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Modeling Flow and Water Quality in Reservoir and River Reaches of the Mahoning River Basin, Ohio





Scientific Investigations Report 2022–5125

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

Cover.

(Top-left). Berlin Lake Dam as seen from the north, Mahoning River, Ohio. Photograph by U.S. Army Corps of Engineers, date unknown.

(Top-right). Mosquito Creek Lake as seen looking from the south, Ohio. Photograph by U.S. Army Corps of Engineers, date unknown.

(Middle-left). Dam on Lake Milton as seen looking from the east, Mahoning River, Ohio. Photograph by Jason Smith, U.S. Geological Survey, May 29, 2019.

(Middle-right). Michael J Kirwan Lake as seen from the east, Ohio. Photograph by U.S. Army Corps of Engineers, date unknown.

(Bottom). Mahoning River as seen looking southeast (downstream) from the Washington Street bridge crossing the Mahoning River, Lowellville, Ohio. Photograph by Jason Smith, U.S. Geological Survey, taken February 14, 2022.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	0.0254	meter (m)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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)
	Area	
square kilometer (km^2)	247.1	acre
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988.

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

ADCP	Acoustic Doppler current profiler
CE-QUAL-W2	two-dimensional flow and water-quality model
DEM	digital elevation model
DOM	dissolved organic matter
DMR	discharge monitoring report
HEC-RAS	Hydrologic Engineering Center's River Analysis System
MAE	mean absolute error
ME	mean error
NWS	National Weather Service
OEPA	Ohio Environmental Protection Agency
POM	particulate organic matter
RES-SIM	reservoir operations model
SOD	sediment oxygen demand
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WWTP	wastewater treatment plant

Modeling Flow and Water Quality in Reservoir and River Reaches of the Mahoning River Basin, Ohio

By Annett B. Sullivan,[1] Gabrielle M. Georgetson,[2] Christina E. Urbanczyk,[3] Gabriel W. Gordon,[1] Susan Wherry,[1] and William B. Long[1]

Executive Summary

The U.S. Army Corps of Engineers (USACE) is considering changes to the management of water surface elevation in four lakes in the Mahoning River Basin. These changes would affect the timing and amounts of water released to the Mahoning River and could affect the water quality of those releases. To provide information on possible water-quality effects from these operational changes, flow and water-quality models were constructed for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, Mosquito Creek, and the Mahoning River from the dams downstream to Lowellville, Ohio.

The models were calibrated for 2 calendar years each, with model years selected depending on the availability of water-quality data. Models were developed with CE-QUAL-W2 version 4.2 (Wells, S.A., 2020, CE-QUAL-W2—A two-dimensional, laterally averaged, hydrodynamic and water quality model [version 4.2]: Portland State University, variously paged), a two-dimensional, laterally averaged hydrodynamic and water-quality model. Modeled constituents included flow, velocity, ice cover, water temperature, total dissolved solids (TDS), sulfate, chloride, inorganic suspended sediment, nitrate, ammonia, total Kjeldahl nitrogen, orthophosphate, total phosphorus, dissolved and particulate organic matter, algae, and dissolved oxygen. Iron was included for the lake models, but not the river.

A whole-basin model, with the four lake models and river model, was used to run model scenarios to examine the effects of altered lake water surface elevations on flow and water quality in the lakes, the lake outflows, and the Mahoning River. The initial whole-basin model, with calendar year 2013 hydrology and measured or typical water quality, was designated as scenario 0. Mahoning River flows for calendar year 2013 were close to a 20-year median flow. Four additional scenarios were constructed based on reservoir operations model (RES-SIM) model water surface elevations for the four lakes as provided by USACE. Scenario 1 was the RES-SIM base case, scenario 2 kept Berlin Lake water surface elevations higher in summer, scenario 3 allowed 25 percent of summer flood storage to extend the guide curve, and scenario 4 allowed more flexibility in lake management by removing any downstream Mahoning River minimum flow requirements. The Mahoning River model was not changed in any scenarios but received altered flows from the lakes. Significant findings from this study include:

- In two of the four lakes (Berlin and Mosquito Creek Lakes), development of lake model grids using recent bathymetric surveys suggests that sedimentation in these lakes has occurred since they were constructed, altering volume-elevation curves.
- Tests of model parameter sensitivity showed that modeled water temperature, TDS, and dissolved oxygen were relatively insensitive to model parameter values. Modeled chlorophyll *a*, a measure of algal concentration, was most sensitive to parameter values; nitrate and total phosphorus concentrations were affected by a few of the parameters tested. As a group, the lake model results were more sensitive to model parameter values compared to the Mahoning River model.
- Data gaps were identified for inflows, both for water quantity and water quality, that could be filled through future sampling programs. Ample data were available from within the waterbodies for model calibration.
- The model simulated the general spatial and temporal patterns of water temperature, TDS, chloride, sulfate, nutrients, suspended sediment, organic matter, chlorophyll *a*, and dissolved oxygen in the lakes and Mahoning River.
- From late spring to autumn in the years modeled (2006, 2013, 2017–19 depending on the lake), all lakes developed thermal stratification and periods of anoxia in bottom waters. Stratification was most stable in Michael J Kirwan Reservoir and least stable in Mosquito Creek Lake. The stratification and anoxia in Berlin Lake, Lake Milton, and Mosquito Creek Lake could be interrupted by high-flow inputs moving through those lakes.

[1]U.S. Geological Survey

[2]U.S. Army Corps of Engineers Pittsburgh District

[3]U.S. Army Corps of Engineers Northwestern Division

- The model predicted the release of ammonia and iron during anoxic periods in the lake hypolimnions.
- Concentrations of TDS, nitrate, orthophosphate, and total phosphorus increased in the Mahoning River down to Lowellville, the end of the river model, in the years modeled. These concentrations were greater than those in upstream lake releases.
- Chloride and sulfate concentrations were underpredicted in the Mahoning River, suggesting the presence of unreported chloride and sulfate inputs to the river, at least in the years modeled.
- Model scenario 4 kept water surface elevations the highest in all lakes in the April to mid-December period, compared to scenarios 1–3. Model scenario 2 kept water surface elevations in Berlin Lake higher in summer and late autumn, compared to scenarios 1 and 3, but to satisfy downstream minimum flow requirements, water surface elevations in the other lakes had periods of lower water surface elevation.
- As a group, scenarios 1–3 had largely similar effects on flow and water surface elevation in the Mahoning River because the lake releases in those scenarios still met downstream Mahoning River flow targets.
- Modeling the removal of downstream flow targets, scenario 4 had periods of lower flow in the Mahoning River from April to mid-September as water was held in the lakes, and periods of higher Mahoning River flow from mid-September through November as the lakes were drawn down to prepare for winter flood-risk management.
- In the four scenarios, all the lakes and lake outflows had generally similar seasonal cycles of water quality, though some differences were predicted. For instance, higher concentrations of iron and ammonia in the Lake Milton hypolimnion were modeled during a period of both low inflows from Berlin Lake and low outflows at Lake Milton dam. It is possible that those changes could be minimized by maintaining more flow or pulses of higher flow through the lake.
- Compared to the scenario 1 base case, changes to Mahoning River water quality were relatively minor for scenarios 2 and 3, which maintained downstream flows but shifted the flow source among the upstream lakes.
- The largest changes in Mahoning River water quality were predicted between Leavittsburg and Lowellville for scenario 4. The periods of lower lake outflows between April and mid-September led to correspondingly higher concentrations of TDS, orthophosphate, total phosphorus, and nitrate in the river, compared to the base case scenario 1. Conversely, the overall greater lake outflows from mid-September through November in scenario 4 led to periods of lower concentrations of TDS and nutrients in that portion of the river, at that time of year.

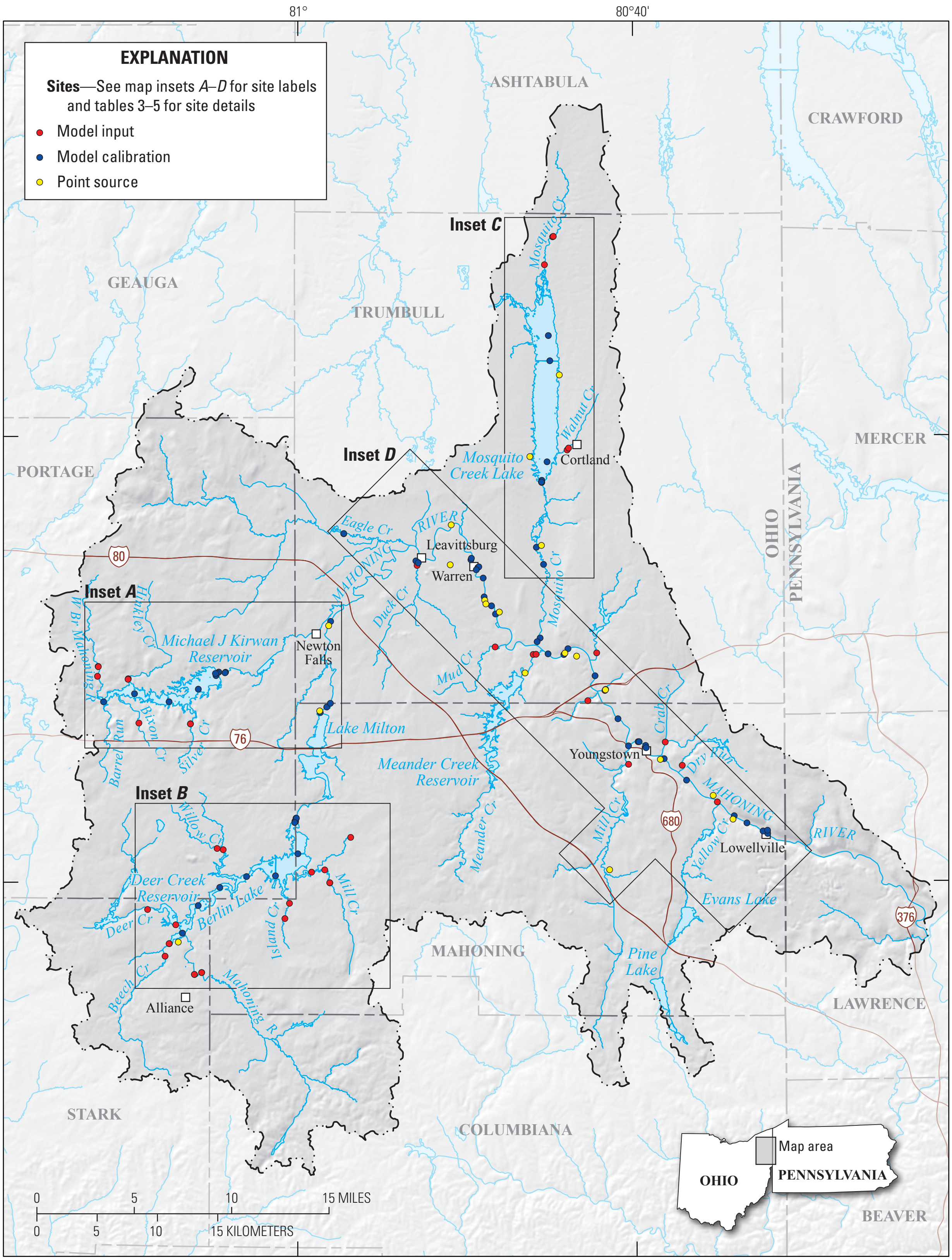
Introduction

The Mahoning River lies in a 1,133-square-mile (mi^2) (2,934 square kilometer [km^2]) formerly glaciated basin in northeastern Ohio. The river begins southeast of Alliance, Ohio, then flows through Berlin Lake and Lake Milton and past cities and towns including Newton Falls, Leavittsburg, Warren, Youngstown, and Lowellville (fig. 1). The Mahoning River receives flows from point sources and tributaries along its reach, including inputs from lake-dominated streams, such as West Branch Mahoning River (which has Michael J Kirwan Reservoir), Mosquito Creek (which has Mosquito Creek Lake), and Meander Creek (which has Meander Creek Reservoir). After passing the state line between Ohio and Pennsylvania, the Mahoning River joins the Shenango River to form the Beaver River, a tributary of the Ohio River. The lakes in this study are all reservoirs, formed by dams, but are often called lakes locally.

Starting in the late 1800s and peaking in the 1900s, the lower Mahoning River Basin became a center for steel production and other industries such as aluminum, electrical products, and steampower. Water from the river, diverted at low-head dams, was used to cool industrial processes. Eventually, the warmed water was released back into the river, causing water temperatures to increase; river water temperatures as high as 120 degrees Fahrenheit (°F) (48.9 degrees Celsius [°C]) have been reported (Cross and others, 1952). As the industries waned, thermal loads to the river decreased, but some legacy effects remain, such as the continued presence of the low-head dams and metal pollution in river sediments (Ohio Environmental Protection Agency, 1996, 2012a, 2012b).

Beyond these legacy issues, other sources of water-quality problems in surface water exist throughout the basin. Several municipal wastewater treatment plants (WWTPs) discharge effluent into the river, and combined sewer overflows may occur during storms (Ohio Environmental Protection Agency, 2018; Stoeckel and Covert, 2002). Discharges from acid mine drainage, oil and natural gas production, urban runoff, failing household sewage treatment systems, and nonpoint agricultural sources also are found in the basin (Bednar and others, 1968; Ohio Environmental Protection Agency, 1996, 2018; Darner, 2002). Upgrades of wastewater treatment plants to include secondary treatment in 1988–89 helped to decrease instream concentrations of ammonia and improve dissolved oxygen concentrations in the lower Mahoning River (Stoeckel and others, 2002).

Historically, the river has had poor habitat for aquatic life and degraded macroinvertebrate communities, though recent studies have found some signs of improvement (Ohio Environmental Protection Agency, 2008, 2012a, 2012b, 2018). Plans to address total phosphorus levels, habitat, siltation, and *Escherichia coli* have been prepared for portions of the basin (U.S. Environmental Protection Agency, 2004; Ohio Environmental Protection Agency, 2011).



Base from U.S. Geological Survey digital data, various scales
Universal Transverse Mercator, zone 17 north
North American Datum of 1983

Figure 1. Site map and detailed insets for (*A*) Michael J Kirwan Reservoir, (*B*) Berlin Lake and Lake Milton, (*C*) Mosquito Creek Lake, and (*D*) the Mahoning River in the Mahoning River Basin, Ohio.

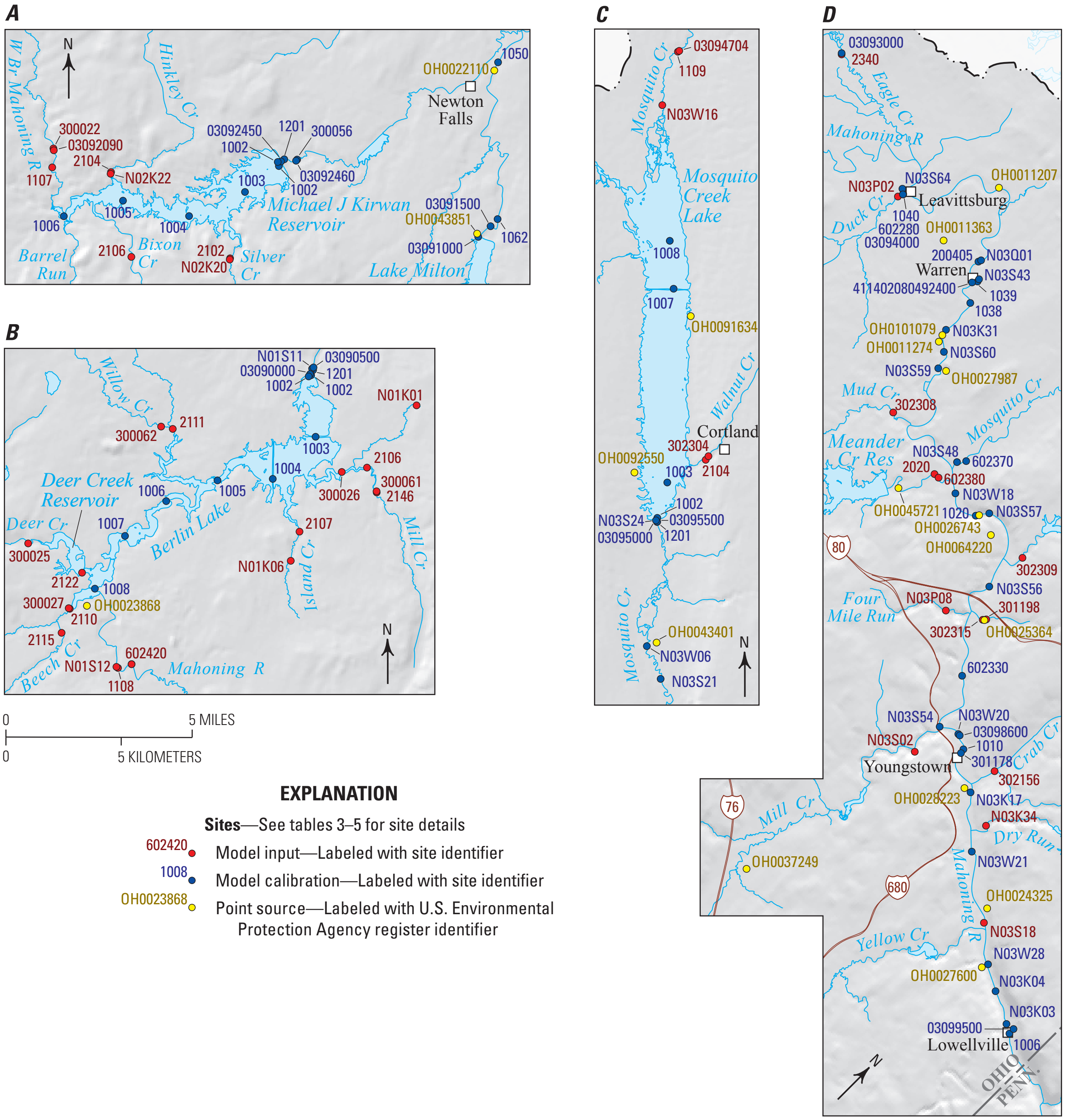


Figure 1.—Continued

Guided by its water control manuals (U.S. Army Engineer District, 1978a–c), the U.S. Army Corps of Engineers (USACE) is tasked with releasing flows from Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake to improve water quality by diluting pollutants in the Mahoning River. Specifically, the lakes are operated to meet minimum flow requirements established by the U.S. Environmental Protection Agency (USEPA; U.S. Army Engineer District, 1978a). The Mahoning River at Leavittsburg should have a minimum flow of 145 cubic feet per second (ft^3/s) during winter and 310 ft^3/s during summer. The water control manuals also state that 64 percent of the flow needed to achieve the minimum flow of 310 ft^3/s should come from Berlin Lake and Lake Milton, and 36 percent of that augmentation flow should come from Michael J Kirwan Reservoir. At Youngstown, the Mahoning River minimum flows are 225 ft^3/s during winter and 480 ft^3/s in late July. Flows at Youngstown also include releases from Mosquito Creek Lake, as Mosquito Creek is a tributary to the Mahoning River between Warren and Youngstown.

Increased recreational use and development around Berlin Lake has led to calls to keep Berlin Lake water levels elevated through the summer. Because changes to Berlin Lake's water surface elevation would also change the amount of water released to the river downstream, this study was initiated to examine the possible changes in water quality that could result from operational changes to Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake water surface elevations and outflows. Modeled water-quality changes were examined in the lakes, the lake outflows, and the downstream Mahoning River.

Purpose and Scope

The purpose of the study was to construct and calibrate flow, temperature, and water-quality models of Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River downstream to Lowellville, Ohio. The models simulate stage, flow, velocity, temperature, and water quality, and provide information on processes that control water quality. The models were used to investigate the changes in water temperature and water quality that would be likely to occur under various lake management scenarios.

Models were developed for 2 calendar years so that calibration could consider different flow and climate conditions. The years were different between waterbodies because of differences in the availability of water-quality data throughout the basin. A whole-basin model was then constructed for calendar year 2013, which was used for the model scenarios. The whole-basin model included construction of a Mosquito Creek model connection between Mosquito Creek Lake and the Mahoning River.

All lake and river models were built with the USGS modification of version 4.2 of CE-QUAL-W2. Modeled constituents included flow, velocity, ice cover, water temperature, total dissolved solids (TDS), sulfate, chloride, inorganic suspended sediment, nitrate, ammonia, total Kjeldahl nitrogen, orthophosphate, total phosphorus, dissolved and particulate organic matter, algae, and dissolved oxygen. Iron was included for the lake models, but not the river.

Environmental Setting and Site Information

The four lakes included in this study are in the upper reaches of the Mahoning River basin (fig. 1). The basin is about 37 percent forested and 24 percent developed urban land (U.S. Geological Survey, 2020). Agricultural land use is also common. The climate in the Mahoning River Basin is typically temperate and humid with a wide range of seasonal temperatures. The normal annual precipitation is about 35 inches per year (U.S. Geological Survey, 2020).

Berlin Lake, located about 11 miles (mi) upstream from Lake Milton dam on the Mahoning River, began operation in 1943. Berlin Lake dam is a concrete gravity dam with earth embankments (U.S. Army Engineer District, 1978a). The lake has a total storage capacity of 91,200 acre-ft with a backwater of 20.2 mi (U.S. Army Engineer District, 1978a). Dam outlets used during the study period included crest gates, ring jets, and ball valves (table 1). Authorized purposes for Berlin Lake include flood-risk management, downstream flow augmentation, and water-quality management along the Mahoning, Beaver, and upper Ohio Rivers.

Lake Milton on the Mahoning River downstream from Berlin Lake was constructed by the city of Youngstown in 1916–17. The dam is a concrete gravity structure with earth embankments (U.S. Army Engineer District, 1978a). The lake has a total storage capacity of 27,120 acre-feet (acre-ft), and the dam releases water through gate valve outlets (table 1). Through an agreement with the City of Youngstown, USACE oversees the operation of Lake Milton dam, in conjunction with operations at Berlin Lake dam.

Michael J Kirwan Reservoir was built on West Branch Mahoning River and controls 80.5 mi^2 of drainage area. The dam began operation in 1966. It is a rolled-earth fill embankment dam with a storage capacity of 78,700 acre-ft and 8.1 mi of backwater (U.S. Army Engineer District, 1978b). The dam has six gates at three different elevations (table 1). Authorized purposes for Michael J Kirwan Reservoir include flood-risk management, water supply, and water-quality management.

Mosquito Creek Lake was built on Mosquito Creek and controls 97.4 mi^2 of drainage area. The dam was constructed and began operation in 1944. The dam is a rolled-earth fill structure, and the lake has a capacity of 104,100 acre-ft with 14.7 mi of backwater (U.S. Army Engineer District, 1978c). Outlets used during the study period include gate valves and gates for USACE releases, as well as a separate withdrawal outflow for the City of Warren's drinking water supply (table 1) that was constructed in 1957 and upgraded in the 1980s (Ohio Environmental Protection Agency, 2003). Authorized purposes for Mosquito Creek Lake include flood-risk management, water supply, and water-quality management.

Other lakes in the Mahoning River Basin, not included in this study, include Deer Creek Lake upstream from Berlin Lake (fig. 1) with 3,180 acre-ft of storage capacity and Meander Creek Reservoir (fig. 1) with 35,400 acre-ft of storage capacity. Meander Creek Reservoir is on Meander Creek, a tributary of the Mahoning River.

The Mahoning River is 109 mi long. The physical habitat and flow are affected by the lakes, lake releases, and a number of low-head dams (Rayamajhi, 2012). For example, the reach of the Mahoning River above Leavittsburg is strongly controlled by the outflows of Berlin Lake, Lake Milton, and Michael J Kirwan Reservoir. Taken together, these dams control 62 percent of the drainage area upstream from Leavittsburg (U.S. Army Engineer District, 1978a).

Table 1. Storage capacity and elevations, Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake, Ohio.

[Elevations are in feet [meters] above the North American Vertical Datum of 1988. Dam outlets used during the study period included gates, crest gates, gate valves, ring jets, and ball valves. Years when operations began: Berlin Lake, 1943; Lake Milton, 1917; Michael J Kirwan Reservoir, 1966; Mosquito Creek Lake, 1944. NA, not applicable]

Storage capacity or elevation	Berlin Lake	Lake Milton	Michael J Kirwan Reservoir	Mosquito Creek Lake
Storage capacity, acre-feet	91,200	27,120	78,700	104,100
Dam height above streambed, foot [meter]	96 [29]	60 [18]	83 [25]	47 [14]
Dam top elevation	1,044.7 [318.4]	959.9 [292.6]	1,010.3 [307.9]	915.4 [279.0]
Spill crest elevation	1,031.7 [314.5]	950.4 [289.7]	992.3 [302.5]	904.4 [275.7]
Full pool elevation	1,031.3 [314.3]	950.4 [289.7]	992.6 [302.5]	903.3 [275.3]
Summer pool elevation	1,024.0 [312.1]	947.4 [288.8]	985.1 [300.2]	900.7 [274.5]
Outlet elevation	1,013.7 [309.0] (Crest gates 1–4)	914.4 [278.7] (Gate valves 1–2)	971.3 [296.1] (Gate 6)	884.4 [269.6] (Gate valves 1–2)
Outlet elevation	956.2 [291.4] (Ring jets 1–2; Ball valves)	907.4 [276.6] (Gate valves 3–4)	955.3 [291.2] (Gate 5)	874.4 [266.5] (Gates 1–4)
Outlet elevation	NA	NA	938.3 [286.0] (Gate 4)	891.4, 885.2, 875.2 [271.7, 269.8, 266.7] (City of Warren 1–3; the 271.7 outlet was used in the model for the Warren outflow)
Outlet elevation	NA	NA	935.3 [285.1] (Gates 1–3)	NA
Area capacity table elevation minimum, maximum	959.3, 1045.3 [292.4, 318.6]	929.4, 960.4 [283.3, 292.7]	929.6, 1010.6 [283.3, 308.0]	875.3, 916.3 [266.8, 279.3]

Methods and Data

Model Description

The Mahoning River Basin models were constructed with a USGS modification of version 4.2 of CE-QUAL-W2 (Wells, 2020; Stratton Garvin and Rounds, 2022), a two-dimensional, laterally averaged hydrodynamic and water-quality model program. This model simulates conditions longitudinally (upstream to downstream) and vertically (water surface to channel bottom) and is laterally averaged (from bank to bank). CE-QUAL-W2 can simulate water level, flow, water velocity, water temperature, ice cover, and many water-quality constituents. It has been applied to hundreds of rivers and lakes around the world (Wells, 2020).

The models used in this study were developed in several steps. First, model grids were constructed to represent the bathymetry of the four lakes and the reaches of the Mahoning River downstream to Lowellville. Then, the required input data were collected and formatted to provide meteorological, hydrological, and water temperature and water-quality boundary conditions.

Water budgets for the modeled waterbodies were calibrated by comparing measured and modeled water levels to estimate the gains or losses of water from ungaged inflows, outflows, and groundwater interactions. Water temperature and water-quality constituents were calibrated by comparing measurements at locations throughout the reach to model predictions at the same date, time, and location.

The CE-QUAL-W2 model uses a variable time step; for these models, the time step generally was between 50 and 800 seconds. The model was set up to run in Eastern Standard Time (EST). Field data in Eastern Daylight Time (EDT) were converted to EST for model input files; model output files in EST were converted to EDT when necessary for comparison with field calibration data.

Model Grids

A CE-QUAL-W2 model grid is formed from model segments (the longitudinal model unit) that connect in the direction of flow. Each segment has layers of defined height that increase in width from the channel bottom to the top of the grid, resembling a cross-sectional shape of stacked rectangles. Segments are grouped together into “branches” and “waterbodies” that define specific river or tributary reaches.

Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake

Raw bathymetric data for most of the modeled lakes were obtained from a publicly available database (Ohio Department of Natural Resources, 2020). Berlin Lake bathymetry was published January 8, 2009, Lake Milton bathymetry was published January 1, 2008, and Mosquito Creek Lake bathymetry was published January 1, 2012. Provisional bathymetric data were used for Michael J Kirwan Reservoir (unpublished data, written communication, Kevin Page, Ohio Department of Natural Resources, October 18, 2019). Using a geographic information system, digital elevation models (DEMs) were created from the raw data, and cross-sectional shapes were extracted to produce the model grids (figs. 2–4). Some adjustments were made to the initial grids so that no cells in the grid had widths of less than 5 m, which can increase model run time, and to ensure that no segments were isolated from mixing. Lake grid segment lengths ranged from 415 to 647 m, and layer heights were uniformly set to 2 feet (ft) (0.61 m). Model “constrictions” were placed at locations where causeways or bridges across the lakes impeded the flow of water.

Volume-elevation curves derived from the lake model grids were compared to USACE volume-elevation curves. The USACE curves were developed from topographic maps, aerial photographs, or aerial surveys made prior to 1978. The volume-elevation curves for the Berlin and Mosquito Creek Lake model grids had less volume than the original USACE volume-elevation curves (figs. 2, 4). Sedimentation in these older lakes in the period between construction and the Ohio Department of Natural Resources surveys likely contribute to these differences (Renwick and Andereck, 2006). The volume-elevation curve for the Michael J Kirwan Reservoir model grid was similar to the USACE curve at lower elevations and had slightly more volume at higher elevations (fig. 3). The USACE Lake Milton volume-elevation curve only went down to an elevation of 930 ft (fig. 2), but the elevations of the outlets are lower than that, and the Ohio Department of Natural Resources survey also showed nonzero lake volumes at elevations below 930 ft.

Lake outflows were specified in the models to be released at the centerline elevations of the dam outlet structures (table 1). If multiple outlets occur at the same elevation, those outflows were grouped together. The City of Warren has their own three municipal water withdrawal outlets from Mosquito Creek Lake, separate from the USACE outlets and at separate elevations. The City of Warren often uses their top outlet, so that was the elevation specified in the models. All outlet structures were set up within CE-QUAL-W2 using the GATE option, which allows dam reaeration to be modeled. In the years modeled, Berlin Lake outflow releases by USACE were mostly through the 956.2 ft (291.4 m) elevation outlets; Lake Milton releases were through the 914.4 ft outlets (278.7 m); Mosquito Creek Lake releases were through three outlet elevations; Michael J Kirwan Reservoir releases were from four outlet elevations.

Mahoning River and Mosquito Creek

The Mahoning River model included the reach below Lake Milton dam down to Lowellville (fig. 5). West Branch Mahoning River also was modeled from below Michael J Kirwan Reservoir dam to the confluence with the main-stem Mahoning River.

The Mahoning River and Mosquito Creek model grids were created with information from several sources, including (1) river bottom channel elevations from a USACE HEC-RAS model, (2) channel width from aerial imagery and a lidar-derived DEM provided by USACE, (3) river cross sections determined via acoustic Doppler current profiler (ADCP) measurements at USGS streamgage locations, and (4) river bottom channel and structure elevations from flood insurance studies (Federal Emergency Management Agency, 2009, 2010). The cross-sectional shapes were interpolated over the entire reach and combined with the initial channel widths to define cross-sectional widths. At several locations, river widths from aerial imagery at known dates and flows were checked against modeled surface widths.

The Mahoning River has multiple low-head dams along its reach (table 2). Some were in good repair and others were crumbling remnants previously used by industry. The river grid was divided into 12 CE-QUAL-W2 waterbodies, with 11 of the waterbodies having a low-head dam at their downstream end. The one waterbody without a dam at its end is located on West Branch Mahoning River between the Newton Falls Dam and the confluence of West Branch and main-stem Mahoning Rivers.

Heights of the Mahoning River low-head dams were obtained from river cross-sections in the flood insurance study. Weir top widths were taken from HEC-RAS models and estimated when not included. Spillway coefficients were taken from the HEC-RAS model and converted to SI units for use in the CE-QUAL-W2 model.

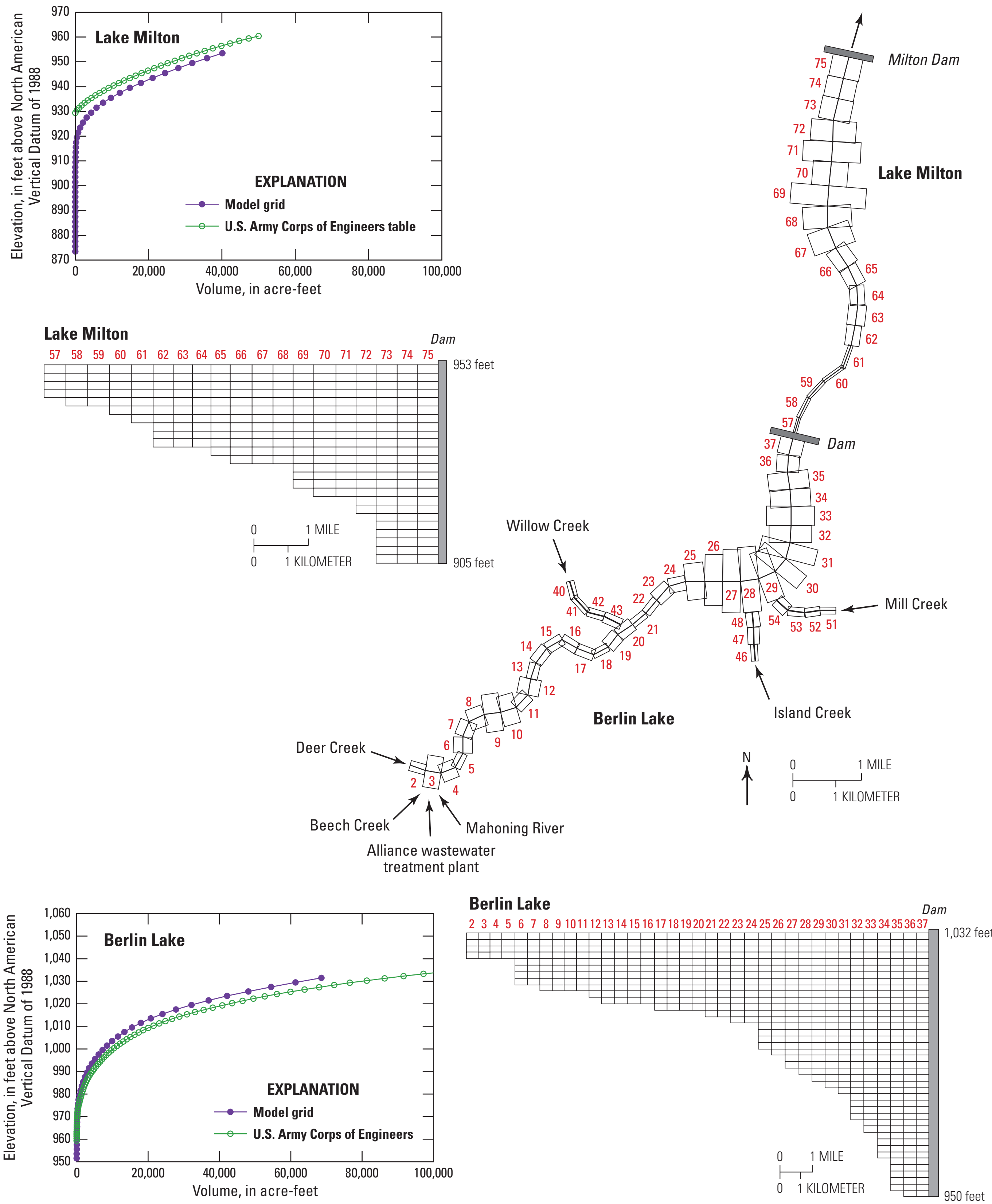


Figure 2. Berlin Lake and Lake Milton, Ohio, volume-elevation curves, grid top views, and main branch side views. Model segment numbers (in red) and inflow locations are noted. The Berlin Lake grid includes segments 2–54, and the Lake Milton grid includes segments 57–75.

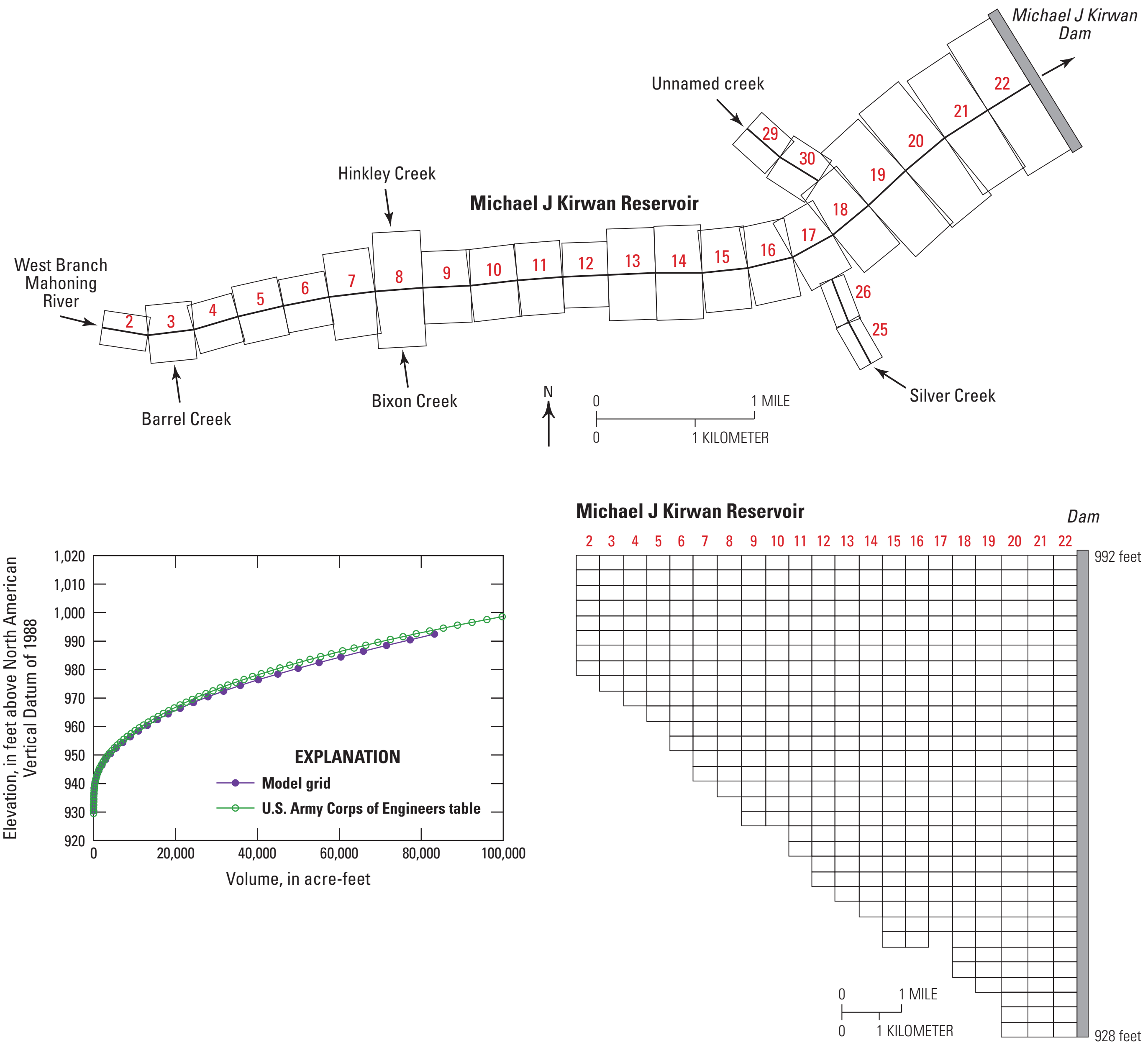


Figure 3. Michael J Kirwan Reservoir grid top view, volume-elevation curve, and main branch side view, Ohio. Model segment numbers (in red) and inflow locations are noted.

