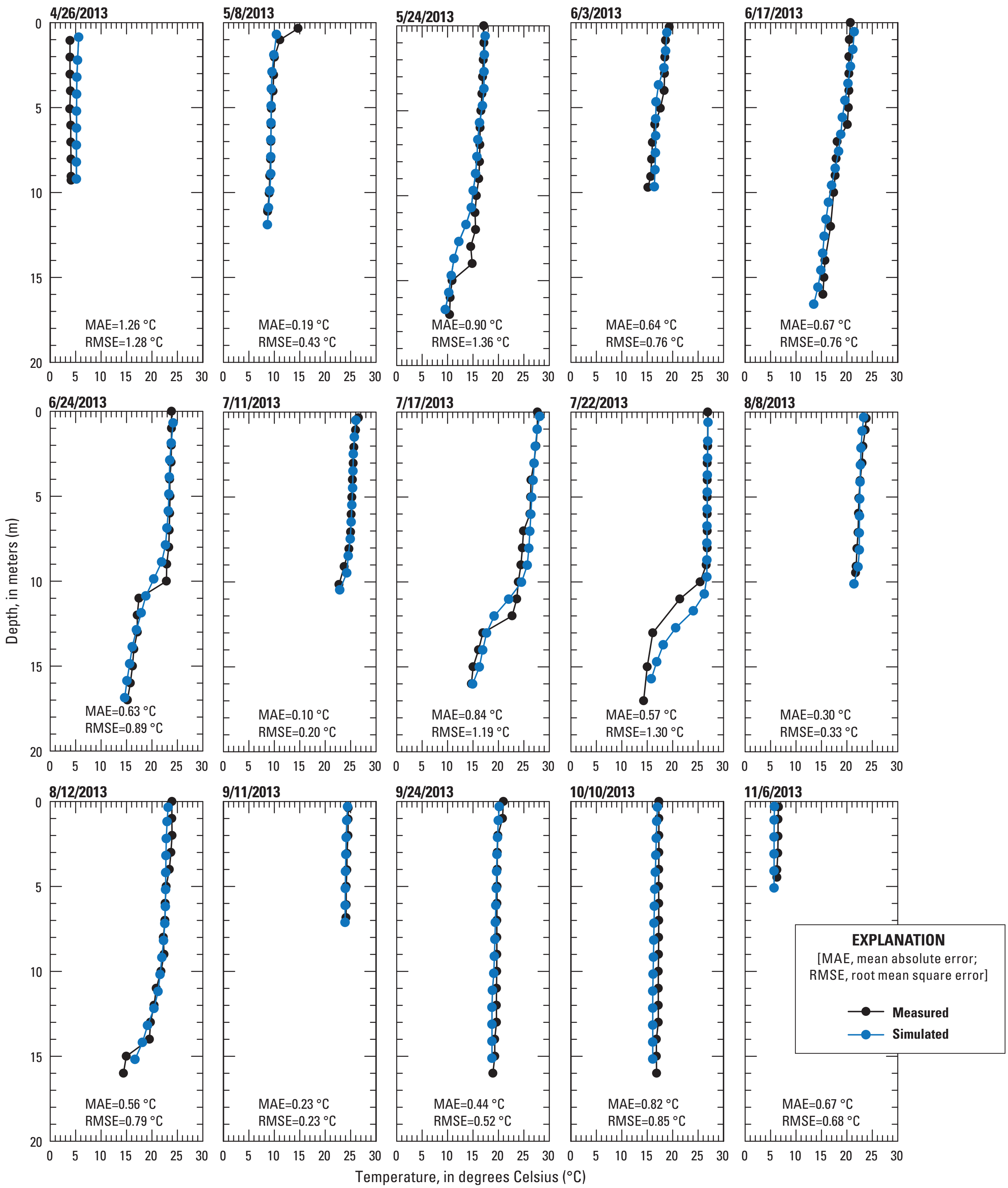


Figure 5. Graphs showing sSimulated and measured vertical water temperature profiles for Troy Beach Pool (pool 2) in Lake St. Croix for 15 dates in 2013, with corresponding mean absolute error and root mean square error values.

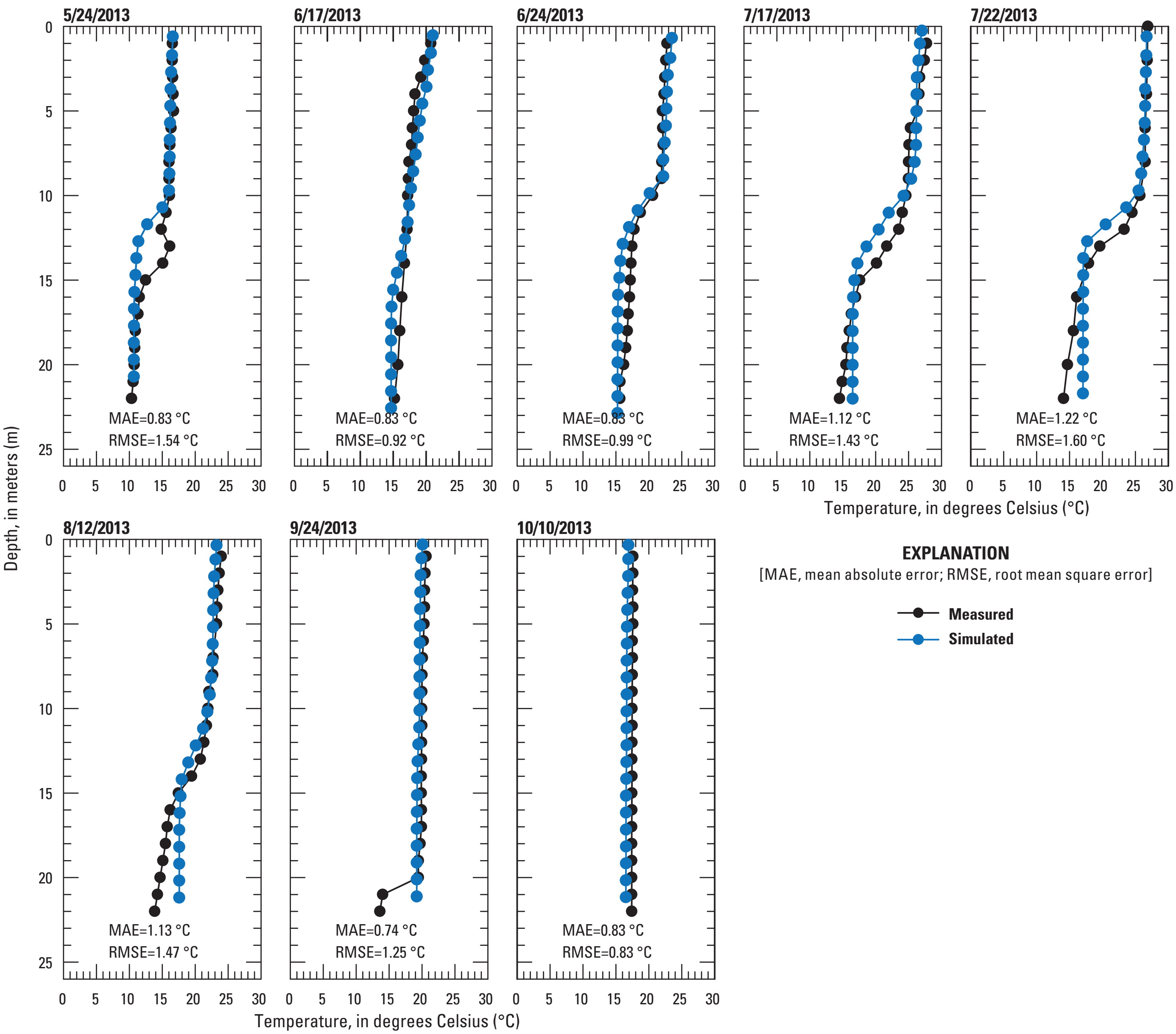


Figure 6. Graphs showing sSimulated and measured vertical water temperature profiles for Black Bass Pool (pool 3) in Lake St. Croix for eight dates in 2013, with corresponding mean absolute error and root mean square error values.

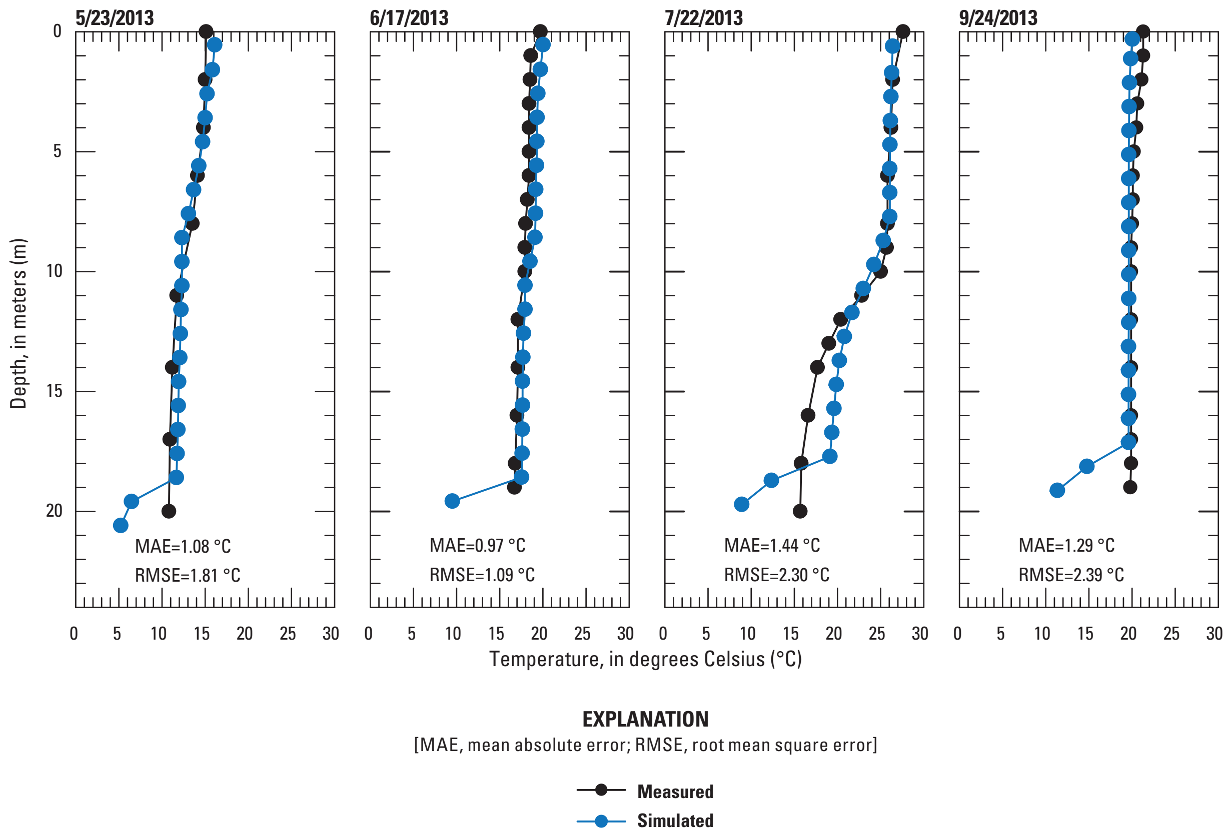


Figure 7. Graphs showing sSimulated and measured vertical water temperature profiles for the upper Kinnickinnic Pool (pool 4) in Lake St. Croix for four dates in 2013, with corresponding mean absolute error and root mean square error values.

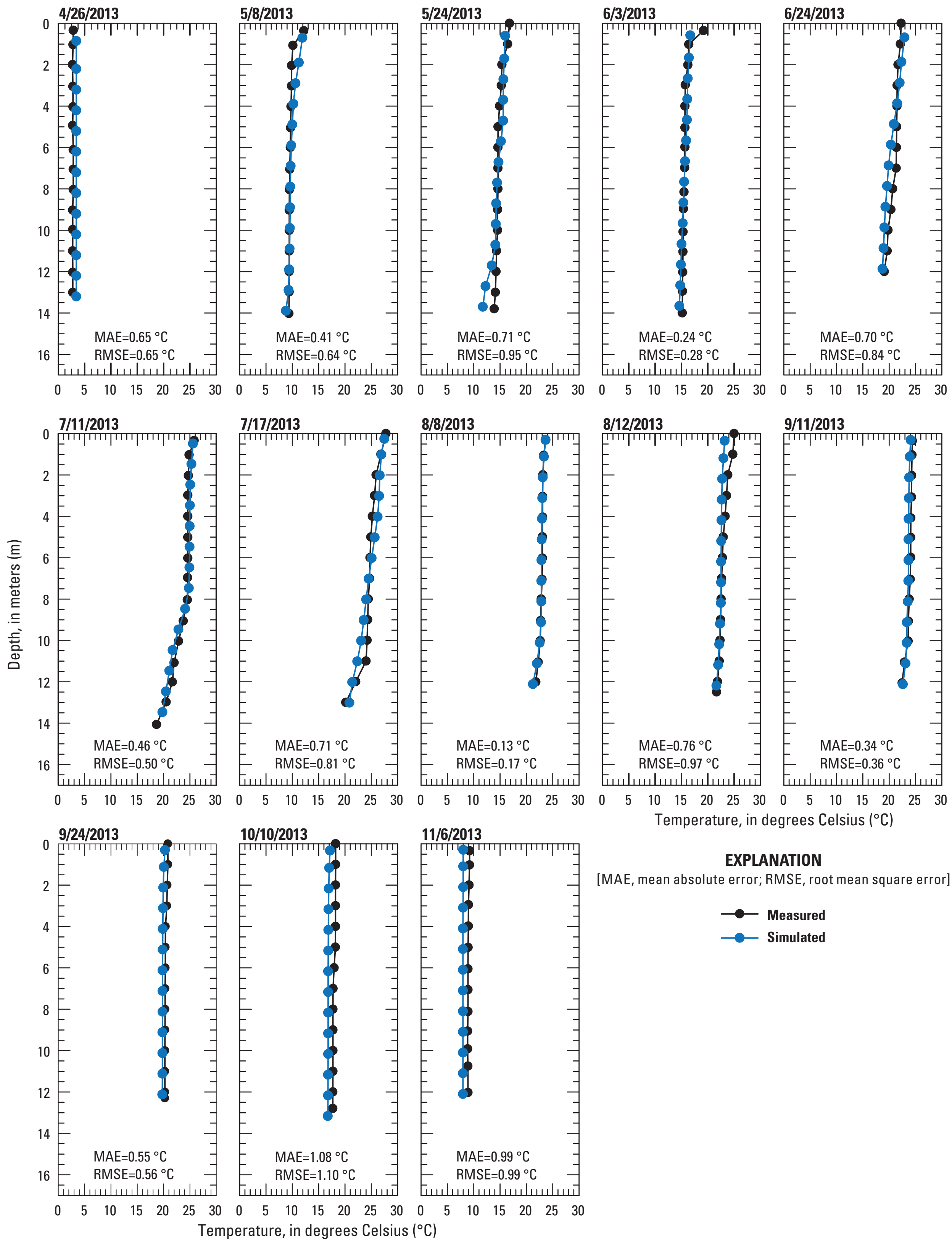


Figure 8. Graphs showing sSimulated and measured vertical water temperature profiles or the lower Kinnickinnic Pool (pool 4) in Lake St. Croix for 13 dates in 2013, with corresponding mean absolute error and root mean square error values.

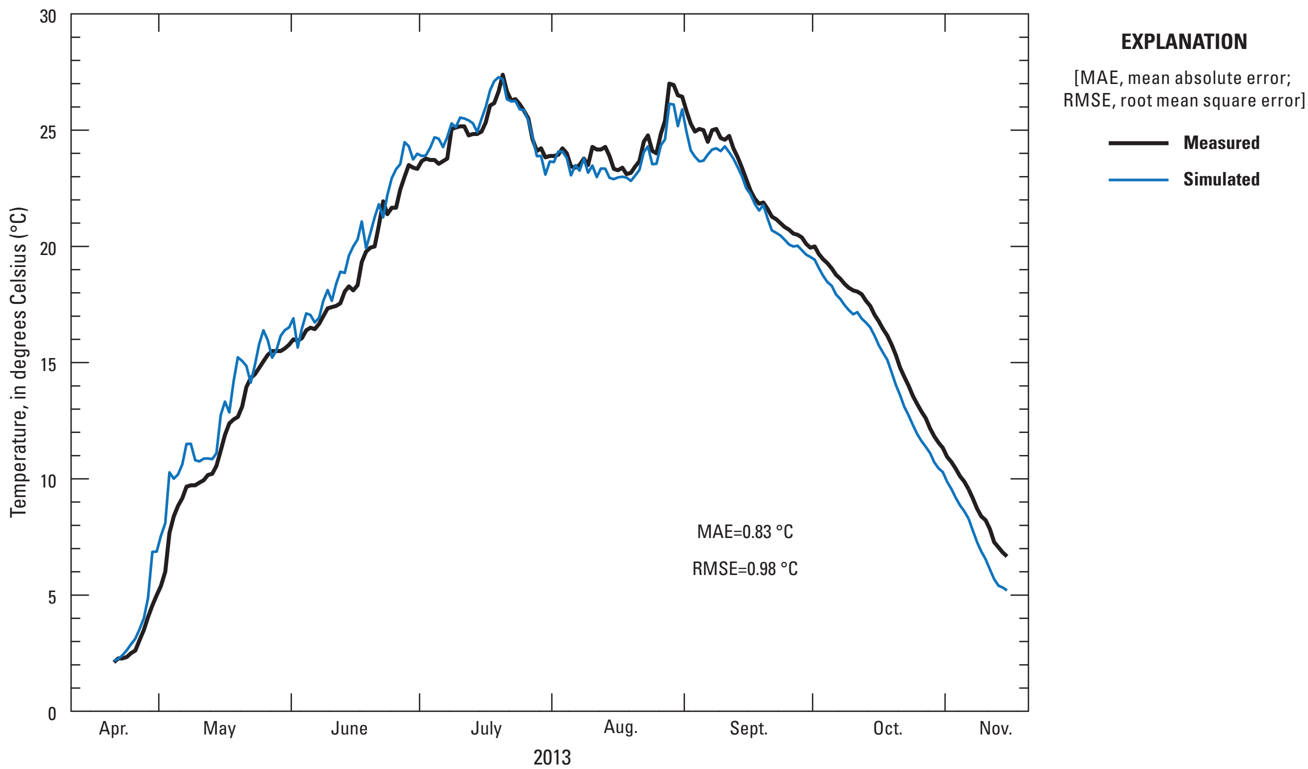


Figure 9. Graphs showing sSimulated and measured surficial water temperature (at 1-meter below the surface) for the outlet temperature at Prescott, Wisconsin, April 20 to November 15, 2013, with corresponding mean absolute error and root mean square error values.

Water Quality

The Lake St. Croix (fig. 1) model was calibrated for dissolved oxygen, dissolved ammonia, dissolved nitrate (measured as nitrate plus nitrite), total nitrogen, dissolved orthophosphate, total phosphorus, and chlorophyll *a*. Dissolved oxygen was calibrated by comparing vertical profiles collected at nine sites, representative of all four pools. Simulated nutrients (dissolved ammonia, dissolved nitrate, total nitrogen, dissolved orthophosphate, total phosphorus) and chlorophyll *a* were compared to discrete samples collected in the epilimnion at five sites. Model calibration was limited by the small number of samples for nutrient and chlorophyll *a* data; therefore, a few very large differences between simulated and observed values sometimes caused undesirably large MAE and RMSE values for calibration purposes.

Dissolved Oxygen

Fish species and other aquatic organisms cannot survive without adequate dissolved oxygen. Accurately simulating dissolved oxygen is critical in determining the size of summer habitat refugia. For certain fish species, thermal requirements may confine them below the epilimnion, where they are vulnerable to mass die offs if dissolved oxygen drops below a lethal limit. For the dissolved oxygen calibration, the principal calibration targets were the lake profile data from the four different pools, available for almost all the same dates, locations, and depths as the temperature profiles. Overall, the model captured the trajectories of the measured dissolved oxygen concentrations at multiple depths over time, and the simulated concentrations matched the depth and slope of the measured concentrations. The model also effectively followed the seasonal changes in measured dissolved oxygen distributions, indicating that the underlying functions used by the model accurately simulate metabolic processes in Lake St. Croix (fig. 1); therefore, the model can be used to further evaluate causes for trophic responses observed in Lake St. Croix. The final aggregate MAE and RMSE values among the four different pools was 0.76 and 1.06 mg/L for the MAE and RMSE values, respectively (table 6). The MAE and RMSE values for most dates were much less than 1.0 mg/L.

Within the CE–QUAL–W2 model, several mechanisms account for dissolved oxygen sources and losses. Source mechanisms include inflows, atmospheric exchange across the lake surface, and algal photosynthesis (Cole and Wells, 2015). Loss mechanisms include decay such as bacterial respiration of dissolved and solid-phase organic matter (labile and refractory) in the water column and lake sediment. Other simulated loss mechanisms include algal respiration, ammonia and nitrite nitrification, and exchange back to the atmosphere and into sediments. The model was seemingly accurate in simulating the underlying metabolic processes in each of the Lake St. Croix pools; however, verifying if specific metabolic rates were accurate was difficult without direct measurements of metabolic processes (for example, algal and bacterial respiration rates).

Complex interactions among several parameters had a strong effect on simulated dissolved oxygen concentrations. Decay rates of the different organic matter pools, such as parameters that control the labile, refractory, and the labile-to-refractory dissolved oxygen matter decay rates (parameters LDOMDK, RDOMDK, and LRDDK, respectively, in table 5), were slightly lower than the recommended default values and comparatively lower than rates in other CE–QUAL–W2 models in Minnesota (Smith and others, 2014). Decay rates had the strongest effect on the dissolved oxygen concentrations in the hypolimnion. Sediment oxygen demand is the rate that dissolved oxygen is removed from the water column during organic matter decomposition (Doyle and Lynch, 2005). Large sediment oxygen demand values can greatly alter dissolved oxygen profiles, particularly in the hypolimnion. Sediment oxygen demand (parameter SOD, table 5) was set at 3.45 grams per square meter per day ($g/m^2/d$) in the Bayport Pool (pool 1) and a small section of Kinnickinnic Pool (pool 4), 0.44 $g/m^2/d$ in Troy Beach Pool (pool 2), and 1.27 $g/m^2/d$ in pools Black Bass Pool (pool 3) and the remainder of Kinnickinnic Pool (pool 4). These large sediment oxygen demand rates were supported by unpublished 2012 phosphorus release rates calculated from Lake St. Croix sediment cores. Back-calculating the measured 2012 sediment oxygen demand range from these measured release rates, based on an assumed sediment release ratio of 0.003 (parameter PO4R, table 5), was 0.3 to 7.2 $g/m^2/d$. The nitrate decay rate (parameter NO3DK, table 5) was set to 0.14 per day, similar to other CE–QUAL–W2 models (Green and others, 2003; Sullivan and Rounds, 2004; Galloway and Green, 2006; Galloway and others, 2008; Sullivan and others, 2011).

Simulated and measured dissolved oxygen concentrations for Bayport Pool (pool 1) are shown for four dates in figure 10; MAE and RMSE values were 0.58 and 0.71 mg/L, respectively (table 6). In figure 11, the simulated and measured vertical profiles of dissolved oxygen concentrations for Troy Beach Pool are shown for 14 dates; mean MAE and RMSE values were 0.61 and 0.90 mg/L, respectively (table 6). In figure 12, the simulated and measured vertical profiles of dissolved oxygen concentrations for Black Bass Pool (pool 3) are shown for seven dates; MAE and RMSE values were 0.87 and 1.18 mg/L, respectively (table 6). Kinnickinnic Pool (pool 4) had more dynamic vertical profiles of dissolved oxygen concentrations than pools 1 through 3. In figures 13 and 14, the simulated and measured dissolved oxygen concentrations for the upper and lower ends, respectively, of Kinnickinnic Pool (pool 4) are shown. The upper end had the poorest fits of any lake locations, but the model still captures the changes in dissolved oxygen concentrations throughout the profiles. The lower end had better fits; overall, the mean MAE and RMSE values for all of pool 4 were 0.84 and 1.14 mg/L, respectively.

Overall, the simulated dissolved oxygen concentrations tracked the measured concentrations, and changes in dissolved oxygen concentrations often followed temperature gradients. The dissolved oxygen profiles also were affected by dissolved oxygen saturation in water, algal dynamics, sediment oxygen demand, and the decay of the different organic matter pools; furthermore, dissolved oxygen deviations among the four different pools were likely related to other factors such as the effect of downstream tributaries, residence time in Lake St. Croix (fig. 1), and the wind speed coefficients.

Nutrients

Nutrients also were important for calibration purposes and for understanding if the CE–QUAL–W2 model can adequately describe nutrient dynamics, with an emphasis on nitrate plus nitrite, ammonia, total nitrogen, orthophosphate, and total phosphorus. The CE–QUAL–W2 model tracked nitrate plus nitrite and total nitrogen throughout the year, and to a lesser extent ammonia concentration. The model accurately predicted large total phosphorus concentrations in spring and early summer, and the subsequent drop in total phosphorus after July. In contrast, orthophosphate concentrations were generally less than 0.02 mg/L throughout most of year in the simulated and measured data.

Nutrient concentrations in Lake St. Croix (fig. 1) are controlled by several processes, such as inflow loads, algal production, and organic matter decay rates. Ammonia sources (both ammonia [NH_3] and ammonium [NH_4^+]) include all inflows, decay of organic matter, sediment release under anaerobic conditions, and algal respiration. Ammonia loss mechanisms include nitrification, algal uptake, and lake outflow (Cole and Wells, 2015). Nitrate plus nitrite sources include all inflows and ammonia nitrification. Loss mechanisms for nitrate plus nitrite include denitrification (in the water column and sediments), algal uptake, and lake outflow (Cole and Wells, 2015). For purposes of comparing simulated and measured concentrations, total nitrogen was classified as the concentration of nitrogen present in ammonia, nitrate plus nitrite, and organically bound nitrogen (in living algal biomass and all organic matter pools). The total amount of nitrogen bound in the different organic matter pools was internally calculated by CE–QUAL–W2 based on the stoichiometric equivalents between nitrogen and algal biomass set for the different algal groups (parameter ALGN, table 5), organic matter set at 8 percent (parameter ORGN, set to 0.08), and zooplankton (parameter ZN, table 5).

Lake St. Croix ammonia concentrations were affected largely by the inflows and the lake hydrodynamics. Simulated and measured ammonia as nitrogen concentrations at 2 m below the water surface are shown in figure 15 for the Bayport (pool 1), Troy Beach (pool 2), Black Bass (pool 3), upper Kinnickinnic (pool 4), and lower Kinnickinnic (pool 4). Simulated and measured ammonia concentrations rose to the largest concentrations by mid-July and then crashed by early August. The simulated concentrations slowly stabilized between 0.03 and 0.04 mg/L, similar to the measured concentrations in Bayport, Troy Beach, and lower Kinnickinnic pools. Some simulated ammonia concentrations underestimated

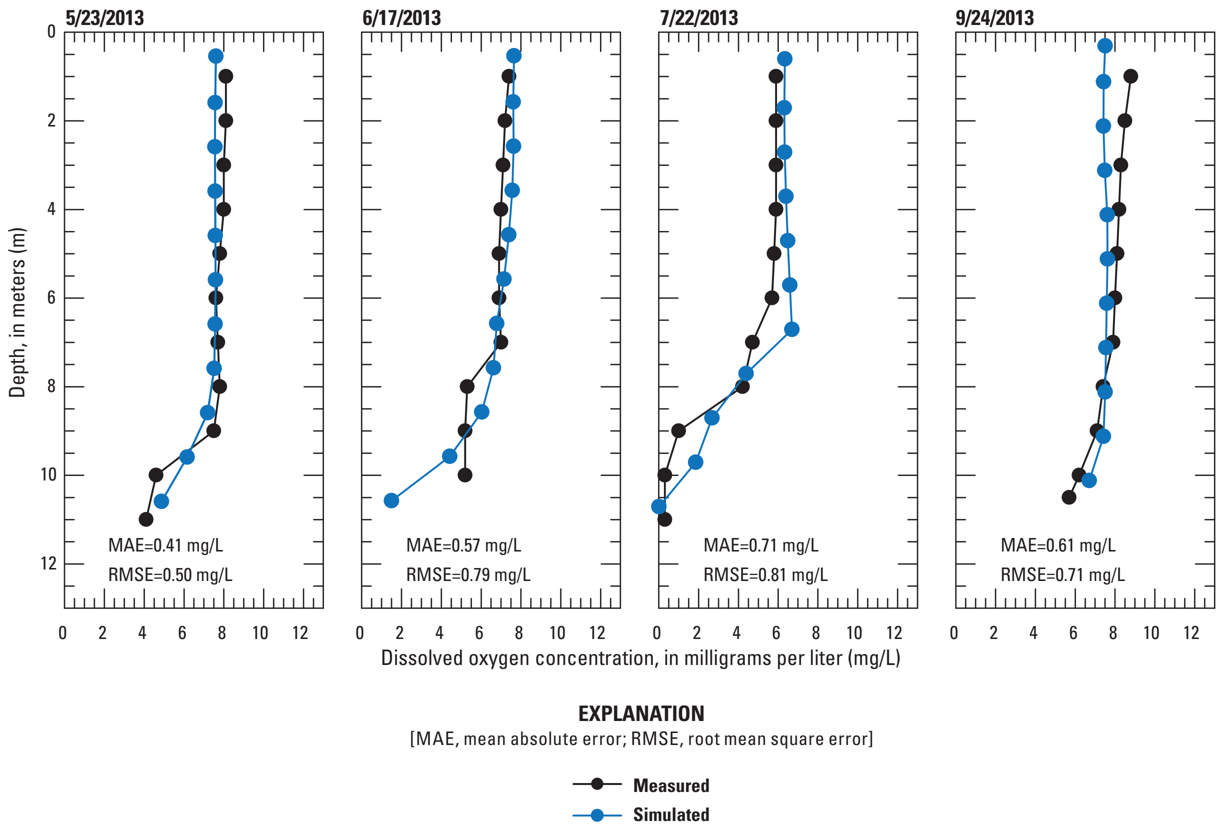


Figure 10. Graphs showing sSimulated and measured vertical profiles of dissolved oxygen concentrations for Bayport Pool (pool 1) in Lake St. Croix for four dates in 2013, with corresponding mean absolute error and root mean square error values.

the measured ammonia concentrations, notably the mid-July measurement in Bayport Pool and the late September measurements in Troy Beach, Black Bass, and the upper Kinnickinnic pools. Otherwise, simulated concentrations tracked the measured concentrations throughout the year for all four pools. The MAE and RMSE values for ammonia ranged from 0.02 to 0.09 mg/L (table 6). Low MAE and RMSE values likely can be attributed to small environmental concentrations being measured in Lake St. Croix.

Simulated and measured nitrate plus nitrite as nitrogen concentrations at 2 m below the water surface are shown in figure 16 for the Bayport (pool 1), Troy Beach (pool 2), Black Bass (pool 3), upper Kinnickinnic (pool 4), and lower Kinnickinnic (pool 4). Distributions of nitrate plus nitrite throughout the four pools of Lake St. Croix were affected by inflows, but concentrations of nitrate plus nitrite were large across all pools throughout the year. After an initial spike in nitrate plus nitrite concentrations after spring runoff, nitrate plus nitrite concentrations became increasingly depleted by denitrification and growth of diatoms; furthermore, the largest concentrations of nitrate plus nitrite was in the late parts of the simulation period (fig. 16). The large concentrations at the beginning and end of the simulation period were caused by large loads upstream at the St. Croix River at Stillwater, Minn. During the early part of the simulation period, nitrate plus nitrite concentration became increasingly depleted because of denitrification and algal growth (mostly diatoms). Later in the year, as more blue-green algae grew (more details in the “Algae and Zooplankton” section) with less demand for internal nitrogen sources, the nitrate plus nitrite concentration became increasingly larger in addition to the steady lake inflow sources. The MAE values for nitrate plus nitrite ranged from 0.07 to 0.24 mg/L, and the largest value was in the lower Kinnickinnic pool; RMSE values for nitrate plus nitrite ranged from 0.07 to 0.22 mg/L (table 6). The MAE values for total nitrogen in the epilimnion (2-m depth) ranged from 0.11 to 0.19 mg/L, and RMSE values for total nitrogen ranged from 0.10 to 0.20 mg/L (fig. 17; table 6). The measured data indicate a stable amount of total nitrogen in the lake, whereas the simulated results indicate a slow and steady decrease over the simulation period (fig. 17).