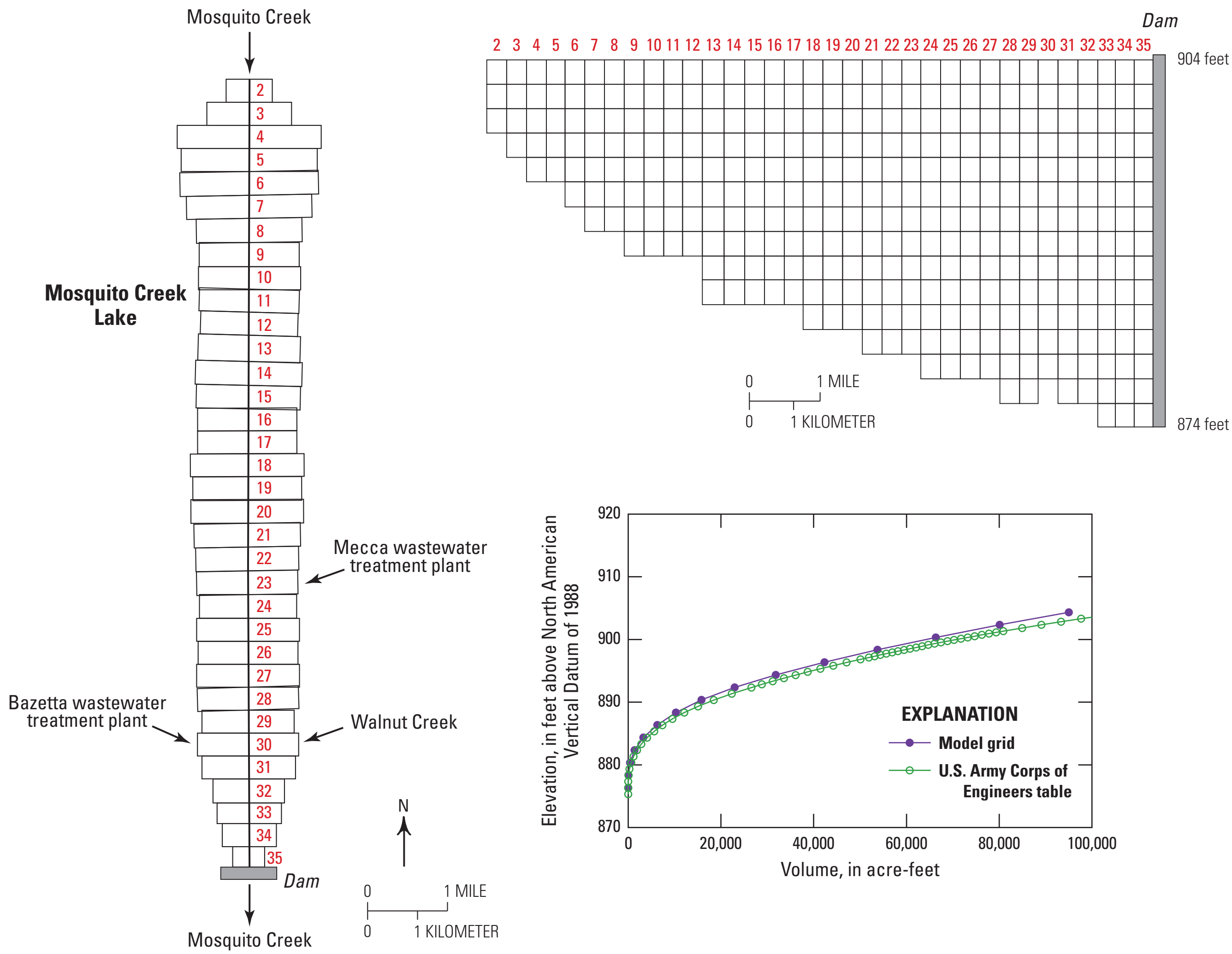


Figure 4. Mosquito Creek Lake grid top view, main branch side view, and volume-elevation curve, Ohio. Model segment numbers (in red) and inflow locations are noted.

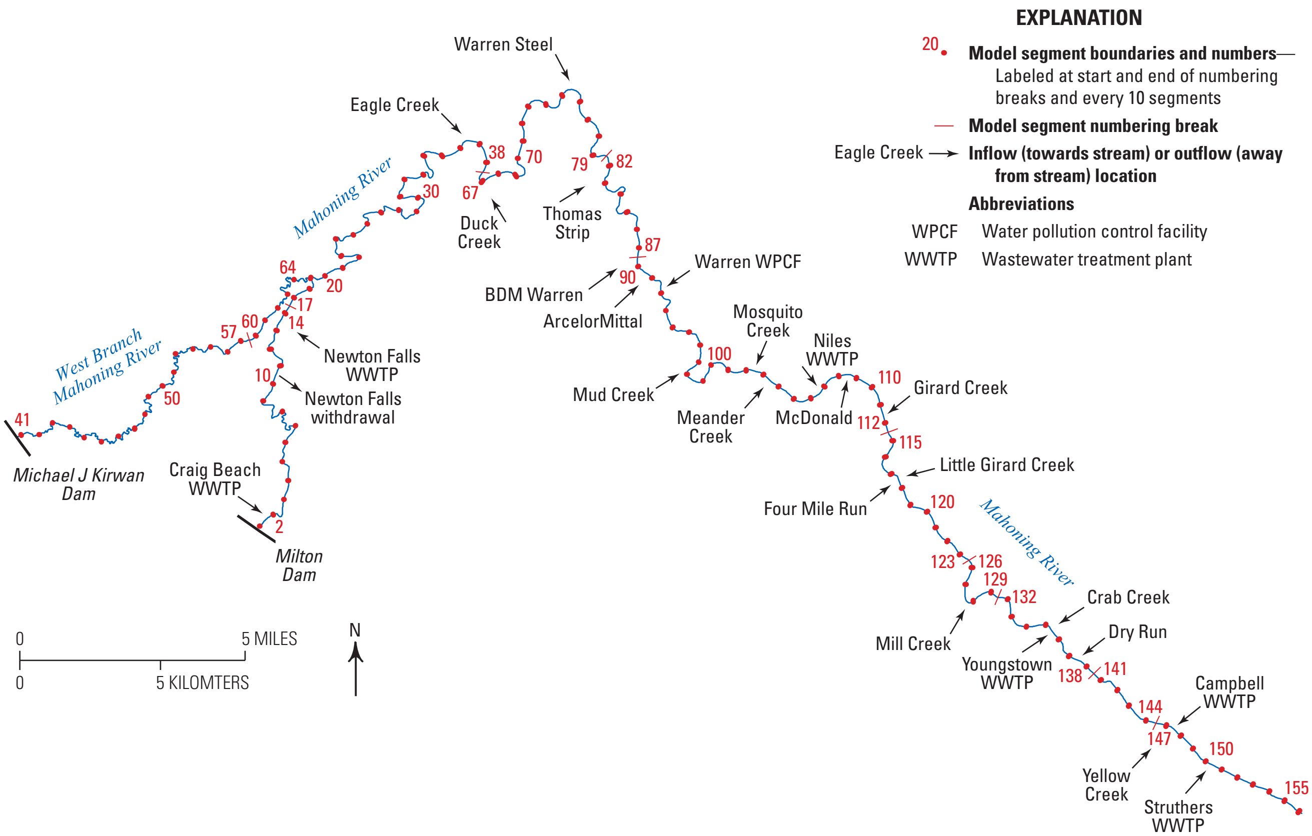


Figure 5. Grid top view, model segment numbers, and inflow and outflow locations, Mahoning River, Ohio, 2013.

Table 2. Low-head dam information for Mahoning River, Ohio.

Model spillway	Low-head dam	Latitude, longitude (decimal degrees)
1	Newton Falls (Mahoning River)	41.1963, –80.9666
2	Leavittsburg Dam	41.2389, –80.8820
3	Newton Falls (West Branch Mahoning River)	41.1891, –80.9791
4	Warren Water Works	41.2440, –80.8272
5	Republic Steel Warren Works	41.2113, –80.8150
6	Girard Mills Dam	41.1544, –80.7059
7	Crescent Street Dam	41.1133, –80.6722
8	Mahoning Avenue Dam	41.1007, –80.6559
9	Center Street Dam	41.0767, –80.6172
10	Struthers Dam	41.0618, –80.5893
11	Lowellville downstream	41.0334, –80.5326

Model Data

The available water-quality data for the Mahoning River Basin were variable in that different lake or river reaches had plentiful data, but often in different years. As CE-QUAL-W2 models depend heavily on the quality and availability of input data, the calendar years for model calibration were different for the various lakes and river reaches:

- Berlin Lake and Lake Milton (2006, 2017)
- Michael J Kirwan Reservoir (2006, 2019)
- Mosquito Creek Lake (2013, 2018)
- Mahoning River (2013, 2019)
- Whole basin model (2013)

For the period 1998–2019, median daily flow in the Mahoning River at Youngtown was 747 ft^3/s. Median daily flow in the calendar years modeled were:

- 1,200 ft^3/s for 2006,
- 721 ft^3/s for 2013,
- 707 ft^3/s for 2017,
- 1,030 ft^3/s for 2018, and
- 919 ft^3/s for 2019.

The available data were divided into two groups: data used to build the model and data used to calibrate the model. Data used to build the model included meteorology, shade, flow, and water temperature and water-quality data to characterize tributaries and point sources that flow into the modeled waterbodies (tables 3–4; fig. 1). Calibration data included measurements at locations within the modeled waterbodies themselves (or just downstream from a waterbody outflow) (table 5; fig. 1) and were used as independent checks of model predictions.

Most water-quality input and calibration data, as well as model output, used units of mg/L. More specifically, concentrations of ammonia, nitrate, total nitrogen, and total Kjeldahl nitrogen (TKN, a measure of organic nitrogen and ammonia) used concentration units of mg/L as N. Orthophosphate and total phosphorus used units of mg/L as P. Sulfate concentrations were mg/L as SO_4. Chlorophyll *a* concentrations were output in units of µg/L.

Meteorology

Meteorological data from the National Weather Service (NWS) at Youngstown, Ohio, was selected to provide most of the meteorological data for the models. These data included air temperature, dewpoint temperature, wind speed, wind direction, and cloud-cover measurements. Cloud-cover data were converted from Automated Surface Observing Systems (ASOS) descriptors into model units. Precipitation was also obtained from the NWS site at Youngstown, and precipitation temperatures were estimated to be equal to air temperature when air temperature was greater than or at 0 °C. Precipitation temperature was set to 0 °C when air temperature was below 0 °C.

Solar radiation data were not available from the NWS, so hourly solar radiation datasets were obtained from the Pennsylvania Department of Environmental Protection for a site at New Castle, Pennsylvania, and from the Ohio Agricultural Research and Development Center at Wooster. The solar dataset from the Pennsylvania Department of Environmental Protection site was selected as model input because it had fewer spurious data points, the site was close geographically to the Mahoning River Basin (approximately 18 mi), and the timing of the daily maximum solar radiation was close to the timing of the theoretical daily maximum solar radiation at Youngstown, Ohio.

Shade

Vegetative shade was included in the Mahoning River and Mosquito Creek models because vegetation was present along most of the channel and at times overhanging across the water. Typical plant species growing between the river channel and the ordinary high-water line included silver maple (*Acer saccharinum*), black willow (*Salix nigra*), sycamore (*Sycamore occidantalis*), box elder (*Acer negundo*), cottonwood (*Populus deltoides*), and slippery elm (*Ulmus rubra*). Vegetation height was estimated as the average height of the most common species in a reach. A lidar-derived DEM provided by USACE was used to derive the distance from the river-centerline to the controlling line of vegetation on both banks for each model segment. Leaf-on and leaf-off dates were set as typical for the region. Canopy density was estimated as 0.4 (40 percent blockage of sunlight) for the period when deciduous leaves were present and as 0.0 (no blockage) for the period when deciduous leaves were not present. These density values were set to be the same for the entire river reach. Vegetative shade was negligible for the lakes and therefore not included in those models. Topographic shading was not implemented for the river or lake models.

Table 3. Sampling sites used for model input, Berlin Lake, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[U.S. Army Corps of Engineers (USACE) data were provided by USACE and are provided as a U.S. Geological Survey (USGS) data release in conjunction with this report (Sullivan, 2022). Ohio Environmental Protection Agency (OEPA) data were downloaded from the Water Quality Portal (National Water Quality Monitoring Council, 2022, https://www.waterqualitydata.us/). USGS data were downloaded from USGS National Water Information System (U.S. Geological Survey, 2022, https://waterdata.usgs.gov/nwis)]

Site name	Site number	Agency	Latitude, longitude (decimal degrees)	Waterbody
Mahoning River	1108	USACE	40.9313, –81.1017	Berlin Lake
Mill Creek	2106	USACE	41.0096, –80.9734	Berlin Lake
Island Creek	2107	USACE	40.9846, –81.0082	Berlin Lake
Beech Creek	2110	USACE	40.9544, –81.1266	Berlin Lake
Willow Creek	2111	USACE	41.0247, –81.0736	Berlin Lake
Beech Creek	2115	USACE	40.9450, –81.1308	Berlin Lake
Deer Creek	2122	USACE	40.9685, –81.1203	Berlin Lake
Mill Creek	2146	USACE	40.9999, –80.9684	Berlin Lake
Deer Creek	300025	OEPA	40.9799, –81.1481	Berlin Lake
Mill Creek	300026	OEPA	41.0079, –80.9864	Berlin Lake
Beech Creek	300027	OEPA	40.9544, –81.1268	Berlin Lake
Mill Creek	300061	OEPA	41.0000, –80.9685	Berlin Lake
Willow Creek	300062	OEPA	41.0256, –81.0796	Berlin Lake
Mahoning River	602420	OEPA	40.9328, –81.0947	Berlin Lake
Mill Creek	N01K01	OEPA	41.0339, –80.9478	Berlin Lake
Island Creek	N01K06	OEPA	40.9732, –81.0127	Berlin Lake
Mahoning River	N01S12	OEPA	40.9314, –81.1019	Berlin Lake
Mahoning River	03086500	USGS	40.9327, –81.0947	Berlin Lake
West Branch Mahoning River	1107	USACE	41.1542, –81.1980	Michael J Kirwan Reservoir
Bixon Creek	2106	USACE	41.1193, –81.1570	Michael J Kirwan Reservoir
Silver Creek	2102	USACE	41.1188, –81.1060	Michael J Kirwan Reservoir
Hinkley Creek	2104	USACE	41.1524, –81.1676	Michael J Kirwan Reservoir
West Branch Mahoning River	300022	OEPA	41.1616, –81.1974	Michael J Kirwan Reservoir
Silver Creek	N02K20	OEPA	41.1187, –81.1061	Michael J Kirwan Reservoir
Hinkley Creek	N02K22	OEPA	41.1520, –81.1678	Michael J Kirwan Reservoir
West Branch Mahoning River	03092090	USGS	41.1613, –81.1972	Michael J Kirwan Reservoir
Mosquito Creek	1109	USACE	41.4827, –80.7468	Mosquito Creek Lake
Walnut Creek	2104	USACE	41.3233, –80.7330	Mosquito Creek Lake
Mosquito Creek	N03W16	OEPA	41.4619, –80.7550	Mosquito Creek Lake
Walnut Creek	302304	OEPA	41.3247, –80.7316	Mosquito Creek Lake
Mosquito Creek	03094704	USGS	41.4830, –80.7461	Mosquito Creek Lake
Meander Creek	2020	USACE	41.1704, –80.7671	Mahoning River
Eagle Creek	2340	USACE	41.2609, –80.9544	Mahoning River

Table 3. Sampling sites used for model input, Berlin Lake, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.—Continued

[U.S. Army Corps of Engineers (USACE) data were provided by USACE and are provided as a U.S. Geological Survey (USGS) data release in conjunction with this report. Ohio Environmental Protection Agency (OEPA) data were downloaded from the Water Quality Portal (National Water Quality Monitoring Council, 2022, https://www.waterqualitydata.us/). USGS data were downloaded from USGS National Water Information System (U.S. Geological Survey, 2022, https://waterdata.usgs.gov/nwis)]

Site name	Site number	Agency	Latitude, longitud (decimal degrees)	Waterbody
Girard Creek	301198	OEPA	41.1441, –80.6957	Mahoning River
Crab Creek	302156	OEPA	41.1046, –80.6370	Mahoning River
Mud Creek	302308	OEPA	41.1761, –80.8048	Mahoning River
Girard Creek	302309	OEPA	41.1715, –80.7044	Mahoning River
Little Girard Creek	302315	OEPA	41.1434, –80.6964	Mahoning River
Meander Creek	602380	OEPA	41.1706, –80.7644	Mahoning River
Dry Run	N03K34	OEPA	41.0872, –80.6203	Mahoning River
Duck Creek	N03P02	OEPA	41.2372, –80.8819	Mahoning River
Four Mile Run	N03P08	OEPA	41.1358, –80.7133	Mahoning River
Mill Creek	N03S02	OEPA	41.0881, –80.6733	Mahoning River
Yellow Creek	N03S18	OEPA	41.0597, –80.5858	Mahoning River

Table 4. Point-source effluent locations, Berlin and Mosquito Creek Lakes and Mahoning River, Ohio.

[Data were uploaded by the point sources to U.S. Environmental Protection Agency (USEPA) and provided by the Ohio Environmental Protection Agency for this study. **Abbreviations**: EPA, U.S. Environmental Protection Agency; WWTP, wastewater treatment plan; WPCF, water pollution control facility; LLC, limited liability corporation]

Name	Ohio identifier	EPA Registry identifier	Waterbody
Alliance WWTP	3PD00000*JD	OH0023868	Berlin Lake
Bazetta WWTP	3PG00140*HD	OH0092550	Mosquito Creek Lake
Mecca	3PG00104*FD	OH0091634	Mosquito Creek Lake
Trumbull Mosquito Creek WWTP	3PK00009*QD	OH0043401	Mosquito Creek
Craig Beach WWTP	3PH00030*GD	OH0043851	Mahoning River
Newton Falls WPCF	3PD00015*GD	OH0022110	Mahoning River
Warren Steel	3ID00050 Outfall 005	OH0011207	Mahoning River
Thomas Strip Steel	3IC00056 Outfall 001	OH0011363	Mahoning River
BDM Warren Steel	3ID00071 Outfall 013	OH0101079	Mahoning River
ArcelorMittal Cleveland LLC	3ID00004 Outfall 014 015	OH0011274	Mahoning River
Warren WPCF	3PE00008 Outfall 001	OH0027987	Mahoning River
Niles WWTP	3PD00036 Outfall 001	OH0026743	Mahoning River
McDonald Steel	3ID00058	OH0064220	Mahoning River
Youngstown WWTP	3PE00006 Outfall 001	OH0028223	Mahoning River
Campbell WWTP	0PD0008	OH0024325	Mahoning River
Struthers WWTP	3PD00026	OH0027600	Mahoning River

Table 5. Sampling sites used for model calibration data, Berlin Lake, Michael J Kirwan Reservoir, Mosquito Creek Lake, Mosquito Creek, and Mahoning Rivers, Ohio, 2013.

[U.S. Army Corps of Engineers data were provided by USACE and are provided as a U.S. Geological Survey (USGS) data release in conjunction with this report. Ohio Environmental Protection Agency data were downloaded from the Water Quality Portal (U.S. Geological Survey, 2022, https://www.waterquality-data.us/). USGS data were downloaded from USGS NWIS (https://waterdata.usgs.gov/nwis). **Abbreviations**: USACE, U.S. Army Corps of Engineers; OEPA, Ohio Environmental Protection Agency; USGS, U.S. Geological Survey; WSEL, water surface elevation]

Site name	Site number	Agency	Latitude, longitude (decimal degrees)	Waterbody
Berlin Lake outflow	1201	USACE	41.0479, –81.0016	Berlin Lake
Berlin Lake	1002	USACE	41.0457, –81.0022	Berlin Lake
Berlin Lake	1003	USACE	41.0216, –80.9999	Berlin Lake
Berlin Lake	1004	USACE	41.0052, –81.0220	Berlin Lake
Berlin Lake	1005	USACE	41.0046, –81.0505	Berlin Lake
Berlin Lake	1006	USACE	40.9964, –81.0769	Berlin Lake
Berlin Lake	1007	USACE	40.9828, –81.0981	Berlin Lake
Berlin Lake	1008	USACE	40.9622, –81.1136	Berlin Lake
Berlin Lake outflow	N01S11	OEPA	41.0483, –81.0017	Berlin Lake
Lake Milton outflow	03091500	USGS	41.1313, –80.9713	Berlin Lake
Berlin WSEL	03090000	USGS	41.0461, –81.0027	Berlin Lake
Berlin outflow	03090500	USGS	41.0483, –81.0013	Berlin Lake
Lake Milton WSEL	3091000	USGS	41.1272, –80.9777	Berlin Lake
Berlin Buoy	1002	USACE	41.0450, –81.0030	Berlin Lake
Michael J Kirwan Reservoir outflow	1201	USACE	41.1575, –81.0780	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	1002	USACE	41.1548, –81.0808	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	1003	USACE	41.1447, –81.0983	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	1004	USACE	41.1352, –81.1272	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	1005	USACE	41.1412, –81.1613	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	1006	USACE	41.1351, –81.1919	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir	300056	OEPA	41.1574, –81.0714	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir WSEL	03092450	USGS	41.1566, –81.0797	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir outflow	03092460	USGS	41.1569, –81.0719	Michael J Kirwan Reservoir
Michael J Kirwan Reservoir Buoy	1002	USACE	41.1564, –81.0814	Michael J Kirwan Reservoir
Mosquito Creek outflow	03095500	USGS	41.2997, –80.7586	Mosquito Creek Lake
Mosquito Creek outflow	1201	USACE	41.2990, –80.7583	Mosquito Creek Lake
Mosquito Creek Lake	1002	USACE	41.3006, –80.7581	Mosquito Creek Lake
Mosquito Creek Lake	1003	USACE	41.3145, –80.7529	Mosquito Creek Lake
Mosquito Creek Lake	1007	USACE	41.3898, –80.7496	Mosquito Creek Lake
Mosquito Creek Lake	1008	USACE	41.4088, –80.7513	Mosquito Creek Lake
Mosquito Creek outflow	N03S24	OEPA	41.2992, –80.7583	Mosquito Creek Lake

Table 5. Sampling sites used for model calibration data, Berlin Lake, Michael J Kirwan Reservoir, Mosquito Creek Lake, Mosquito Creek, and Mahoning Rivers, Ohio, 2013.—Continued

[U.S. Army Corps of Engineers data were provided by USACE and are provided as a U.S. Geological Survey (USGS) data release in conjunction with this report. Ohio Environmental Protection Agency data were downloaded from the Water Quality Portal (U.S. Geological Survey, 2022, https://www.waterquality-data.us/). USGS data were downloaded from USGS NWIS (https://waterdata.usgs.gov/nwis). **Abbreviations**: USACE, U.S. Army Corps of Engineers; OEPA, Ohio Environmental Protection Agency; USGS, U.S. Geological Survey; WSEL, water surface elevation]

Site name	Site number	Agency	Latitude, longitude (decimal degrees)	Waterbody
Mosquito Creek	N03W06	OEPA	41.2506, –80.7638	Mosquito Creek
Mosquito Creek	N03S21	OEPA	41.2378, –80.7567	Mosquito Creek
Mosquito Creek	602370	OEPA	41.1828, –80.7603	Mosquito Creek
Mosquito Creek	N03S48	OEPA	41.1800, –80.7633	Mosquito Creek
Mosquito Creek WSEL	03095000	USGS	41.2994, –80.7586	Mosquito Creek Lake
Mahoning River	1006	USACE	41.0359, –80.5362	Mahoning River
Mahoning River	1010	USACE	41.1021, –80.6563	Mahoning River
Mahoning River	1020	USACE	41.1703, –80.7368	Mahoning River
Mahoning River	1038	USACE	41.2277, –80.8165	Mahoning River
Mahoning River	1039	USACE	41.2356, –80.8216	Mahoning River
Mahoning River	1040	USACE	41.2393, –80.8808	Mahoning River
Mahoning River	1050	USACE	41.1954, –80.9675	Mahoning River
Mahoning River	1062	USACE	41.1341, –80.9677	Mahoning River
West Branch Mahoning River	3000	USACE	41.1978, –80.9699	Mahoning River
Mahoning River	200405	OEPA	41.2414, –80.8286	Mahoning River
Mahoning River	301178	OEPA	41.1004, –80.6559	Mahoning River
Mahoning River	602280	OEPA	41.2392, –80.8808	Mahoning River
Mahoning River	602330	OEPA	41.1222, –80.6836	Mahoning River
Mahoning River	N03K03	OEPA	41.0378, –80.5408	Mahoning River
Mahoning River	N03K04	OEPA	41.0439, –80.5567	Mahoning River
Mahoning River	N03K17	OEPA	41.0922, –80.6381	Mahoning River
Mahoning River	N03K31	OEPA	41.2136, –80.8156	Mahoning River
Mahoning River	N03Q01	OEPA	41.2425, –80.8281	Mahoning River
Mahoning River	N03S43	OEPA	41.2361, –80.8208	Mahoning River
Mahoning River	N03S54	OEPA	41.1019, –80.6733	Mahoning River
Mahoning River	N03S56	OEPA	41.1544, –80.7061	Mahoning River
Mahoning River	N03S57	OEPA	41.1747, –80.7328	Mahoning River
Mahoning River	N03S59	OEPA	41.2008, –80.8044	Mahoning River
Mahoning River	N03S60	OEPA	41.2069, –80.8083	Mahoning River
Mahoning River	N03S64	OEPA	41.2406, –80.8831	Mahoning River
Mahoning River	N03W18	OEPA	41.1709, –80.7525	Mahoning River
Mahoning River	N03W20	OEPA	41.1050, –80.6638	Mahoning River
Mahoning River	N03W21	OEPA	41.0761, –80.6161	Mahoning River
Mahoning River	N03W28	OEPA	41.0493, –80.5692	Mahoning River
Eagle Creek	03093000	USGS	41.2611, –80.9544	Mahoning River
Leavittsburg	03094000	USGS	41.2391, –80.8808	Mahoning River
Warren	411402080492400	USGS	41.2338, –80.8233	Mahoning River
Youngstown	03098600	USGS	41.1050, –80.6627	Mahoning River
Lowellville	03099500	USGS	41.0383, –80.5363	Mahoning River

Tributary and Point Source Flows

Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake

Calculated total inflows on an hourly basis for Berlin Lake and Michael J Kirwan Reservoir were provided by USACE. These estimates included precipitation. Precipitation was included as a separate meteorological input to the model as described previously, so that amount of hourly precipitation was subtracted from the USACE total inflow timeseries. These inflows were then apportioned into individual tributary inflows by assuming that flow was proportional to watershed area; watershed areas were determined with the USGS StreamStats application (U.S. Geological Survey, 2020). Measured USGS inflow data from the 1940s was available for individual tributaries to Berlin Lake. The flows estimated by watershed area were similar to those measured flows from the subwatersheds, showing that this approach was appropriate for the unregulated tributaries. The Deer Creek tributary to Berlin Lake was dammed and regulated, thus the timing and amounts of flow over short time periods for that inflow may differ from that estimated by a watershed approach. However, since recent flow data for Deer Creek were not available, the watershed area approach to estimating flow also was used for Deer Creek.

Calculated total inflows for Mosquito Creek Lake from USACE had numerous negative values, possibly due to wind-caused variability in the measured water surface elevation, which USACE used in the calculation of total inflows (oral communication, John Sourbeer, USACE, April 4, 2020). Thus, total USACE inflows were not used for this lake. Measured flow was available for Mosquito Creek upstream from Mosquito Creek Lake and used to define that lake inflow. Walnut Creek inflows were estimated using Mosquito Creek flows and the ratio of Walnut Creek to Mosquito Creek watershed areas.

Due to the different ways that inflows were determined for the lakes, evaporative loss of water was included for Mosquito Creek Lake, but not for Berlin Lake, Lake Milton, and Michael J Kirwan Reservoir since those losses were part of the determination by USACE of total inflows.

Effluent discharge data were available for the most important point sources included in the model from discharge monitoring reports (DMRs) submitted to USEPA and provided to this study by OEPA (table 4). These important point sources included the Alliance WWTP outflow to Berlin Lake (fig. 2) and the Bazetta and Mecca WWTP outflows to Mosquito Creek Lake (fig. 4).

Dam outflows for Berlin Lake, Michael J Kirwan Reservoir, and Mosquito Creek Lake were provided by USACE. Flows were provided for each outlet or group of outlets at the same elevation (table 1). The total of these computed outflows was compared to measured flows downstream from the dams (table 5). Generally, these matched well, but in a few instances the computed outflows were modified slightly to better match the total measured flow just downstream from the dams.

Mahoning River and Mosquito Creek

Only limited flow data were available for tributary creeks and streams of the Mahoning River for the years of interest. One unregulated tributary is Eagle Creek for which streamflow has been measured since 1926 (USGS 03093000). Flows for the other, unmeasured, tributaries were estimated by multiplying measured Eagle Creek flows by a ratio of the tributary watershed area to Eagle Creek's total watershed area. These tributaries included Duck Creek, Mud Creek, Girard Creek, Little Girard Creek, Meander Creek, Four Mile Run, Crab Creek, Mill Creek, Dry Run, and Yellow Creek. Watershed areas were determined with the USGS StreamStats application (U.S. Geological Survey, 2020). The Meander Creek tributary to the Mahoning River was dammed and regulated; however, lake outflow or other flow data were not available. Thus, the watershed drainage area ratio approach to estimating flow also was used for Meander Creek. A Mosquito Creek model was constructed for the whole-basin model; its upstream boundary was the outflow from Mosquito Creek Lake.

Effluent discharge flow data on a daily to weekly basis were available for most of the point sources included in this model from DMRs submitted to USEPA (table 4). These included Craig Beach WWTP, Newton Falls WWTP, Warren Steel, Thomas Strip, BDM Warren, Arcelor Mittal, Warren Water Pollution Control Facility, Niles WWTP, McDonald Steel, Youngstown WWTP, Campbell WWTP, and Struthers WWTP. Trumbull Mosquito Creek was a point source discharge to Mosquito Creek, between Mosquito Creek Lake and the Mahoning River. Some WWTP discharges released effluent close to the Mahoning River, but the discharge point was into a creek or stream rather than the Mahoning River directly; this included Meander Creek and Girard WWTPs. To some extent, water-quality effects of these point sources were captured by including the water quality of the creek as an input, though the OEPA or USACE sampling of the tributary creeks was less frequent than DMR data.

One municipal withdrawal of water at Newton Falls was included in the Mahoning River model. Average monthly withdrawal rates were provided by OEPA (written communication, Gregory Orr, OEPA, March 9, 2020).

Tributary and Point Source Water Temperatures

A few tributary inflow locations, such as Mosquito Creek north of Mosquito Creek Lake, Mahoning River above Berlin Lake, and West Branch Mahoning River inflow to Michael J Kirwan Reservoir, had continuous water temperature data available, measured at frequent intervals (hourly to sub-hourly) with a submerged sensor, and those datasets were used to prepare input files for those locations. Mosquito Creek was missing temperature data from the first part of 2013; the nearby Pymatuning Creek (~8 mi away) USGS site (USGS 03102950) had similar water temperatures for periods when both sites had data and was used to estimate the missing Mosquito Creek data.

Continuous measured water temperatures for the Mahoning River above Berlin Lake and for Pymatuning Creek were available for all modeled years except 2006. While some differences were apparent in their daily variations, the two datasets were similar as a daily average (R^2=0.99 and slope=0.96). Daily average Pymatuning Creek or Mahoning River water temperature data were used for other tributary inflows that had limited or no water temperature data. Tributary water temperature data in 2006 were extremely limited, thus inflow water temperature was estimated from air temperature with a correlation model in that year (R^2=0.93 and slope=0.90).

Effluent water temperature data were available for most point sources. For those few industrial point sources to the Mahoning River that were not subject to temperature monitoring, their temperatures were assumed to be similar to the creeks and streams in the basin and were estimated were estimated to be equivalent to daily average Pymatuning Creek water temperatures. Temperatures of the model distributed tributaries, used in flow-balancing, were estimated similarly.

Tributary Water Quality

Some water-quality data to characterize tributary inflows were available for the years of interest from OEPA and USACE. The collection frequency varied among sites, from a couple of samples per year to as frequent as every few weeks in summer. Generally, sampling frequency was greater in summer and lesser in winter. Analyses for the determination of TDS, sulfate, chloride, orthophosphate, ammonia, nitrate, iron, and dissolved oxygen were often done for water samples collected from the watershed's tributaries. Thus, these constituents were directly included into model water-quality boundary conditions. Occasionally, when TDS values were not available, specific conductance values were used to estimate TDS with the equation (Hem, 1985):

$$\text{Total dissolved solids} = A \times SC \qquad (1)$$

where

SC is specific conductance in µS/cm and

A is a coefficient estimated as 0.65 for this study by comparing samples that had both TDS and specific conductance data available.

Natural dissolved and particulate organic matter is central to biogeochemical processes in lakes, but it is rarely measured directly in most water-quality sampling programs. Both are required as model inputs and thus had to be estimated. At first, estimates derived from nitrogen and phosphorus data were tested. However, the fact that orthophosphate concentrations were frequently below detection in the lake inflows led to greater difficulty using phosphorus measurements to estimate organic matter concentrations. Thus, nitrogen species were used to estimate organic matter levels. First, total organic nitrogen was calculated by subtracting ammonia concentrations from total Kjeldahl nitrogen (TKN, a measure of organic nitrogen and ammonia) laboratory measurements. This organic nitrogen concentration was converted into a total organic matter concentration using the model's ORGN parameter (table 6), which is the mass fraction of nitrogen in the modeled organic matter. The USGS National Water Information System (NWIS; U.S. Geological Survey, 2022) database was queried for historical data in eastern Ohio and western Pennsylvania that had both particulate and dissolved organic matter data available. The evidence from this query was used to support an estimate that divided the total organic matter estimates into 80 percent dissolved organic matter (DOM) and 20 percent particulate organic matter (POM). This division is also consistent with the fact that most freshwater DOM concentrations are greater than POM concentrations (Hope and others, 1994).

CE-QUAL-W2 further divides organic matter into labile (fast-decomposing) and refractory (slow-decomposing) organic matter. For that division, DOM was estimated as 8 percent labile (LDOM) and 92 percent refractory (RDOM), and POM was estimated as 80 percent labile (LPOM) and 20 percent refractory (RPOM). The DOM was partitioned this way because most freshwater DOM is refractory (Docherty and others, 2006). Values of POM were partitioned into relatively more labile material because algal-derived particulate organic matter tends to be more labile during the summer-autumn bloom times. These constants and ratios were used consistently across all waterbodies and years in the Mahoning River Basin models. Although these ratios were based on published literature values, they could be updated within the model framework in the future, if better information on the elemental composition or nature of organic matter in the Mahoning River Basin should become available. A sensitivity run for Mosquito Creek Lake was tested with input DOM of 18 percent LDOM, 82 percent RDOM, 70 percent LPOM, and 30 percent RPOM. Compared to the original model, this run resulted in changes of 0–6 percent concentration of nutrients and algae in the lake outflow, suggesting that the initial values selected were adequate for this study.

Three groups of planktonic algae were simulated in the models: (1) blue-greens, (2) diatoms, and (3) "other" as a catch-all to include all other algal species. USACE collected phytoplankton algal species data for some of the tributaries and within the modeled lakes and river. The data on individual species were grouped into these three model groups. Measured algal biovolume data (cubic microns per milliliter) were first converted to algal carbon concentrations (Rocha and Duncan, 1985), and then the algal carbon to organic matter ratio used in the CE-QUAL-W2 models was applied to provide the required model algal inputs in units of dry weight concentration. If algal biovolume data were not available, then chlorophyll *a* concentrations were converted into organic matter units and divided into algal groups by using similar patterns as observed in USACE datasets.