Orthophosphate sources include all inflows, decay of organic matter, sediment release under anaerobic conditions, and algal respiration; orthophosphate losses include particles settling with adsorbed phosphorus, algal uptake, and lake outflow. Total phosphorus was classified as the concentration of phosphorus present in orthophosphate and bound up in organic matter (algal biomass, all organic matter pools, and

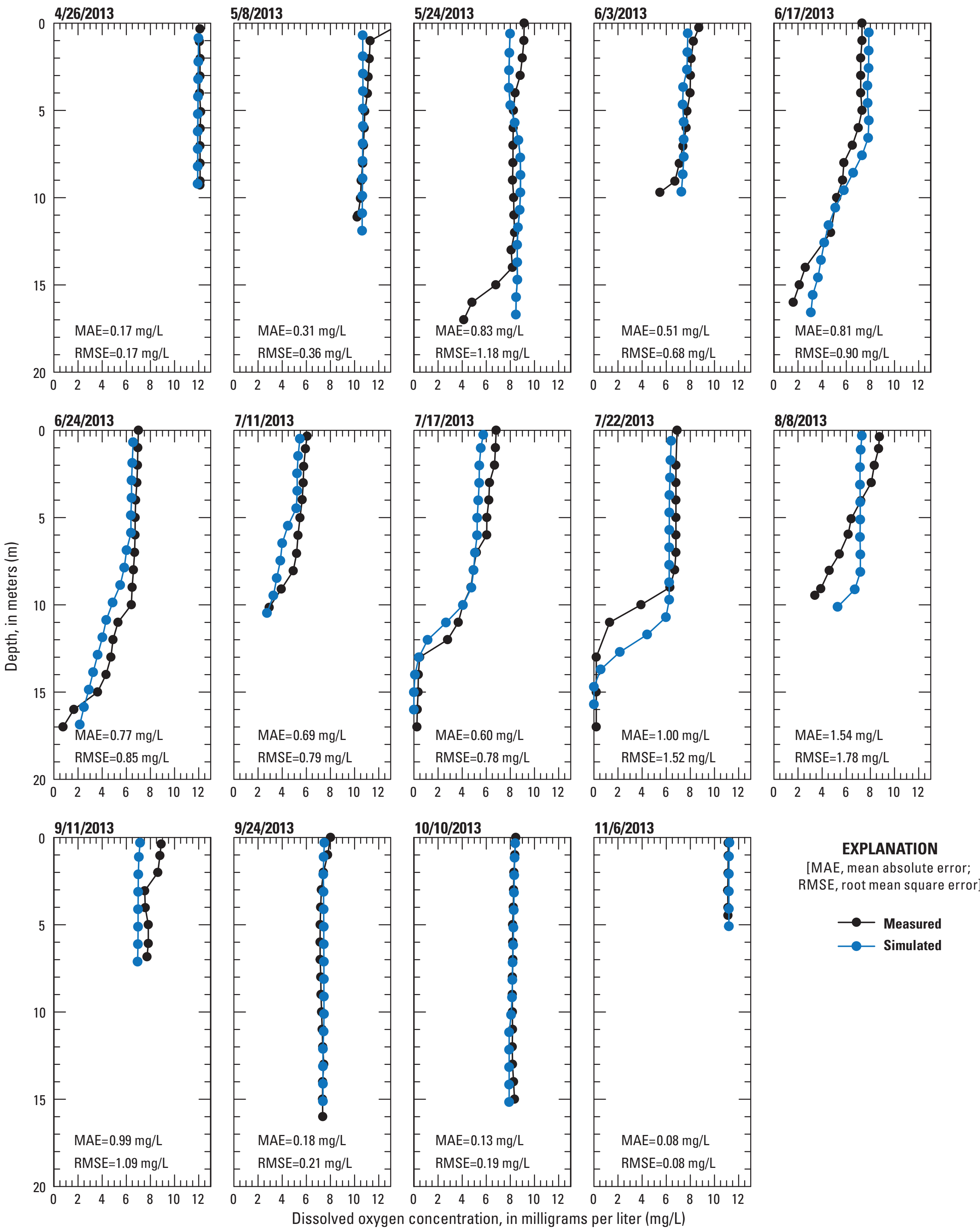


Figure 11. Graphs showing sSimulated and measured vertical profiles of dissolved oxygen concentrations for Troy Beach Pool (pool 2) in Lake St. Croix for 14 dates in 2013, with corresponding mean absolute error and root mean square error values.

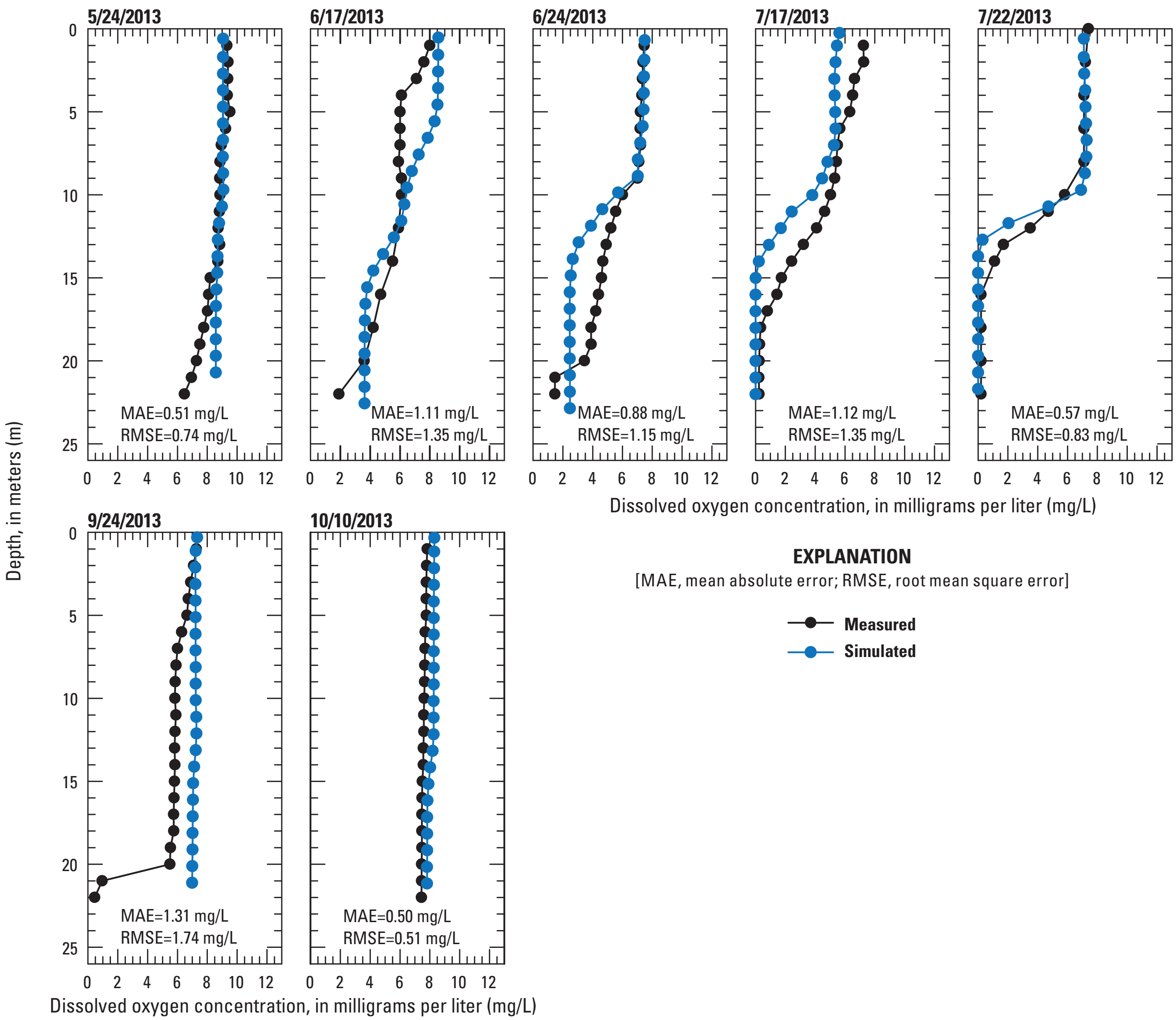


Figure 12. Graphs showing sSimulated and measured vertical profiles of dissolved oxygen concentrations for Black Bass Pool (pool 3) in Lake St. Croix for seven dates in 2013, with corresponding mean absolute error and root mean square error values.

zooplankton pools). Phosphorus bound in organic matter was internally calculated by CE–QUAL–W2 based on the stoichiometric equivalent between phosphorus and algal biomass set for the different algal groups (parameter ALGP, table 5), organic matter (parameter ORGP, set to 0.035), and zooplankton (parameter ZP, table 5). The nitrogen-to-phosphorus ratio for organic matter in the Lake St. Croix model was 25:1 based on the stoichiometric equivalent parameters of ORGN (0.08) and ORNP (0.035), which was comparable to the average nitrogen-to-phosphorus ratio of 20:1 calculated by Robertson and Lenz (2002).

Lake St. Croix (fig. 1) simulated and measured orthophosphate as phosphorus concentrations are shown in figure 18 for the same locations as the previous figures. In simulated and measured data, orthophosphate concentrations were small for most of the year and mirror the ammonia concentrations in terms of the simulation growth and decay. In contrast to ammonia, orthophosphate concentrations remained close to zero for most of the period from mid-July to mid-October. At the end of the simulation period, a steady increase in orthophosphate concentrations was primarily because of less algal uptake or smaller losses out of Lake St. Croix. The MAE and RMSE values for orthophosphate were small overall because of the small concentrations, and all were between less than 0.01 and 0.02 mg/L (table 6). Total phosphorus concentrations (fig. 19) were affected by the same factors as total nitrogen concentrations, but concentrations of total phosphorus were as much as two orders of magnitude less than total nitrogen concentrations (fig. 19). The MAE for total phosphorus ranged from 4 to 17 µg/L, and RMSE values ranged from 5 to 19 µg/L (table 6).

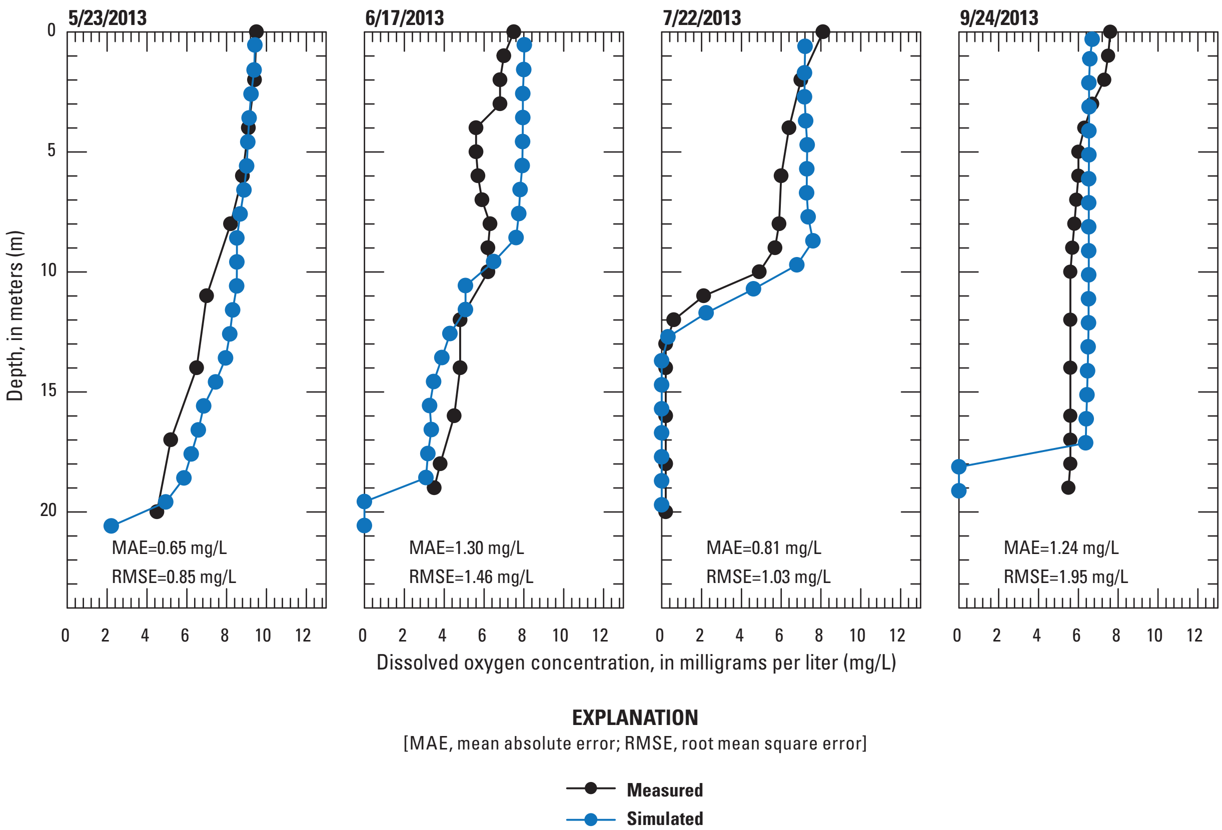


Figure 13. Graphs showing sSimulated and measured vertical profiles of dissolved oxygen concentrations for the upper Kinnickinnic Pool (pool 4) in Lake St. Croix for four dates in 2013, with the mean absolute error and root mean square error values.

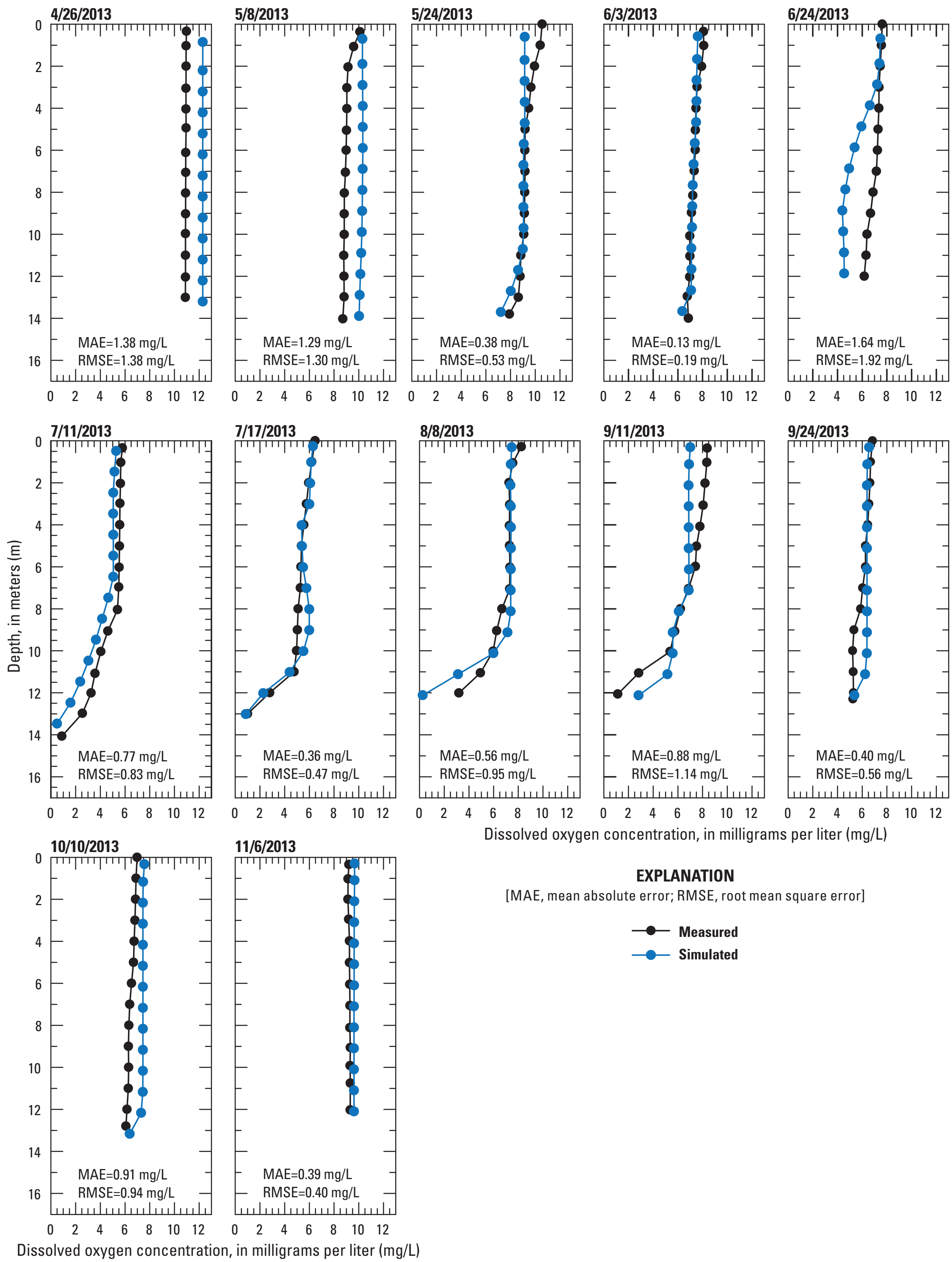


Figure 14. Graphs showing sSimulated and measured vertical profiles of dissolved oxygen concentrations for the lower Kinnickinnic Pool (pool 4) in Lake St. Croix for 12 dates in 2013, with the mean absolute error and root mean square error values.