Table 6. Model parameters used to model flow and water quality in Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[**Abbreviations:** m^2/g, square meter per gram; °C, degrees Celsius; m/d, meter per day; P, phosphorus; N, nitrogen; C, carbon; OM, organic matter; O_2, oxygen; g, gram; g/m^3, gram per cubic meter; g/m^2, gram per square meter; m, meter; SOD, sediment oxygen demand; W, Watts; $(W/m^2)/°C$, Watt per square meter per degree Celsius]

Parameter	Value				Description
	Berlin Lake-Lake Milton	Michael J Kirwan Reservoir	Mosquito Creek Lake	Mahoning River	
WSC	1.0	1.0	1.0	1.0	Wind sheltering coefficient, dimensionless
AFW	9.2	9.2	9.2	9.2	Coefficient in wind speed formulation
BFW	0.46	0.46	0.46	0.46	Coefficient in wind speed formulation
CFW	2.0	2.0	2.0	2.0	Coefficient in wind speed formulation
EXH2O	0.8	0.85	0.4	0.6	Light extinction coefficient for water and dissolved constituents, m^{-1}
EXSS	0.05	0.05	0.05	0.05	Light extinction due to inorganic suspended solids, m^2/g
EXOM	0.1	0.1	0.1	0.1	Light extinction due to organic suspended solids, m^2/g
BETA	0.45	0.45	0.45	0.45	Fraction of solar radiation absorbed at water surface, dimensionless
TSED	9.4	9.4	9.4	9.4	Sediment temperature, °C
CBHE	0.3	0.3	0.3	0.3	Coefficient of bottom heat exchange, $(W/m^2)/°C$
LDOMDK	0.1	0.1	0.1	0.1	Labile dissolved organic matter decay rate, day^{-1}
RDOMDK	0.001	0.001	0.001	0.001	Refractory dissolved organic matter decay rate, day^{-1}
LRDDK	0.01	0.01	0.01	0.01	Labile to refractory dissolved organic matter conversion rate, day^{-1}
LPOMDK	0.04	0.04	0.04	0.04	Labile particulate organic matter decay rate, day^{-1}
RPOMDK	0.0008	0.0008	0.0008	0.0008	Refractory particulate organic matter decay rate, day^{-1}
LRPDK	0.01	0.01	0.01	0.01	Labile to refractory particulate organic matter conversion rate, day^{-1}
POMS	0.05	0.05	0.05	0.05	Particulate organic matter settling rate, m/d
OMT1	4	4	4	4	Lower temperature parameter for organic matter decay, °C
OMT2	25	25	25	25	Upper temperature parameter for organic matter decay, °C
OMK1	0.10	0.10	0.10	0.10	Fraction of organic matter decay rate at OMT1
OMK2	0.99	0.99	0.99	0.99	Fraction of organic matter decay rate at OMT2
ORGP	0.005	0.005	0.005	0.005	Stoichiometric equivalent between organic matter and phosphorus, g P/g OM
ORGN	0.08	0.08	0.08	0.08	Stoichiometric equivalent between organic matter and nitrogen, g N/g OM
ORGC	0.45	0.45	0.45	0.45	Stoichiometric equivalent between organic matter and carbon, g C/g OM
PARTP	0.0	0.0	0.0	0.0	Phosphorus partitioning coefficient for suspended solids, dimensionless
PO4R	0.00002	0.0005	0.002	0.001	Release rate of phosphorus from sediment, as a fraction of SOD
NH4R	0.15	0.04	0.06	0.001	Release rate of ammonium, as a fraction of SOD
NH4DK	0.1	0.1	0.1	1.2	Ammonia nitrification rate, day^{-1}
NH4T1	4	4	4	4	Lower temperature parameter for ammonia nitrification, °C

Table 6. Model parameters used to model flow and water quality in Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.—Continued

[**Abbreviations:** m^2/g, square meter per gram; °C, degrees Celsius; P, phosphorus; N, nitrogen; C, carbon; OM, organic matter, O_2, oxygen; g, gram; g/m^3, gram per cubic meter; g/m^2, gram per square meter; m, meter; SOD, sediment oxygen demand; W, Watts; (W/m^2)/°C, Watt per square meter per degree Celsius]

Parameter	Value				Description
	Berlin Lake-Lake Milton	Michael J Kirwan Reservoir	Mosquito Creek Lake	Mahoning River	
NH4T2	25	25	25	25	Upper temperature parameter for ammonia nitrification, °C
NH4K1	0.10	0.10	0.10	0.10	Fraction of nitrification rate at NH4T1
NH4K2	0.99	0.99	0.99	0.99	Fraction of nitrification rate at NH4T2
NO3DK	2.3	2.3	2.3	0.03	Denitrification rate, day^{-1}
NO3S	0.001	0.001	0.001	0.001	Denitrification rate, loss to sediments, m/d
NO3T1	4	4	4	4	Lower temperature parameter for nitrate denitrification, °C
NO3T2	25	25	25	25	Lower temperature parameter for nitrate denitrification, °C
NO3K1	0.10	0.10	0.10	0.10	Fraction of denitrification rate at NO3T1
NO3K2	0.99	0.99	0.99	0.99	Fraction of denitrification rate at NO3T2
O2NH4	4.57	4.57	4.57	4.57	Oxygen stoichiometry for nitrification, g O_2/ g N
O2OM	1.4	1.4	1.4	1.4	Oxygen stoichiometry for organic matter decay, g O_2/ g OM
O2AR	1.1	1.1	1.1	1.1	Oxygen stoichiometry for algal respiration, g O_2/g algae
O2AG	1.4	1.4	1.4	1.4	Oxygen stoichiometry for algal primary production, g O_2/g algae
O2LIM	0.1	0.1	0.1	0.1	Dissolved oxygen concentration at which anaerobic processes are at 50 percent of maximum, g/m^3
SODT1	4	4	4	4	Lower temperature parameter for zero-order SOD or first-order sediment decay, °C
SODT2	25	25	25	25	Upper temperature parameter for zero-order SOD or first-order sediment decay, °C
SODK1	0.10	0.10	0.10	0.10	Fraction of SOD or sediment decay rate at SODT1
SODK2	0.99	0.99	0.99	0.99	Fraction of SOD or sediment decay rate at SODT2
SOD	1.6–2.2	1.2–2.7	1.4–2.6	0.6–2.2	Zero-order SOD for each segment, g O_2/ m^2/day
FSOD	1	1	1	1	Fraction of the zero-order SOD rate used
SSS	0.05	0.05	0.05	0.1	Inorganic suspended solids settling rate, m/day
TYPE	LAKE	LAKE	LAKE	RIVER	Reaeration type
EQN#	6	6	6	8	Reaeration equation number

Inorganic suspended-sediment concentrations were estimated by subtracting POM and algae (in concentration units) from total suspended solids (TSS) concentrations.

When no water-quality data were available for an inflow in the modeled year, historical data were examined for similarities in water quality to tributaries that did have data in the modeled year. If the historical data were similar, that other tributary's water-quality data were used to estimate the missing tributary's inflow water quality. The water quality of the distributed tributary was estimated to be the same as that of the largest inflow to the lake; for the river model, it was estimated to be the same as a nearby tributary that had available data. The distributed tributary is a model input file that accounts for flows from ungaged streams, groundwater inflow, and other nonpoint sources. Nonpoint sources have been identified as significant sources of nutrient inputs in the Mosquito Creek Lake watershed (Yahaya, 2004).

During calibration of the Mahoning River model (by itself, without using upstream lake models as inputs) for flow and water temperature in 2013, the model comprised the entire reach from Lake Milton and Michael J Kirwan Reservoir dams to Lowellville. This reach was also calibrated for flow, water temperature, and water quality in 2019. Due to sparse water-quality data at the outflow of Lake Milton and Michael J Kirwan Reservoir dams in 2013, the upstream boundary condition input was set at Leavittsburg, where OEPA collected water-quality grab samples in that year.

Point Source Water Quality

Point source effluent water-quality data came from DMRs; data downloads for the period modeled were provided by OEPA. Data were available at different frequencies and different constituents were monitored for each source. Linear interpolation was used to create water-quality input files with constituents at consistent timesteps.

Measured point source TDS, orthophosphate, ammonia, nitrate, and dissolved oxygen concentrations were directly included as model water-quality boundary conditions when available. Point source organic matter concentrations were estimated for point source inflows as follows (ORGN and ORGP are described in table 6):

- Organic N = (Total Kjeldahl nitrogen) – ammonia,
- Total organic matter = (Organic N)/ORGN,
- Organic P = (Total organic matter) × ORGP,
- Ortho-P = (Total P) – (Organic P) (if Ortho-P was measured directly, then that was used instead),
- TSS = Volatile suspended solids (VSS) + inorganic suspended solids (ISS). Assume the approximate ratio is (0.80 VSS):(0.20 ISS),
- POM (particulate organic matter) = VSS = 0.8×TSS, and
- DOM (dissolved organic matter) = (Total organic matter) – VSS.

The ratios between ISS, VSS, and TSS depend on the influent source and the type and effectiveness of the treatment process. Without any available data on these items for the Mahoning River Basin point sources, literature values were used to estimate the approximate VSS:ISS ratio (Ekama and Wentzel, 2004; Ekama and others, 2006; He and others, 2019).

With these assumptions, occasionally the estimated VSS concentration was greater than the total organic matter (TOM). This likely represents either instances where inorganic suspended sediment was being discharged or instances where organic matter ratios were different than the model default. In these cases, the VSS value was set to be equal to the TOM estimate, and the “excess” VSS (difference between VSS and TOM) was put into the ISS pool, while ensuring that TSS=VSS+ISS.

To partition dissolved organic matter and particulate organic matter into labile and refractory components, DOM was estimated as 8 percent labile (LDOM) and 92 percent refractory (RDOM), and POM was estimated as 80 percent labile (LPOM) and 20 percent refractory (RPOM). This approach, keeping these ratios the same as those for other organic matter sources, was taken because no measurements or other direct characterizations were available to characterize the point source organic matter.

For point-source inputs for which no water-quality measurements were available, concentrations were generally set to zero. For instance, sulfate and chloride concentration data were not available for any point source. Also, data were not available for inorganic suspended sediment, nutrients (nitrogen and phosphorus), or organic matter for Warren Steel, BDM Warren, ArcelorMittal, and McDonald. Missing dissolved oxygen and TDS concentrations were not set to zero. For TDS, missing values were estimated as a constant 200 mg/L, similar to the lowest measured TDS concentrations of Mahoning River tributary inflows, and missing dissolved oxygen values were set to saturated conditions at the water temperature on that day.

Model Calibration Data

Measured data from USGS, USACE, and OEPA within a modeled waterbody, or immediately downstream from a waterbody outflow, were used to compare to model output at the same location and date/time to check model predictions. Mahoning River Basin model calibration data included (table 5; fig. 1):

- Water surface elevation for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake;
- Flow, water temperature, and water-quality data collected just downstream from the dam outflows (few water-quality data were available within Lake Milton or downstream from the Lake Milton dam outflow);
- Water temperature and water-quality depth-profiles within Michael J Kirwan Reservoir and Mosquito Creek Lake;
- Continuous water temperature and limited continuous water-quality data collected from in-lake sensors suspended in the water columns of Berlin Lake and Michael J Kirwan Reservoir; and
- Flow, water temperature and water-quality data at various locations in the Mahoning River, including continuous measurements from instream sensors and from grab samples.

Model Development

After model grids were developed and model data inputs were collected and processed, the model was initiated and run with default model parameters (rates and coefficients). The water balance was completed to identify any missing inflows and outflows, then water temperature and water quality were calibrated for the individual model years by adjusting model parameters within reasonable bounds to optimize the fit between model output and measured calibration data. Finally, a whole-basin water-quality model was constructed to be used in model scenarios. More details on several points of model development are discussed below.

Water Balance

Initial model runs included precipitation as well as measured or estimated inflows and outflows. These initial runs identified differences between modeled and measured water surface elevations (for the lakes) or flow (for the river). These difference are mostly due to the presence of ungaged surface water inflows or outflows, streamgage errors, or groundwater inflow or loss.

A distributed tributary was added to each lake and river during the water balance process to account for ungaged inputs or withdrawals and thereby allow the model to accurately simulate water surface elevation, water velocity, and flow. The distributed tributary is applied along all model segments and can be positive or negative. Positive inflows from distributed tributaries require estimated time series of water temperature and water quality to properly characterize those inflows.

Ideally, most inflows could be streamgaged or estimated so that the ungaged flows were relatively small compared to total flows. The Berlin Lake 2006 and 2017 models had distributed tributaries that were, on average, 11 and 4 percent of total inflows respectively. The Lake Milton 2006 and 2017 models had distributed tributaries that were 20 and 9 percent of total inflows. The Michael J Kirwan Reservoir 2006 and 2019 models had distributed tributaries that were 2 percent of total inflows in both years. Mosquito Creek Lake 2013 and 2018 models had distributed tributaries that made up 39 and 37 percent of total inflows in both years. One reason that Mosquito Creek Lake models had a greater amount of distributed tributary flow are the numerous small tributary creeks with uncharacterized flow rates. The larger Mosquito Creek and Walnut Creek tributaries to Mosquito Creek Lake, whose inflows were measured or estimated, only comprised 40 percent of the watershed area contributing to Mosquito Creek Lake. Modeled and measured lake water surface elevations, lake outflows, and river flows are shown in figures 6 and 7.

Light Extinction Coefficients

The amount of sunlight that penetrates into surface water is important in modeling water temperature and algal growth. The CE-QUAL-W2 model uses light extinction coefficients to simulate the extent of penetration of sunlight into the water column. In the model, light extinction can be affected by dissolved constituents, algae, and inorganic and organic suspended solids, which vary spatially and temporally.

Total light extinction coefficients were calculated from Secchi depth measurements and light meter measurements through the water column following the methods of Poole and Atkins (1929) and Williams and others (1980). The amount of available data to calculate these values was inconsistent among the lakes and the values varied over time, so the calculated values were used as a starting point, but light extinction values were also adjusted during the calibration process.

Sediment Oxygen Demand

Both zero and first-order sediment oxygen demands (SOD) were activated in the lake and river models. Conceptually, first-order SOD is derived from the decomposition of organic material that is modeled to settle out from the water column onto the sediment during the annual time period included in the model. The zero-order SOD was used to capture a baseline oxygen demand, potentially from material accumulated in the sediments during previous years. This combined approach to SOD modeling is recognized as a reliable option in the CE-QUAL-W2 user manual (Wells, 2020). Zero-order SOD rates applied in the various models ranged between 0.6 and 2.7 g $O_2/m^2/d$ (table 6), with the default temperature rate multipliers. Without any SOD measurements available for these waterbodies, SOD values were determined through model calibration and informed by the realistic ranges of measurements published in the scientific literature and documented in the CE-QUAL-W2 user manual.

Algal Data, Rates, and Coefficients

A first step in modeling algae was to examine the algal species data. For 2006–19, with some years not sampled and limited data during winter, a diverse set of algal species had been identified from USACE sampling. Samples from Berlin and Mosquito Creek Lakes detected more than 180 species of algae. Michael J Kirwan Reservoir had more than 150 species and overall lower algal densities than in the other lakes. No algal data were available for Lake Milton.

The most commonly found blue-green algae, in terms of the sum of percent biovolume per taxa, in Berlin Lake were *Aphanizomenon flos aquae*, *Limnothrix* sp., and *Anabaena flos-aquae*. In Mosquito Creek Lake the most commonly found blue-green algae were *Anabaenopsis* sp (note: years after these samples were collected and classified, *Anabaena* algae has been reclassified as *Dolichospermum*), *Aphanizomenon flos-aquae*, *Anabaena flos-aquae*, and *Cylindrospermopsis.* In Michael J Kirwan Reservoir, the most commonly found blue-green algae were *Anabaena planctonica*, *Aphanizomenon flos-aquae*, and *Anabaena flos-aquae*.

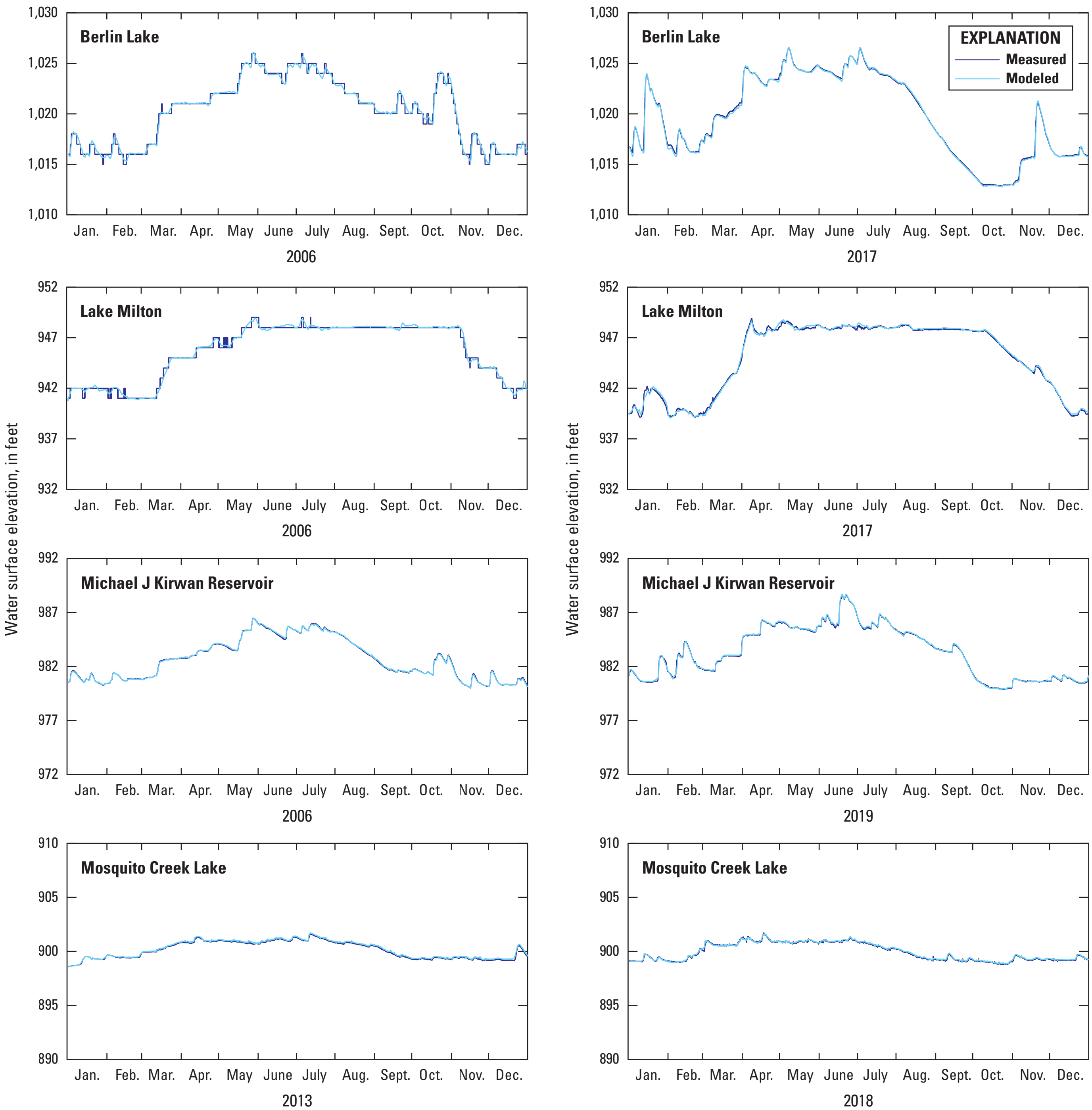


Figure 6. Measured and modeled Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake water surface elevations, Ohio, 2006, 2013, and 2017–19.

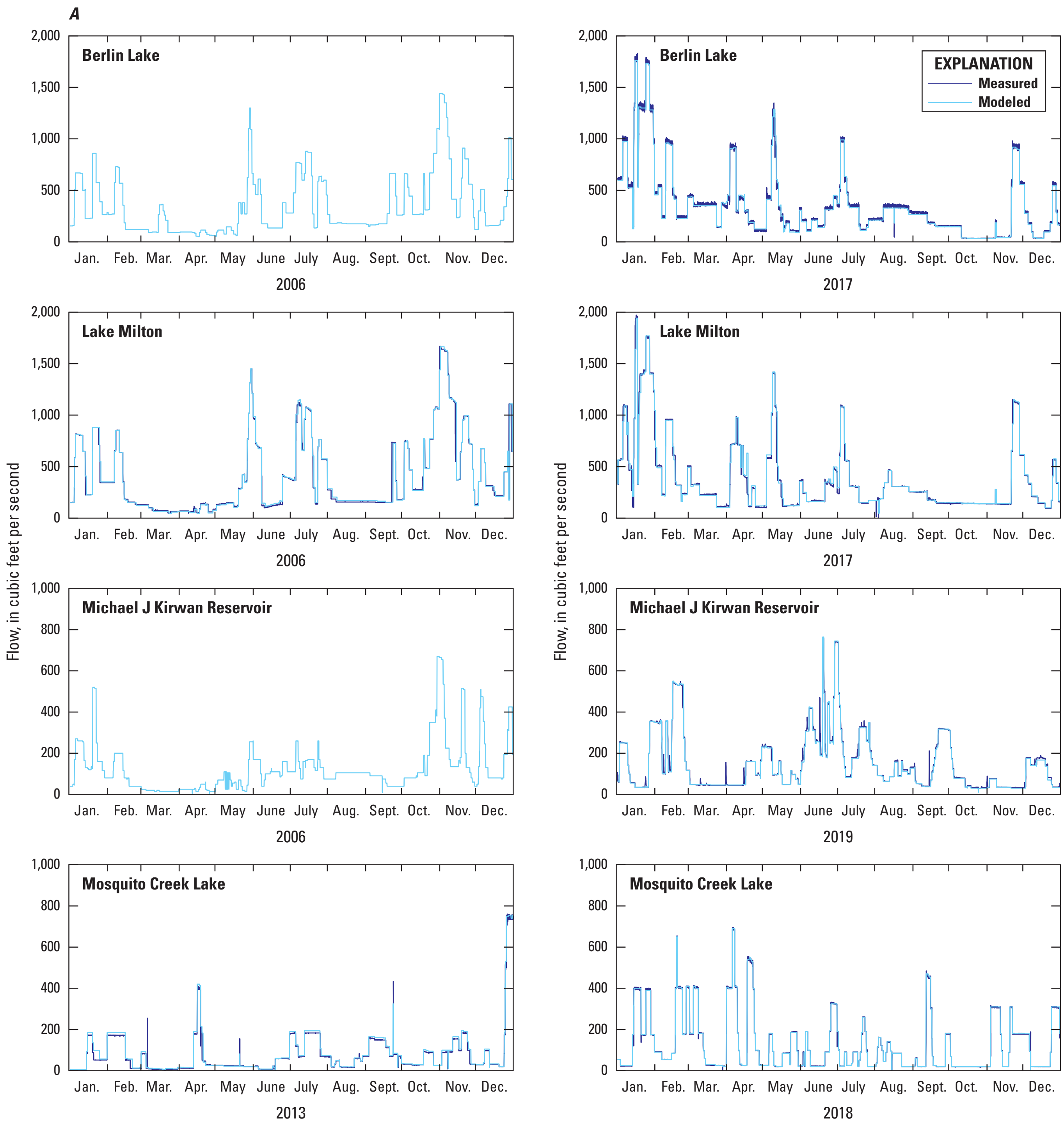


Figure 7. (*A*) Modeled Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake outflows and measured streamflow at streamgages just downstream from dams in 2006, 2013, and 2017–19, and (*B*) measured and modeled river flow for 2013 and 2019 in the Mahoning River, Ohio. Measured data were unavailable for Berlin Lake and Michael J Kirwan Reservoir in 2006.

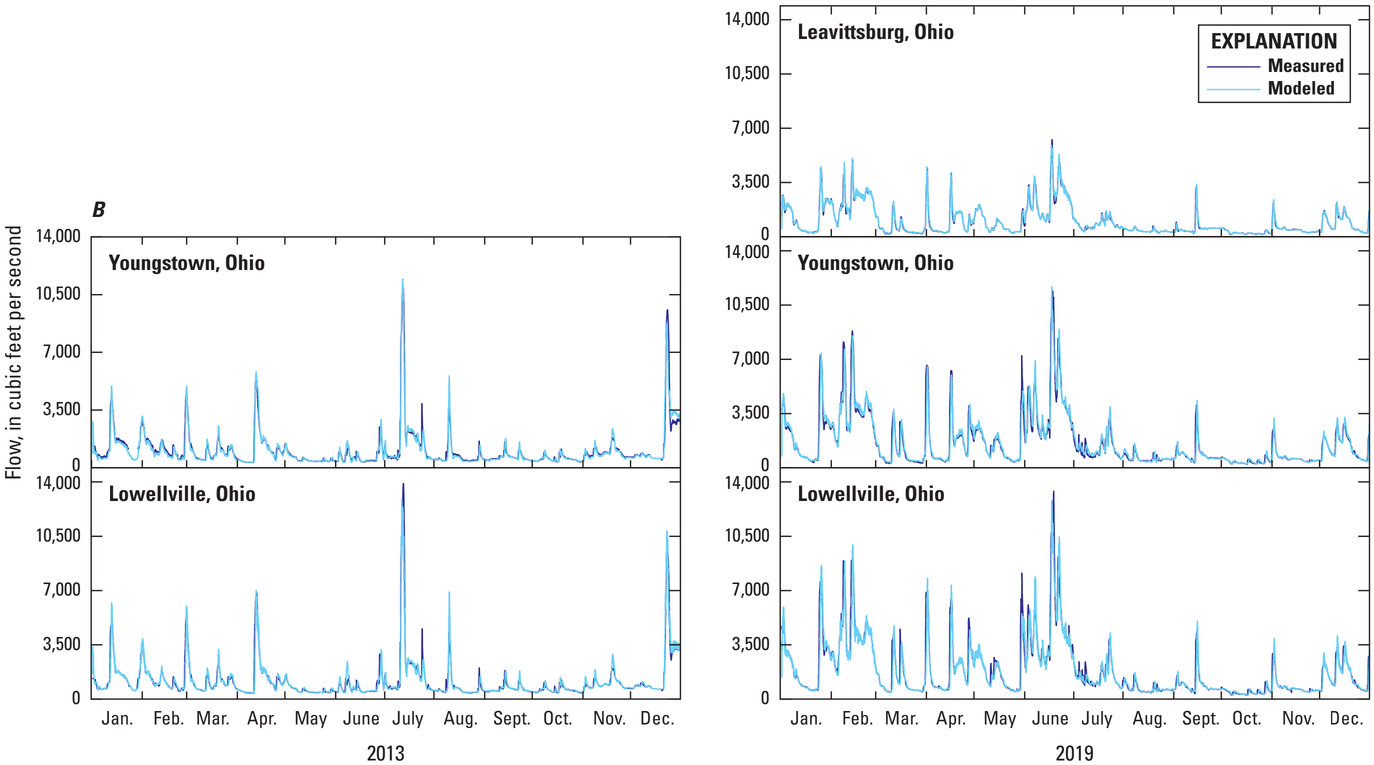


Figure 7.—Continued

The most commonly found diatoms in Berlin Lake were *Synedra radians*, *Stephanodiscus hantzschii*, and *Melosira distans alpigena*. In Mosquito Creek Lake, the most commonly found diatoms were *Melosira ambigua*, *Synedra radians*, and *Asterionella Formosa*. In Michael J Kirwan Reservoir, the most commonly found diatoms were *Synedra radians*, *Cyclotella ocellata*, *Melosira distans alpigena*, and *Asterionella formosa*.

The most common algae in the "Other" group in Berlin Lake were *Cryptomonas erosa*, *Trachelomonas volvocina*, and *Trachelomonas scabra*. The most common Other algae in Mosquito Creek Lake were *Cryptomonas erosa*, *Trachelmonas volvocina*, and *Chlamydomonas*. The most commonly found Other algae in Michael J Kirwan Reservoir were *Ceratium hirundinella*, *Cryptomonas*, and *Trachelmonas volvocina*.

The CE-QUAL-W2 model allows unlimited algal groups or species to be modeled. However, the inclusion of each algal group requires the definition of a set of parameters and ratios to characterize the group's growth and respiration rates, light and temperature preferences, and elemental stoichiometry (table 7). That level of supporting data is rarely available, so algae are often modeled in lumped groups with parameters that are typical of that group.

It is typical to differentiate among the modeled algal groups through input parameters that express their growth rates, preferred temperature ranges, and their dependence on light and nutrients. In all these Mahoning models, the blue-green algae were characterized as growing relatively rapidly at relatively warm temperatures and with some group members having the capability to fix nitrogen, which results in half-saturation values for nitrogen set to zero. Diatoms were characterized as having the capability to grow at cooler temperatures. The group of "Other" algae comprised all remaining algal species and was given a more moderate temperature preference.

Without any available data on Mahoning River Basin algal stoichiometry, the algae were given default CE-QUAL-W2 C:N:P stoichiometric ratios, as well as the default mass ratio between algal biomass and chlorophyll *a* (table 7).

Model Parameter Sensitivity

Model parameter sensitivity testing was completed to examine the response of a changed model parameter on selected model results. These tests were completed by increasing a parameter of interest by 20 percent while keeping all other parameters constant and calculating the percentage change in water temperature and the concentrations of TDS, nitrate, dissolved oxygen, total phosphorus, and chlorophyll *a* in each of the lake model outflows and in the Mahoning River model at Lowellville (table 8).

Table 7. Algal parameters used in modeling water quality in Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[**Abbreviations:** m^2/g, square meter per gram; Ber-Mil, Berlin Lake and Lake Milton; Kir, Michael J Kirwan Reservoir; Mos, Mosquito Creek Lake; MahR, Mahoning River; m/d, meter per day; g/m^3, gram per cubic meter; W/m^2, Watt per square meter; °C, degrees Celsius; g/g, gram per gram]

Parameter	Blue-green algae	Diatoms	Other algae	Description
EXA	0.2	0.2	0.2	Light extinction due to algae, m^2/g
AG	Ber-Mil: 2.7 Kir: 2.5 Mos: 3.8 MahR: 1.5	Ber-Mil: 1.2 Kir: 1.05 Mos: 0.8 MahR: 0.9	Ber-Mil: 1.2 Kir: 1.15 Mos: 1.05 MahR: 0.9	Maximum algal growth rate, day^{-1}
AR	0.04	0.04	0.04	Maximum respiration rate, day^{-1}
AE	0.05	0.04	0.04	Maximum algal excretion rate, day^{-1}
AM	Ber-Mil: 0.32 Kir: 0.32 Mos: 0.32 MahR: 0.2	0.1	0.1	Maximum algal mortality rate, day^{-1}
AS	0.3	Ber-Mil: 0.08 Kir: 0.08 Mos: 0.08 MahR: 0.10	Ber-Mil: 0.08 Kir: 0.08 Mos: 0.08 MahR: 0.18	Settling rate, m/day
AHSP	0.003	0.003	0.003	Algal half-saturation for phosphorus limited growth, g/m^3
AHSN	0.0	0.014	0.014	Algal half-saturation for nitrogen limited growth, g/m^3
ASAT	100	100	100	Light saturation intensity at maximum photosynthetic rate, W/m^2
AT1	16	2	5	Lower temperature parameter for rising rate function, °C
AT2	26	9	20	Upper temperature parameter for rising rate function, °C
AT3	35	25	25	Lower temperature parameter for falling rate function, °C
AT4	40	28	35	Upper temperature parameter for falling rate function, °C
AK1	0.1	0.1	0.1	Fraction of rate at AT1
AK2	0.99	0.99	0.99	Fraction of rate at AT2
AK3	0.99	0.99	0.99	Fraction of rate at AT3
AK4	0.1	0.1	0.1	Fraction of rate at AT4
AP	0.005	0.005	0.005	Stoichiometric equivalent between biomass and phosphorus, g/g
AN	0.08	0.08	0.08	Stoichiometric equivalent between biomass and nitrogen, g/g
AC	0.45	0.45	0.45	Stoichiometric equivalent between biomass and carbon, g/g
ACHLA	0.025	0.025	0.025	Ratio between algal biomass and chlorophyll *a*, milligram algae/µg chla
ALPOM	0.8	0.8	0.8	Fraction of algal biomass converted to particulate organic matter when algae die
ANPR	0.001	0.001	0.001	Algal half saturation preference constant for ammonium

Table 8. Results from sensitivity testing demonstrating the percentage effect of increasing model parameter values by 20 percent for January–December 2013 for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[Tables 6 and 7 provide more details on each parameter, **Abbreviations**: MosC, Mosquito Creek]

Parameter	Waterbody	Water temperature, percentage change	Total dissolved solids percentage change	Nitrate (NO_3) percentage change	Dissolved oxygen percentage change	Total phosphorus percentage change	Chlorophyll *a* percentage change
WSC	Berlin Lake	–4	0	4	1	0	1
	Lake Milton	0	0	3	0	0	12
	Michael J Kirwan Reservoir	4	0	0	0	–1	5
	MosC Lake	–2	1	–6	0	–2	–3
	Mahoning R	–1	0	0	0	0	0
EXH2O	Berlin Lake	0	0	1	0	0	–12
	Lake Milton	0	0	1	0	1	–26
	Michael J Kirwan Reservoir	–1	0	1	0	2	–43
	MosC Lake	–1	0	3	0	1	–5
	Mahoning R	0	0	0	0	0	0
EXSS	Berlin Lake	0	0	0	0	0	–3
	Lake Milton	0	0	0	0	0	–7
	Michael J Kirwan Reservoir	–1	0	1	0	1	–18
	MosC Lake	0	0	0	0	0	–1
	Mahoning R	0	0	0	0	0	0
AG, blue-green	Berlin Lake	0	0	–1	0	–1	27
	Lake Milton	0	0	–2	0	–2	47
	Michael J Kirwan Reservoir	–1	0	–1	0	0	44
	MosC Lake	0	0	–2	0	–2	8
	Mahoning R	0	0	0	0	0	9
AR, blue-green	Berlin Lake	1	0	1	0	0	–11
	Lake Milton	0	0	1	0	1	–16
	Michael J Kirwan Reservoir	0	0	0	0	0	–18
	MosC Lake	0	0	4	0	0	–6
	Mahoning R	0	0	0	0	0	–1
AM, blue-green	Berlin Lake	0	0	0	0	1	–24
	Lake Milton	0	0	0	0	1	–34
	Michael J Kirwan Reservoir	0	0	1	0	1	–49
	MosC Lake	0	0	2	0	0	–19
	Mahoning R	0	0	0	0	0	–3

Table 8. Results from sensitivity testing demonstrating the percentage effect of increasing model parameter values by 20 percent for January–December 2013 for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.—Continued

[Tables 6 and 7 provide more details on each parameter, **Abbreviations**: MosC, Mosquito Creek]

Parameter	Waterbody	Water Temperature, percentage change	Total Dissolved Solids percentage change	Nitrate (NO_3) percentage change	Dissolved oxygen percentage change	Total Phosphorus percentage change	Chlorophyll *a* percentage change
AS, blue-green	Berlin Lake	0	0	0	0	0	–6
	Lake Milton	0	0	–1	0	0	–5
	Michael J Kirwan Reservoir	0	0	0	0	1	–12
	MosC Lake	0	0	–2	0	0	–3
	Mahoning R	0	0	0	0	0	–5
AT2, blue-green	Berlin Lake	–1	0	–1	0	0	11
	Lake Milton	–1	0	–1	0	0	4
	Michael J Kirwan Reservoir	0	0	0	0	0	–11
	MosC Lake	0	0	–5	0	1	10
	Mahoning R	0	0	0	0	0	–1
LDOMDK	Berlin Lake	–1	0	0	0	0	–1
	Lake Milton	0	0	0	0	0	0
	Michael J Kirwan Reservoir	0	0	0	0	0	0
	MosC Lake	0	0	0	0	0	1
	Mahoning R	0	0	0	0	0	0
LPOMDK	Berlin Lake	0	0	0	0	0	5
	Lake Milton	0	0	0	0	1	7
	Michael J Kirwan Reservoir	0	0	1	0	1	–3
	MosC Lake	0	0	3	0	1	9
	Mahoning R	0	0	0	0	0	0
POMS	Berlin Lake	1	0	0	0	–1	1
	Lake Milton	0	0	–1	0	–2	0
	Michael J Kirwan Reservoir	–1	0	1	0	0	–10
	MosC Lake	0	0	–3	0	–3	–3
	Mahoning R	0	0	0	0	0	0

Table 8. Results from sensitivity testing demonstrating the percentage effect of increasing model parameter values by 20 percent for January–December 2013 for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.—Continued

[Tables 6 and 7 provide more details on each parameter, **Abbreviations**: MosC, Mosquito Creek]

Parameter	Waterbody	Water Temperature, percentage change	Total Dissolved Solids percentage change	Nitrate (NO_3) percentage change	Dissolved oxygen percentage change	Total Phosphorus percentage change	Chlorophyll *a* percentage change
SSS	Berlin Lake	–1	0	0	0	0	1
	Lake Milton	0	0	–1	0	0	6
	Michael J Kirwan Reservoir	0	0	0	0	1	–6
	MosC Lake	0	0	–1	0	0	1
	Mahoning R	0	0	0	0	0	0
NH4DK	Berlin Lake	–1	0	1	0	0	–3
	Lake Milton	–1	0	0	0	0	0
	Michael J Kirwan Reservoir	0	0	1	0	1	–10
	MosC Lake	0	0	0	0	0	0
	Mahoning R	0	0	0	0	0	0
NH4R	Berlin Lake	0	0	0	0	0	0
	Lake Milton	0	0	2	0	0	0
	Michael J Kirwan Reservoir	0	0	3	0	0	–7
	MosC Lake	0	0	2	0	0	0
	Mahoning R	0	0	0	0	0	0
NO3DK	Berlin Lake	1	0	–4	0	0	0
	Lake Milton	0	0	–4	0	0	0
	Michael J Kirwan Reservoir	0	0	–4	0	1	–13
	MosC Lake	0	0	–7	0	0	0
	Mahoning R	0	0	0	0	0	0
PO4R	Berlin Lake	0	0	0	0	0	0
	Lake Milton	0	0	0	0	0	0
	Michael J Kirwan Reservoir	0	0	1	0	1	–7
	MosC Lake	0	0	2	0	2	5
	Mahoning R	0	0	0	0	0	0

Table 8. Results from sensitivity testing demonstrating the percentage effect of increasing model parameter values by 20 percent for January–December 2013 for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.—Continued

[Tables 6 and 7 provide more details on each parameter, **Abbreviations**: MosC, Mosquito Creek]

Parameter	Waterbody	Water Temperature, percentage change	Total Dissolved Solids percentage change	Nitrate (NO_3) percentage change	Dissolved oxygen percentage change	Total Phosphorus percentage change	Chlorophyll *a* percentage change
FSOD	Berlin Lake	–1	0	–2	0	0	–1
	Lake Milton	0	0	0	0	0	–1
	Michael J Kirwan Reservoir	0	0	2	0	3	–3
	MosC Lake	0	0	5	0	3	9
	Mahoning R	0	0	0	–1	0	0

Modeled water temperature results were relatively insensitive to altered model parameters. Increasing the wind sheltering coefficients (WSC) by 20 percent, which has the effect of increasing wind speeds, changed water temperatures by up to 4 percent, but the other tested parameters had little effect on water temperature. Instead, water temperatures were controlled by factors other than the model parameters, such as the temperature and rate of inflows, elevation of lake outlets, and meteorology. TDS is conservative (nonreactive) in the model, so model parameters have little to no effect on its concentration in the model, as confirmed by this sensitivity test. Dissolved oxygen concentrations were also relatively insensitive to the selected parameter set for sensitivity testing. Nitrate and total phosphorus concentrations in the lakes were affected by a few of the tested parameters. For instance, increasing the denitrification rate (NO3DK) by 20 percent decreased the nitrate concentrations by 4–7 percent in the lakes; however, it did not change river nitrate concentrations because denitrification only occurs in the model when dissolved-oxygen concentrations are less than the O2LIM parameter (0.1 mg/L), and anoxic conditions occurred mainly in the hypolimnions of the lakes and not in the river.