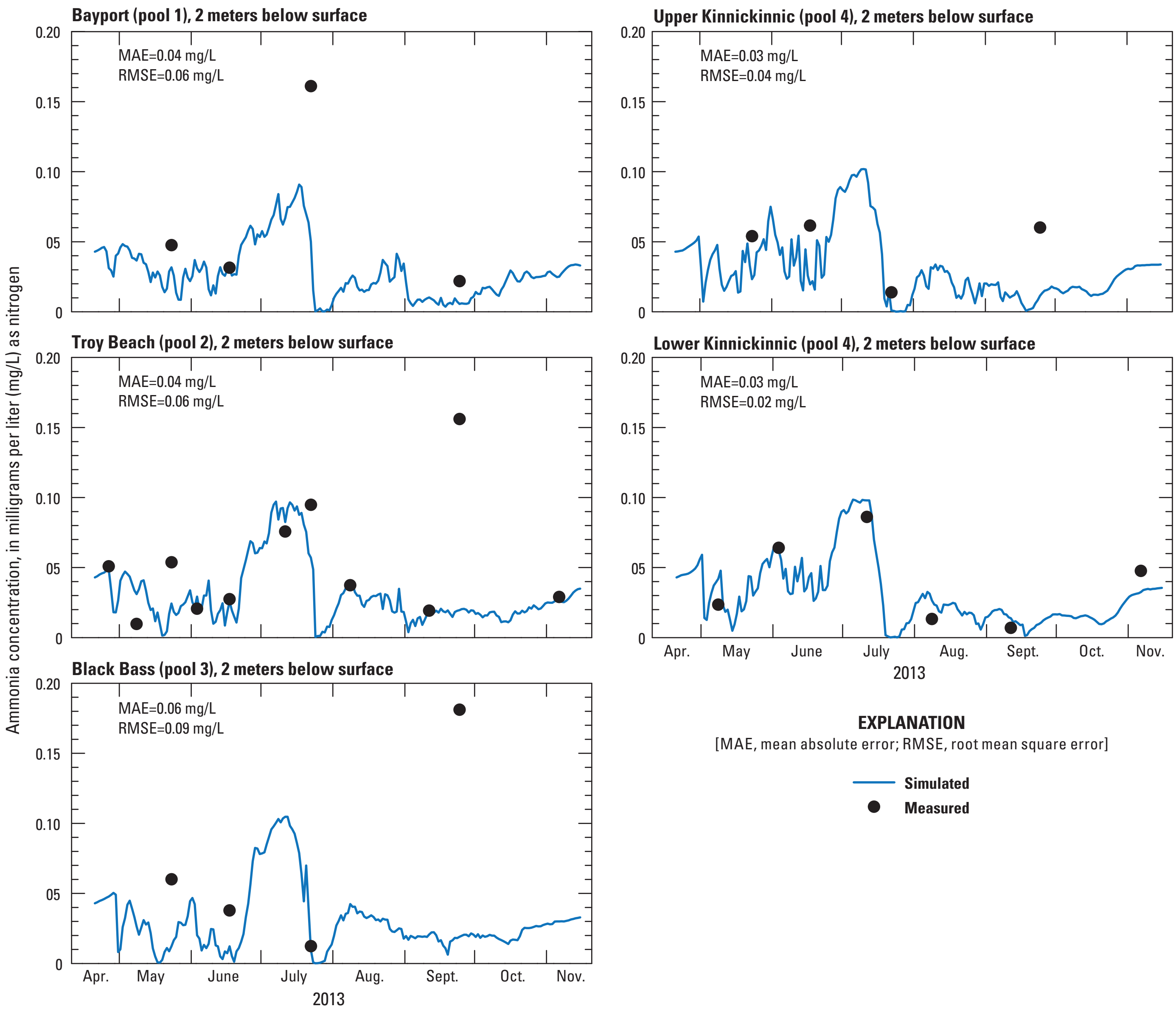


Figure 15. Graphs showing sSimulated and measured ammonia concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013.

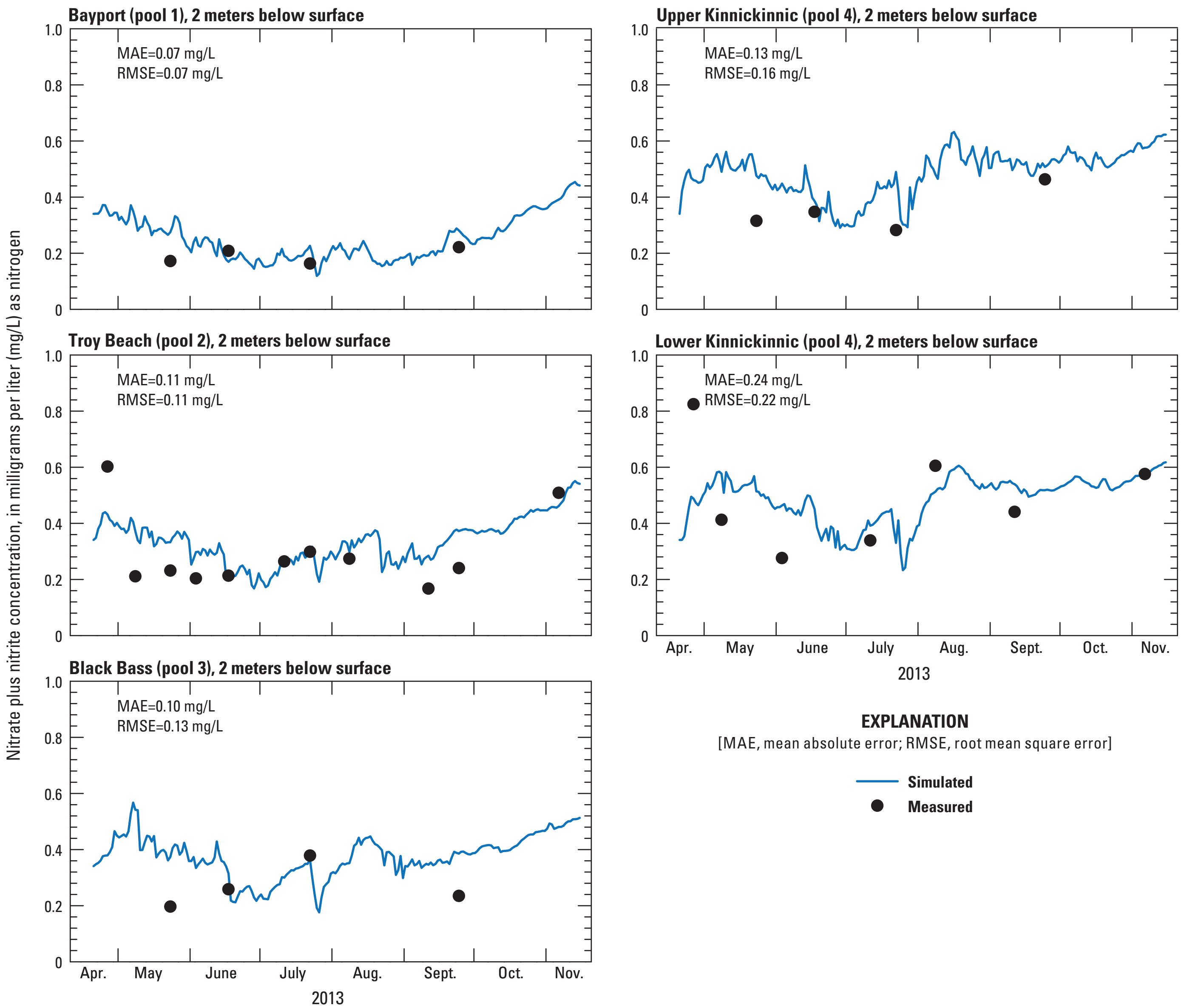


Figure 16. Graphs showing sSimulated and measured nitrate plus nitrite concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 through November 15, 2013.

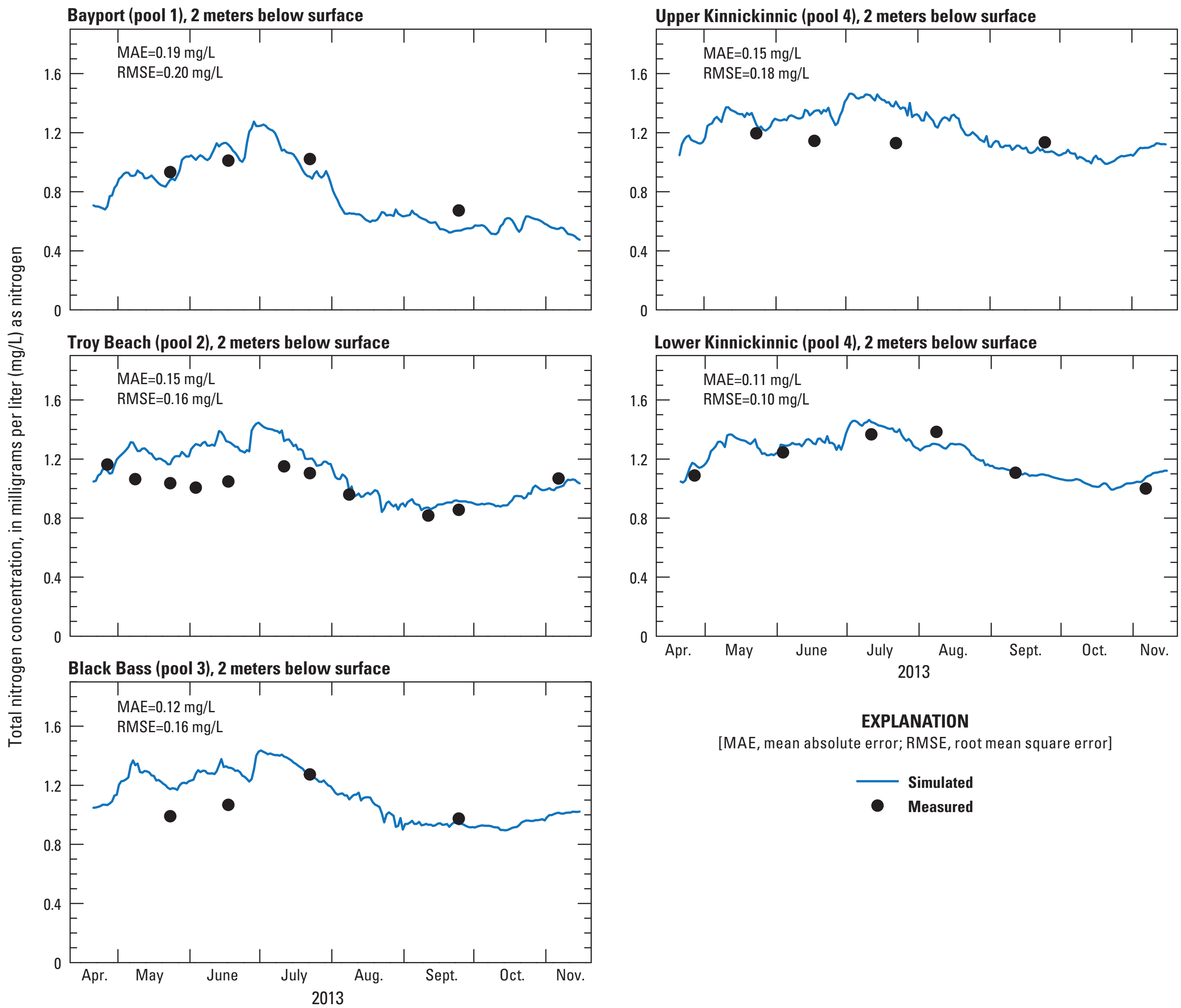


Figure 17. Graphs showing sSimulated and measured total nitrogen concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 through November 15, 2013.

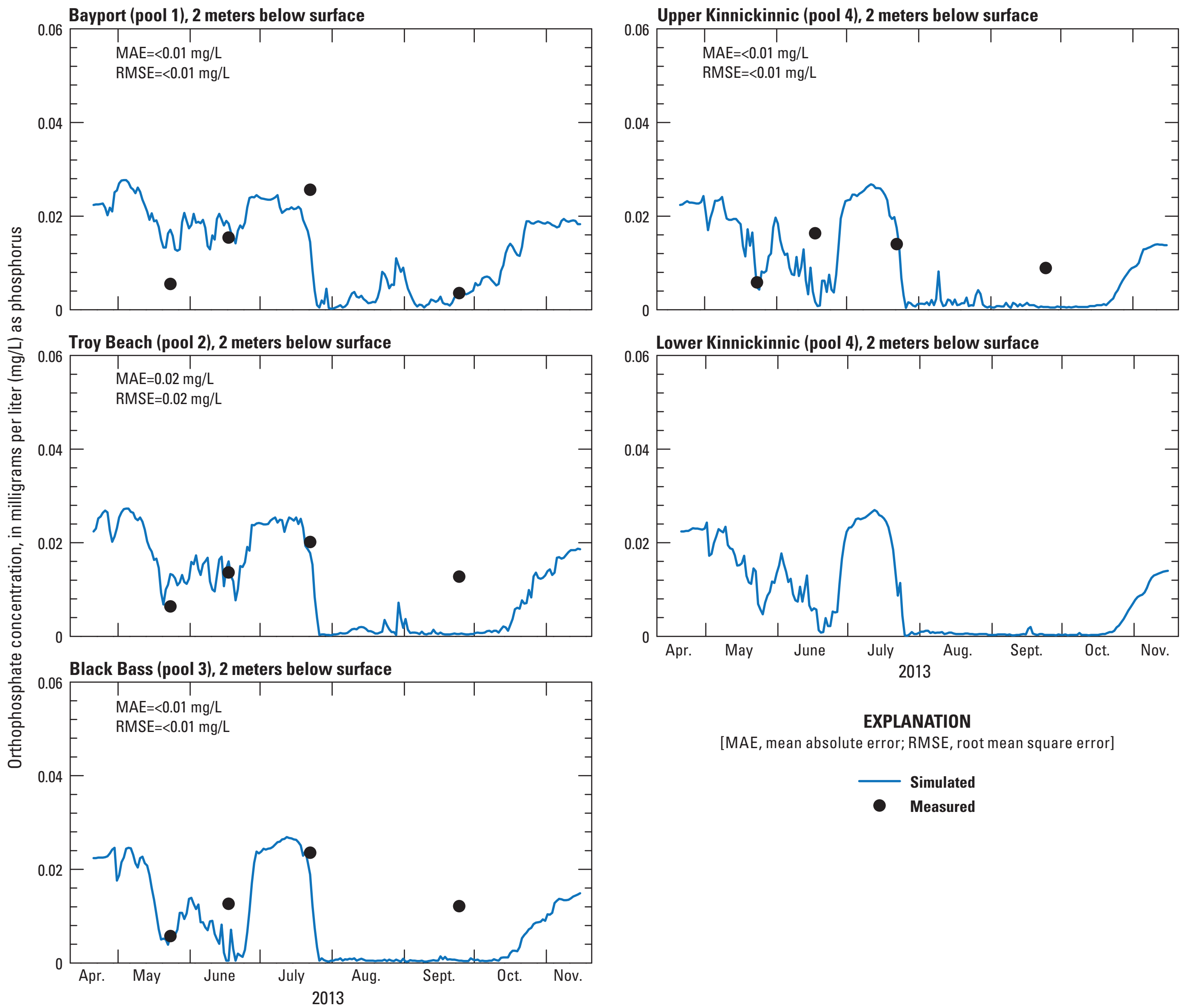


Figure 18. Graphs showing sSimulated and measured orthophosphate concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013.

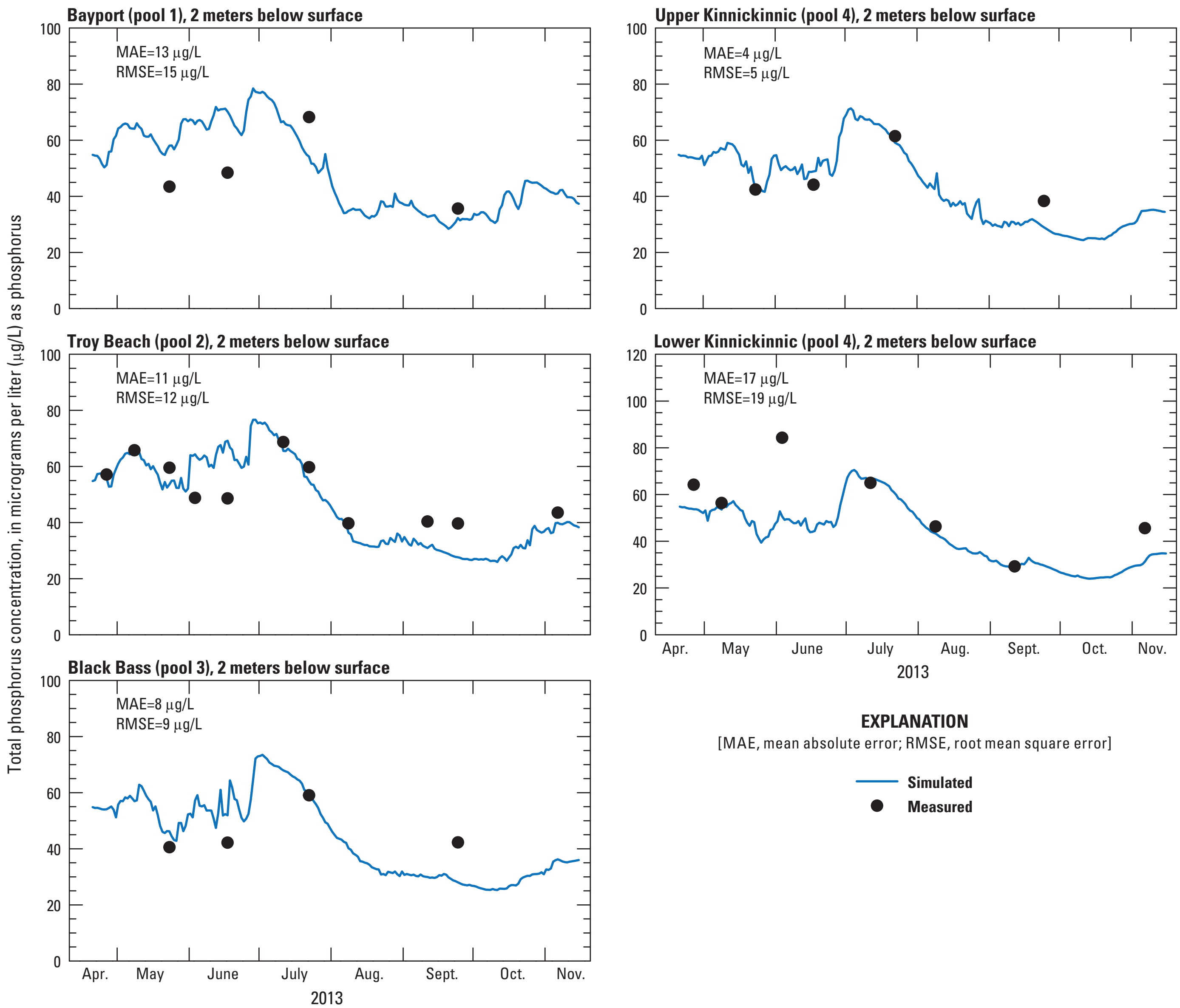


Figure 19. Graphs showing sSimulated and measured total phosphorus concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013.