Chlorophyll *a* concentrations, reflecting algal concentrations, were sensitive to many model parameters in the lakes. Increasing the algal growth rate for one algal group (AG) by 20 percent caused chlorophyll *a* concentrations to increase by as much as 47 percent. On the other hand, increasing algal respiration, mortality, and settling parameters (AR, AM, AS) for that same group decreased chlorophyll *a* concentrations by as much as 49 percent. The highest percentage changes were for Michael J Kirwan Reservoir, which had overall low concentrations of algae and low chlorophyll *a* concentrations, so while the percentage change was high for that lake, the absolute changes were not. Increasing the light extinction coefficients (EXH2O and EXSS), which allowed less light penetration into the water column and decreased the available light for photosynthesis, resulted in decreased chlorophyll *a* concentrations in the lakes.

Overall, the Mahoning River model was less sensitive to model parameters than the four lake models. Because the residence time of water in the river was shorter than in the lakes, and perhaps partly because the river was partly shaded and thereby less likely to grow as much algae, river water quality was more controlled by the inflow water quality from upstream and the tributaries and point sources and less by in-waterbody biogeochemical processes and the associated model parameter rates and coefficients.

Model Uncertainty and Data Needs

Some model uncertainty is tied to the fact that models are simplified representations of nature. CE-QUAL-W2 is a mechanistic model and as such includes many equations that describe flow, heat, and biogeochemistry. While many of the heat and flow equations are based on well-understood processes, a greater uncertainty is inherent in the representation of some of the water-quality processes. For example, the factors that control algal blooms in these lakes and the details of their interaction with nutrients, sunlight, and other parts of the food web (grazing by zooplankton and fish, for example) are less well understood in general; locally specific data to the Mahoning waterbodies are also lacking. The higher parts of the food web in natural waters are not included in these models, including zooplankton, aquatic plants, and zebra mussels (*Dreissena polymorpha*) (all of which are present in parts of the Mahoning River Basin), due to the lack of field data on their distribution and also a lack of process-based knowledge regarding their interaction with other modeled water-quality constituents. If such information was available, CE-QUAL-W2 can model zooplankton and aquatic plants.

Excellent datasets were collected within the waterbodies and were used for calibration, but some notable data gaps were evident in the input data for these models. Data gaps were filled with estimates, but measured data are preferred, would improve these models, and could be targeted for future sampling programs and for future model updates. These data gaps include:

- Outflows for Deer Creek Reservoir that form an input to Berlin Lake;
- Outflows for Meander Creek Reservoir or flow estimates for the Meander Creek tributary to the Mahoning River;
- Detailed data on vegetation density and tree heights along the Mahoning River and Mosquito Creek between Mosquito Creek Lake dam and the Mahoning River;
- Flow, water temperature, and water quality to characterize smaller tributaries, groundwater, or other ungaged inflows along the lakes and river;
- Higher frequency water temperature and water-quality data for tributaries to the lakes and rivers. The model was configured to linearly interpolate between data points collected at a range of sampling frequencies. Sometimes a tributary was only sampled a few times in a year, and tributaries were rarely sampled during storm events, which can be important for some constituents. For example, analysis of streams and rivers in Ohio showed that 90 percent of suspended sediment was discharged during only 10 percent of the time, typically during higher flows (Antilla and Tobin, 1976);
- Water-quality data within or at the outflow of Lake Milton;
- Data to characterize natural organic matter concentrations, stoichiometry, and reactivity in tributaries and point sources. Dissolved and particulate organic matter are connected to many facets of lake and river biogeochemistry but are rarely sampled directly, often because the laboratory analyses are relatively expensive and because natural organic matter is rarely targeted by water-quality criteria or regulating agencies;
- Sulfate and chloride data from all point sources;
- Complete point source data. DMR data for the point sources were generally only available for those constituents specified in permits, so more water-quality data were available for some point sources than others;
- SOD measurements in the lakes and rivers.

Water-Quality Calibration

Ideally, model parameters are based on values that are known for the given waterbodies, but that level of information was not available for the Mahoning River Basin, so model default or literature values were used to begin the model calibration. During the calibration process, certain parameters were adjusted within reasonable bounds to improve the fit between model output and measured values at the same location and date/time. Typically, the modeler will look for time periods during the model simulation when certain processes can be isolated and key model parameter values associated with those processes can be optimized. Moving from nonreactive to more sensitive modeled constituents, the modeler tries to lock down the more basic parameters before moving to the more complex set of parameters associated with, for example, the algal groups. It is a process that involves much iteration, comparison with measurements, consultation of literature, and de-facto sensitivity testing to arrive at an optimized set of model parameter values.

Model performance was evaluated by comparing model output to measured data at the same location, date/time, and depth. This was done graphically as well as through the calculation of goodness-of-fit statistics, including the primary statistics mean error (ME) and mean absolute error (MAE), and secondary statistics percentage bias and coefficient of determination. The latter two statistics can be problematic in certain situations. For instance, the usefulness of the coefficient of determination varies depending on the range of the data; for situations with a small range in data values, the coefficient of determination can be low, despite acceptable ME and MAE statistics.

Ideally, these goodness-of-fit statistics would compare model output and measured values that characterize the same volume of water. However, that was impossible, given spatial and scale differences between the model output and measured values. For instance, model water quality was an average through the volume of a model cell that was 2 ft high, approximately 1,500 ft long, and of variable width, whereas measured water-quality data are often from a grab sample or sensor location that measures a much smaller volume. Also, sometimes the locations of comparison are slightly different, such as when model output of a dam release (at the point of release) is compared to a streamgage within a short distance downstream from the dam. This comparison of model output and measured data are still useful, but exact matches are not expected.

Because the four lakes are in close geographic proximity, with similar climate, geology, and hydrology, parameters typically were selected that made sense for the lakes as a group, rather than having widely different parameters for the individual lakes, even if the latter choice may have improved goodness-of-fit statistics slightly. Also, with some gaps in data to characterize lake inflows, processes, and rates, as listed above, a “perfect” calibration was impossible without overtuning the model. Overtuning or over-calibration would result in a model that might be able to fit the available measurements more closely or at least more closely during certain time periods but could increase the likelihood of predictive failure when the model is asked to simulate a changed set of conditions, such as the testing of a set of management scenarios. The goal was to build and calibrate models with reasonable parameter sets that captured most major water-quality processes and the magnitudes of spatial and temporal patterns in modeled constituent concentrations.

Whole-Basin Model

A whole-basin model was constructed for calendar year 2013. The Mahoning River and Mosquito Creek Lake year 2013 models were already constructed, as described above. Year 2013 models were constructed for Berlin Lake, Michael J Kirwan Reservoir, and Mosquito Creek between Mosquito Creek Lake and the Mahoning River using actual meteorology and hydrology and estimated water temperature and water quality.

The year 2013 Berlin Lake and Michael J Kirwan Reservoir models were constructed by using measured 2013 meteorology and precipitation, lake inflows, outflows, and water surface elevations. Inflow water temperature was estimated based on 2013 water temperature data that were collected for inflow streams when available. Missing inflow temperature data were estimated from nearby streams with 2013 water temperature data. The water quality of inflows was estimated by examining concentration ranges and seasonal patterns in the water quality of inflows for the two model years that had been developed, as well as other historical data. Berlin Lake point source water-quality data for the Alliance WWTP were taken from year 2013 DMRs.

The model grid of Mosquito Creek, downstream from Mosquito Creek Lake to the Mahoning River, was constructed with segment lengths and bearings extracted from a geographic information system, bottom channel elevations extracted from a HEC-RAS model, and a general channel shape from an ADCP survey at a USGS streamgage. The upstream inflow was the outflow of the Mosquito Creek Lake model. The Trumbull WWTP was included as a tributary. Some limited water-quality data were available within this reach of Mosquito Creek in 2013 and used to compare to modeled water quality.

Model Water Quality

Water Temperature

Water temperature in the models was affected by inflows and outflows (including the elevations at which water was withdrawn), heat exchange across the water surface, light extinction, and wind mixing. In the years modeled, Berlin Lake, Michael J Kirwan Reservoir, Lake Milton, and Mosquito Creek Lake typically began the calendar year cold and well-mixed; flows out of the dams are typically cold also (figs. 8–19). In late spring, with increased solar radiation and warmer inflows, each lake began to warm, and a thermocline began to develop, separating warmer surface water from cooler bottom waters. The elevation of the thermocline in Michael J Kirwan Reservoir deepened through the summer, but the thermal separation of surface and bottom waters persisted to early autumn. In Berlin Lake, Lake Milton, and Mosquito Creek Lake, warmer surface waters were mixed through the lakes by early to mid-summer. In autumn, with the decrease of solar radiation, the lake surface cooled and eventually the lakes became isothermal and well-mixed again.

The lake outflow temperatures generally were cold in winter (often less than 5 °C), warming to temperatures greater than 20 °C in summer (figs. 11, 16, 19). Lake outflow temperatures were affected by the thermal structure within the lakes and the elevations at which water was withdrawn through the dams' outlets.

The lake outflow temperatures generally were cold in winter (often <5 °C), warming to temperatures greater than 20 °C in summer (figs. 11, 16, 19). Lake outflow temperatures were affected by the thermal structure within the lakes and the elevations at which water was withdrawn through the dams' outlets.

Mahoning River water temperatures were similarly cold in winter, often <5 °C and sometimes near 0 °C, and greater than 20 °C in summer (figs. 20–22). While excessive water temperature was historically one of the Mahoning River's major water-quality issues, the only included point source with elevated water temperature in the years modeled was the Arcelor Mittal 014 release, which had periods of effluent temperatures greater than 50 °C in summer; the flows from that point source were relatively low at <5 ft^3/s. The other point sources and tributary streams rarely exceeded 25 °C in summer. Thus, in the years modeled, only relatively small differences in water temperature occurred between Leavittsburg and Lowellville (fig. 23). A more detailed representation of shade along the river could improve the modeling of water temperature along the river, including variations in tree heights and vegetation density for each model segment.

Goodness-of-fit statistics comparing modeled and measured temperatures in the lakes, lake outflows, and at Mahoning River locations gave ME of –0.88 to 0.25 °C and MAE of 0.81 to 1.60 °C (table 9), depending on the waterbody and year. The higher MAE were associated with lake depth profiles, whereas the MAE in the river was <1 °C.

Figures 8–23 Figures 8–23 are at the back of this report.

Table 9. Goodness-of-fit statistics between model output and measured data for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[Statistics include mean error and mean absolute error. Secondary statistics include percent bias and coefficient of determination (R^2). **Abbreviations**: C, Celsius; mg/L, milligram per liter; n, number; ME, mean error; MAE, mean absolute error; PB, percent bias; µg/L, microgram per liter]

Lake depth profiles

Constituent	Berlin Lake, 2017					Michael J Kirwan Reservoir, 2019					Mosquito Creek Lake, 2018				
	n	ME	MAE	PB	R^2	n	ME	MAE	PB	R^2	n	ME	MAE	PB	R^2
Temperature, degrees C	201	0.07	1.06	0.3	0.90	134	0.02	1.60	0.1	0.82	115	–0.70	1.02	–4	0.98
Total dissolved solids, mg/L	38	52	52	19	0.36	49	36	50	18	0.36	34	15	17	9	0.04
Chloride, mg/L	40	–0.3	4.0	–0.7	0.02	51	7.9	9.5	26	0.44	34	2.2	2.5	7	0.11
Sulfate, mg/L	40	8.1	8.7	20	0.00	51	–0.4	3.3	–2	0.10	34	1.0	1.715	10	0.04
Total Kjeldahl Nitrogen, mg/L	40	–0.24	0.67	–15	0.57	51	–0.14	0.24	–25	0.36	34	–0.07	0.20	–10	0.01
Nitrate+Nitrite, mg/L	40	0.01	0.50	1.7	0.53	51	0.00	0.05	4	0.46	34	0.06	0.14	59	0.18
Ammonia, mg/L	40	–0.09	0.13	–42	0.13	51	0.00	0.13	0.2	0.57	34	0.00	0.11	2	0.02
Total phosphorus, mg/L	40	0.06	0.06	124	0.10	51	–0.04	0.04	–54	0.00	34	–0.02	0.03	–31	0.00
Orthohosphate, mg/L	40	0.01	0.02	289	0.05	51	0.01	0.01	178	0.05	34	0.00	0.01	–34	0.00
Chlorophyll a, µg/L	40	–7.2	16.9	–22	0.20	51	–0.7	5.0	–8	0.32	34	–5.7	17.4	–26	0.06
Total iron, mg/L	40	–0.22	0.28	–75	0.02	51	0.05	0.80	10	0.49	34	–0.04	0.50	–13	0.00
Dissolved oxygen, mg/L	201	0.36	1.79	6	0.60	134	0.20	1.32	4	0.65	115	–0.40	1.37	–5	0.75

Lake outflow

Constituent	Berlin Lake, 2006, 2017					Michael J Kirwan Reservoir, 2006, 2019					Mosquito Creek Lake, 2013, 2018				
	n	ME	MAE	PB	R^2	n	ME	MAE	PB	R^2	n	ME	MAE	PB	R^2
Sulfate, mg/L	15	9.1	9.2	20	0.89	10	–0.7	3.0	–3	0.81	19	–0.2	2.6	–1	0.73
Total Kjeldahl Nitrogen, mg/L	17	–0.08	0.47	–6	0.42	10	–0.06	0.15	–14	0.12	20	0.03	0.12	4	0.10
Nitrate+Nitrite, mg/L	17	–0.11	0.24	–19	0.58	10	–0.18	0.20	–63	0.02	19	–0.20	0.34	–57	0.07
Ammonia, mg/L	16	–0.16	0.20	–40	0.10	10	–0.03	0.07	–22	0.30	19	–0.03	0.06	–24	0.11
Total phosphorus, mg/L	17	0.03	0.04	54	0.15	10	–0.02	0.03	–35	0.18	19	–0.01	0.02	–10	0.11
Orthohosphate, mg/L	17	0.01	0.01	168	0.18	8	0.01	0.01	229	0.00	13	0.00	0.01	–25	0.00
Chlorophyll a, µg/L	9	–3.0	5.1	–34	0.49	9	–0.1	2.9	–5	0.00	10	–1.7	18.9	–9	0.47
Dissolved oxygen, mg/L	15	–0.13	0.60	–1	0.79	8	0.26	0.32	3	0.83	16	1.00	1.05	12	0.82

Table 9. Goodness-of-fit statistics between model output and measured data for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio. —Continued

[Statistics include mean error and mean absolute error. Secondary statistics include percent bias and coefficient of determination (R^2). **Abbreviations**: C, Celsius; mg/L, milligram per liter; n, number; ME, mean error; MAE, mean absolute error; PB, percent bias; µg/L, microgram per liter]

Mahoning River										
	2013					2019				
	n	ME	MAE	PB	R^2	n	ME	MAE	PB	R^2
Chloride, mg/L	147	–14	15	–20	0.33	53	2.4	5.8	7	0.45
Sulfate, mg/L	147	–5.0	8.1	–10	0.06	53	–2.8	4.5	–9	0.35
Total Kjeldahl Nitrogen, mg/L	147	0.04	0.12	6	0.56	53	0.20	0.22	32	0.57
Nitrate+Nitrite, mg/L	147	0.20	0.47	13	0.46	53	0.26	0.28	40	0.73
Ammonia, mg/L	147	0.05	0.07	57	0.33	53	0.09	0.11	57	0.08
Total phosphorus, mg/L	147	0.02	0.05	18	0.37	53	–0.05	0.05	–38	0.78
Orthohosphate, mg/L	50	0.04	0.05	54	0.43	53	0.02	0.02	56	0.76
Chlorophyll a, ug/L	45	–14.3	14.8	–82	0.10	53	–3.1	5.1	–39	0.27
Dissolved oxygen, mg/L	103	0.28	0.76	3	0.63	30	–0.36	0.73	–4	0.60
Dissolved oxygen, mg/L, continuous	4,940	–0.04	0.51	–0.4	0.91	19319	–0.26	0.63	–3	0.91

Dissolved Oxygen

Dissolved oxygen concentrations in the modeled lakes and river were controlled by factors such as water temperature, inflows and outflows, algal processes, decomposition of organic matter, nitrification, and atmospheric exchange. The greatest dissolved oxygen concentrations in the modeled lakes occurred in winter when the cold water provided a higher solubility of dissolved oxygen and when temperature-mediated decomposition rates of organic material were minimal (figs. 9–10, 14–15, 17–18, 24–26). With the development of the thermocline in late spring, lake bottom waters became isolated from mixing and decomposition processes in the water column and lake sediments resulted in periods of anoxia in bottom waters of the lakes in late spring through early autumn. This anoxia in the hypolimnion could be interrupted during periods of high flows and velocities through the lakes; this was true for Berlin Lake and Lake Milton, and especially Mosquito Creek Lake, which may also experience more wind-mixing due to its greater ratio of surface area to depth. With cooling and mixing of lakes in the autumn, waters again became oxygenated throughout.

As water is released at the dams, turbulent mixing and aeration occurs as water falls from the dam outlets to the stream below the dam. This reaeration moves the released water closer to equilibrium with atmospheric oxygen. Initial model runs without reaeration enabled in the model resulted in model output with periods of low dissolved oxygen concentrations, which did not match measured downstream dissolved oxygen concentrations. Reaeration was then enabled in the model, which resulted in improved comparisons between modeled and measured dissolved oxygen concentrations in the lake outflows (figs. 11, 16, 19). This result suggests that reaeration at the dams is a process that increases dissolved oxygen concentrations to the Mahoning River and Mosquito Creek downstream from Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake.

Modeled dissolved oxygen in the river ranged from values near 15 mg/L during winter to values around 8 mg/L near the river surface in summer (figs. 22–23, 27). Without any measured SOD values for guidance, SOD was implemented with lower values in upstream reaches of the river and higher values in downstream reaches where industry and urbanization were present. During model development, sensitivity testing of different spatial distributions of the SOD rate showed that modest changes in the SOD rate did not affect river dissolved oxygen concentrations substantially. Formal sensitivity testing also showed only minor changes in dissolved oxygen concentrations from changes to SOD (via the FSOD parameter, table 8). Some areas of the river may have higher SOD rates from legacy wastes and nonpoint sources, which could explain sites that have lower measured dissolved oxygen concentrations than simulated by the model. Continuous measurements of dissolved oxygen had more daily variation than model output (fig. 27), which could be explained by photosynthetic activity by aquatic plants or periphyton in the river, which were not included in the model. There were also data gaps in dissolved oxygen for some point sources, which were estimated to be at saturation with atmospheric oxygen, but their actual dissolved oxygen concentrations were not known.

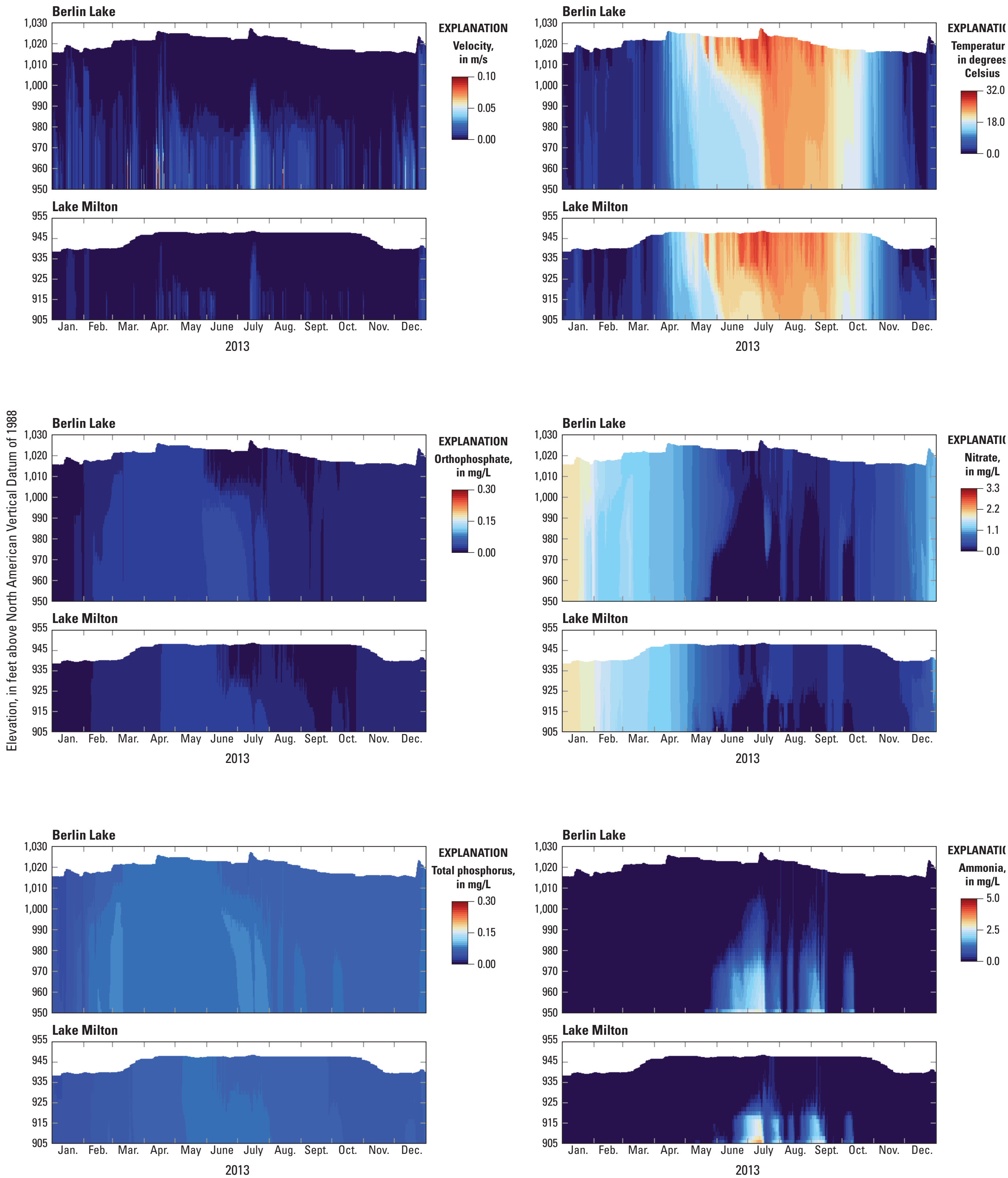


Figure 24. Modeled depth profiles for scenario 0 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are output at midnight and noon every day through 2013 from the model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Abbreviations: m/s, meter per second; mg/L, milligrams per liter; µg/L, micrograms per liter.

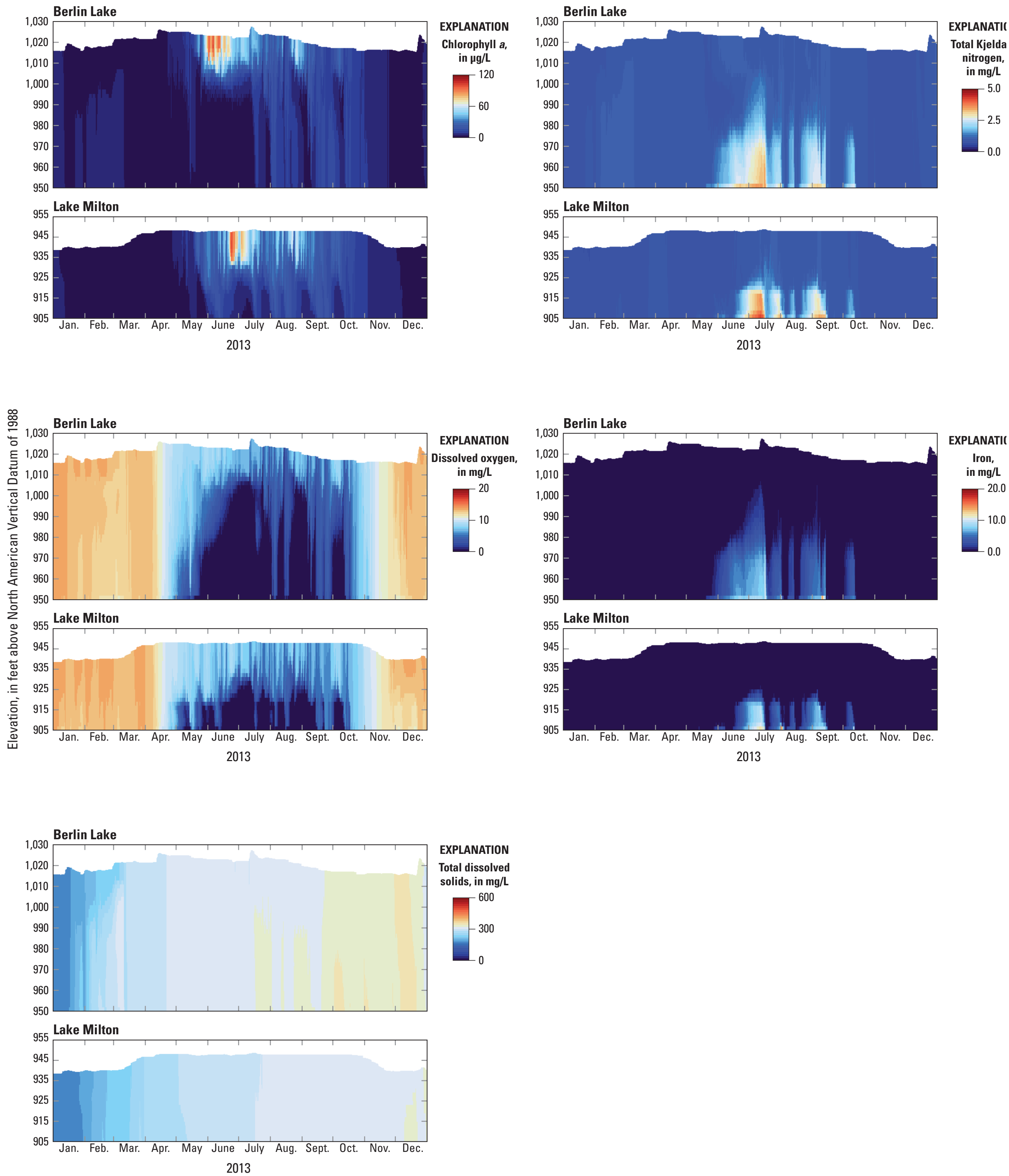


Figure 24.—Continued

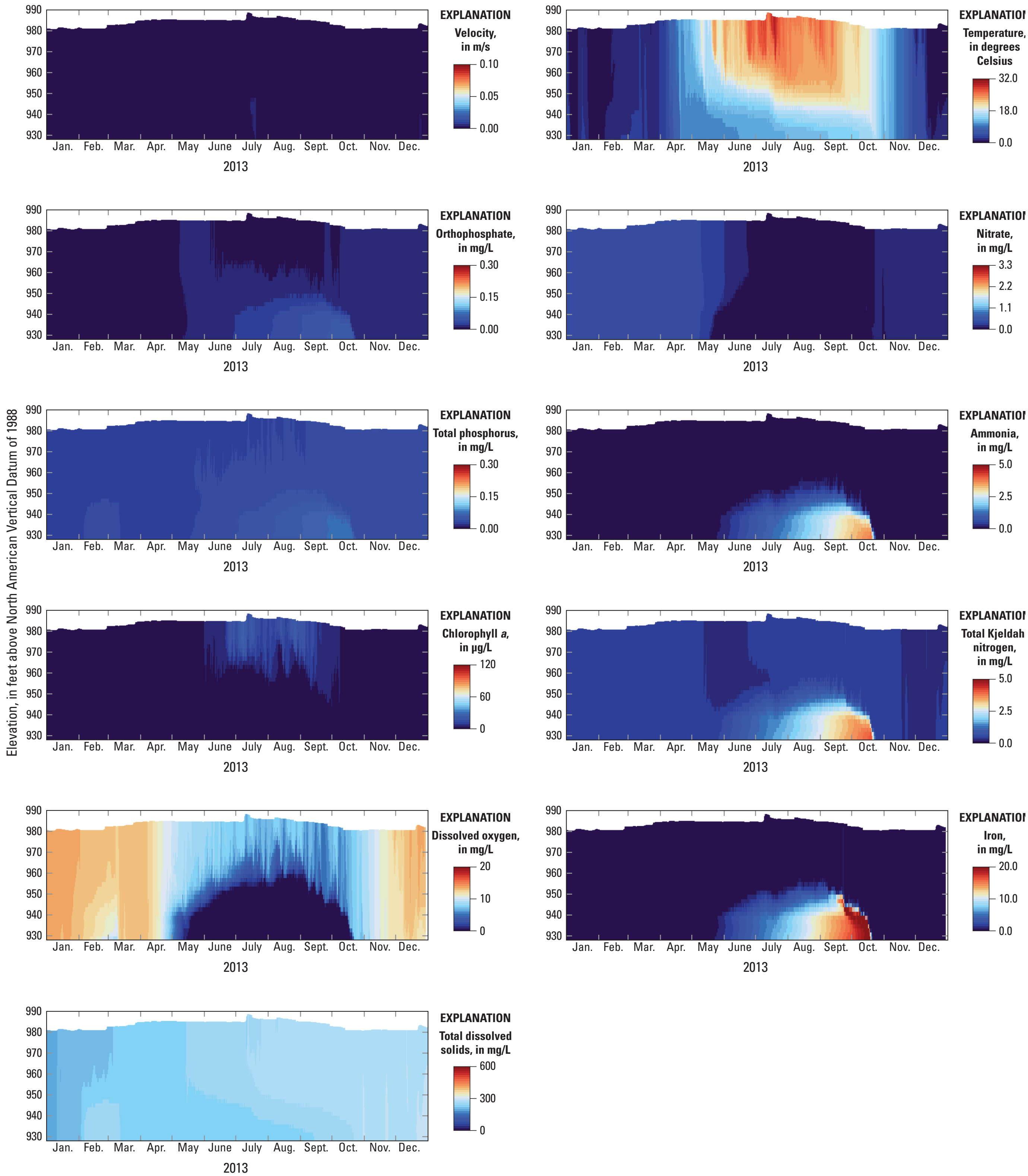


Figure 25. Modeled depth profiles for scenario 0 in Michael J Kirwan Reservoir, Ohio, 2013. The depth profiles are output at midnight and noon every day in 2013 from model segment 22, just upstream from the dam. Scenario 0 is described in table 10.

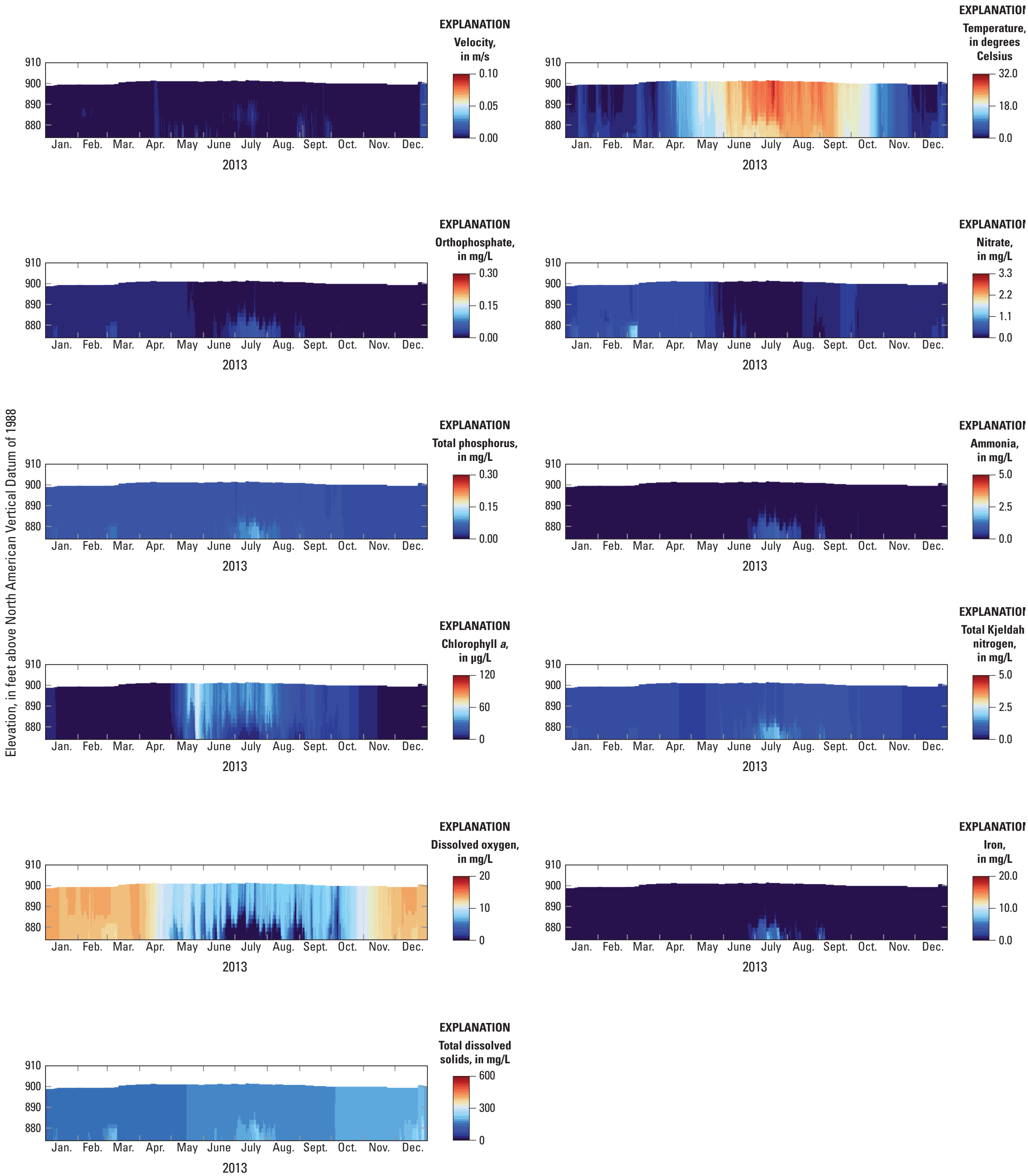


Figure 26. Modeled depth profiles for scenario 0 in Mosquito Creek Lake, Ohio, 2013. The depth profiles are output at midnight and noon every day through 2013 from model segment 35, just upstream from the dam. Scenario 0 is described in table 10.

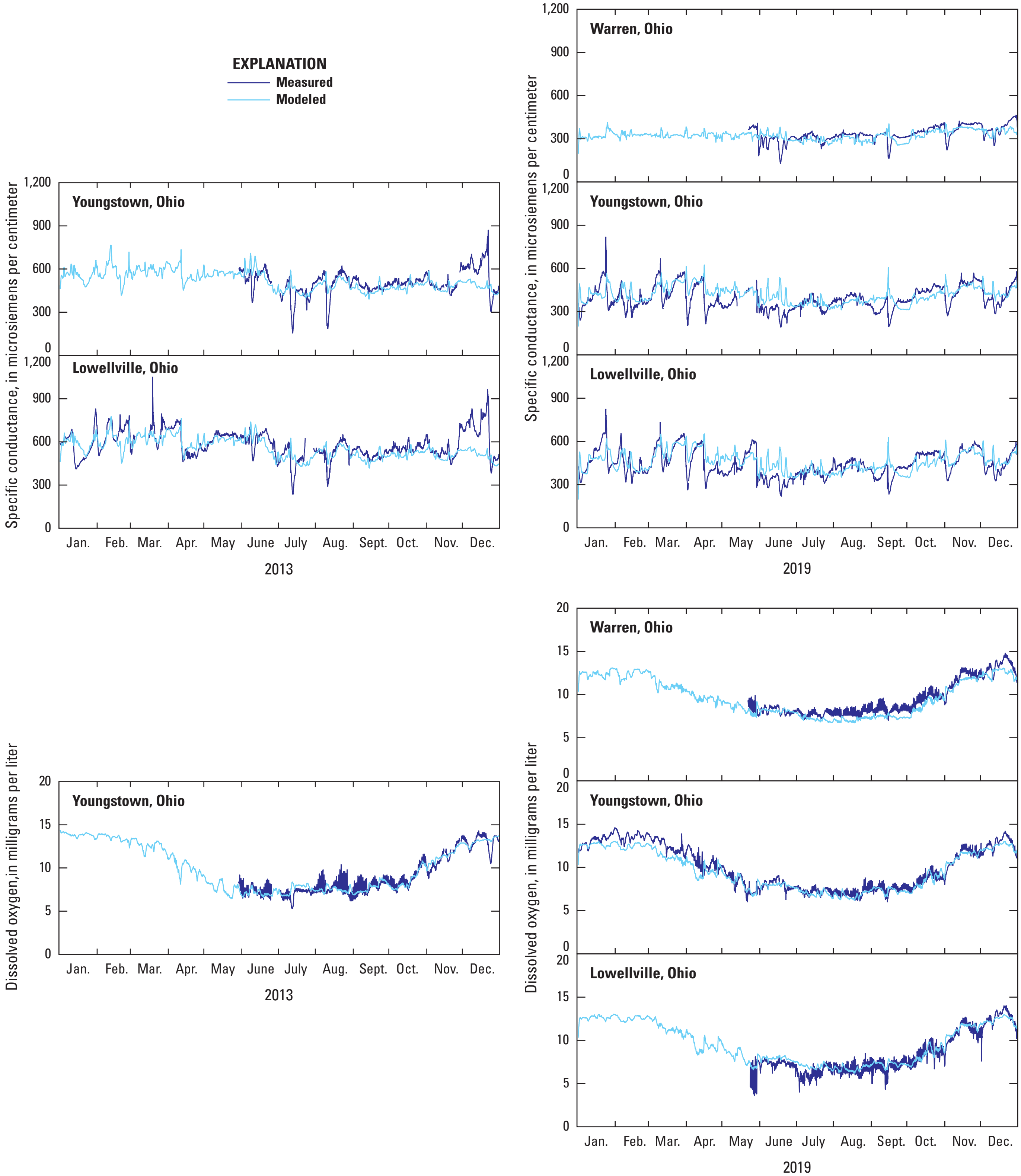


Figure 27. Model output and measured dissolved oxygen, and specific conductance data from continuous water-quality monitors at Mahoning River sites, Ohio, 2013 and 2019.

Goodness-of-fit statistics comparing modeled and measured dissolved oxygen concentrations in the lakes, lake outflows, and Mahoning River locations resulted in ME of –0.40 to 1.00 mg/L and MAE of 0.32 to 1.79 mg/L (table 9), depending on the waterbody and year. Again, the higher MAE were associated with lake depth profiles, whereas the MAE for dissolved oxygen in the river was no more than 0.63 mg/L for the years simulated.

Iron

Iron is sensitive to redox conditions. In well-oxygenated environments, iron tends to be in the form of particulates and iron oxides, whereas in anoxic environments the iron will be reduced into more dissolved and mobile forms. In the model, iron tended to be released in dissolved and reduced forms from bottom sediments during anoxic conditions and then was oxidized, precipitated, and settled out under oxic conditions. As the anoxic hypolimnion was disturbed by high velocity or storm events through the lake, the production of hypolimnetic iron also could be disrupted (figs. 9–10, 14–15, 17–18, 24–26). Modeled iron concentrations were not reported for the lake outflows or river, since CE-QUAL-W2 does not yet include all the water-column processes that control iron in rivers, such as pH-dependent sorption onto particles, or precipitation to and dissolution from mineral phases.

Goodness-of-fit statistics comparing modeled and measured iron concentrations in the lakes resulted in ME of –0.22 to 0.05 mg/L and MAE of 0.28 to 0.80 mg/L (table 9), depending on the waterbody and year.

Nitrogen and Phosphorus

Phosphorus and nitrogen are essential nutrients in surface water biogeochemistry. Some forms of these nutrients are found in excess in surface waters and are subject to water-quality regulation. In the models, nutrients cycled between dissolved inorganic nutrients, such as orthophosphate, nitrate+nitrite, ammonia, and in dissolved organic matter, as well as in particulate forms such as algae or particulate organic matter. Ammonia was released from decomposing organic matter in lake bottom waters when the hypolimnions become anoxic (figs. 9–10, 14–15, 17–18, 24–26). Nitrate, an oxidized form of dissolved inorganic nitrogen, was not found in the anoxic hypolimnion, but instead in other parts of the lake and during other times.

In the lake outflows, in the two years modeled which varied between lakes, modeled concentrations of TKN typically ranged between 0.0 and 2.5 mg/L, ammonia between 0.0 and 1.5 mg/L, nitrate between 0.0 and 2.0 mg/L, orthophosphate between 0.00 and 0.04 mg/L, and total phosphorus between 0.03 and 0.15 mg/L (figs. 11, 16, 19).

In the Mahoning River, in the years modeled, concentrations of these nutrients were sometimes high and sometimes low, but seasonal patterns varied between years (figs. 21–22). Concentrations of nitrogen and phosphorus increased in the downstream direction between Lowellville and Leavittsburg on many of the modeled dates in 2013 and 2019 (fig. 23) due mostly to higher-concentration inflows from tributaries and point sources in this reach. Seven municipal wastewater treatment facilities and several industrial point sources discharged effluent to the Mahoning River in the years modeled, along with two other municipal discharges into creeks that flow in the Mahoning River. While many of the point sources were well-characterized with respect to nutrients, there were several for which nutrient inputs to the Mahoning River were unknown. At the Mahoning River at Lowellville, average modeled concentrations for calendar years 2013 and 2019 together were 1.0 mg/L TKN, 0.3 mg/L ammonia, 2.1 mg/L nitrate, 0.13 mg/L orthophosphate, and 0.18 mg/L total phosphorus. The concentrations of nitrate, orthophosphate, and total phosphorus, in particular, increased in concentration downstream through the Mahoning River, relative to the lower concentrations in lake outflows.

Goodness-of-fit statistics comparing modeled and measured values for TKN, nitrate, and ammonia in the lakes, lake outflows, and at Mahoning River locations resulted in ME of –0.24 to 0.20 mg/L and MAE of 0.12 to 0.67 mg/L for TKN, ME of –0.20 to 0.26 mg/L and MAE of 0.05 to 0.50 mg/L for nitrate, and ME of –0.16 to 0.09 mg/L and MAE of 0.06 to 0.20 mg/L for ammonia (table 9), depending on the waterbody and year. For total phosphorus, the ME were –0.05 to 0.06 mg/L and MAE were 0.02 to 0.06 mg/L; for orthophosphate, the ME were 0.00 to 0.04 mg/L and MAE were 0.01 to 0.05 mg/L.

Algae

Algal populations in natural waters can be beneficial because they provide food for aquatic organisms and produce dissolved oxygen during photosynthesis. However, algal respiration and decomposition of algal-derived biomass consumes oxygen, and certain algal species can produce toxins. Algal populations in the CE-QUAL-W2 model are controlled by factors such as light, nutrients, settling, and water temperature. When algae die and decompose, they transform into other water-quality components, such as particulate organic matter and dissolved organic matter and nutrients. The model calculates chlorophyll *a* by multiplying algal concentrations by the ACHLA parameter, so chlorophyll *a* concentrations represent total algal concentrations in the model.

Modeling algae in lakes is challenging because not all algal processes are captured (for example, vertical movements in the water column in response to light or grazing by zooplankton or fish), and the three algal groups in the model are proxies for many algal species that each have their own characteristic growth, respiration, and settling rates. Despite these challenges, the models were able to simulate the overall magnitude and some of the seasonal patterns in concentrations of algae and chlorophyll *a* in the lakes. In the years modeled, Michael J Kirwan Reservoir had the lowest concentrations of algae and chlorophyll *a,* and Berlin and Mosquito Creek Lakes had locations and days with higher concentrations.

In its lake outflows, Michael J Kirwan Reservoir had especially low measured and modeled concentrations of chlorophyll *a*, typically under 10 µg/L. Measured and modeled chlorophyll *a* at Berlin Lake and Michael J Kirwan Reservoir were <30 µg/L in the years modeled. Mosquito Creek Lake had somewhat greater concentrations of modeled and measured chlorophyll *a*, but still typically <50 µg/L.

In the Mahoning River in 2013 and 2019, measured chlorophyll *a* was typically <40 µg/L, and the model generally had similar levels of chlorophyll *a*. In 2013, a period of elevated chlorophyll *a* in August was underpredicted in the model, likely because the inflow tributaries did not have frequent enough chlorophyll *a* sampling data to properly describe the inputs during that short-term event.

Goodness-of-fit statistics comparing modeled and measured chlorophyll *a* concentrations in the lakes, lake outflows, and at Mahoning River locations resulted in ME of –14.3 to –0.1 µg/L and MAE of 2.9 to 18.9 µg/L (table 9), depending on the waterbody and year.

Total Dissolved Solids, Sulfate, and Chloride

The CE-QUAL-W2 model considers TDS, sulfate, and chloride as conservative (nonreactive) constituents, with concentrations only dependent on inflows, outflows, and hydrodynamic mixing. The models and measured depth profiles did not show strong gradients in TDS, sulfate, or chloride within the lakes (figs. 9–10, 14–15, 17–18, 24–26). TDS was overpredicted in the lakes (table 9); one reason for this may be the fact that storm or rain events can dilute tributary inputs, but sampling generally took place on days without storms. The model interpolates between measured input data, so inputs likely missed those lower-TDS conditions during storm events.

Values of TDS in the outflows of all lakes ranged between 150 and 300 mg/L in the years modeled (figs. 11, 16, 19). Measured outflow sulfate concentrations were greatest at Berlin Lake (35–65 mg/L), middling at Michael J Kirwan Reservoir (15–45 mg/L), and least at Mosquito Creek Lake (5–25 mg/L) in the years modeled. Measured outflow chloride concentrations were 25–55 mg/L in the years modeled. No consistent seasonal patterns in the outflows were observed for these constituents.

The model was able to simulate seasonal and spatial patterns of TDS in the river well (figs. 21–22). Modeled and measured sulfate and chloride concentrations in the river matched well at upstream Mahoning River sites in 2013 and at most sites in 2019. In 2013, modeled sulfate and chloride concentrations were lower than measured concentrations at downstream Mahoning River sites (fig. 21). Several point sources and tributary streams had elevated TDS values that led to increased TDS between Leavittsburg and Lowellville in 2013 and 2019 (fig. 23). Likely some part of those TDS consisted of sulfate or chloride. However, point source sulfate and chloride concentrations were set to zero in the model, given a lack of measured data in the DMRs. Tributary streams had available sulfate and chloride data and thus had non-zero concentrations. The difference in the modeled and measured results suggests that unmeasured sources of sulfate and chloride to the river indeed did exist. Some portion of the modeled deficit is accounted by the point sources, but other unmeasured sources of sulfate and chloride to the river are likely.

Goodness-of-fit statistics comparing modeled and measured values for TDS, sulfate, and chloride in the lakes, lake outflows, and at Mahoning River locations resulted in ME of –6 to 52 mg/L and MAE of 9 to 52 mg/L for TDS, ME of –5.0 to 9.2 mg/L and MAE of 1.7 to 9.2 mg/L for sulfate, and ME of –14 to 7.9 mg/L and MAE of 1.8 to 15 mg/L for chloride, depending on the waterbody and year.

Model Application

The whole-basin model was used to construct model scenarios that examined how altered lake water surface elevations and lake outflows could affect flow and water-quality conditions in the lakes, the lake outflows, and the Mahoning River downstream. The whole-basin model that was constructed using observed lake water surface elevations and outflows from calendar year 2013 was designated as scenario 0 (table 10).

Four additional model scenarios were constructed by modifying scenario 0 using lake water surface elevations generated by USACE with a RES-SIM model for each of the four lakes. Scenario 1 was the RES-SIM base case (fig. 28). This scenario had water surface elevations aligned with existing operational guidelines in the current water control manual (U.S. Army Engineer District, 1978a, b, c). Flow and water-quality results from scenario 1 were used as a comparison to results from scenarios 2, 3, and 4 that considered future operational changes. Scenario 2 proposed to keep Berlin Lake water surface elevations higher in summer, delaying drawdown until September 7. Scenario 3 considered that 25 percent of flood storage during the summer could be used to extend the guide curve. Scenarios 2 and 3 both removed the requirement that 64 percent of flow augmentation should come from Berlin Lake and Lake Milton, and 36 percent should come from Michael J Kirwan Reservoir; in these two scenarios, the percentages could change but downstream flow targets on the Mahoning River remained unchanged. Scenario 4 removed the consideration of Mahoning River minimum flow requirements at Leavittsburg and Youngstown, which allowed more water to be stored in the lakes during summer. Model water-quality results were assessed by comparing the RES-SIM scenario 1 base case to the RES-SIM scenarios 2–4.

Table 10. Summary of model scenarios that simulated the effects of altered lake water surface elevations and lake outflows, Mahoning River Basin, Ohio.

[**Abbreviation**: RES-SIM, reservoir operations model]

Scenario No.	Scenario identifier	Scenario description
0	CalBase	Initial whole-basin model, with measured year 2013 hydrology.
1	RBase	RES-SIM base case lake elevations.
2	LDay	RES-SIM lake elevations that extended Berlin Lake summer pool to Labor Day (drawdown began September 7) and removed the percentages of augmentation flow from Berlin Lake, Lake Milton and Michael J Kirwan Reservoir.
3	Extend	RES-SIM lake elevations that used 25 percent of the flood storage during the summer to extend the guide curve, and removed the percentage of augmentation flow from Berlin Lake, Lake Milton and Michael J Kirwan Reservoir.
4	NoMinQ	RES-SIM lake elevations without minimum flow requirements at Leavittsburg and Youngstown.

Model scenarios were run and analyzed to examine the effects of these lake water surface elevations on water quality in the lakes, in the lake outflows, and in the Mahoning River downstream. Results were taken from various model output files and further analyzed with R, Perl, or Excel. Results were also compared to water-quality action levels used by USACE in planning operations (tables 11–12). These action levels were guided by state and local water-quality criteria but were sometimes more conservative. Since the Mahoning River is a tributary to the Beaver River in Pennsylvania, some action levels were based on Pennsylvania standards.

Scenario Lake Elevations and Outflows

To achieve the target water surface elevations in scenarios 1–4, lake outflows were modified in the CE-QUAL-W2 whole-basin model (fig. 28). RES-SIM model outflows could not be used directly in the CE-QUAL-W2 models due to the differences in USACE and CE-QUAL-W2 volume-elevation curves (figs. 2–4). After appropriate modification of the lake outflows for each scenario, daily water surface elevations matched well between the RES-SIM and CE-QUAL-W2 scenario models with limited instances of difference: (1) during storm events when the lake water surface elevation changed more rapidly than the approximately daily changes in outflow and (2) when a lake outflow was calculated to be zero, but some minimal outflow (minimum ~14 ft^3/s) was needed to keep the downstream CE-QUAL-W2 river models computationally stable.

Compared to the initial whole-basin model scenario 0, the RES-SIM scenarios 1–4 had mostly lower lake water surface elevations (fig. 28); the exceptions were Berlin Lake from August–October for scenarios 2 and 4 and Lake Milton in November–December for scenarios 1–4. The RES-SIM scenarios had lake water surface elevations that were almost identical in January–March, after which time they and their associated lake outflows began to differ. The model of Mosquito Creek downstream from Mosquito Creek Lake and the Mahoning River model were not altered for the scenarios but received the changed lake outflows.

Berlin Lake

Berlin Lake for scenarios 1 and 3 had the lowest water surface elevation in August–October, with scenario 4 (followed by scenario 2) having the highest water surface elevations at that time. By December, scenarios 1–4 had similar water surface elevations again. Maintaining higher water surface elevations in summer for scenarios 2 and 4 meant that Berlin Lake outflows were low compared to scenarios 1 and 3 for August and part of September. After mid-September, scenario 2 and especially scenario 4 outflows were greater than the others, as greater amounts of stored water were released to draw down the lake and prepare for flood season.

Lake Milton

For Lake Milton, scenario 1 had the lowest water surface elevation from late May to mid-July, and scenario 2 had the lowest water surface elevation from August through mid-October (fig. 28). From mid-April through November, scenario 4 had the highest water surface elevations. Lake outflows in scenarios 2 and 4 were lowest in August through mid-September, but greater than other outflows for most of October (both 2 and 4) and through November (scenario 4).

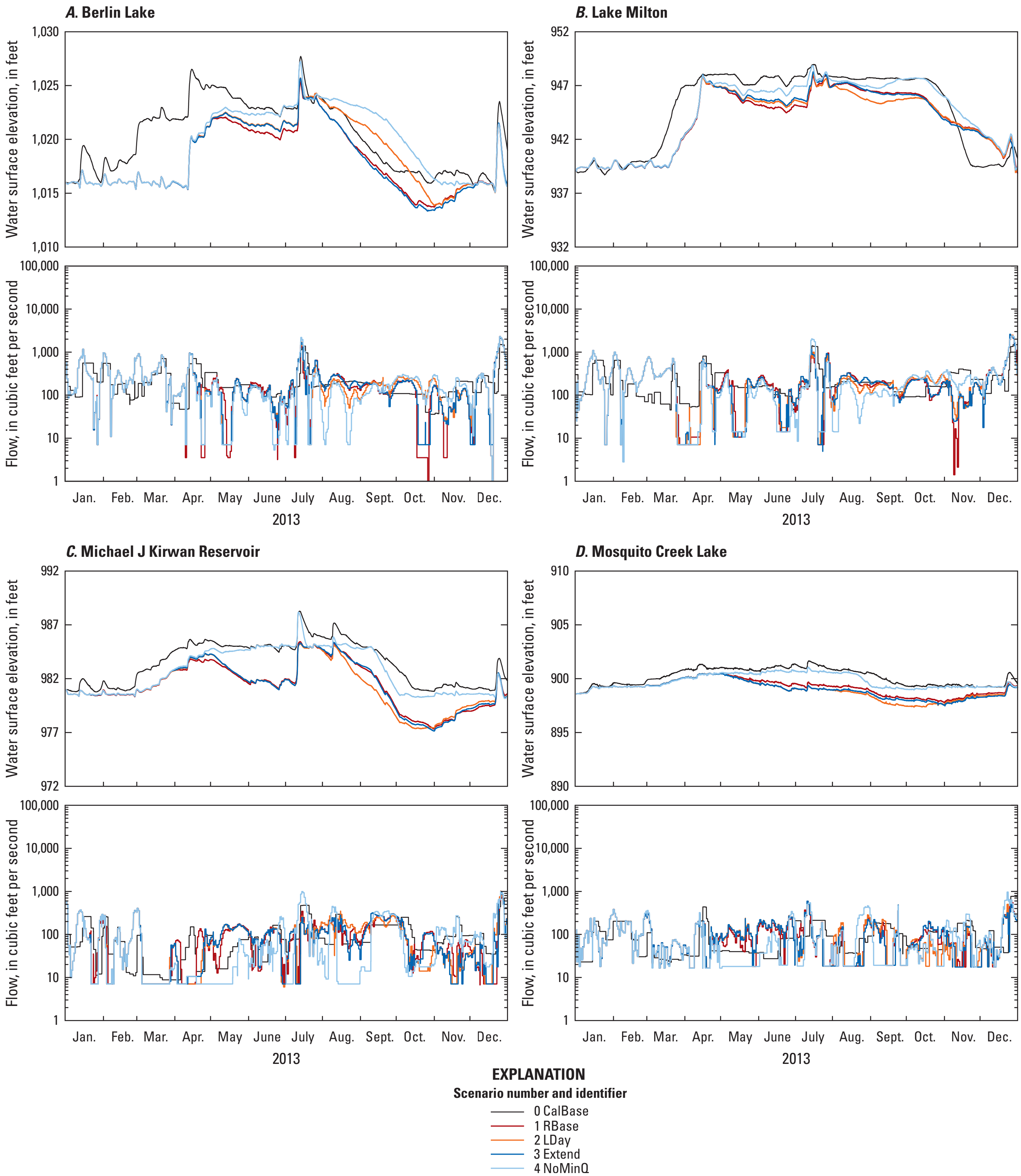


Figure 28. Model scenario lake water surface elevations and lake outflows through (*A*) Berlin Lake, (*B*) Lake Milton, (*C*) Michael J Kirwan Reservoir, and (D) Mosquito Creek Lake, Ohio, 2013.

Table 11. U.S. Army Corps of Engineers water-quality action levels used to evaluate model scenario results for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

[**Abbreviations:** USACE, U.S. Army Corps of Engineers; mg/L, milligram per liter; ORSANCO, Ohio River Valley Water Sanitation Commission]

Parameter	Maximum or minimum	Unit	USACE lake action level	USACE lake outflow and river action level	Notes
Total chloride	Maximun	mg/L	90	90	Ohio aquatic life standard=250
Chlorophyll *a*	Maximun	mg/L	40	20	
Dissolved oxygen	Minimum	mg/L	*4	5	Ohio aquatic life standard=4 (minimum), 5 average
Total iron	Maximun	mg/L	1.5	1.5	Pennsylvania 30-day average standard=1.5
Total nitrate + nitrite	Maximun	mg/L	10	10	ORSANCO human health=10
Total phosphorus	Maximun	mg/L	50	50	Pennsylvania aquatic life=50
Total sulfate	Maximun	mg/L	100	100	Ohio human health drinking=250
Total dissolved solids	Maximun	mg/L	340	340	Ohio aquatic life standard=1,500

*Applies to lake epilimnion (near-surface waters) 0–10 feet

Table 12. Daily maximum water temperature criteria used to evaluate the model scenario results for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River, Ohio.

Month	Day	Lake and lake outflows		Mahoning River, Leavittsburg to state line	
		Daily maximum (degrees Fahrenheit)	Daily maximum (degrees Celsius)	Daily maximum (degrees Fahrenheit)	Daily maximum (degrees Celsius)
January	1–31	52	11.1	53	11.7
February	1–29	52	11.1	53	11.7
March	1–15	56	13.3	57	13.9
March	16–31	59	15.0	61	16.1
April	1–15	65	18.3	65	18.3
April	16–30	70	21.1	70	21.1
May	1–15	73	22.8	76	24.4
May	16–31	76	24.4	79	26.1
June	1–15	80	26.7	84	28.9
June	16–30	85	29.4	89	31.7
July	1–31	85	29.4	89	31.7
August	1–31	85	29.4	89	31.7
September	1–15	85	29.4	89	31.7
September	16–30	78	25.6	83	28.3
October	1–15	76	24.4	77	25.0
October	16–31	70	21.1	72	22.2
November	1–30	65	18.3	66	18.9
December	1–31	52	11.1	55	12.8

Michael J Kirwan Reservoir

Scenario 4 water surface elevations were highest of the four scenarios through most of the year (fig. 28) with the other scenarios having lower, water surface elevations with minor differences between them. For instance, scenario 2 had lower water surface elevations in August-October, and scenario 1 had the lowest water surface elevations in early December. To maintain the higher water surface elevations in scenario 4, releases from Michael J Kirwan Reservoir to downstream were lower in April through mid-June and at other certain times of the year. Releases were somewhat greater for scenario 4 in November.

Mosquito Creek Lake

The scenario 4 water surface elevations were higher than those from the other RES-SIM scenarios for most of the year in Mosquito Creek Lake. Scenario 1 was the next highest, followed by scenarios 3 and 2. To achieve the higher water surface elevations, scenario 4 outflows were lowest among the four RES-SIM scenarios for May to mid-June and also for most of September.

Mahoning River

The river flows and water surface elevations caused by altered lake outflows were assessed at four locations within the Mahoning River model: Leavittsburg, Warren, Youngstown, and Lowellville (fig. 29). In the Mahoning River, the RES-SIM scenarios as a group had periods of both higher and lower flow and water surface elevation, compared to scenario 0 based on measured 2013 conditions (fig. 29). As a group, model scenarios 1–3 had largely similar effects on flow and water surface elevation in the Mahoning River, because they still were required to meet the downstream flow targets. Scenario 4 effects were similar for many periods, especially for January–March, but also had periods of markedly lower or higher flow and water surface elevation between May and mid–November, due to the elimination of downstream flow targets. The effects of the potentially changed river flows on river recreation, aquatic habitat, and other uses of the Mahoning River were not analyzed in this study.

Scenario Water Quality

Berlin Lake and Lake Milton

Model scenarios 1–4 of Berlin Lake and Lake Milton had generally similar seasonal patterns of water quality. The lakes shifted from isothermal and oxygenated in January–April to development of a thermocline and an anoxic hypolimnion from May–mid-October and again to well-mixed and oxygenated from mid-October through December (figs. 30–34). The thermal stratification and related anoxia were at times interrupted by higher flow events with elevated water velocity through the lakes (figs. 31, 32). With the main lake releases for these lakes located at relatively low elevations in the lakes, the horizontal velocities were greatest in the lower portions of the water column.

Differences between scenarios 1 and 4 were evident in the extent of anoxia and how much ammonia and dissolved iron built up in the hypolimnion (figs. 35–36; table 13), especially in Lake Milton. The instances with the largest concentrations of iron and ammonia in late June and early July correspond to periods of both low inflows to Lake Milton from Berlin Lake, just upstream, and low outflows at Lake Milton dam. Stormflows through the lakes in mid-July interrupted the stratification and development of high concentrations of ammonia and iron and possibly chlorophyll *a* (figs 35–37). This connection between water quality and flow appeared to be especially strong in Lake Milton, since both its outflows and most of its inflows were regulated. Berlin Lake, with more unregulated inflows and low elevation releases, maintained greater horizontal velocities in bottom waters in the scenarios (fig. 32) and was not as affected by these processes in the lake or in the outflows (figs. 38–39). While minimum in- and outflows were not part of these scenarios, they could be considered in operational planning and future model scenarios as a way to increase circulation and help manage the extent of anoxia within Lake Milton.

Lake Milton was slightly cooler with a shallower thermocline in scenarios 2–4 than in the scenario 1 base case, possibly due to the higher water surface elevations through late July in those scenarios. Lake Milton outflows for scenarios 2–4 were also cooler in the April–July period (table 14; fig. 39) compared to scenario 1. These cooler temperatures may have led to the lower chlorophyll *a* concentrations within Lake Milton and the outflow for those scenarios (tables 14–15; figs. 37, 39), as algal growth rates are temperature dependent.

Figures 30–49. Figures 30–49 are at the back of this report.

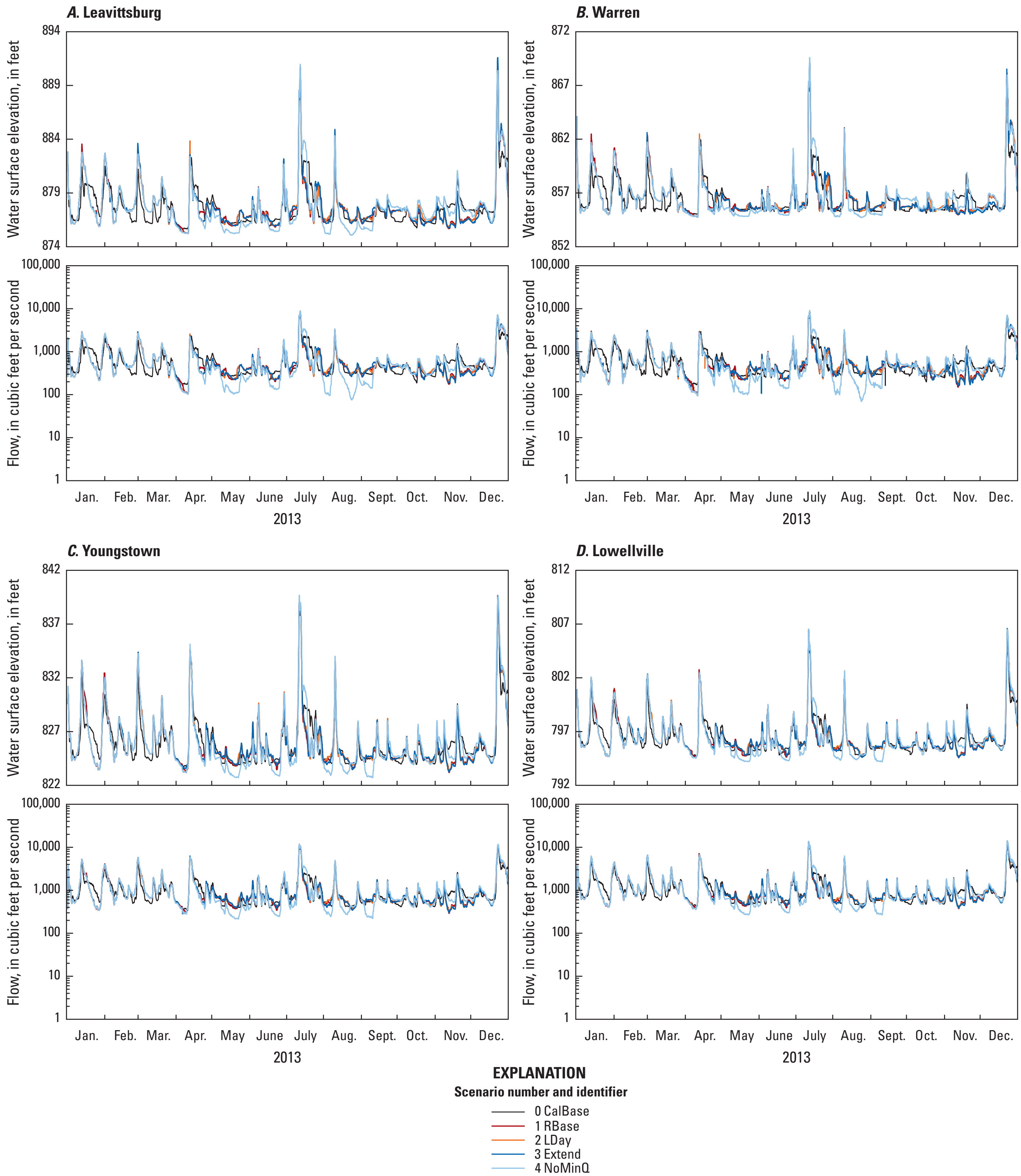


Figure 29. Mahoning River model scenario water surface elevations and streamflows for Mahoning River at (*A*) Leavittsburg, (*B*) Warren, (*C*) Youngstown, and (*D*) Lowellville, Ohio, 2013.

Table 13. Difference between whole-lake annual average water quality in scenarios 2, 3, 4, and the base case scenario 1, Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake, Ohio.

[Scenarios are discussed in table 10. Negative values represent a scenario value less than the base case. **Abbreviations**: Total P, total phosphorus; TDS, total dissolved solid; Ortho-P, orthophosphate; mg/L, milligram per liter; TKN, total Kjeldahl nitrogen; µg/L, microgram per liter]

Lake	Model scenario	Water temperature (Celsius)	TDS (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Ortho-P (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Iron (mg/L)	Total P (mg/L)	TKN (mg/L)	Chlorophyll *a* (ug/L)	Dissolved oxygen (mg/L)	Depth (feet)
Berlin	2	0.4	0.0	[1]0.1	0.0	0.000	0.00	–0.02	0.00	0.000	0.0	0.5	–0.1	0.5
	3	0.0	0.0	0.0	0.0	0.000	0.00	0.00	0.00	[1]0.000	0.0	0.2	0.0	0.1
	4	[1]0.6	–0.8	0.0	–0.1	[2]–0.001	[2]–0.01	[2]–0.06	–0.01	[2]–0.001	[2]0.0	[1]0.7	–0.2	1.0
Milton	2	–0.2	–0.6	[2]–0.1	0.0	0.000	0.02	[1]0.01	0.05	–0.001	0.0	–1.0	–0.1	–0.2
	3	–0.1	–0.2	0.0	0.0	0.000	0.02	0.00	0.07	0.000	[1]0.0	–0.5	[2]–0.2	–0.1
	4	0.1	–0.8	–0.1	–0.1	[1]0.001	[1]0.02	–0.01	[1]0.09	0.000	0.0	[2]–2.4	–0.2	0.2
Michael J Kirwan	2	[2]–0.3	[1]0.2	0.0	[1]0.1	0.000	0.01	0.00	0.05	0.000	0.0	0.2	–0.1	–0.1
	3	0.0	0.1	0.0	0.0	0.000	0.00	0.00	0.00	0.000	0.0	0.0	0.0	0.1
	4	0.3	[2]–1.0	–0.1	[2]–0.2	0.000	0.00	–0.01	[2]–0.02	0.000	0.0	–0.3	–0.1	[1]1.3
Mosquito Creek	2	–0.2	[1]0.2	0.0	0.0	0.000	0.00	0.00	0.00	0.000	0.0	–0.3	[1]0.1	[2]–0.2
	3	–0.1	[1]0.2	0.0	0.0	0.000	0.00	0.00	0.00	0.000	0.0	–0.3	0.0	–0.2
	4	0.4	–0.6	–0.1	0.0	0.000	0.00	–0.01	0.01	0.000	0.0	0.5	–0.1	0.5

[1]10-percent highest values in column

[2]10-percent lowest values in column

Table 14. Difference between lake outflow seasonal average water quality in scenarios 2, 3, 4, and the base case scenario 1, Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake, Ohio.

[Scenarios are described in table 10. Negative values represent a scenario value less than the base case. **TDS:** Total dissolved solids. **Ortho-P:** Orthophosphorus. **Total P:** Total phosphorus. **TKN:** Total Kjeldahl nitrogen. **Abbreviations**: °C, degrees Celsius; mg/L, milligram per liter; µg/L, microgram per liter]

Lake outflow	Model scenario	Season	Water temp (°C)	TDS (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Ortho-P (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Total P (mg/L)	TKN (mg/L)	Chlorophyll a (µg/L)	Dissolved oxygen (mg/L)
Berlin	2	Jan.–Mar.	0.0	0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	–0.1	–0.2	0.0	0.0	0.000	0.0	0.0	0.000	0.0	–0.4	0.0
		July–Sept.	0.0	–1.5	–0.2	–0.1	0.000	[2]0.0	0.0	0.000	0.0	–0.6	0.0
		Oct.–Dec.	0.0	–3.0	–0.4	–0.2	[2]–0.001	0.0	0.0	[2]–0.001	0.0	0.1	0.0
	3	Jan.–Mar.	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	–0.1	–0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	–0.4	0.0
		July–Sept.	0.0	–0.1	0.1	0.0	0.000	[2]0.0	[1]0.0	0.000	[2]0.0	[1]0.3	0.0
		Oct.–Dec.	[1]0.1	0.6	0.0	0.0	0.000	0.0	0.0	[1]0.001	0.0	0.0	[2]0.0
	4	Jan.–Mar.	0.0	0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	–0.3	–0.5	–0.1	–0.1	0.000	0.0	[2]0.0	0.000	0.0	–1.1	0.1
		July–Sept.	[1]0.1	[2]–3.4	–0.5	–0.3	0.001	0.0	[1]0.0	[2]–0.001	[2]0.0	–0.9	0.0
		Oct.–Dec.	–0.1	[2]–8.0	[2]–1.0	–0.5	[2]–0.002	0.0	[2]–0.1	[2]–0.002	0.0	–0.2	0.0
Milton	2	Jan.–Mar.	0.0	–0.3	–0.1	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	–0.7	–1.1	–0.1	0.0	[1]0.001	[1]0.3	[2]0.0	[1]0.001	[1]0.3	[2]–4.2	0.1
		July.–Sept.	–0.5	–2.3	–0.4	–0.2	[2]–0.001	0.2	0.0	[2]–0.001	0.2	–2.8	0.1
		Oct.–Dec.	–0.1	0.9	0.1	0.0	0.000	0.0	[1]0.0	0.000	0.0	–0.3	0.0
	3	Jan.–Mar.	0.0	–0.2	–0.1	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	[2]–1.5	–1.4	–0.1	0.0	[1]0.002	[1]0.4	[2]–0.1	[1]0.001	[1]0.3	[2]–5.2	[1]0.3
		July–Sept.	–0.5	–0.6	–0.1	–0.1	0.000	0.1	0.0	–0.001	0.1	–2.3	0.1
		Oct.–Dec.	–0.1	0.1	0.0	0.0	[2]–0.001	0.0	0.0	0.000	0.0	–0.2	0.0
	4	Jan.–Mar.	0.0	–0.3	–0.1	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	[2]–0.8	–2.4	–0.3	–0.1	[1]0.003	[1]0.3	0.0	[1]0.001	[1]0.3	[2]–7.6	[1]0.2
		July–Sept.	–0.7	[2]–3.3	[2]–0.7	–0.3	[1]0.001	[1]0.3	0.0	0.000	[1]0.3	[2]–3.9	0.1
		Oct.–Dec.	0.0	–0.4	–0.2	–0.1	0.001	[2]0.0	[1]0.0	0.001	[2]–0.1	–1.4	0.0
Michael J Kirwan	2	Jan.–Mar.	0.0	–2.4	–0.5	[2]–0.8	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	[2]–1.1	–0.3	–0.1	–0.1	0.000	0.0	0.0	0.000	0.0	–0.9	[1]0.2
		July.–Sept.	[2]–1.2	–0.2	0.0	–0.1	0.001	0.0	0.0	0.001	0.0	–0.1	[1]0.2
		Oct.–Dec.	–0.1	[1]1.1	[1]0.2	[1]0.2	0.000	0.0	0.0	0.000	0.0	0.1	0.0
	3	Jan.–Mar.	0.0	–2.4	–0.5	[2]–0.8	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	0.0	–0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	–0.1	0.0
		July–Sept.	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Oct.–Dec.	0.0	0.3	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.1	0.0
	4	Jan.–Mar.	0.0	–2.5	[2]–0.5	[2]–0.8	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	–0.6	–0.8	–0.2	–0.3	0.000	0.0	0.0	0.000	0.0	–0.8	0.1
		July–Sept.	[1]0.2	[1]1.4	[1]0.2	[1]0.2	0.000	[2]–0.1	0.0	0.000	[2]–0.1	–0.6	[2]0.0
		Oct.–Dec.	[1]0.3	[2]–4.2	[2]–0.6	[2]–0.9	0.001	0.0	0.0	0.000	0.0	–0.3	[2]–0.1

Table 14. Difference between lake outflow seasonal average water quality in scenarios 2, 3, 4, and the base case scenario 1, Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake, Ohio.—Continued

[Scenarios are described in table 10. Negative values represent a scenario value less than the base case. **TDS:** Total dissolved solids. **Ortho-P:** Orthophosphorus. **Total P:** Total phosphorus. **TKN:** Total Kjeldahl nitrogen. **Abbreviations**: °C, degrees Celsius; mg/L, milligram per liter; µg/L, microgram per liter]

Lake outflow	Model scenario	Season	Water temp (°C)	TDS (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Ortho-P (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Total P (mg/L)	TKN (mg/L)	Chlorophyll a (µg/L)	Dissolved oxygen (mg/L)
Mosquito Creek	2	Jan.–Mar.	0.0	–0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	0.0	0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	[1]0.2	0.0
		July–Sept.	0.0	0.7	0.1	0.0	–0.001	0.0	0.0	0.000	0.0	–0.5	0.0
		Oct.–Dec.	0.0	[1]1.5	[1]0.2	[1]0.1	0.000	0.0	0.0	0.000	0.0	0.0	0.0
	3	Jan.–Mar.	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	0.0	0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	[1]0.2	0.0
		July–Sept.	0.0	0.6	0.1	0.0	–0.001	0.0	0.0	0.000	0.0	–0.5	0.0
		Oct.–Dec.	0.0	[1]1.3	[1]0.1	[1]0.2	0.000	0.0	0.0	[2]–0.001	0.0	–0.1	0.0
	4	Jan.–Mar.	0.0	–0.1	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.0
		Apr.–June	0.1	–0.2	0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.1	0.0
		July–Sept.	0.0	–1.5	–0.1	0.0	0.000	0.0	0.0	0.001	0.0	[1]0.6	0.0
		Oct.–Dec.	0.1	–2.0	–0.2	0.0	0.000	0.0	0.0	0.000	0.0	0.1	[2]0.0

[1]10-percent highest values in column

[2]10-percent lowest values in column

Table 15. Modeled change in the number of days when lake outflow was outside a water-quality criterion, for model scenarios 2, 3, and 4 compared to scenario 1, Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, and Mosquito Creek Lake, Ohio.

[Scenarios are described in table 10. A negative result indicates that scenario had fewer days outside the criterion compared to the RES-SIM base case.]