Inflow nutrient contributions (loads), largely dominated by upstream St. Croix River loads, were the most important controls on Lake St. Croix (fig. 1) water quality. A detailed 2013 phosphorus budget for the Lake St. Croix model is displayed in table 7, provided in monthly increments for the entire year. The total phosphorus was divided into two subcomponents, phosphorus derived from organic matter and phosphorus derived from orthophosphate. Close to 60 percent of total phosphorus entering the lake was derived from organic matter (147.5 metric tons), and the total phosphorus budget in 2013 was 248.6 metric tons. About 89 percent of phosphorus entering Lake St. Croix was delivered by the St. Croix River inflow (220.2 metric tons). The combined load from the other four tributaries (Willow River, Kinnickinnic River, Valley Creek, and Trout Brook) was 6.1 percent of the total load. The Willow River (through Lake Mallalieu) delivered 6.111 metric tons per year, and the Kinnickinnic River delivered 8.672 metric tons per year. Distributed tributary flow, which included the ungaged surface water inputs, point sources, and groundwater, delivered almost the same amount of phosphorus as the Willow River at 6.102 metric tons per year. Finally, 7.025 metric tons per year of orthophosphate was released into Lake St. Croix through zero-order sediment release as calculated internally by the model. Loads from the Willow River, Trout Brook, the distributary tributary flow, and the zero-order sediment release were only available during the model run period from April 20 to November 13, 2013; however, phosphorus loads would be expected to be low during the nonmodel run period based on available load estimates for January through March and December.

Algae and Zooplankton

Three general algal groups were used in the Lake St. Croix (fig. 1) model: diatoms, green algae, and blue-green algae. The Lake St. Croix CE–QUAL–W2 model illustrated potential mechanisms for the effect of external and internal loadings on the biotic response regarding these algal community types. In addition to tracking the algal biomass accumulation within Lake St. Croix, the model simulation incorporated dynamic loads of riverine algal biomass entering the lake at Stillwater, Minn., back-calculated from chlorophyll *a* loads. The simulation tracked changes in total algal biomass in the upper two pools of the lake under rapidly changing conditions associated with large inflow. More importantly, simulated chlorophyll *a* concentrations closely matched available monitoring data in Troy Beach, Black Bass, and Kinnickinnic pools. The model also suggested the seasonal dominance of blue-green algae in all four pools of the lake. Model simulations indicated that production and biomass accumulation of blue-green algae (also known as cyanobacteria) in Lake St. Croix resulted from complex interactions between algal physiology and lake stratification.

Algal growth temperature ranges were selected to favor diatoms earlier in the year at cooler temperatures, and algal growth temperature ranges selected for summer months favored green and blue-green algae. The temperature ranges selected were controlled by parameters AT1 through AT4 and parameters AK1 through AK4 (table 5). Algal growth rates (parameter AG, table 5) were similar for the three groups, whereas the light saturation intensity at the maximum photosynthetic rate (parameter ASAT, table 5) favored blue-green algae at low light levels (25 watts per square meter) and favored diatoms (105 watts per square meter) and green algae (52 watts per square meter) at higher light regimes. Another important difference between the three groups was the blue-green algae had a very low half-saturation constant for nitrogen (0.001; parameter AHSN, table 5) to simulate algal nitrogen fixation (Cole and Wells, 2015).

Zooplankton were modeled as a single group to capture algal grazing dynamics, although most parameters were left as CE–QUAL–W2 default values because of a lack of specific parameter information (Cole and Wells, 2015). Additionally, zooplankton grazing dynamics were captured within algal specific constants such as the algal growth rate (parameter AG, table 5) and the algal mortality rate (parameter AM, table 5). Guidance for selecting coefficients for the algal and zooplankton groups was provided by other CE–QUAL–W2 modeling efforts, specifically the Sentinel Lakes models (Smith and others, 2014, 2017).

The simulated concentration of three primary algal groups at 2 m below the water surface is shown in figure 20 for the model segments containing Bayport (pool 1), Troy Beach (pool 2), Black Bass (pool 3), upper Kinnickinnic (pool 4), and lower Kinnickinnic (pool 4). It should be noted there were no direct measurements of algal biomass in 2013 available for this study. Growth trends of the three algal groups did not vary much across all five locations.

For all four pools (including upper/lower Kinnickinnic), diatoms were the first group to peak, starting in early May, peaking in mid-June to around 1.5 mg/L in the Black Bass Pool, and then approaching 0 mg/L in most pools by early July. Diatoms exhibited more sustained growth in the upper pools of Lake St. Croix (pools 1 through 3) and had smaller overall growth in the upper and lower Kinnickinnic pools (pool 4). Towards the end of June, as diatoms senesced, green and blue-green algae replaced diatoms as the primary algal groups.

The green and blue-green algae were more abundant in the Black Bass (pool 3) and Kinnickinnic (pool 4) pools than in the Bayport (pool 1) and Troy Beach (pool 2) pools, although the differences were not as large as for the diatom abundance earlier in the year. Also, blue-green algal biomass exhibited a large, short duration spike in the first two pools, whereas the spike was more subdued in pools 3 and 4.

Table 7. Lake St. Croix phosphorus loading in 2013, according to load estimates (provided by LOADEST) and internal CE–QUAL–W2 calculations.

[Minn., Minnesota; --, not applicable]

Source	Component	Phosphorus loading in 2013, in metric tons per month					
		January	February	March	April	May	June
St. Croix River at Stillwater, Minn.	Organic matter[1]	1.308	1.329	2.081	14.81	33.19	37.92
	Orthophosphate	1.630	1.586	1.969	12.53	21.54	18.13
	Total phosphorus	2.938	2.915	4.050	27.34	54.73	56.05
Willow River[2]	Organic matter	--	--	--	0.320	0.617	0.602
	Orthophosphate	--	--	--	0.885	1.654	0.033
	Total phosphorus	--	--	--	1.205	2.271	0.635
Valley Creek	Organic matter	0.012	0.012	0.014	0.022	0.025	0.027
	Orthophosphate	0.015	0.013	0.013	0.015	0.015	0.014
	Total phosphorus	0.027	0.025	0.027	0.037	0.040	0.041
Trout Brook[2]	Organic matter	--	--	--	0.000	0.001	0.002
	Orthophosphate	--	--	--	0.001	0.002	0.003
	Total phosphorus	--	--	--	0.001	0.003	0.005
Kinnickinnic River	Organic matter	0.600	0.542	0.600	0.580	0.571	0.446
	Orthophosphate	0.143	0.092	0.150	0.572	0.386	0.411
	Total phosphorus	0.743	0.634	0.750	1.152	0.957	0.857
Distributed tributary/flow[2] (groundwater, ungaged flow)	Organic matter	--	--	--	0.108	0.699	0.438
	Orthophosphate	--	--	--	0.200	1.197	0.833
	Total phosphorus	--	--	--	0.308	1.896	1.271
Zero-order sediment release	Orthophosphate	--	--	--	0.003	0.058	0.711
Total phosphorus (from orthophosphate)	--	1.788	1.691	2.132	14.21	24.85	20.14
Total phosphorus (derived from organic matter)	--	1.920	1.883	2.695	15.84	35.10	39.44
Total phosphorus	--	3.708	3.574	4.827	30.05	59.95	59.58

Table 7. Lake St. Croix phosphorus loading in 2013, according to load estimates (provided by LOADEST) and internal CE–QUAL–W2 calculations—Continued

[Minn., Minnesota; --, not applicable]

Source	Component	Phosphorus loading in 2013, in metric tons per month						Phosphorus loading in 2013, in metric tons per year
		July	August	September	October	November	December	
St. Croix River at Stillwater, Minn.	Organic matter[1]	18.63	5.656	4.942	7.727	5.698	3.187	136.5
	Orthophosphate	7.571	1.946	2.198	5.408	5.391	3.828	83.73
	Total phosphorus	26.20	7.602	7.140	13.14	11.09	7.015	220.2
Willow River[2]	Organic matter	0.516	0.400	0.360	0.417	0.151	--	3.383
	Orthophosphate	0.030	0.027	0.034	0.047	0.018	--	2.728
	Total phosphorus	0.546	0.427	0.394	0.464	0.169	--	6.111
Valley Creek	Organic matter	0.027	0.026	0.021	0.021	0.018	0.018	0.243
	Orthophosphate	0.015	0.015	0.016	0.017	0.018	0.018	0.184
	Total phosphorus	0.042	0.041	0.037	0.038	0.036	0.036	0.427
Trout Brook[2]	Organic matter	0.001	0.001	0.001	0.001	0.001	--	0.008
	Orthophosphate	0.002	0.002	0.002	0.002	0.001	--	0.015
	Total phosphorus	0.003	0.003	0.003	0.003	0.002	--	0.023
Kinnickinnic River	Organic matter	0.325	0.317	0.342	0.304	0.246	0.249	5.122
	Orthophosphate	0.186	1.033	0.117	0.144	0.142	0.174	3.550
	Total phosphorus	0.511	1.350	0.459	0.448	0.388	0.423	8.672
Distributed tributary/flow[2] (groundwater, ungaged flow)	Organic matter	0.330	0.183	0.210	0.172	0.077	--	2.217
	Orthophosphate	0.562	0.311	0.349	0.303	0.130	--	3.885
	Total phosphorus	0.892	0.494	0.559	0.475	0.207	--	6.102
Zero-order sediment release	Orthophosphate	2.639	2.084	1.439	0.085	0.006	--	7.025
Total phosphorus (from orthophosphate)	--	11.01	5.418	4.155	6.006	5.706	4.020	101.1
Total phosphorus (derived from organic matter)	--	19.83	6.583	5.876	8.642	6.191	3.454	147.5
Total phosphorus	--	30.84	12.00	10.03	14.65	11.90	7.474	248.6

[1]Also includes equivalent phosphorus from inflow algal biomass.

[2]Only includes period of model run, April 20–November 9, 2013.

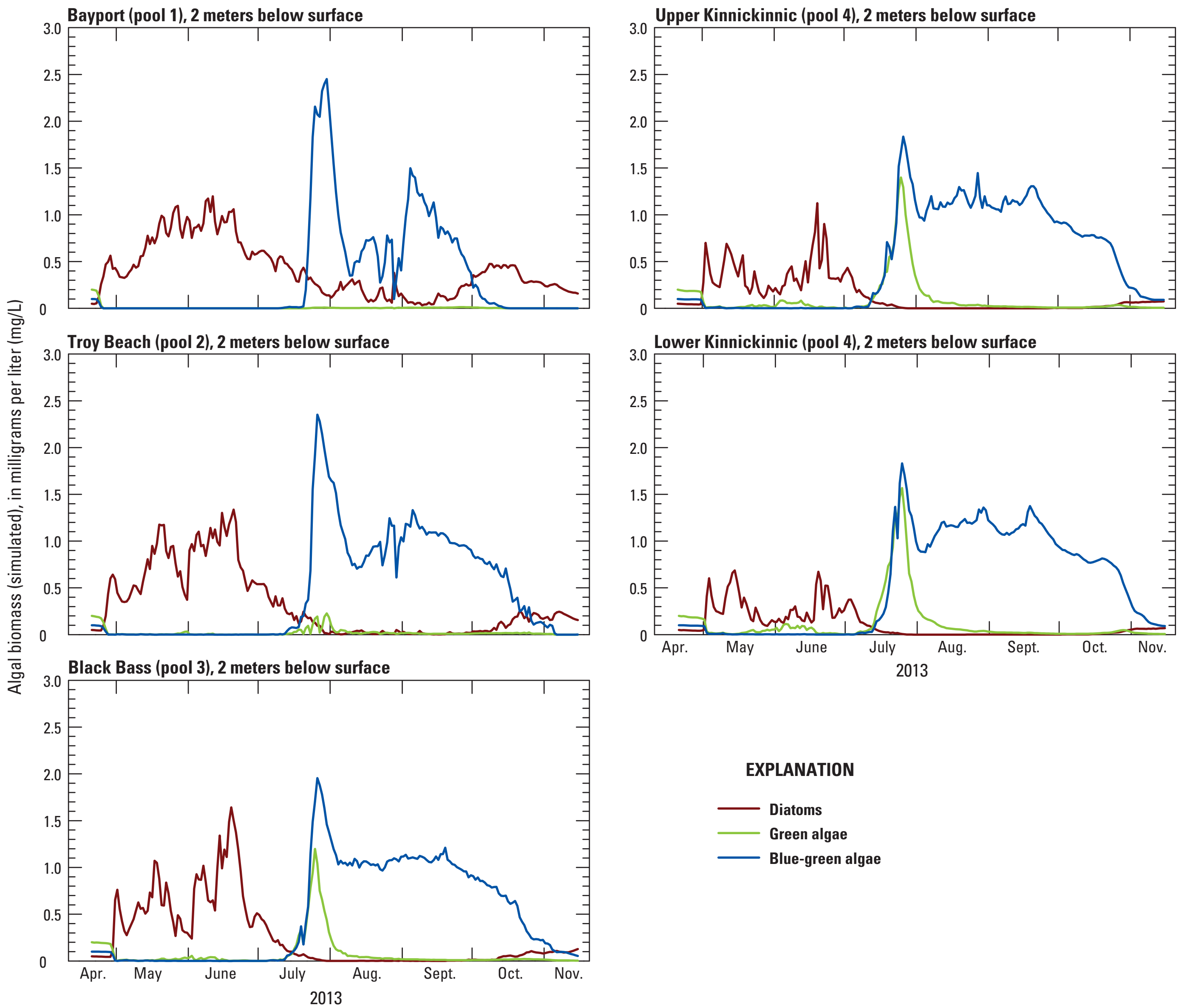


Figure 20. Graphs showing sSimulated algal group distributions (diatoms, green, and blue-green algae) for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013.

Instead, more green algae grew in pools 3 and 4 during the July spike. Blue-green algae were more abundant throughout this period, peaking at around 1.6–1.7 mg/L by early August in Kinnickinnic Pool with a second peak of about 2.0 mg/L in late September.

Of the four different pools, Bayport Pool exhibits the most erratic behavior with several short-lived blue-green algae peaks, partially because of the effect of upstream inflow on algal dynamics. Green algae started growing in the lake at the same time as blue-green algae, but the green algae biomass abundance over the course of the growing season was much smaller than diatoms or blue-green algae, and largely disappeared from the lake by August. For blue-green algae, the overall algal biomass slowly began to recede by mid- to late-September and continued through end of the simulation in early November. This coincides with the period when the nitrate plus nitrite concentration (fig. 16) became increasingly larger with less algal growth demand for nitrogen and a steady source from lake inflows.

Chlorophyll *a* concentration data were used to help interpret if the overall magnitude of the algal group composition was within a reasonable range. Photosynthetic pigments, such as chlorophyll *a*, are accepted in the literature as surrogates for algal biomass given the high expense of measuring algal biomass directly (Lindenberg and others, 2008). Simulated chlorophyll *a* concentrations are shown in figure 21 for the same locations as shown in figures 15–20. Measured chlorophyll *a* data were collected primarily in the surface layer in three of the four pools. The simulated chlorophyll *a* concentrations are shown for all four pools, including both ends of Kinnickinnic Pool. Overall, simulated values closely approximated measured values where measurements were available, including the early and late season chlorophyll *a* concentrations; however, the simulated chlorophyll *a* underestimated the measured August chlorophyll *a* concentrations. One potential reason was the relation between chlorophyll *a* concentration and algal biomass, governed by the ACHLA parameter (table 6), was not correct. The final ACHLA parameters for the three algal groups ranged from 0.04 to 0.066. The MAE and RMSE values for the three locations (table 6) with available data ranged from 3 to 6 µg/L and 5 to 9 µg/L, respectively (fig. 21).