Lake	Scenario	Dissolved oxygen	Total dissolved solids	Sulfate	Chloride	Chlorophyll *a*	Total phosphorus	Nitrate
Berlin	2	0	–17	0	0	–1	0	0
	3	0	3	0	0	–1	0	0
	4	0	–54	0	0	–2	0	0
Milton	2	0	0	0	0	–34	0	0
	3	0	0	0	0	–35	0	0
	4	0	0	0	0	–41	0	0
Michael J Kirwan	2	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0
Mosquito Creek	2	0	0	0	0	–2	0	0
	3	0	0	0	0	–2	0	0
	4	0	0	0	0	4	0	0

Michael J Kirwan Reservoir

Model scenarios 1–4 of Michael J Kirwan Reservoir showed generally similar seasonal patterns of thermal structure and hypolimnetic anoxia in the lake with some small variability in the thermocline depth (figs. 40–41). With only relatively small differences in water surface elevation (–0.1 and 0.1 ft as an annual average), the modeled water-quality conditions in scenarios 2 and 3 in the lake and outflow were also similar to that in the scenario 1 base case (tables 13–15; figs. 33–34, 40–42). Some cooler release temperatures occurred in scenario 2 in late spring and summer (table 14; fig. 42) and a slightly greater percentage anoxic volume (fig. 33) appeared to be related to a slightly shallower thermocline. Scenario 4 water quality had some minor differences compared to the scenario 1 base case, with cooler outflows April–June and slightly warmer conditions through the rest of the year, though seasonal average temperature changes were <0.7 C (table 14). Scenario 4 also showed some differences in outflow TDS, chloride, and sulfate, compared to the scenario 1 base case; seasonal average concentration differences were <5 mg/L for TDS and <1 mg/L for chloride and sulfate (table 14).

Mosquito Creek Lake

Modeled water-quality changes in Mosquito Creek Lake, between scenarios 1 and 2–4, were relatively small (figs. 33–34, 43–44; table 13). Water-quality changes in the outflow of Mosquito Creek Lake, between scenarios 1 and 2–4, were also relatively minor (fig. 45; tables 14–15).

Mahoning River

Model scenario water quality in the Mahoning River was assessed at Leavittsburg, Warren, Youngstown, and Lowellville (tables 16–17; figs. 46–49). The Leavittsburg and Warren sites received releases from Lake Milton and Michael J Kirwan Reservoir and the Youngstown and Lowellville sites received releases from those two along with Mosquito Creek.

Scenarios 1–3 maintained the minimum flow requirements in the river. Consequently, the total USACE lake contributions to flow were similar, but the proportion of flow contributed by each lake could be different on different days. The modeled effect of these changes for scenarios 2 and 3 compared to the scenario 1 base case were relatively small at all four locations along the river.

The largest changes in Mahoning River water quality were observed between Leavittsburg and Lowellville for scenario 4. The periods of lower lake outflows between April and mid-September led to correspondingly higher concentrations of TDS and nutrients for those same periods in that portion of the river, compared to the base case scenario 1. Minimum flow targets were set in the Mahoning River to dilute the Mahoning River water; with those targets removed in this scenario, less dilution led to higher concentrations of TDS, orthophosphate, total phosphorus, and nitrate. Conversely, the overall greater lake outflows from mid-September through November in scenario 4 led to greater dilution and periods of lower concentrations of TDS and nutrients in that portion of the river compared to the base case scenario 1. At Leavittsburg and Warren, similar effects were seen, but the concentration changes were lower than those seen at Youngstown and Lowellville.

Table 16. Difference between seasonal average water quality in scenarios 2, 3, 4 and the base case scenario 1, Mahoning River, Ohio.

[Scenarios are described in table 10. Negative values represent a scenario value less than the base case. **Abbreviations:** Water temp, water temperature; °C, degrees Celsius; mg/L, milligram per liter; TKN total Kjeldahl nitrogen; ug/L, microgram per liter]

River site	Model scenario	Season	Water temp (°C)	TDS (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Ortho-P (mg/L)	Am-monia (mg/L)	Nitrate (mg/L)	Total P (mg/L)	TKN (mg/L)	Chlorophyll a (ug/L)	Dissolved oxygen
Leavittsburg	2	Jan–Mar	0.0	0	–0.1	0.1	0.000	0.00	0.00	0.000	[2]0.00	0.0	0.0
		Apr–Jun	–0.2	0	–0.3	0.5	0.000	0.03	0.02	0.000	0.02	–1.5	0.0
		July–Sep	[2]–0.4	–3	–1.0	0.0	0.000	0.04	0.01	–0.001	0.02	–1.6	0.0
		Oct–Dec	0.1	[1]7	[1]1.8	0.3	0.000	0.00	0.01	0.002	0.03	[1]0.5	[1]0.1
	3	Jan–Mar	0.0	0	–0.1	0.1	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	–0.1	0	–0.4	0.6	0.000	0.04	0.03	0.000	0.03	–1.6	0.0
		July–Sep	0.1	4	0.8	0.4	0.000	0.03	0.01	0.001	[1]0.05	–0.7	0.0
		Oct–Dec	0.0	1	0.2	0.2	0.000	0.01	0.02	0.000	0.01	–0.1	[1]0.0
	4	Jan–Mar	0.0	0	0.0	0.2	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	[1]0.7	3	0.4	[1]2.1	0.003	0.02	0.14	0.003	0.01	[2]–2.6	[1]0.1
		July–Sep	[2]–0.3	[2]–5	–0.9	[2]–0.7	0.003	[1]0.05	0.10	0.000	0.01	–2.6	[2]–0.1
		Oct–Dec	[1]0.2	5	1.6	–0.5	0.000	[2]–0.02	[2]–0.06	0.002	0.01	[1]0.3	0.0
Warren	2	Jan–Mar	0.0	0	–0.1	0.0	0.000	0.00	0.00	0.000	[2]0.00	0.0	0.0
		Apr–Jun	–0.1	0	–0.4	0.5	0.000	0.03	0.02	0.000	0.02	–1.5	0.0
		July–Sep	[2]–0.3	–3	[2]–1.0	0.0	0.000	0.03	0.01	–0.002	0.01	–1.6	0.0
		Oct–Dec	0.1	7	[1]1.8	0.3	0.000	0.00	0.01	0.002	0.03	[1]0.5	[1]0.1
	3	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	–0.1	0	–0.4	0.6	0.001	0.04	0.03	0.000	0.03	–1.6	0.0
		July–Sep	0.0	4	0.8	0.4	0.000	0.03	0.01	0.000	[1]0.04	–0.7	0.0
		Oct–Dec	0.0	1	0.1	0.2	0.000	0.01	0.02	0.000	0.01	–0.1	0.0
	4	Jan–Mar	0.0	0	0.0	0.1	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	[1]0.7	4	0.3	[1]2.2	0.005	0.02	0.14	0.005	0.01	–2.6	0.0
		July–Sep	–0.2	[2]–6	[2]–1.2	[2]–0.6	0.004	[1]0.04	0.11	0.002	0.01	[2]–2.7	–0.1
		Oct–Dec	0.2	5	1.8	–0.3	0.000	[2]–0.02	[2]–0.06	0.002	0.01	[1]0.3	0.0
Youngstown	2	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	0.0	–2	–0.6	0.4	–0.001	0.02	–0.01	–0.002	0.02	0.0	0.0
		July–Sep	–0.2	–4	–0.8	–0.2	[2]–0.002	0.02	–0.01	[2]–0.003	0.00	–1.2	0.0
		Oct–Dec	0.0	[1]8	1.8	0.3	0.003	0.00	0.04	0.004	0.02	0.2	0.0
	3	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	0.0	–1	–0.6	0.5	0.000	0.02	0.00	–0.001	0.02	–0.1	0.0
		July–Sep	0.0	4	0.7	0.2	0.000	0.02	0.01	0.000	0.02	–0.8	0.0
		Oct–Dec	0.0	2	0.1	0.4	0.002	0.00	0.05	0.002	0.01	–0.1	0.0
	4	Jan–Mar	0.0	0	0.0	0.1	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	[1]0.3	[1]36	[1]2.6	[1]6.0	[1]0.048	[1]0.08	[1]0.57	[1]0.050	[1]0.12	[2]–3.1	[2]–0.3
		July–Sep	[2]–0.2	3	[2]–2.2	–0.1	[1]0.022	0.03	[1]0.26	[1]0.021	0.01	–1.9	[2]–0.1
		Oct–Dec	0.1	[2]–5	0.3	[2]–2.3	[2]–0.011	[2]–0.01	[2]–0.24	[2]–0.010	[2]0.00	0.2	0.0

Table 16. Difference between seasonal average water quality in scenarios 2, 3, 4 and the base case scenario 1, Mahoning River, Ohio.—Continued

[Scenarios are described in table 10. Negative values represent a scenario value less than the base case. **Abbreviations:** Water temp, water temperature; °C, degrees Celsius; mg/L, milligram per liter; TKN total Kjeldahl nitrogen; ug/L, microgram per liter]

River site	Model scenario	Season	Water temp (°C)	TDS (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Ortho-P (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Total P (mg/L)	TKN (mg/L)	Chlorophyll a (ug/L)	Dissolved oxygen
Lowellville	2	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	0.0	–2	–0.5	0.3	–0.002	0.01	–0.01	–0.002	0.01	0.0	0.0
		July–Sep	–0.2	–4	–0.8	–0.1	[2]–0.002	0.02	–0.01	[2]–0.003	0.00	–1.1	0.0
		Oct–Dec	0.0	7	1.5	0.2	0.003	0.00	0.04	0.004	0.02	0.2	0.0
	3	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	0.0	–1	–0.5	0.4	–0.001	0.02	0.00	–0.001	0.01	–0.1	0.0
		July–Sep	0.0	3	0.7	0.2	0.000	0.02	0.01	0.000	0.02	–0.8	0.0
		Oct–Dec	0.0	2	0.1	0.3	0.002	0.00	0.04	0.002	0.00	–0.1	0.0
	4	Jan–Mar	0.0	0	0.0	0.0	0.000	0.00	0.00	0.000	0.00	0.0	0.0
		Apr–Jun	0.2	[1]39	[1]2.5	[1]4.5	[1]0.056	[1]0.07	[1]0.58	[1]0.059	[1]0.12	[2]–2.9	[2]–0.2
		July–Sep	–0.2	6	[2]–2.3	–0.5	[1]0.030	0.03	[1]0.33	[1]0.030	0.02	–1.9	–0.1
		Oct–Dec	0.0	[2]–6	0.1	[2]–1.8	[2]–0.013	[2]–0.01	[2]–0.23	[2]–0.012	[2]–0.01	0.2	0.0

[1]10-percent highest values in column

[2]10-percent lowest values in column

Table 17. Modeled change in the number of days when the river water was outside a water-quality criterion for model scenarios 2, 3, and 4 compared to scenario 1, Leavittsburg, Warren, Youngstown, and Lowellville, Ohio.

[Scenarios are described in table 10. A negative result indicates that scenario had fewer days outside the criterion compared to the reservoir operations model base case.]

	Scenario	Dissolved oxygen	Total dissolved solids	Sulfate	Chloride	Chlorophyll *a*	Total phosphorus	Nitrate
				Change, in days				
Leavittsburg	2	0	0	0	0	–1	–10	0
	3	0	0	0	0	–1	2	0
	4	0	0	0	0	–1	23	0
Warren	2	0	0	0	0	–1	3	0
	3	0	0	0	0	–1	–4	0
	4	0	0	0	0	–1	25	0
Youngstown	2	0	16	0	0	–1	*0	0
	3	0	8	0	0	–1	*0	0
	4	0	55	0	2	–1	*0	0
Lowellville	2	0	0	0	0	0	*0	0
	3	0	–4	0	0	0	*0	0
	4	0	30	0	1	0	*0	0

*For Youngstown and Lowellville, all model scenarios showed exceedance of the total phosphorus criterion on all days, so there was no change between scenarios.

Summary

Flow and water-quality models were constructed for Berlin Lake, Lake Milton, Michael J Kirwan Reservoir, Mosquito Creek Lake, and the Mahoning River from the dams downstream to Lowellville, Ohio. Models were calibrated for two historic years in which adequate data was available; the years varied between waterbodies. A whole-basin model was constructed for year 2013. That model was used to examine the effects of altered lake water surface elevations on water quality in the lakes, the lake outflows and the Mahoning River. The altered lake elevations were based on reservoir operations models and were provided by the U.S. Army Corps of Engineers.

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Figures 8–23

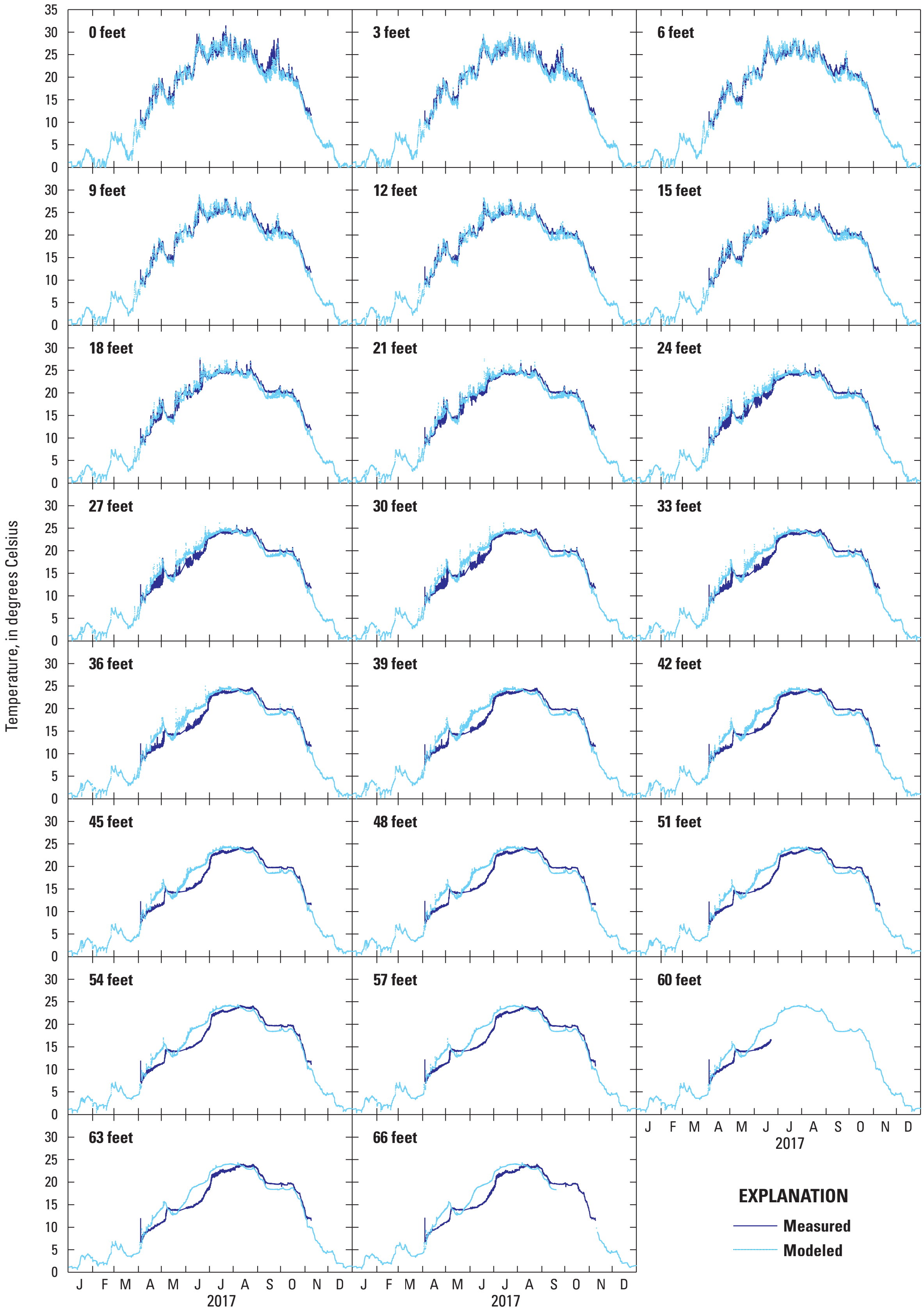


Figure 8. Berlin Lake modeled water temperature at segment 37 and measured water temperature just upstream from Berlin Lake dam, Ohio, 2017. Measured values are from a thermistor string with sensors every 3 feet into the water column. Model output was extracted at the same depth.

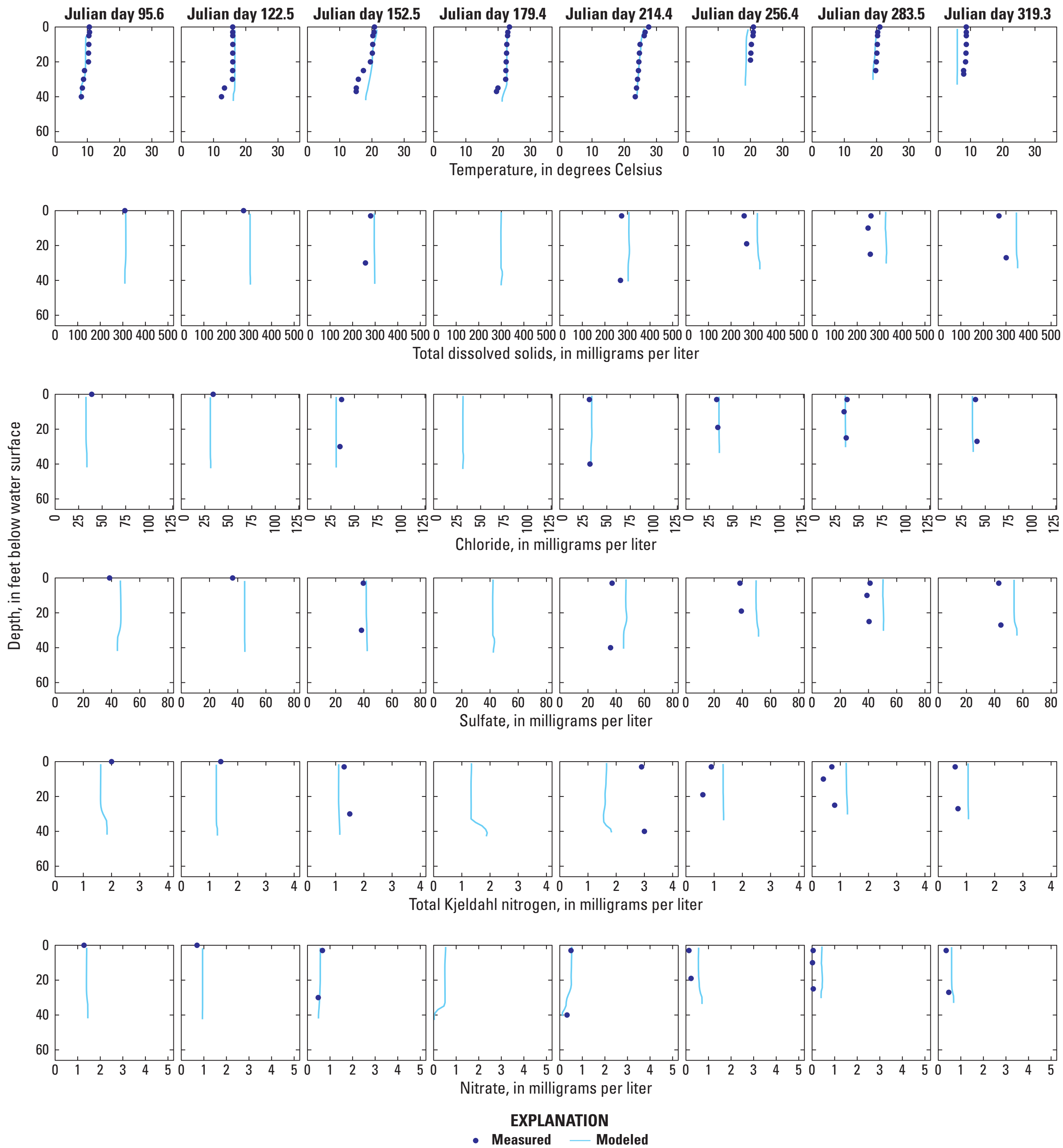
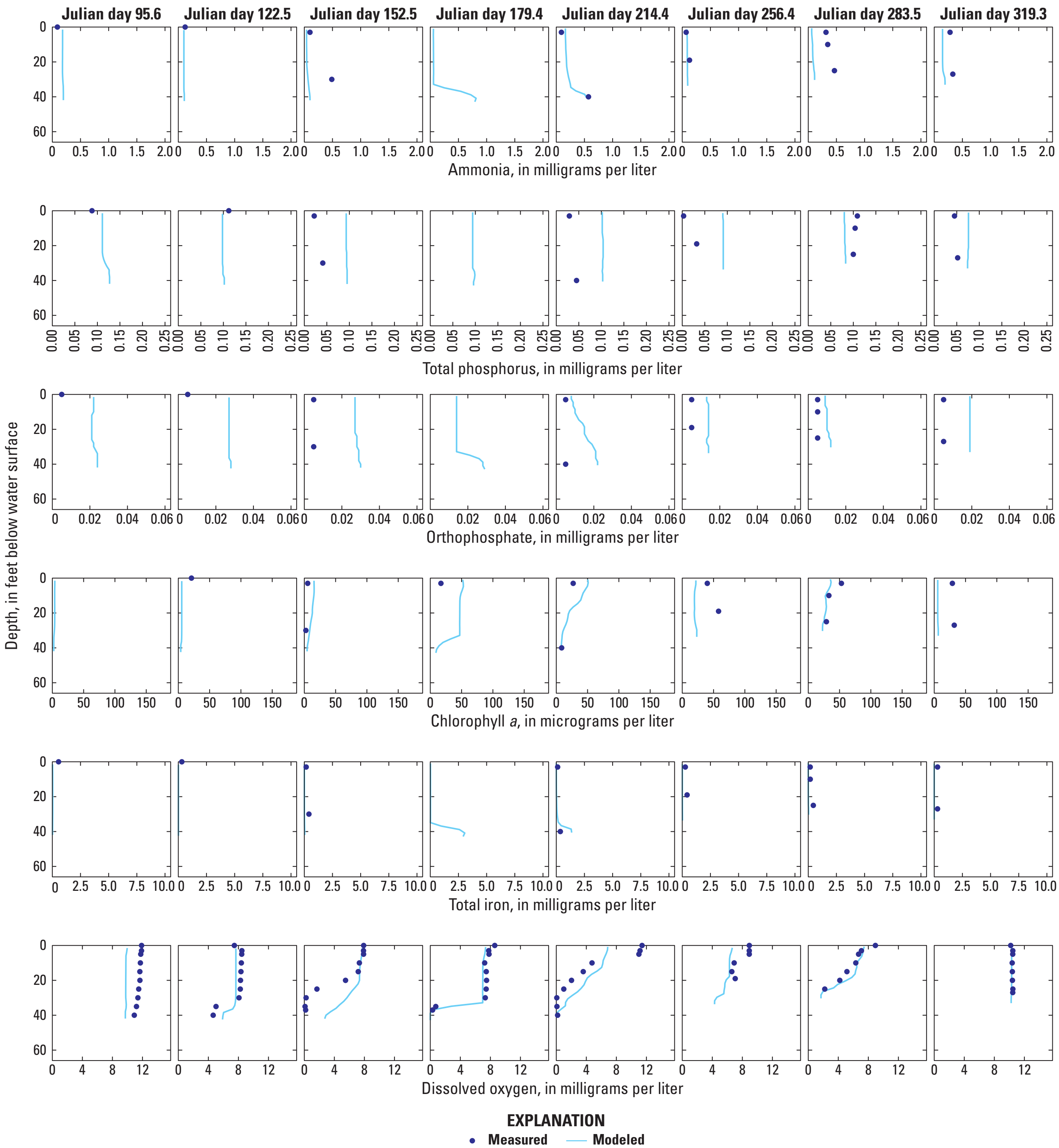


Figure 9. Berlin Lake measured and modeled depth profiles at site 1003 and model segment 31 on sampling dates in 2017, Ohio.



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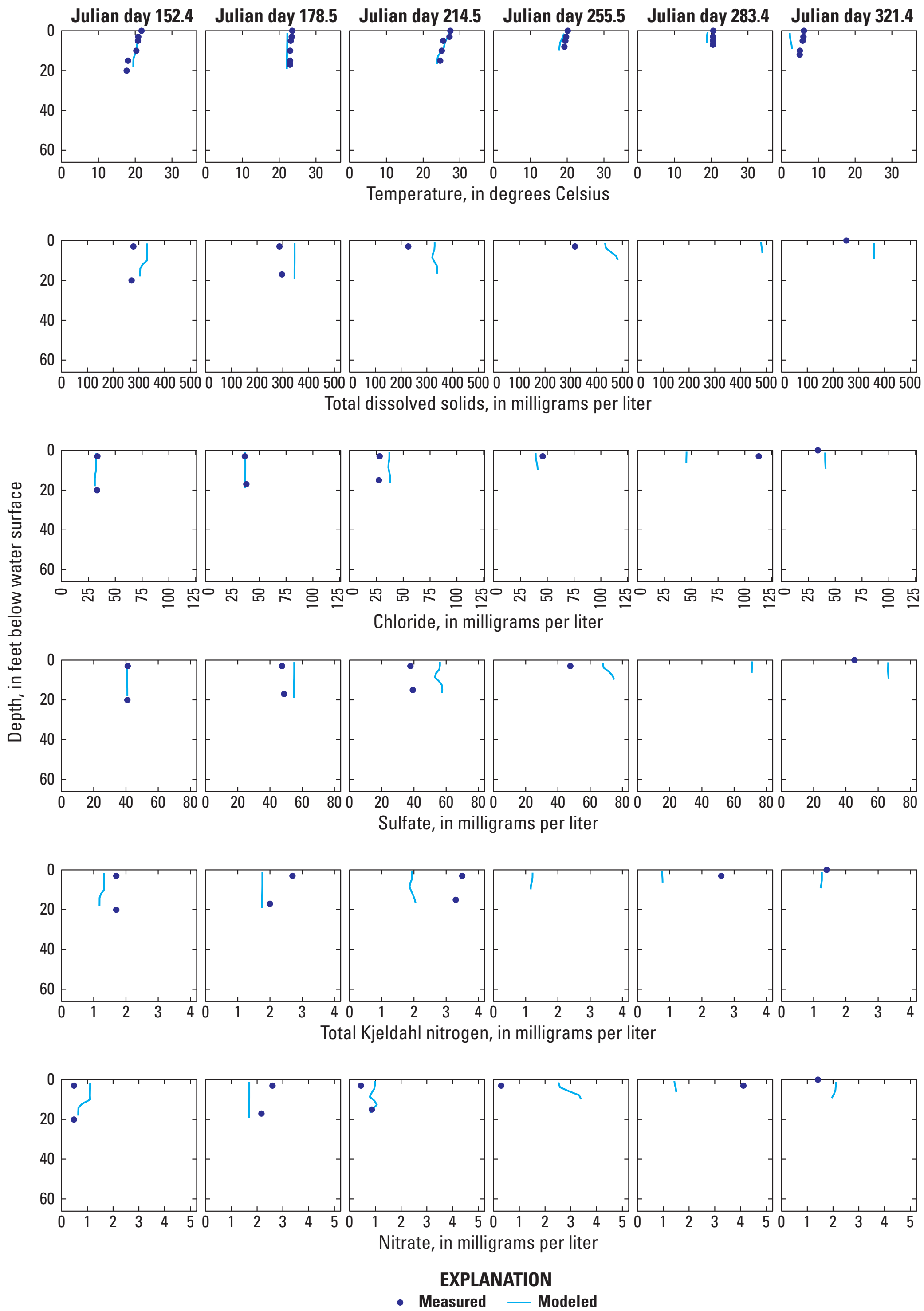
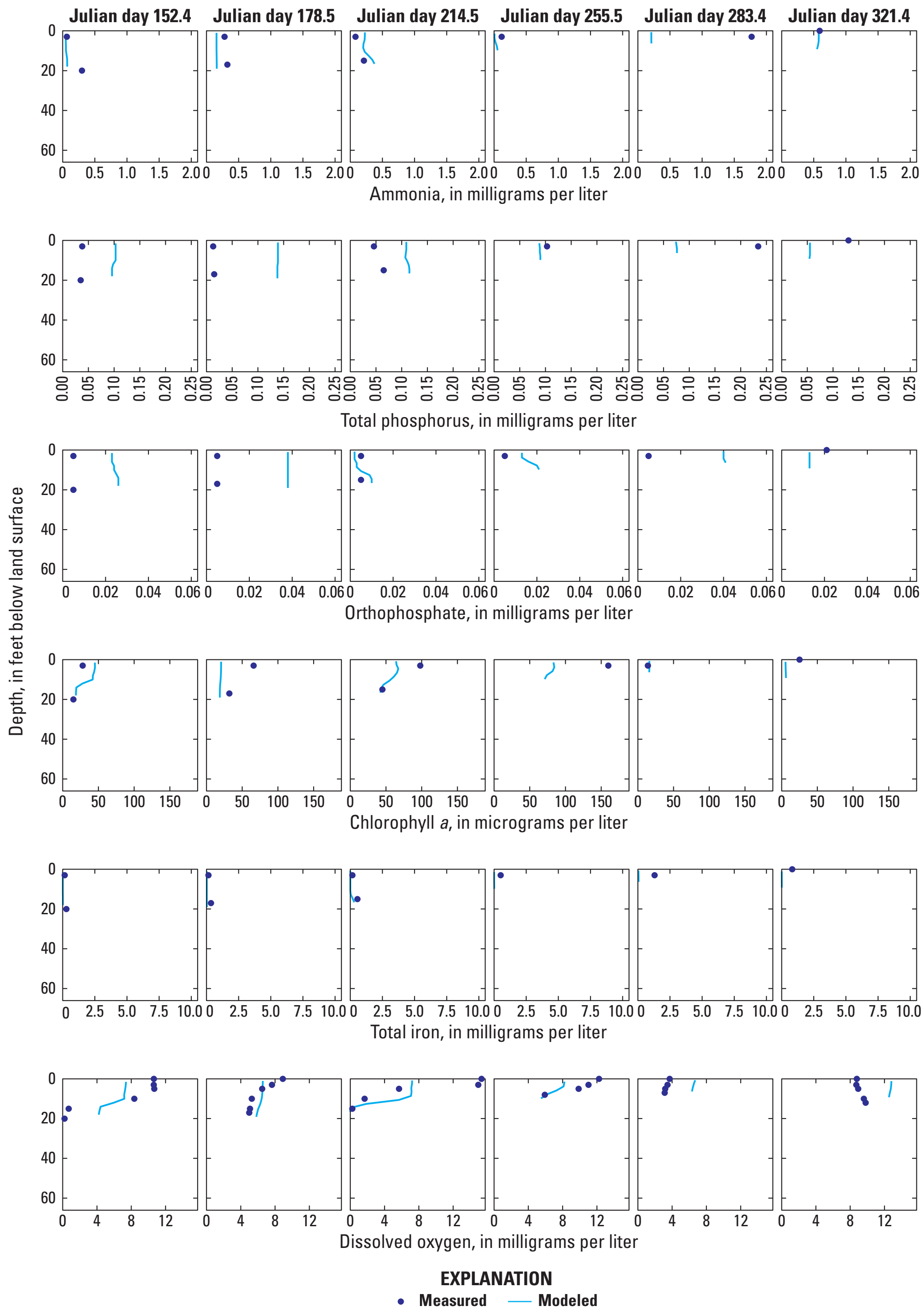


Figure 10. Berlin Lake measured and modeled depth profiles at site 1005 and model segment 21 on sampling dates in 2017, Ohio.



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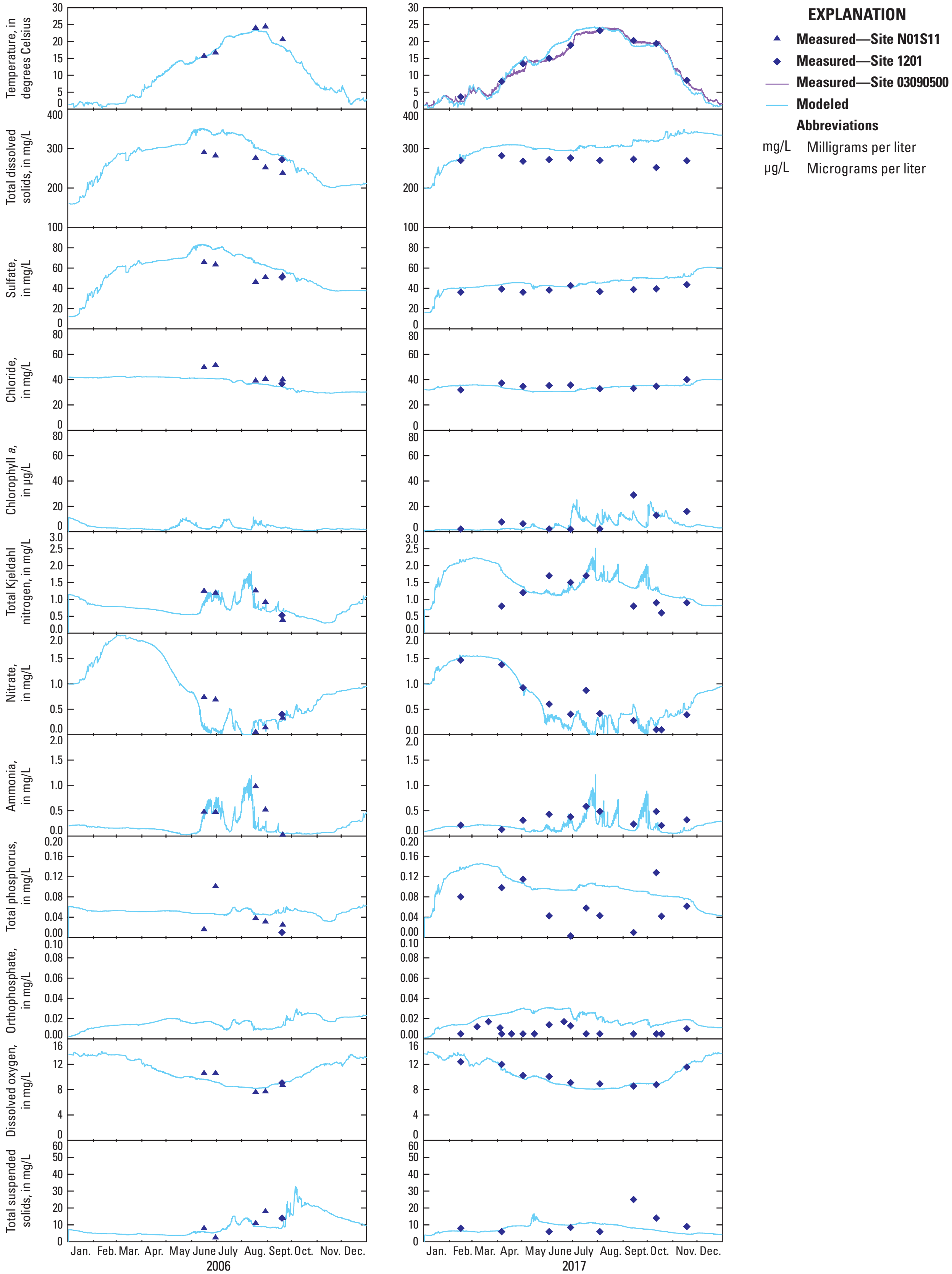


Figure 11. Modeled Berlin Lake outflow water quality and measured water quality sampled just downstream from the dam in 2006 and 2017, Ohio. Sites with measured data include site 1201, 03090500, and N01S11 (table 5).

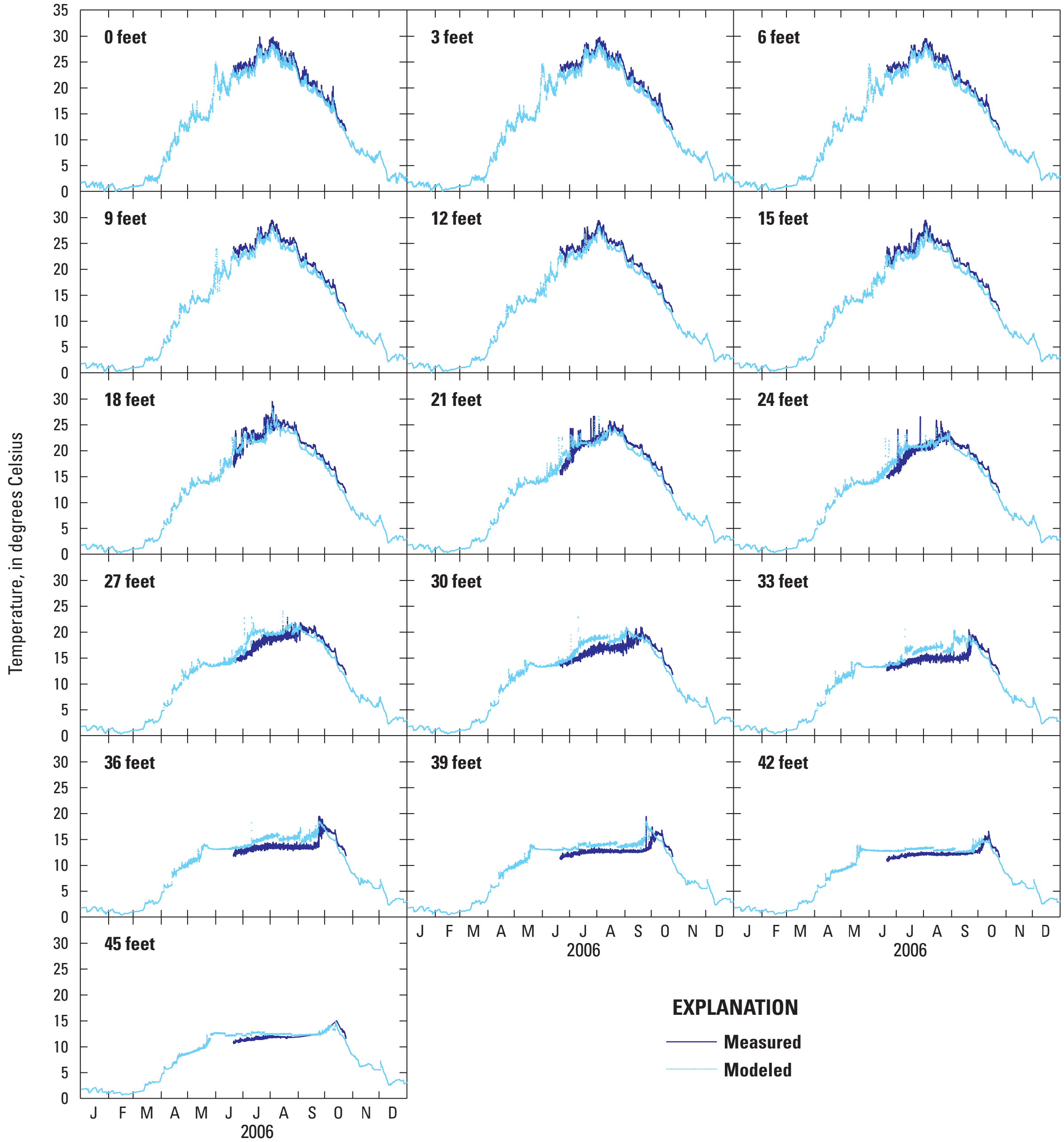


Figure 12. Michael J Kirwan Reservoir modeled and measured water temperature just upstream from the dam in 2006, Ohio. Measured values are from a thermistor string with sensors every 3 feet into the water column. Model output was extracted at the same depth.