The simulated concentrations of the algal groups and chlorophyll *a* were greatly dependent on the parameterization of the algal groups. Given the several parameters related to the algal groups (table 5) and their overall effect on the dissolved oxygen, these parameters can be extremely difficult to quantify. Several of the parameters were greatly sensitive, such as the algal mortality, algal settling rate, temperature coefficients on maximum growth, and the algal half-saturation constants for nitrogen- and phosphorus-limited growth; however, several of the parameters were fixed for each group. The maximum algal respiration rate (parameter AR, table 5),

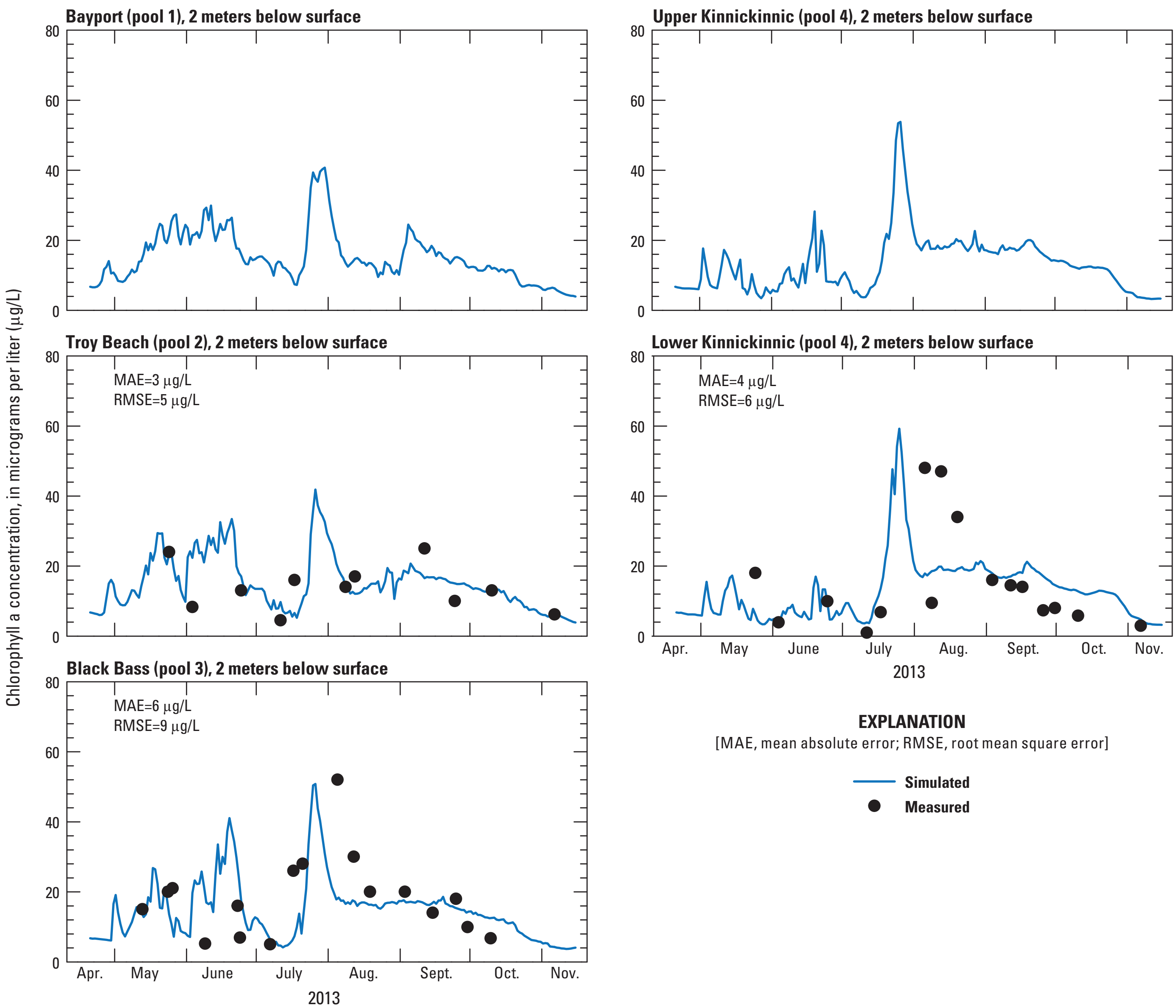


Figure 21. Graphs showing sSimulated and measured chlorophyll *a* concentrations for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013.

algal excretion rate (parameter AE, table 5), algal mortality (parameter AM, table 5), and the algal half-saturation for both nitrogen- (parameter AHSN, table 5) and phosphorus-limited growth (parameter AHSP, table 5) were varied to optimize the fit between the chlorophyll *a* data and the dissolved oxygen profiles. The settling rate (parameter AS, table 5), which limited algal growth, was largest for diatoms among the three algal groups (table 5). Another group of parameters that limited growth was the constants chosen for the nitrogen- and phosphorus-limited growth (Cole and Wells, 2015). The algal growth also was related strongly to the availability of nutrients, which was dependent on the initial lake concentrations and the ongoing replenishment of nutrients from the various inflow sources. The chlorophyll *a* concentrations were affected by the same factors as the algal group composition.

Sensitivity Analysis

A sensitivity analysis was completed to understand the effects on the model results of controlled departures in the calibrated model parameters and input loads. Because of the State and Federal interagency goal of reducing phosphorus loads to Lake St. Croix by 20 percent by 2020, the model was used to test the reduction scenario responses of total phosphorus and chlorophyll *a*. Comparisons were made by calculating the median value over the year for all daily values, broken up by the individual pools. The segments for the sensitivity analysis were meant to represent the individual pools: (1) Bayport Pool (segment 9); (2) Troy Beach Pool (segment 15); (3) Black Bass Pool (segment 22); (4) Kinnickinnic Pool (segments 32 and 37) (fig. 2). The percent change from the baseline (calibrated) model median value to the corresponding sensitivity analysis median value was calculated for each of the individual pools (table 8), in addition to all the combined locations (table 9), for total phosphorus and chlorophyll *a*.

For each of the following parameters or input loads, the calibrated lake model value was increased by 20 percent or decreased by 20 percent: inflow orthophosphate, total inflow organic matter, combined total inflow organic matter (included inflow orthophosphate and algal biomass), phosphorus sediment release rate, inflow nitrogen, sediment oxygen demand, and the light extinction coefficient. In the case of the light extinction coefficient, all the component light extinction coefficients were adjusted including the light extinction coefficients for pure water (parameter EXH20, table 5), inorganic suspended solids (parameter EXSS, table 5), organic suspended solids (parameter EXOM, table 5), zooplankton (parameter EXZ1, table 5), and the three different algal groups (diatoms [parameter EXA1, table 5], green algae [parameter EXA2, table 5], and blue-green algae [parameter EXA3, table 5]). These constituents or parameters chosen for sensitivity analysis were some of the most sensitive parameters or input loads for the Lake St. Croix model, as well as in previous CE–QUAL–W2 lake models (Green and others, 2003; Sullivan and Rounds, 2004; Galloway and Green, 2006; Galloway and others, 2008; Smith and others, 2014).

The existing management plan assumes that reducing phosphorus loading should decrease Lake St. Croix (fig. 1) total phosphorus concentrations, decrease chlorophyll *a* concentrations, and reduce the frequency of algal blooms in Lake St. Croix (MPCA, 2013). As shown in tables 8 and 9, 20-percent reductions in the inflow orthophosphate and the combined total inflow organic matter all reduced total phosphorus concentrations. In the case of the combined total inflow organic matter, the closest proxy to the 20 percent by 2020 scenario, total phosphorus was -20.1 percent (table 9) for the combined locations, ranging from -18.3 to -20.3 percent across the four pools (table 8; fig. 22). When total phosphorus contributions were broken up into inflow orthophosphate and total inflow organic matter, affects from total inflow organic matter reductions (-12.9 percent) had almost twice the effect over inflow orthophosphate (-6.8 percent) across the combined locations (table 9). In the case of increasing phosphorus loads from the combined total inflow organic matter (including orthophosphate and algal biomass), rising trends were comparable to the decreasing trends, with a 20.7 percent increase in total phosphorus (table 9) with a range from 16.3 to 23.2 percent increase in total phosphorus (table 8; fig. 23).

Changes such as altering the inflow nitrogen load (combined nitrate plus nitrite and ammonia) or the sediment oxygen demand had a smaller effect on total phosphorus. The light extinction coefficient increase caused an 8.2 percent increase in total phosphorus (table 9). Algal growth rates were negatively affected by increased light extinction coefficient, causing less uptake of phosphorus in the algal biomass; decreasing the light extinction coefficient decreased total phosphorus by an average of -2.8 percent across the combined locations (table 9).

Of more significance than reductions in phosphorus loads were the changes in chlorophyll *a* from reductions in the inflow orthophosphate, total inflow organic matter, and the combined total inflow organic matter. Chlorophyll *a* concentrations did not decrease in the same proportional amounts as the total phosphorus concentrations had decreased for the combined total inflow organic matter (tables 8, 9; fig. 24). This model result indicates that the TMDL phosphorus reductions would not necessarily lead to the same magnitude reductions in algal growth rates. The mean reduction in total chlorophyll *a* was -12.2 percent (table 9) for the combined locations, ranging from -8.7 to -15.8 percent across the four pools (table 8; fig. 24). The diatom and green algae responses were similar, but blue-green algae did decrease, likely resulting from increased light penetration that is less favorable to blue-green algae because of the smaller loads (fig. 25). Increasing the combined total inflow organic matter (including orthophosphate and algal biomass) load resulted in a mean chlorophyll *a* increase of 15.5 percent (table 9), ranging from 6.2 to 17.9 percent across all pools (table 8; fig. 26). Intuitively, an increase in combined total inflow organic matter would seem to cause more algal growth because of an increase in nutrients, both from increased orthophosphate and the breakdown of more organic matter; furthermore, decreased light penetration

Table 8. Sensitivity analysis, in percent change from the calibration run median, for total phosphorus and chlorophyll *a*. Also, the baseline (calibrated) values for the minimum, maximum, and median are shown for each of the four different pools (Bayport, Troy Beach, Black Bass, and Kinnickinnic).

[The baseline (calibrated) values for the minimum, maximum, and median are shown for each of the four different pools (Bayport, Troy Beach, Black Bass, and Kinnickinnic; --, not applicable]

Constituent	Input, in percent change from calibrated value	Total phosphorus, in micrograms per liter	Chlorophyll *a*, in micrograms per liter
Bayport Pool			
Baseline, median	--	45.33	13.82
Baseline, minimum	--	28.46	3.97
Baseline, maximum	--	43.40	40.75
Bayport Pool output, in percent change from baseline (calibrated) value			
Inflow orthophosphate	-20	-8.3	-5.0
	+20	8.7	4.3
Total inflow organic matter	-20	-10.3	-2.0
	+20	20.4	0.8
Combined total inflow organic matter (included inflow orthophosphate and algal biomass)	-20	-19.7	-11.5
	+20	19.9	17.9
Sediment release rate, phosphorus	-20	0.1	-1.1
	+20	0.6	1.6
Inflow nitrogen	-20	0.6	3.9
	+20	0.1	-2.2
Sediment oxygen demand	-20	-0.5	-6.3
	+20	0.6	3.4
Light extinction coefficient	-20	-0.6	2.8
	+20	1.3	0.7
Troy Beach Pool			
Baseline, median	--	42.80	13.90
Baseline, minimum	--	25.94	3.90
Baseline, maximum	--	76.69	41.87
Troy Beach Pool output, in percent change from baseline (calibrated) value			
Inflow orthophosphate	-20	-4.3	-6.9
	+20	6.1	5.6
Total inflow organic matter	-20	-13.3	-2.9
	+20	25.6	3.7
Combined total inflow organic matter (included inflow orthophosphate and algal biomass)	-20	-18.3	-15.8
	+20	23.2	12.4
Sediment release rate, phosphorus	-20	-1.9	-0.2
	+20	3.1	2.0
Inflow nitrogen	-20	2.7	-1.1
	+20	-1.4	-0.4
Sediment oxygen demand	-20	-3.7	-2.9
	+20	5.4	0.4
Light extinction coefficient	-20	-5.6	3.0
	+20	17.5	1.4

Table 8. Sensitivity analysis, in percent change from the calibration run median, for total phosphorus and chlorophyll *a*. Also, the baseline (calibrated) values for the minimum, maximum, and median are shown for each of the four different pools (Bayport, Troy Beach, Black Bass, and Kinnickinnic).—Continued

[The baseline (calibrated) values for the minimum, maximum, and median are shown for each of the four different pools (Bayport, Troy Beach, Black Bass, and Kinnickinnic; --, not applicable]

Constituent	Input, in percent change from calibrated value	Total phosphorus, in micrograms per liter	Chlorophyll *a*, in micrograms per liter
	Black Bass Pool		
Baseline, median	--	43.40	14.33
Baseline, minimum	--	25.27	3.70
Baseline, maximum	--	73.45	50.82
	Black Bass Pool output, in percent change from baseline (calibrated) value		
Inflow orthophosphate	-20	-5.7	-2.1
	+20	8.0	9.0
Total inflow organic matter	-20	-13.5	2.2
	+20	17.6	5.4
Combined total inflow organic matter (included inflow orthophosphate and algal biomass)	-20	-20.0	-9.6
	+20	20.3	10.2
Sediment release rate, phosphorus	-20	-0.5	-3.3
	+20	0.0	4.0
Inflow nitrogen	-20	-1.0	1.6
	+20	-0.3	4.6
Sediment oxygen demand	-20	-0.7	3.5
	+20	1.2	5.5
Light extinction coefficient	-20	-2.5	8.6
	+20	10.2	3.7
	Kinnickinnic Pool		
Baseline, median	--	43.21	12.31
Baseline, minimum	--	23.95	3.23
Baseline, maximum	--	71.37	59.26
	Kinnickinnic Pool output, in percent change from baseline (calibrated) value		
Inflow orthophosphate	-20	-6.2	-4.8
	+20	7.0	22.1
Total inflow organic matter	-20	-13.7	2.2
	+20	16.3	16.6
Combined total inflow organic matter (included inflow orthophosphate and algal biomass)	-20	-20.3	-8.7
	+20	20.7	6.2
Sediment release rate, phosphorus	-20	-0.4	-3.1
	+20	1.5	9.8
Inflow nitrogen	-20	0.6	10.5
	+20	0.4	9.0
Sediment oxygen demand	-20	-0.7	2.5
	+20	0.4	13.6
Light extinction coefficient	-20	-2.6	12.1
	+20	8.3	2.6

Table 9. Sensitivity analysis, in percent change from the calibration run median, for total phosphorus and chlorophyll *a* for the combined pool locations (Bayport, Troy Beach, Black Bass, and Kinnickinnic). Also, the baseline (calibrated) values for the minimum, maximum, and median are shown for the combined locations.

[Also, the baseline (calibrated) values for the minimum, maximum, and median are shown for the combined locations; --, not applicable]

Constituent	Input, in percent change from calibrated value	Total phosphorus, in micrograms per liter	Chlorophyll *a*, in micrograms per liter
Lake St. Croix (combined locations)			
Baseline, median	--	43.84	13.43
Baseline, minimum	--	23.95	3.23
Baseline, maximum	--	76.69	59.26
Lake St. Croix (combined locations), in percent change from baseline (calibrated) value			
Inflow orthophosphate	-20	-6.8	-5.6
	+20	7.5	12.6
Total inflow organic matter	-20	-12.9	-0.0
	+20	16.5	7.5
Total inflow organic matter + inflow orthophosphate	-20	-20.1	-12.2
	+20	20.7	15.5
Sediment release rate, phosphorus	-20	-0.5	-2.2
	+20	1.3	6.0
Inflow nitrogen	-20	0.7	4.5
	+20	-0.3	1.8
Sediment oxygen demand	-20	-0.9	-2.2
	+20	1.1	6.1
Light extinction coefficient	-20	-2.8	6.6
	+20	8.2	3.9

likely established favorable conditions for enhanced blue-green algae blooms that sustained longer into the fall season (fig. 27).

Other factors that caused increased chlorophyll *a* concentrations included increased sediment oxygen demand, caused by the liberation of sediment bound phosphorus and an increase in the phosphorus sediment release rate. Decreases in both factors did cause a slight decrease but only -2.2 percent in both cases across the combined pool locations (table 9). Increases and decreases in the inflow nitrogen caused slight chlorophyll *a* increases, as did the increases and decreases in the light extinction coefficients. Lake St. Croix is phosphorus limited based on the 25:1 ratio of nitrogen to phosphorus (Correll, 1998), so altering inflow nitrogen should not have had much of an effect on the chlorophyll *a* concentrations.

An important conclusion from the sensitivity analysis is that a reduction in total phosphorus as part of TMDL would not necessarily lead to corresponding reductions in algal growth rates. The CE–QUAL–W2 model accounts for many other loads and highlights that although inflow phosphorus loads are important, other constituents also can affect the algal response of the lake and can interfere with the simple assumption that algae and phosphorus are always directly related.

Figure 22. Graphs showing sSimulated and measured total phosphorus concentrations (in micrograms per liter) for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent reduction in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

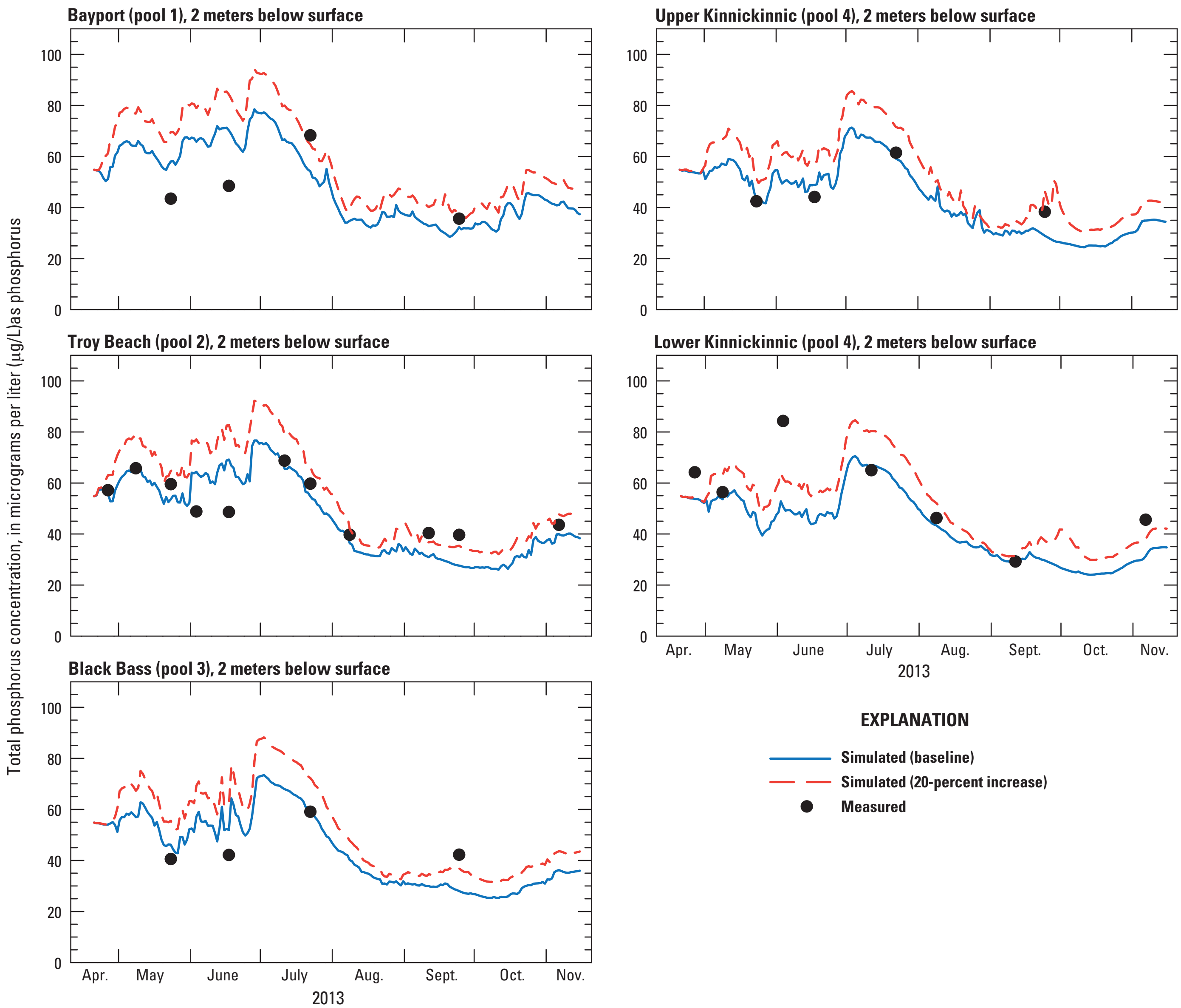


Figure 23. Graphs showing sSimulated and measured total phosphorus concentrations (in micrograms per liter) for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent increase in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

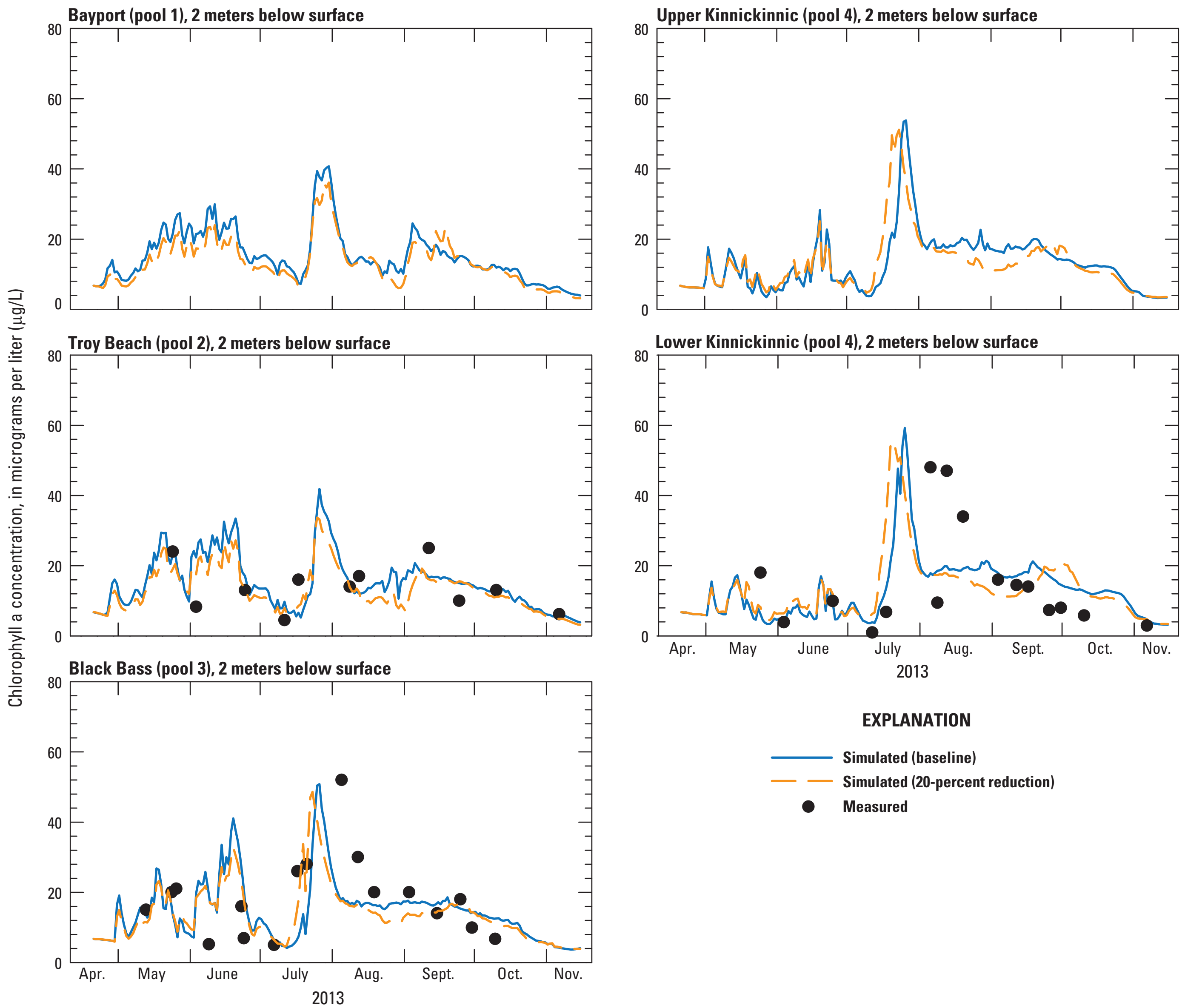


Figure 24. Graphs showing sSimulated and measured chlorophyll *a* for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent reduction in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

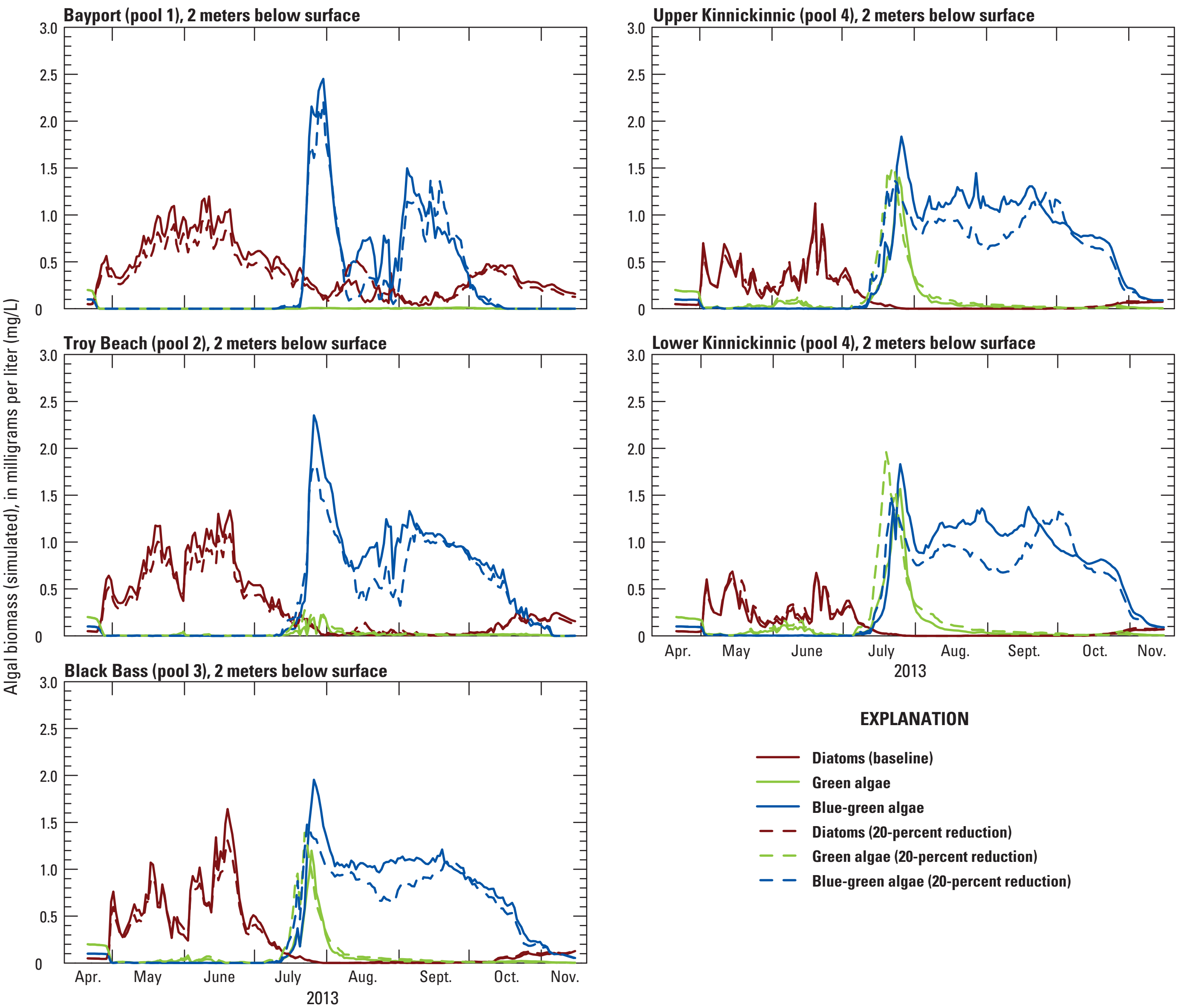


Figure 25. Graphs showing sSimulated algal biomass concentrations (diatoms, green, and blue-green algae) for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent reduction in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

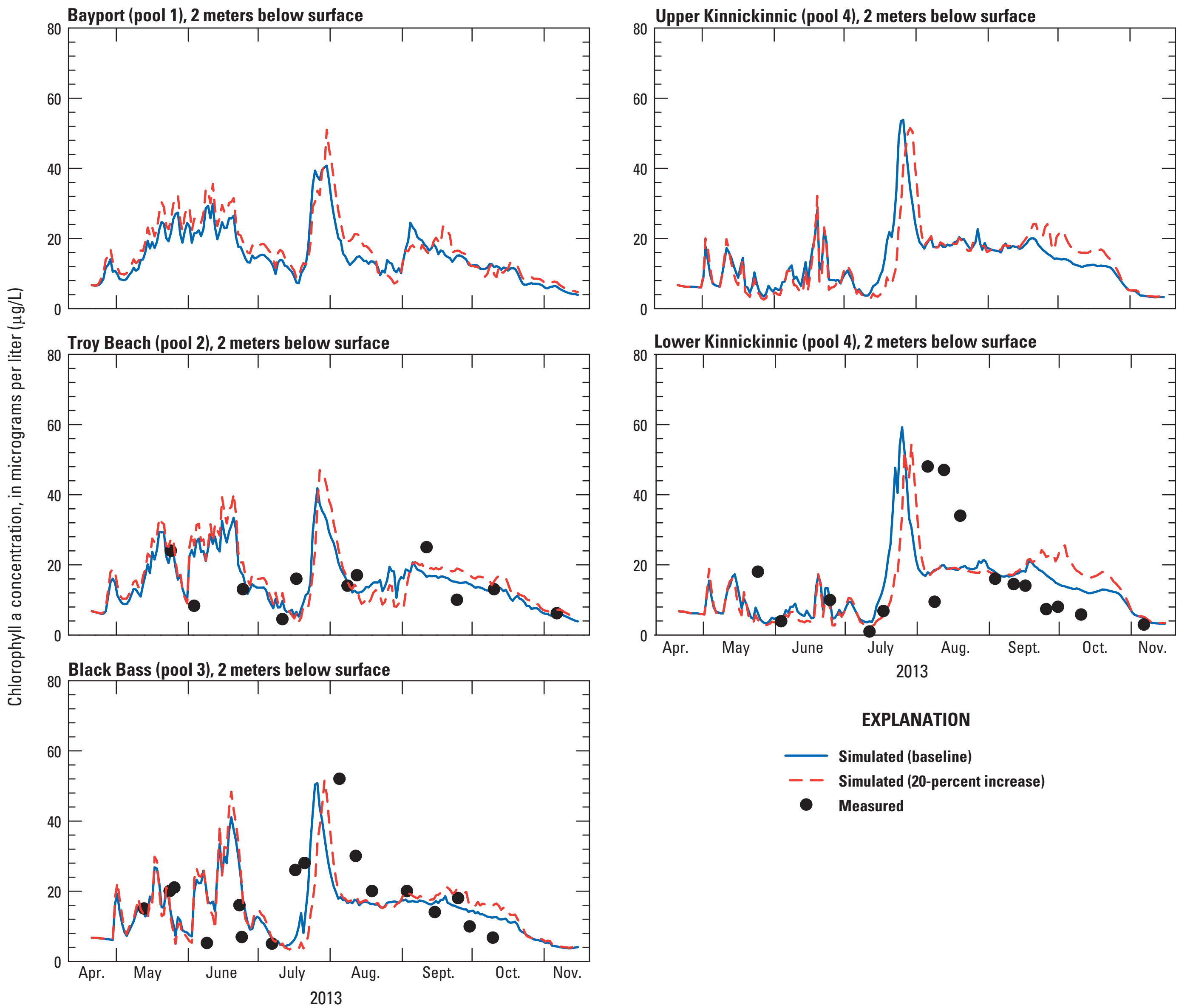


Figure 26. Graphs showing sSimulated and measured chlorophyll *a* for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent increase in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

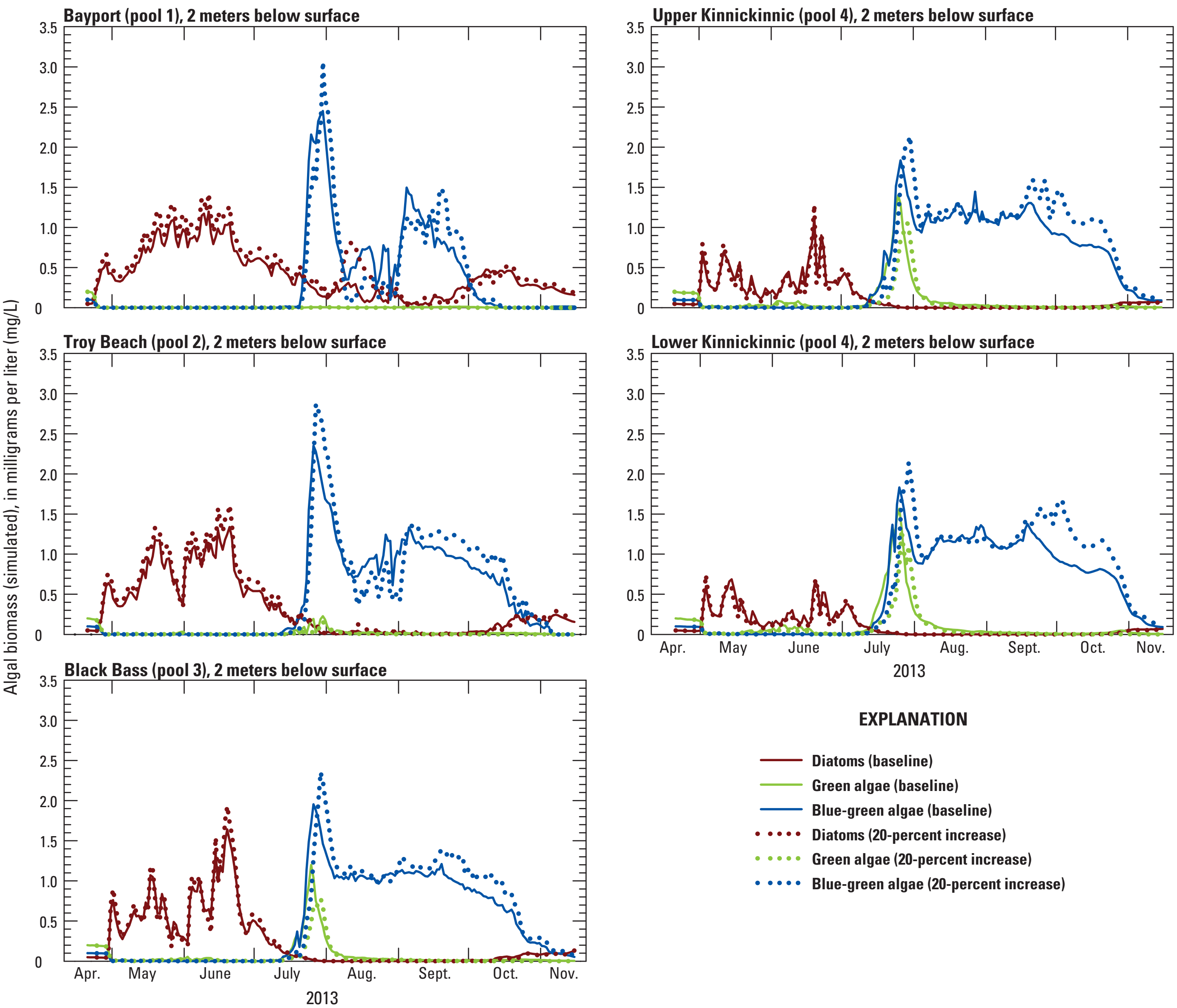


Figure 27. Graphs showing sSimulated algal biomass concentrations (diatoms, green, and blue-green algae) for all four pools (upper and lower Kinnickinnic represented in two graphs) for Lake St. Croix, April 20 to November 15, 2013, with the 20-percent increase in the combined total inflow organic matter load (included inflow orthophosphate and algal biomass) and the baseline (calibrated) model.