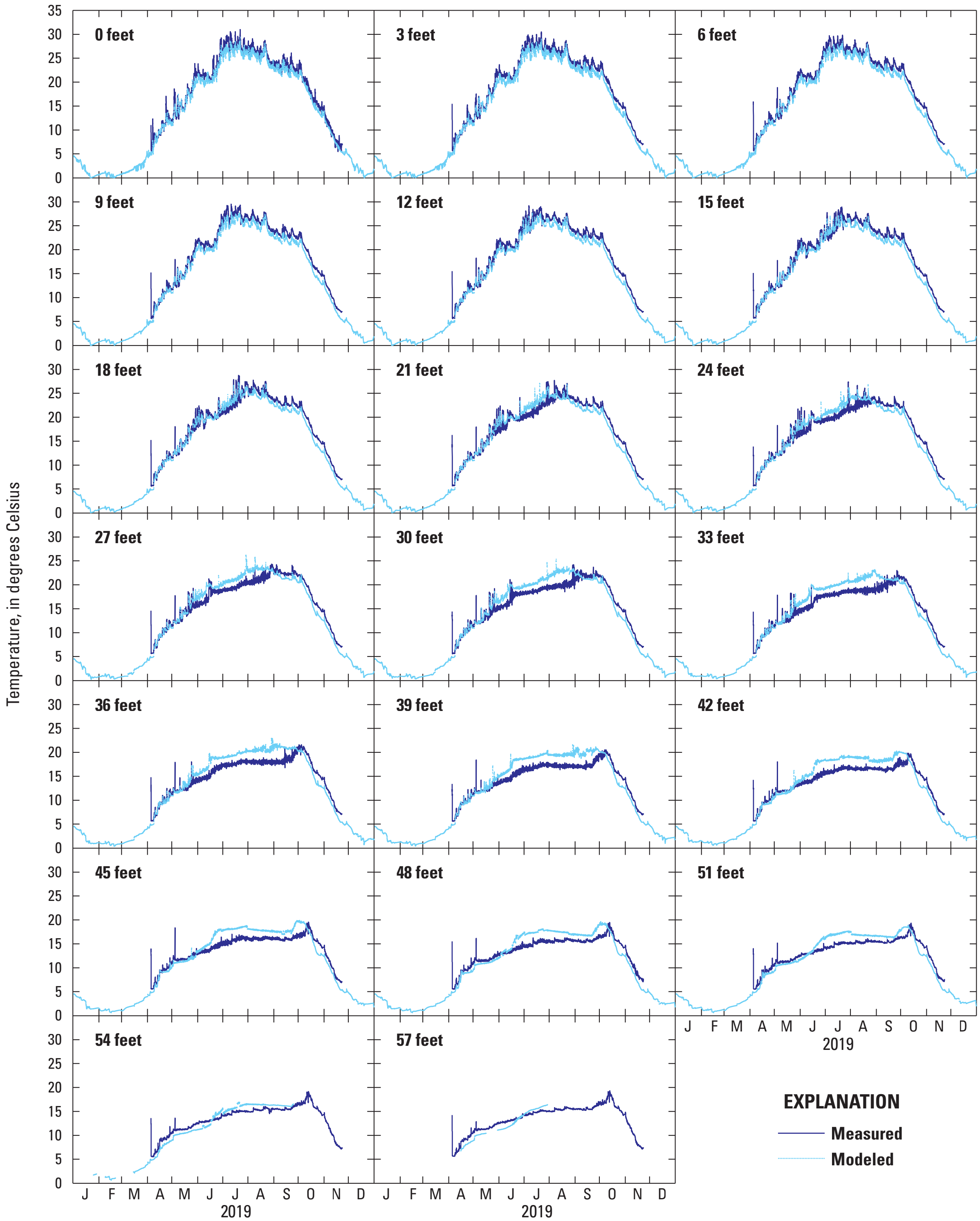


Figure 13. Michael J Kirwan Reservoir modeled and measured water temperature just upstream from the dam in 2019, Ohio. Measured values are from a thermistor string with sensors every 3 feet into the water column. Model output was extracted at the same depth.

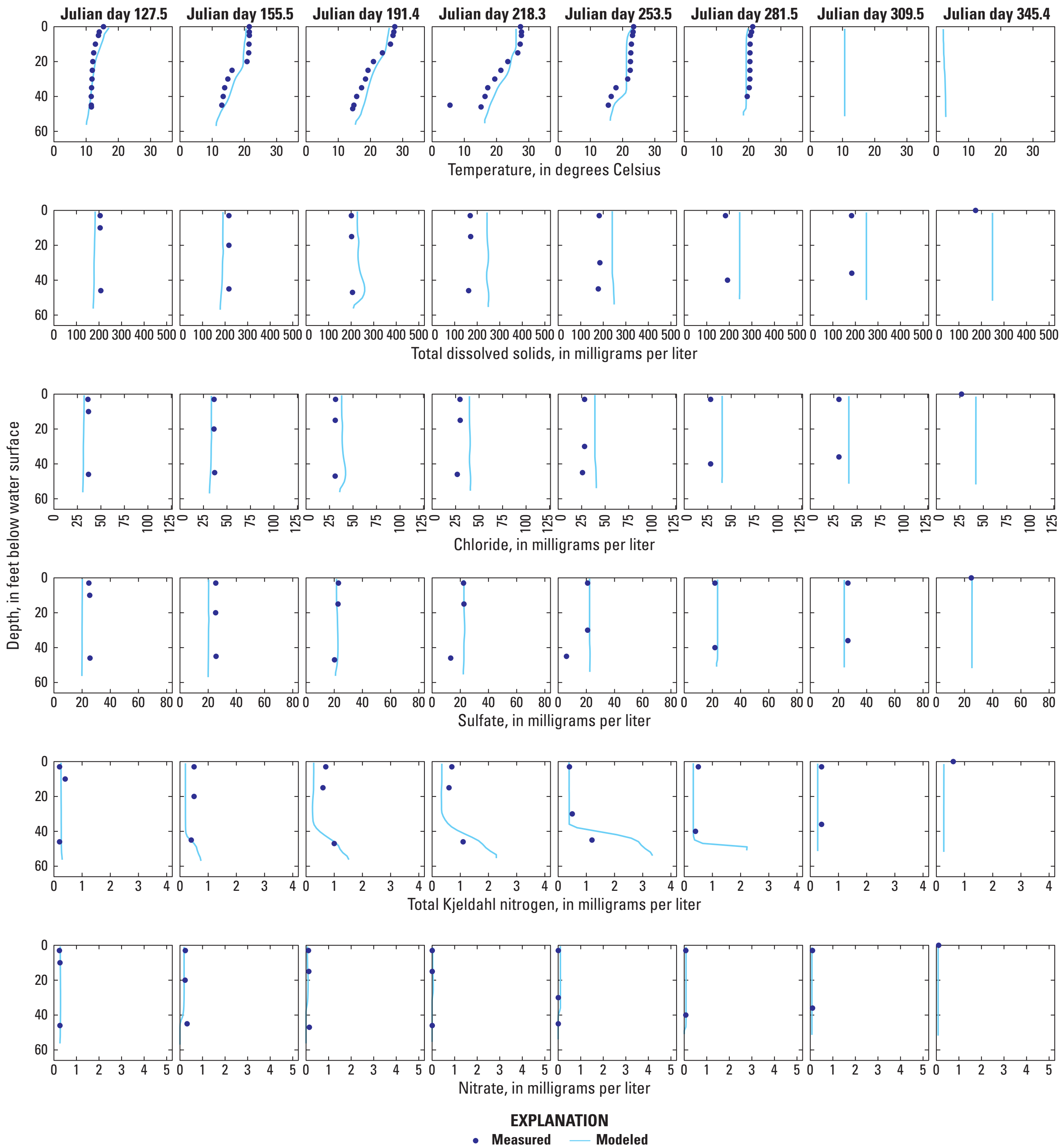
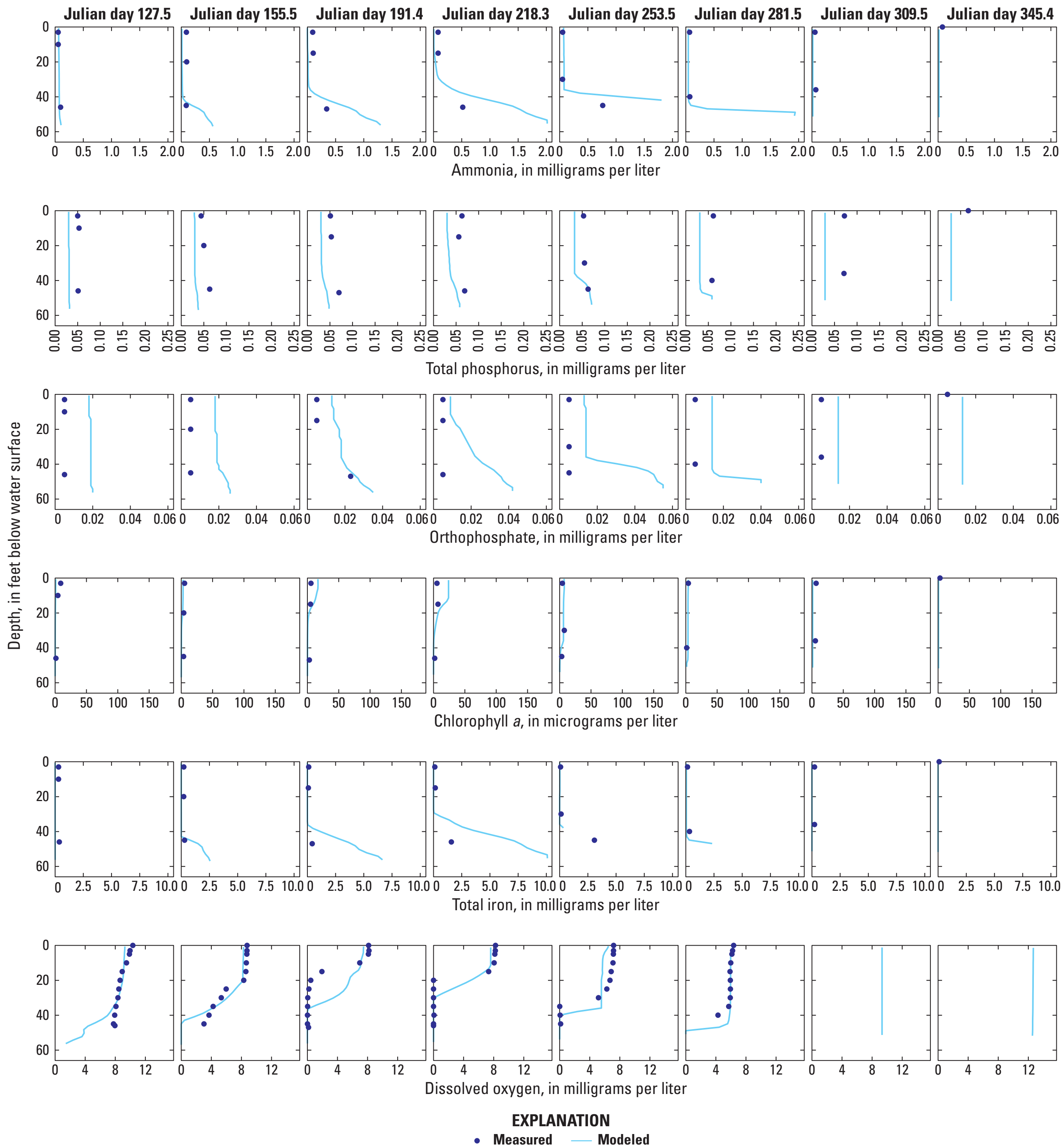


Figure 14. Michael J Kirwan Reservoir measured and modeled depth profiles at site 1002 and model segment 22 on sampling dates in 2019, Ohio.



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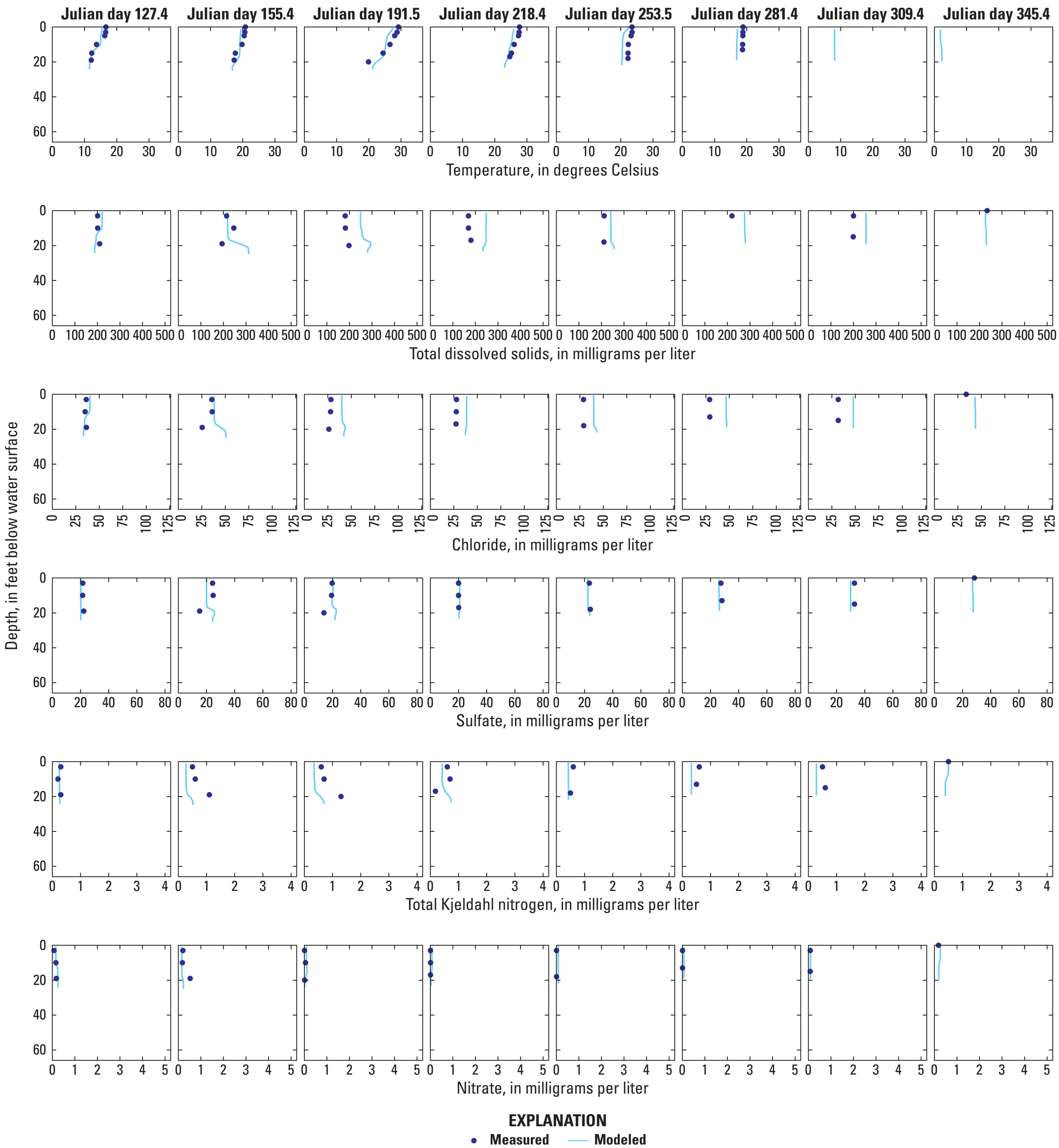
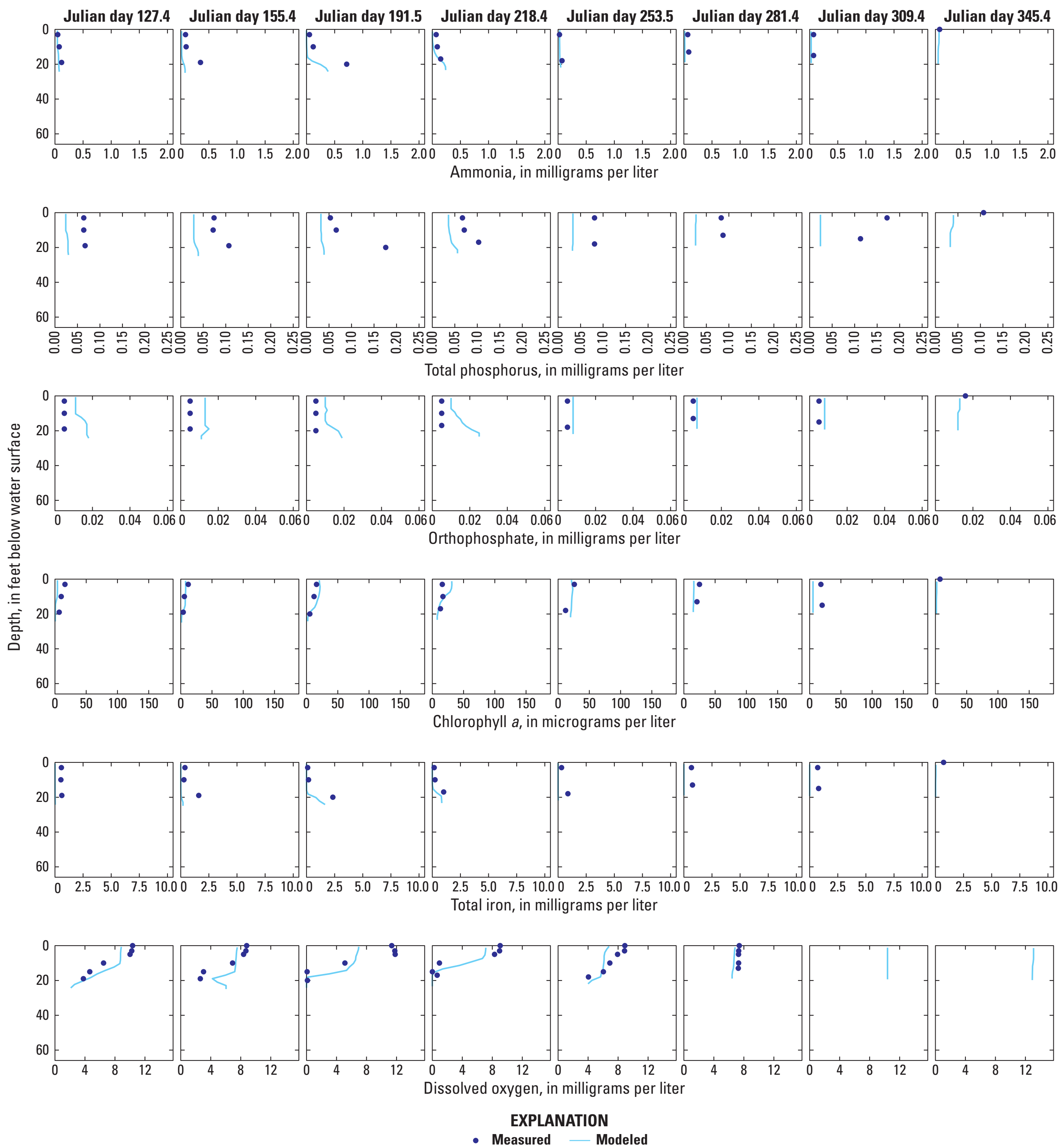


Figure 15. Michael J Kirwan Reservoir measured and modeled depth profiles at site 1005 and model segment 8 on sampling dates in 2019, Ohio.



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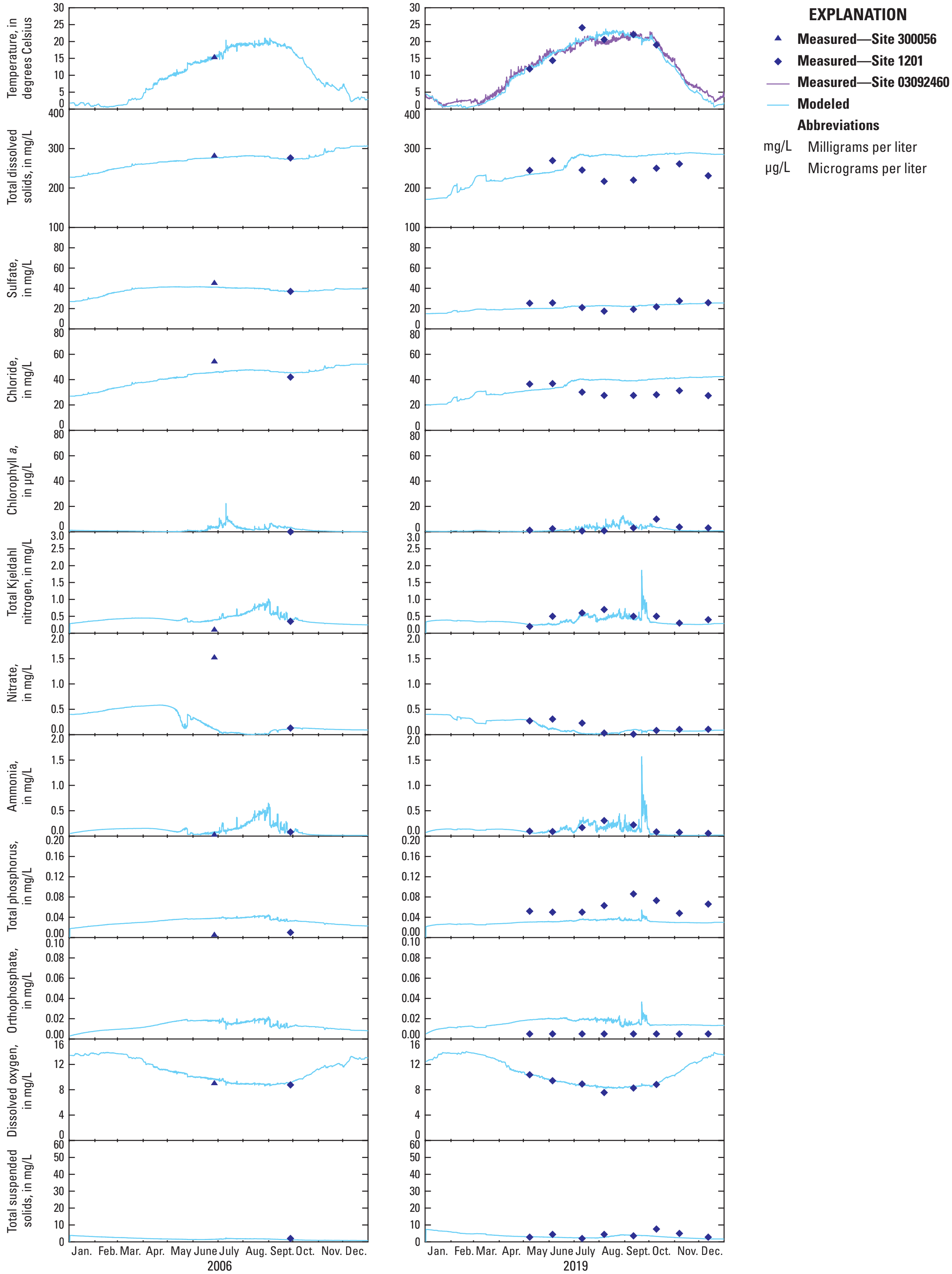


Figure 16. Modeled Michael J Kirwan Reservoir outflow water quality and measured water quality sampled just downstream from the dam in 2006 and 2019, Ohio. Sites with measured data include site 1201, 03092460, and 300056 (table 5).

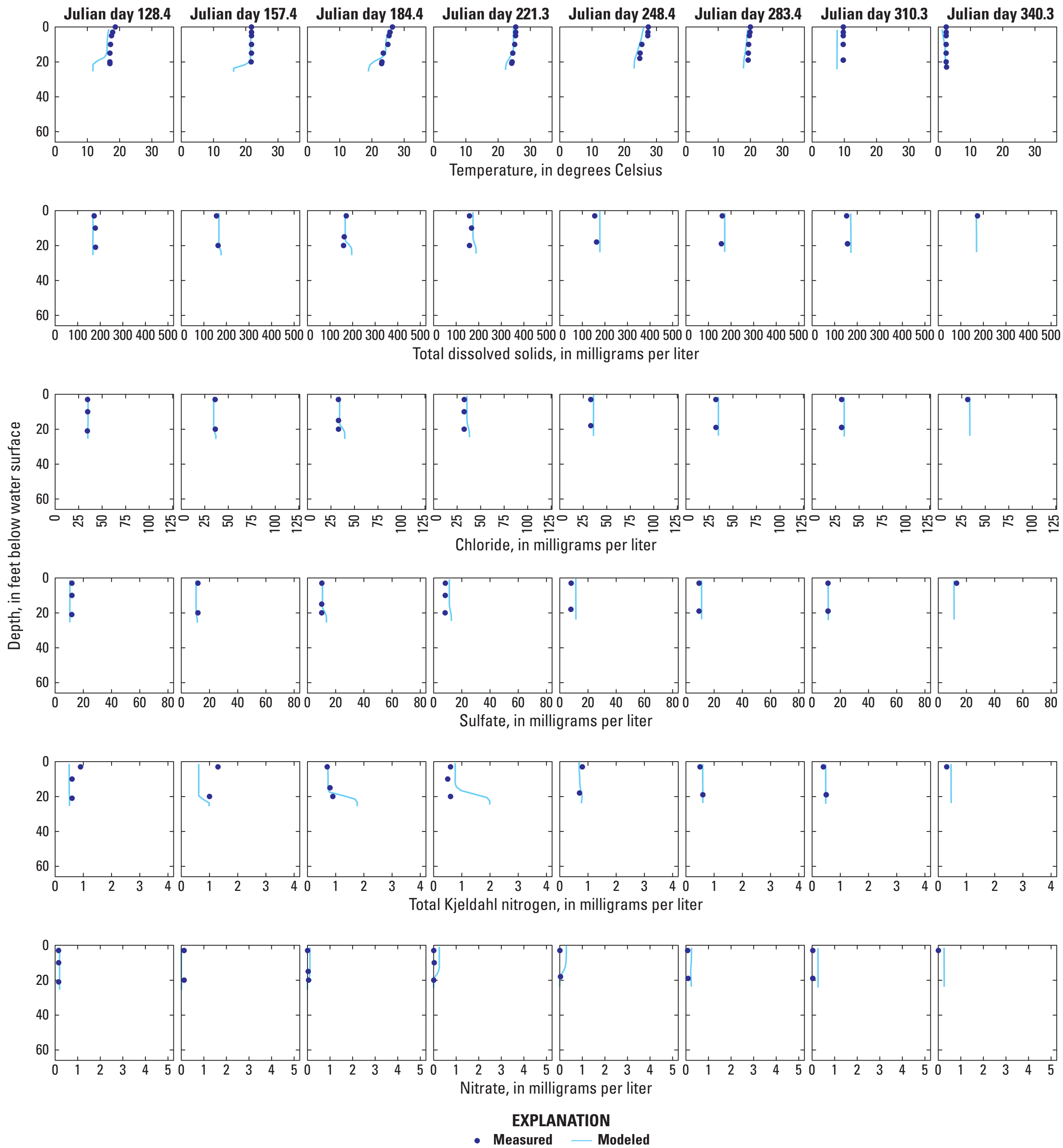
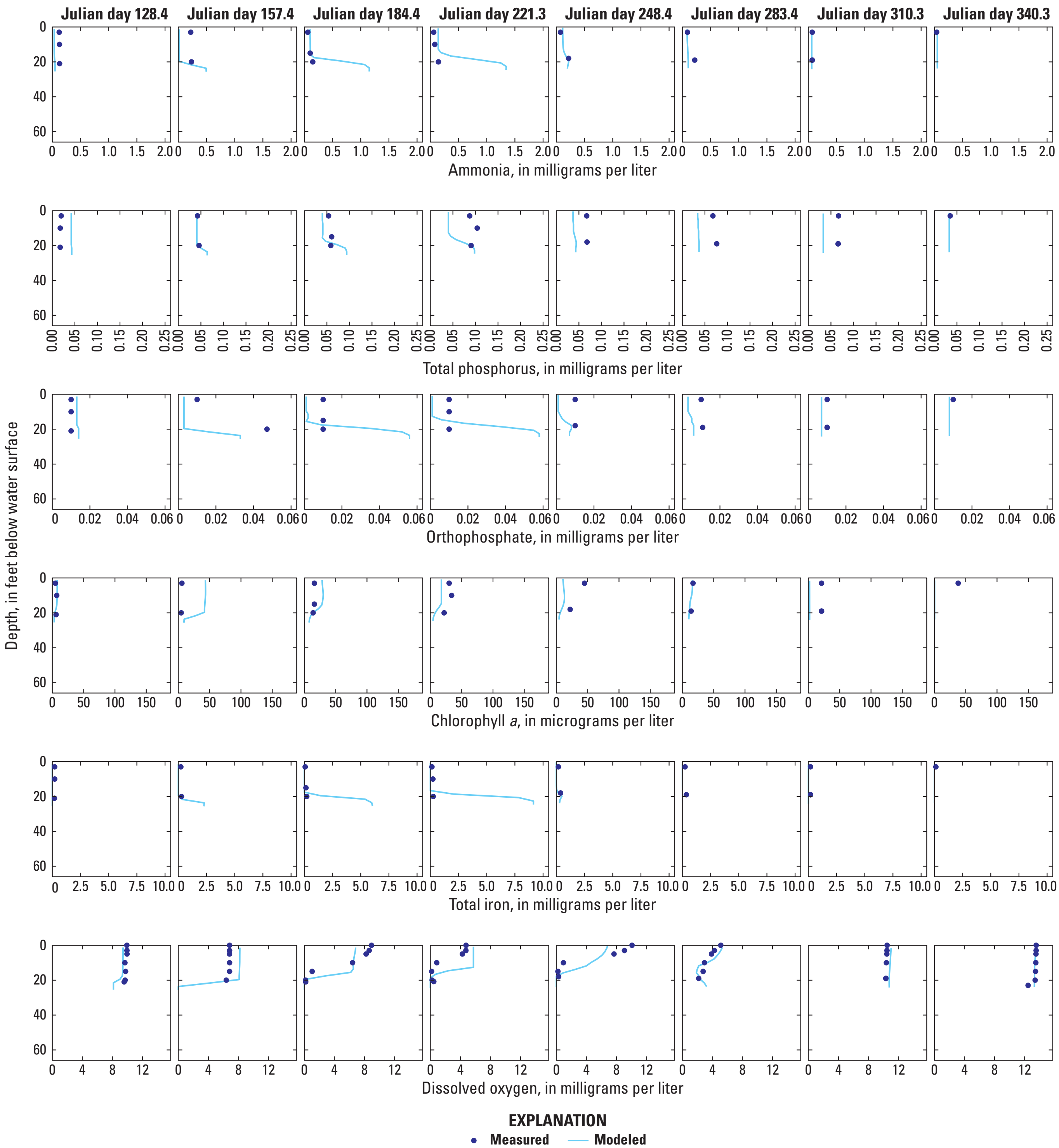


Figure 17. Mosquito Creek Lake measured and modeled depth profiles at site 1002 and model segment 35 on sampling dates in 2018, Ohio.



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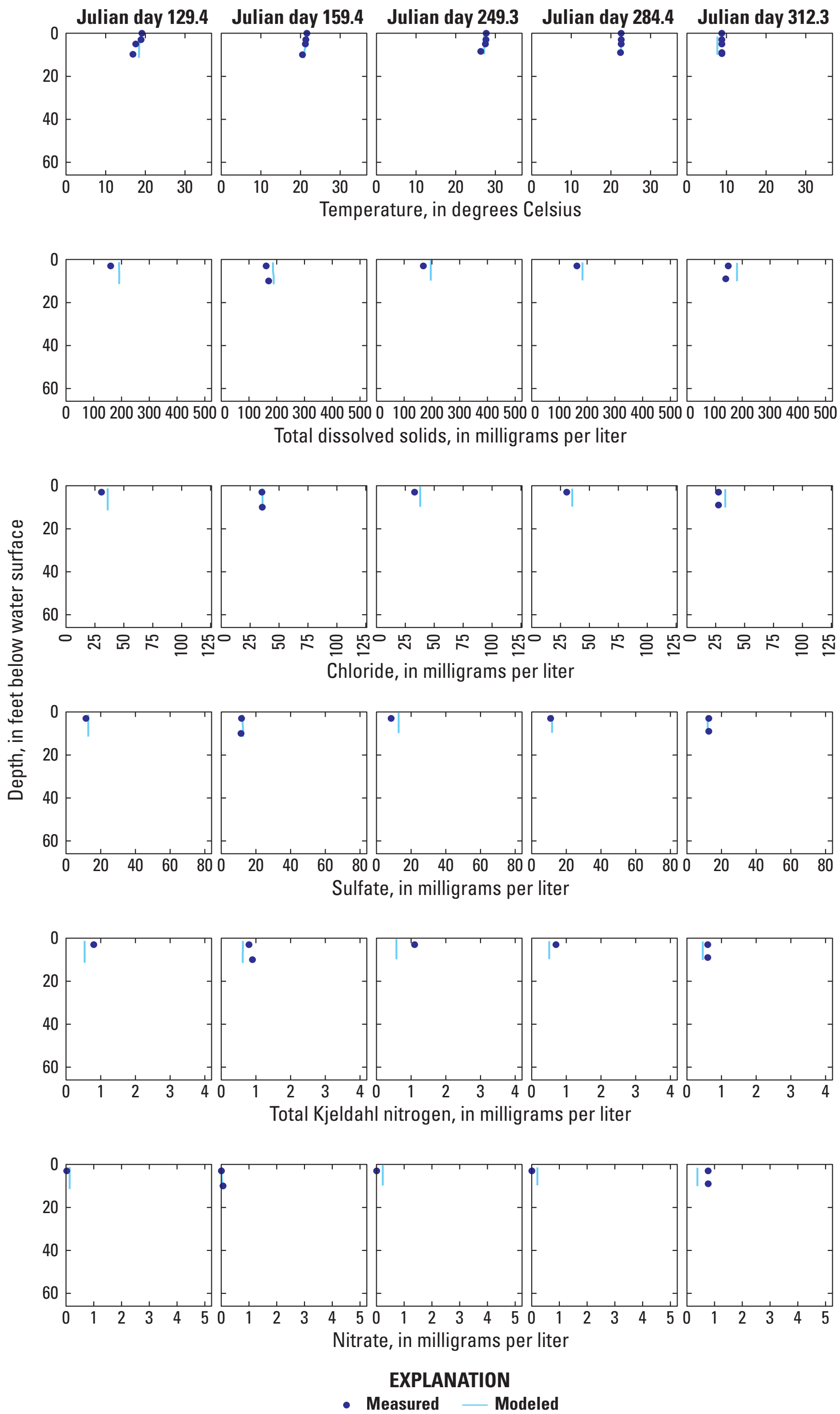
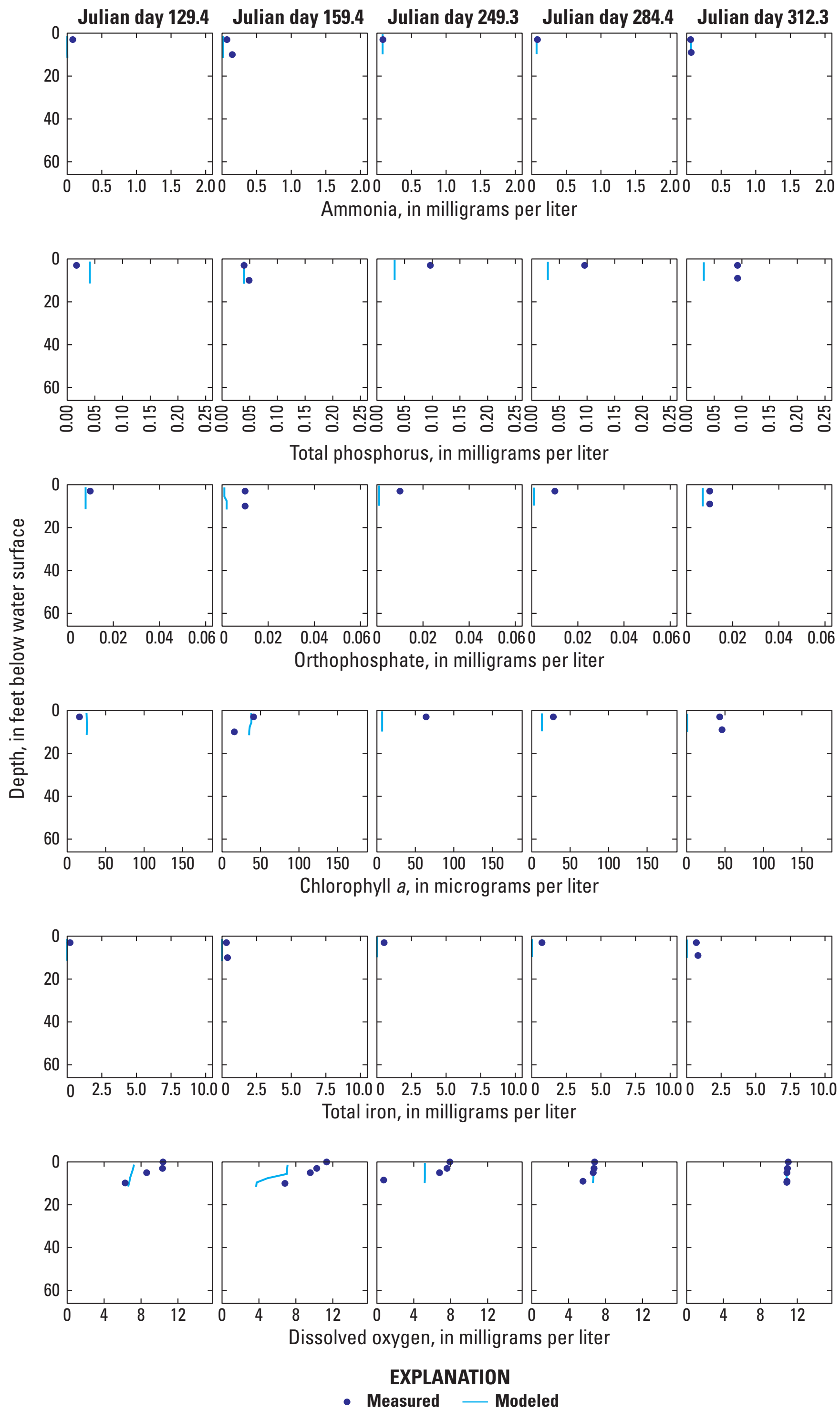


Figure 18. Mosquito Creek Lake measured and modeled depth profiles at site 1008 and model segment 9 on sampling dates in 2017, Ohio.