Lake Sturgeon Habitat

Models frequently are used to simulate fish responses to changes in climate and land-use patterns; for example, statistically based models have used predicted climate data and land-use data to demonstrate habitat losses that could cause localized extinctions of smallmouth bass in a Midwestern, large-river, flood plain ecosystem (Peterson and Kwak, 1999). In Minnesota, fish thermal and dissolved oxygen-based habitats were modeled in lakes over a range of existing and proposed climate change scenarios using the program MINLAKE96, a one-dimensional (vertical), year-round lake water quality model (Fang and others, 1999). Jacobson and others (2008) evaluated the lethal oxy-thermal niche boundary for ciscos (*Coregonus artedii*) in several Minnesota lakes and measured progressively smaller lethal temperatures as dissolved oxygen concentrations dropped. Fang and others (1999) used good-growth habitat areas and good-growth habitat volumes as metrics to evaluate habitat units on a normalized scale, and the results demonstrated that fish habitat parameters depended more strongly on geometry and less on trophic state in inland, temperate lakes; however, MINLAKE96 does not use a dynamic, trophic-dynamic model to predict fish habitat change, nor does it include drainage basin effects.

The CE–QUAL–W2 model, on the other hand, can be used to simulate biological responses to changing environmental conditions. Researchers have used CE–QUAL–W2 to model distribution and survival of white sturgeon (*Acipenser transmontanus*) over varying hydrologic conditions (Sullivan and others, 2003), the movements of blueback herring (*Alosa aestivalis*) in a southern impoundment (Nestler and others, 2002), as well as ongoing work by the USGS to model cisco habitat in Minnesota lakes under varying conditions of climate and nutrient loading.

The available oxy-thermal habitat suitable for lake sturgeon was evaluated by the model for total volume of good-growth habitat, optimal growth habitat, and lethal temperature habitat. These ranges were developed through regression equations from Jobling (1981) and similar applications such as Young and Cech (1996) and Ziegeweid and others (2008). Good-growth habitat for lake sturgeon was defined as between 14 and 26 °C, optimal growth habitat was defined as between 21.5 and 22.4 °C, and the lethal temperature range was set to above 28 °C. For all three ranges, the dissolved oxygen minimum was set at 3 mg/L.

The good-growth and optimal growth habitats for lake sturgeon during the simulation period are shown on figure 28. The absence of good-growth habitat does not necessarily correlate to optimal or lethal habitats, only outside the range such as below 14 °C in the hypolimnion or throughout the lake early or late during the simulation period. Optimal thermal habitat is present during short periods during the early and late summer because of the narrow range of temperatures associated with optimum growth. Some short periods of optimal

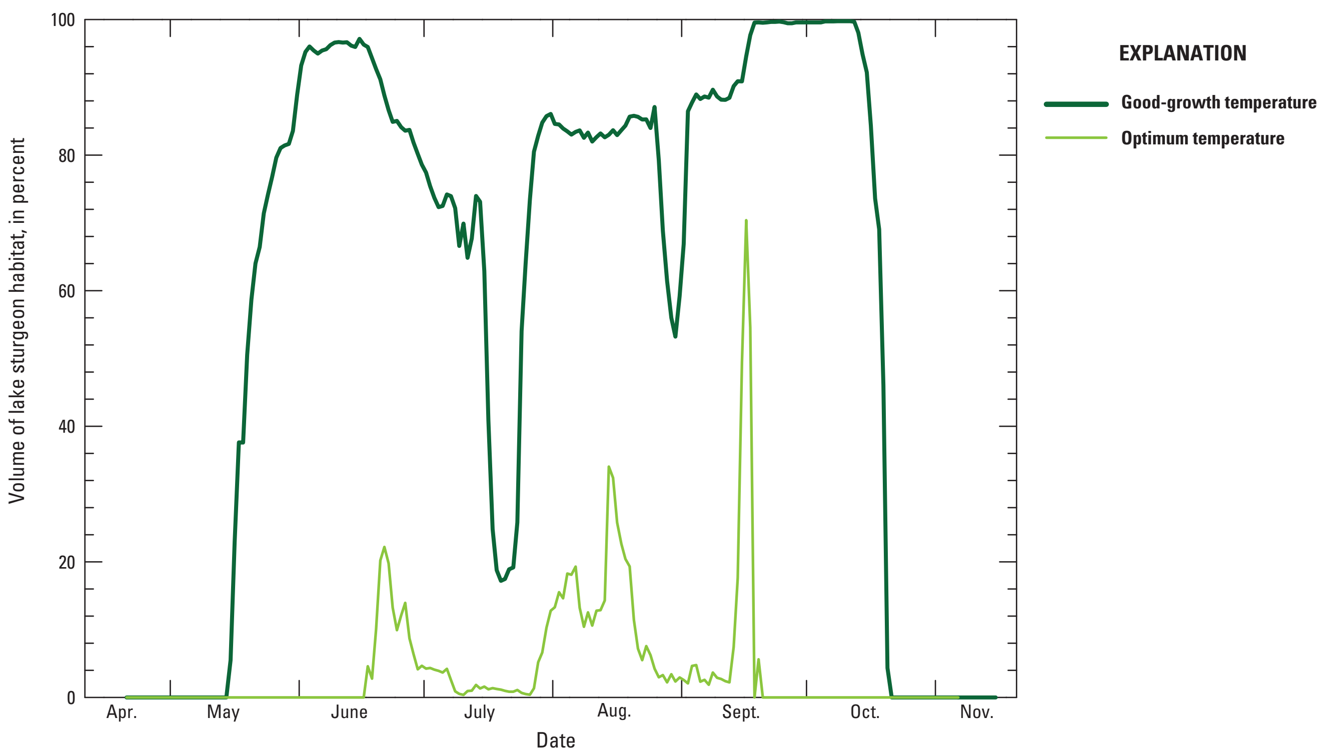


Figure 28. Graph showing gGood-growth and optimal growth temperature habitat for lake sturgeon in Lake St. Croix, April 20 to November 15, 2013.

thermal habitat are related to large inflow that change water temperatures favorably. Other sustained periods of optimal habitat are related to general optimal temperatures caused by combinations of weather, streamflow, and lake mixing patterns. With the calibrated model, the fish habitat volume generally contained a large proportion of good-growth habitat and sustained periods of optimal growth habitat in the summer. Only brief periods of lethal oxy-thermal habitat were present in Lake St. Croix during the model simulation (as much as 13 percent in mid-July). Also, the drop in good-growth habitat in July did highlight the effect of warm temperatures on oxy-thermal habitat. If temperatures had been warmer or more hypoxia had happened at depth, the lake sturgeon could be threatened with lethal oxy-thermal habitat, particularly in the future with warmer summer temperatures predicted with climate change.

Model Limitations

A full understanding of model limitations is necessary to evaluate the performance of any water-quality model better. Because the CE–QUAL–W2 model is averaged laterally, processes that could impose variations perpendicular to the primary flow axis of the lake will not be represented in the model. Water-quality limitations include the simplification of a complex aquatic ecosystem into a series of kinetic reactions expressed in source and loss terms (Cole and Wells, 2015). Also, the fixed number of water-quality samples to which the model is calibrated may not have captured the full range of conditions in this dynamic system. Specific water-quality modules with shortcomings for the CE–QUAL–W2 model include the zero-order sediment oxygen demand model. The sediment oxygen demand model is user-defined, decoupled from the water column, and sediment oxygen demand only varies with temperature. A complete sediment diagenesis model, with fully integrated sediment kinetics and the sediment-water interface, does exist within CE–QUAL–W2 version 4.0 but was not applied for this investigation because of the lack of data for parameterization.

Not only do data limitations exist, but structural selections, such as segment geometry, the number of vertical layers, and the numerical transport scheme, can potentially impose a bias in the outcome of the model. Boundary conditions are not fixed in nature; however, boundary conditions are limited by the availability of data. In addition, extrapolation of the data was necessary to fit the requirements of the CE–QUAL–W2 model; for example, water-quality data were linearly interpolated between sampling dates, or the sampling data were used as input into load-estimation software to generate daily time steps for the model. Gaps within the continuous record also caused shorter calibration than desired.

Regarding the final model parameter set (table 5), a potential exists for multiple parameter sets that are all compatible with the current calibration dataset. To deal with this issue, as much calibration data was used as possible, in particular the dissolved oxygen calibration which included four to 14 profiles for five unique locations. Therefore, the prospect of multiple model parameter sets is limited by the sheer number of calibration points used, although subtle differences in the final parameter set are a real possibility.

Summary

Lake St. Croix is a naturally impounded, riverine lake that makes up the last 40 kilometers of the St. Croix River. Lake St. Croix consists of four successive pools (upstream to downstream): Bayport Pool, Troy Beach Pool, Black Bass Pool, and Kinnickinnic Pool. The St. Croix River Basin drains 20,098 square kilometers, and Lake St. Croix has a surface area of about 35 square kilometers, resulting in a basin to lake area ratio of 574:1. Substantial land-use changes during the past 150 years, including increased agriculture and urban development, have reduced Lake St. Croix water quality and increased nutrient loads delivered to Lake St. Croix. Additionally, human population within the lower St. Croix Basin is expected to increase by 39 percent by 2020, as predicted from the 2000 census.

Currently (2017), the St. Croix National Scenic Riverway has designated the protection of water quality as the primary natural resource management goal under the National Park Service Centennial Strategies Initiative; furthermore, a total maximum daily load plan set the objective to better understand mechanisms of internal and external phosphorus loading, improve nutrient mass-balance estimates, and assess the ecological health of Lake St. Croix. The total maximum daily load phosphorus-reduction goal is to reduce total phosphorus loads by 20 percent by 2020 and reduce frequencies of algal blooms in Lake St. Croix. This reduction goal was also supported by BATHTUB (a water-quality model) simulations of decreased phosphorus loading into Lake St. Croix, although no ecosystem-based framework has existed up to this point to assess the relation between nutrient loading, hydrodynamics, lake metabolism, and temperature and oxygen (oxy-thermal) dependent fish habitat in Lake St. Croix.

As part of the National Park Service Centennial Strategies Initiative, the U.S. Geological Survey, in cooperation with the National Park Service, developed and calibrated a mechanistic, biophysical water-quality model for Lake St. Croix. The modeling framework, CE–QUAL–W2, is a carbon-based, laterally averaged, two-dimensional water-quality model that was built using meteorological, hydrodynamic, and water-quality conditions from April through November 2013. Loads developed for the model were based on water-quality data collected by various agencies, including the U.S. Geological Survey. A sensitivity analysis was done to better understand model response for total phosphorus and chlorophyll *a* to changes in nutrient loads, sediment release rates of phosphorus, sediment oxygen demand, and light extinction coefficients. Because CE–QUAL–W2 addresses trophic dynamics, the calibrated model was also used to evaluate good- and optimal-growth habitat availability for lake sturgeon, based on cool-water fish oxygen and thermal requirements.

A key metric to determine the accuracy of the Lake St. Croix model's calibration was water temperature. Although the measured vertical temperature profiles did not exhibit uniform behavior across the four different Lake St. Croix pools, the simulated water temperature profiles closely matched the measured profiles throughout the year, including the prediction of thermocline transition depths (often within 1 meter), the absolute temperature of the thermocline transitions (often within 1.0 degree Celsius), and profiles without a strong thermocline transition. Aggregate mean absolute error and root mean square error values across the four different pools were 0.74 and 1.10 degrees Celsius, respectively.

Accurate dissolved oxygen model simulations were critical in determining the size of summer habitat refugia. For certain fish species, thermal requirements may confine them below the epilimnion, where they are vulnerable to mass die offs if dissolved oxygen drops below a lethal limit. The principal calibration targets for dissolved oxygen were the lake profile data from the four different pools. Overall, the model captured the trajectories of the measured dissolved oxygen concentrations at multiple depths over time, and the simulated concentrations matched the depth and slope of the measured concentrations. The model also effectively followed the seasonal changes in measured dissolved oxygen distributions, an indication that the underlying metabolic processes reproduced by the model can explain Lake St. Croix trophic responses. The final average of the four different pools was 0.76 and 1.06 milligrams per liter for the mean absolute error and root mean square error values, respectively, and was much less than 1.0 milligram per liter for most dates.

Nutrients, in conjunction with dissolved oxygen, were important for calibration purposes and for understanding if the CE–QUAL–W2 model could adequately describe nutrient dynamics. For the nitrogen species, the CE–QUAL–W2 model tracked nitrate plus nitrite and total nitrogen throughout the year, and to a lesser extent ammonia concentration. For total phosphorus, the model reproduced the spring to early summer large total phosphorus concentrations, and the subsequent drop after July. Inflow nutrient contributions (loads), largely dominated by upstream St. Croix River loads, were the most important controls on Lake St. Croix water quality. Close to 60 percent of total phosphorus to the lake was from phosphorus derived from organic matter (147.5 metric tons), and about 89 percent of phosphorus to Lake St. Croix was delivered through St. Croix River inflows (220.2 metric tons).

Three general algal groups were used in the Lake St. Croix model: diatoms, green algae, and blue-green algae. The Lake St. Croix CE–QUAL–W2 model offered potential mechanisms for the effect of external and internal loadings on the biotic response regarding these algal community types. Available chlorophyll *a* monitoring data from Troy Beach, Black Bass, and Kinnickinnic pools, used as a surrogate for tracking algal biomass, were closely matched by simulated chlorophyll *a* for these locations. The model also suggested the seasonal dominance of blue-green algae in all fours pools of the lake. The model simulation provided an understanding of how blue-green algae (also known as cyanobacteria) production and biomass accumulation in Lake St. Croix resulted from complex interactions between algal physiology and lake stratification.

A sensitivity analysis was completed to test the total maximum daily load phosphorus-reduction scenario responses of total phosphorus and chlorophyll *a*. The existing management plan assumes that reducing phosphorus loading should decrease Lake St. Croix total phosphorus concentrations, decrease chlorophyll *a* concentrations, and reduce the frequency of algal blooms in Lake St. Croix. The model showed that phosphorus reductions would result in similar Lake St. Croix concentrations, although chlorophyll *a* concentrations did not decrease in the same proportional amounts as the total phosphorus concentrations had decreased. The smaller than expected reduction in algal growth rates highlighted that although inflow phosphorus loads are important, other constituents also can affect the algal response of the lake, such as changes in light penetration and the breakdown of organic matter releasing nutrients.

The available habitat suitable for lake sturgeon was evaluated using the model for total volume of good-growth habitat, optimal growth habitat, and lethal temperature habitat. Overall, with the calibrated model, the fish habitat volume in general contained a large proportion of good-growth habitat and sustained period of optimal growth habitat in the summer. Only brief periods of lethal oxy-thermal habitat were present in Lake St. Croix during the model simulation.

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