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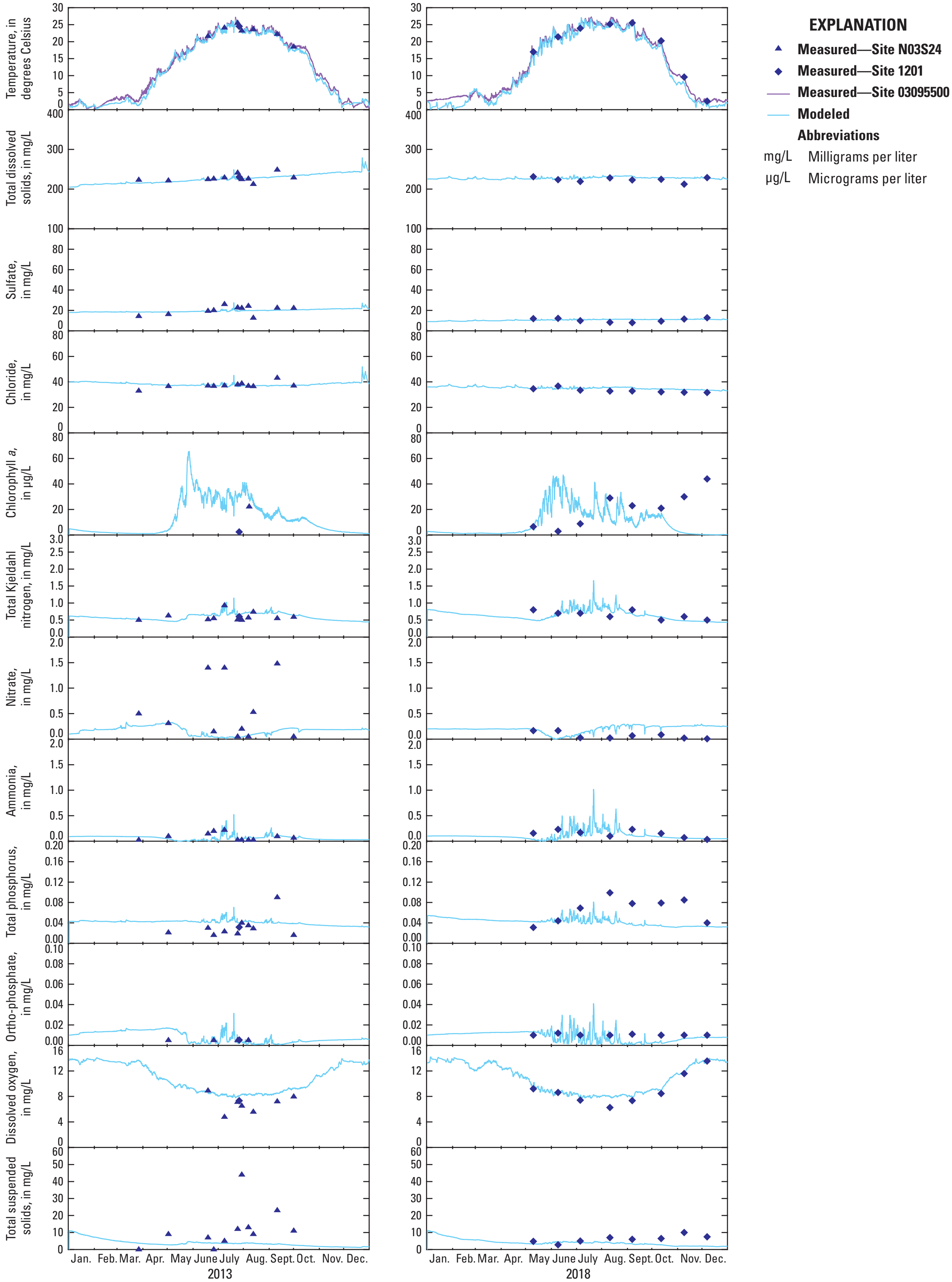


Figure 19. Modeled Mosquito Creek Lake outflow water quality (blue lines) and measured water quality at sampling locations just downstream from the dam (black points and lines) in 2013 and 2018, Ohio. Sites with measured data include site 1201, 03095500, and N03S24 (table 5).

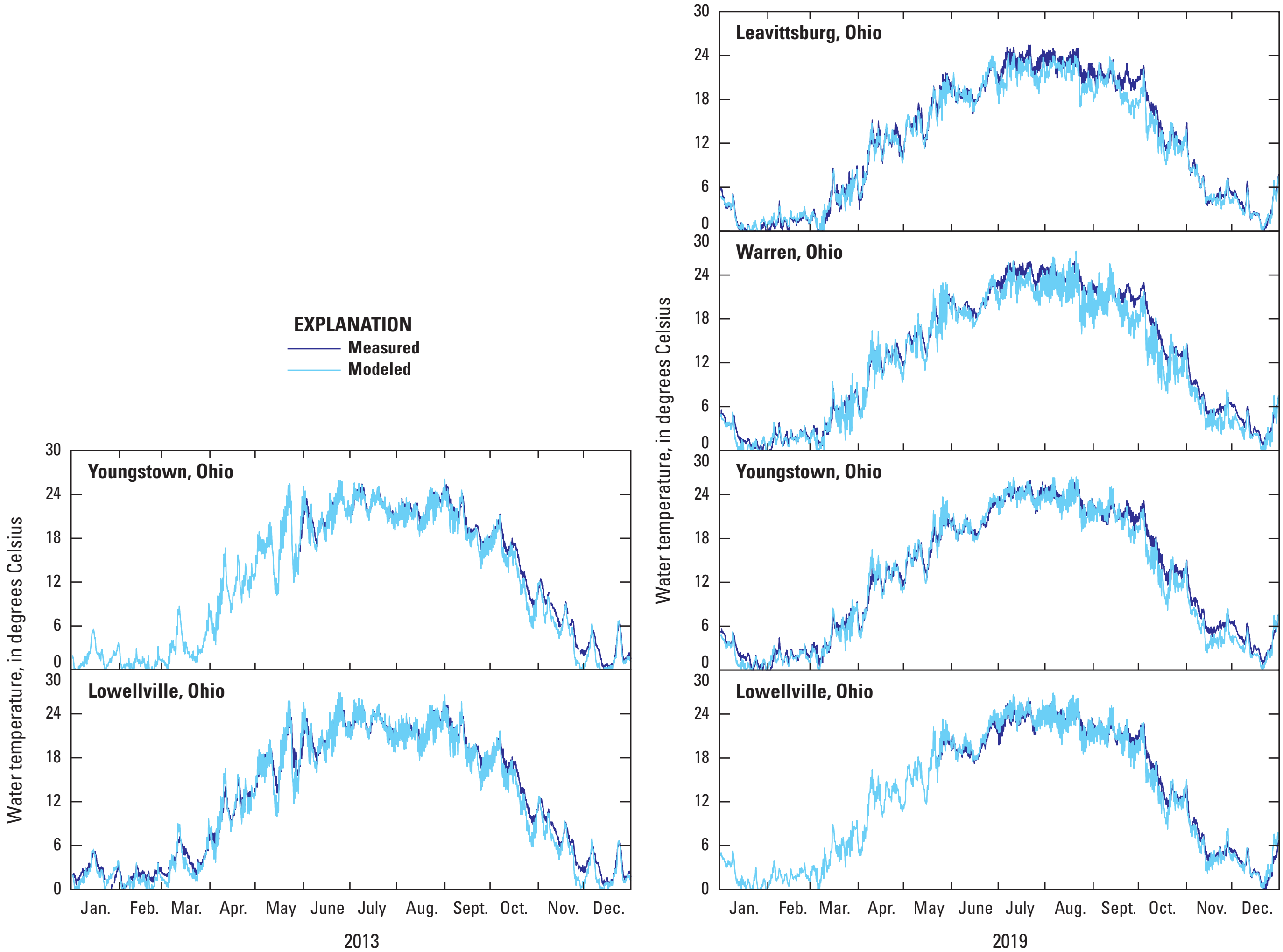


Figure 20. Model output and measured water temperature data from continuous water-quality monitors at Mahoning River sites in 2013 and 2019, Ohio.

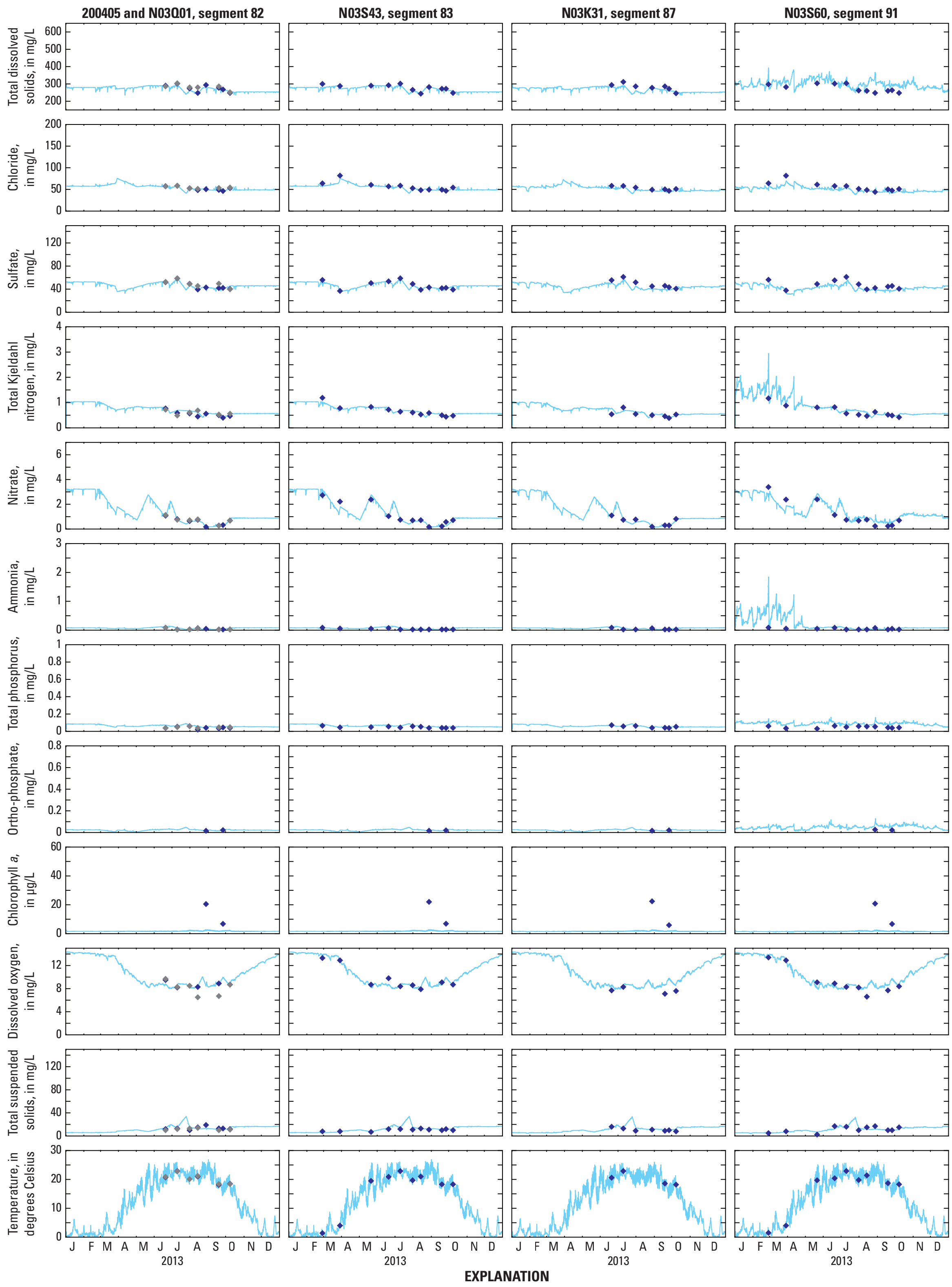
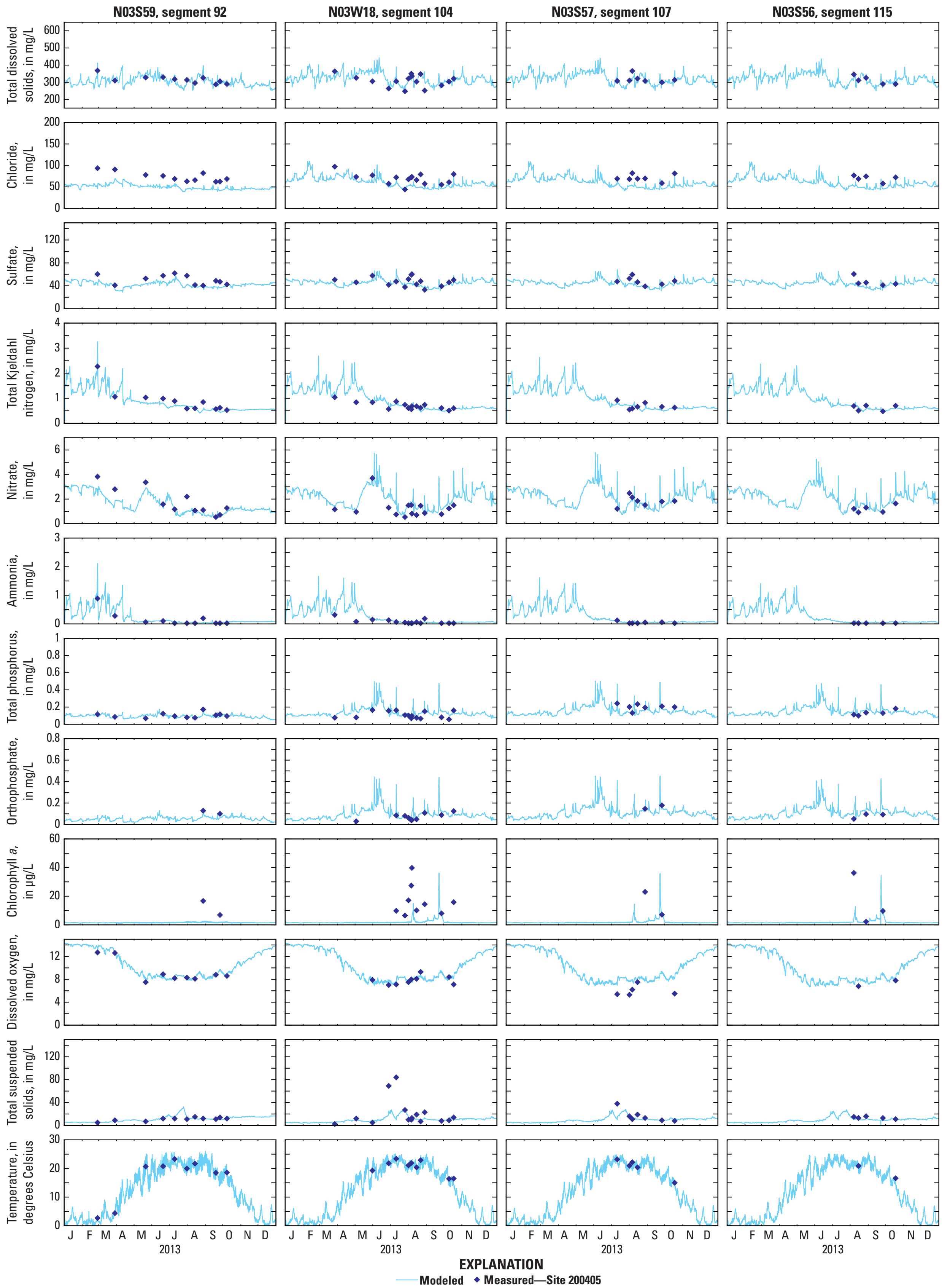


Figure 21. Model output and measured grab sample water-quality data in the Mahoning River, Ohio, 2013. Each column of graphs represents water quality from one location in the river. Sites are organized from upstream (left) to downstream (right). Site locations are given in figure 1 and table 5; model segments are shown in figure 5. Model output is the blue line, measured data the black or gray points. Abbreviations: mg/L, milligram per liter; µg/L, microgram per liter.



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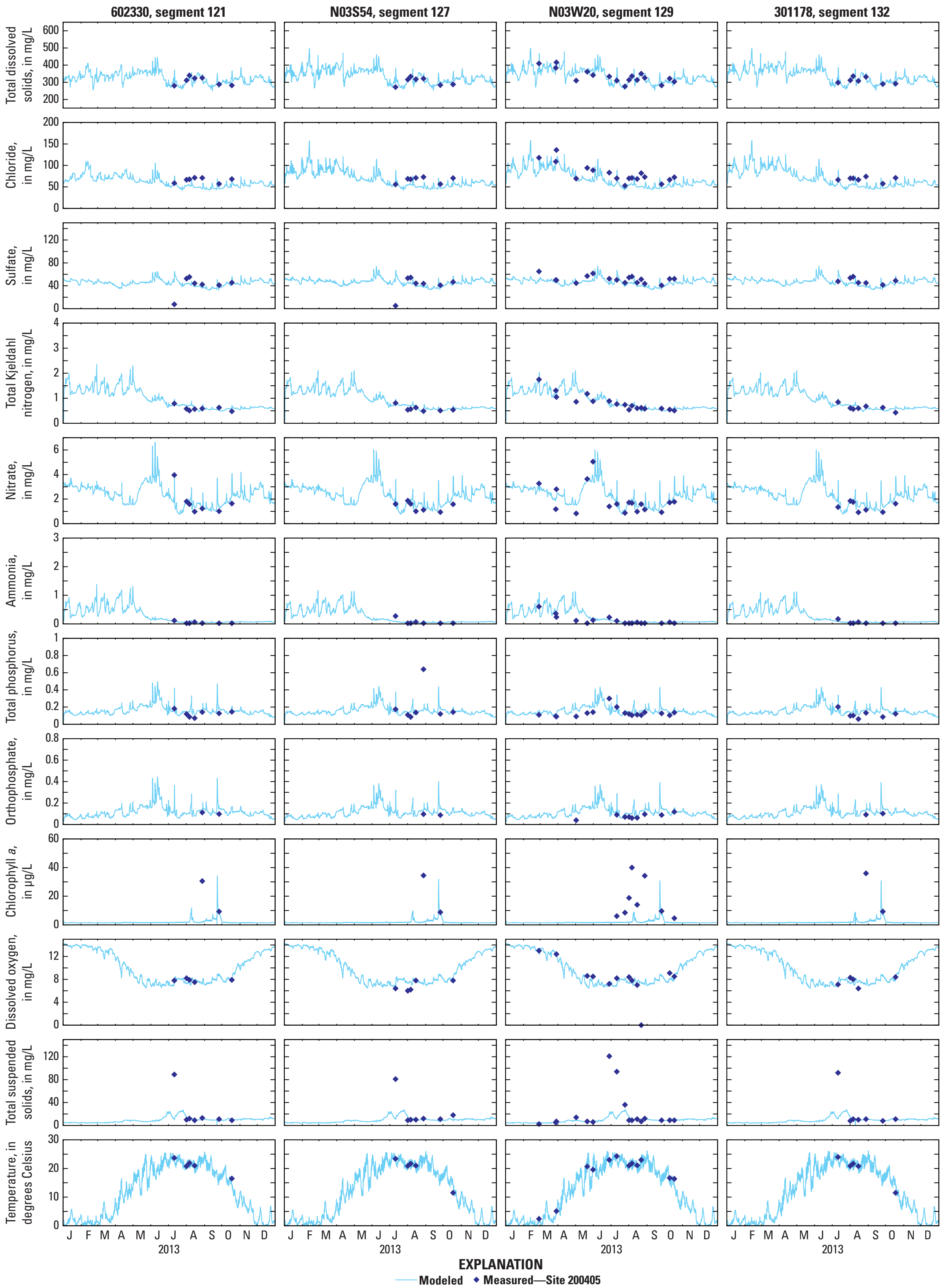

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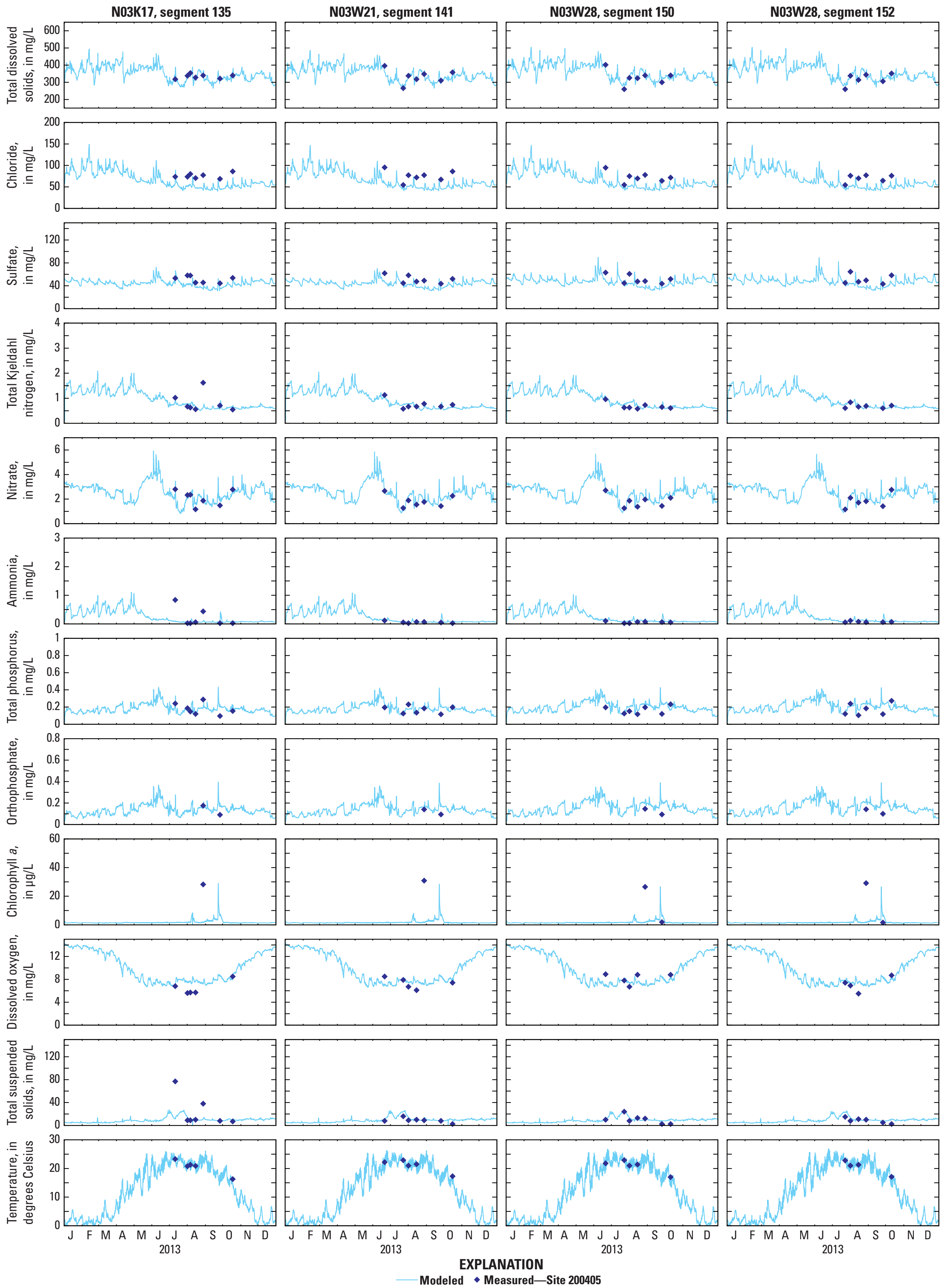

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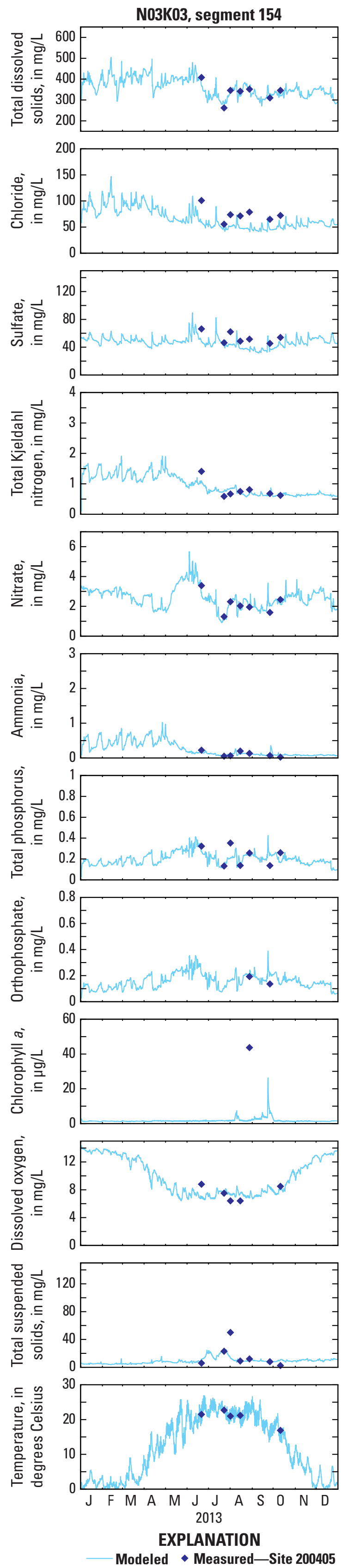

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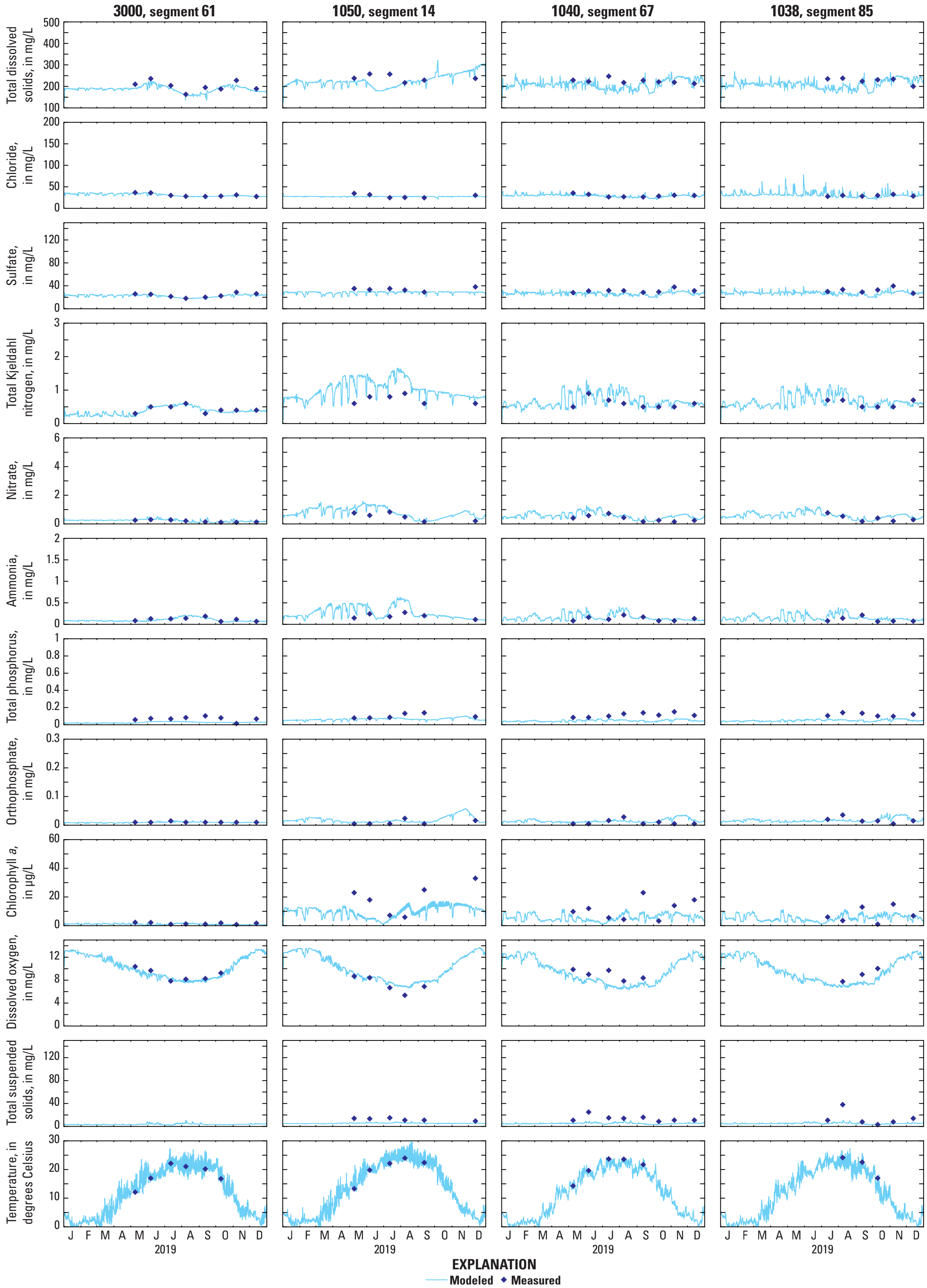
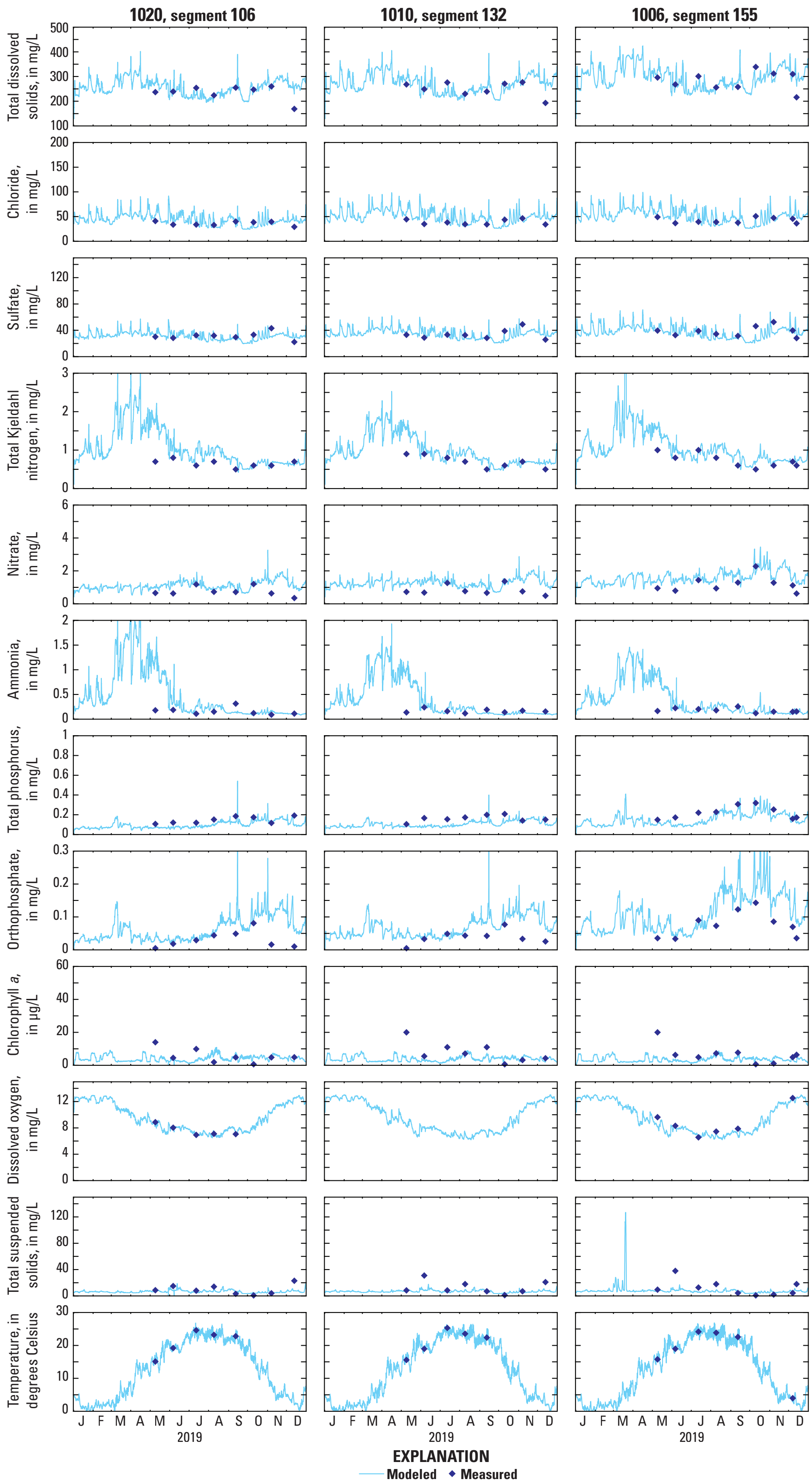


Figure 22. Model output and measured grab sample water-quality data in the Mahoning River, Ohio, 2019. Each column of graphs represents water quality from one location in the river. Sites are organized from upstream (left) to downstream (right). Site locations are given in figure 1 and table 5; model segments are shown in figure 5. Abbreviations: mg/L, milligram per liter; µg/L, microgram per liter.



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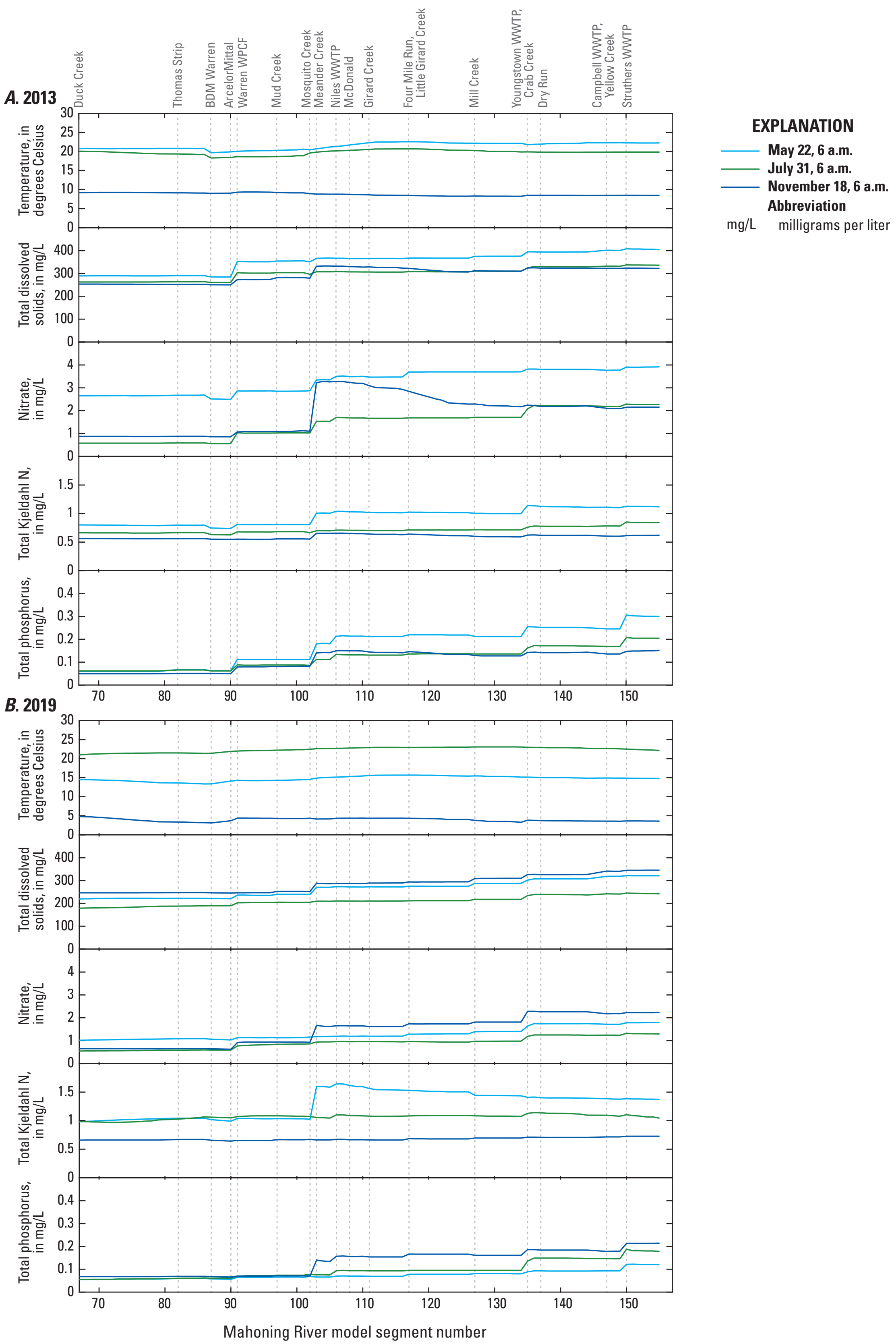

Figure 23. Modeled depth-average water quality on three dates in (*A*) 2013 between Leavittsburg (model segment 67) and Lowellville (model segment 155) and (*B*) in 2019 between Leavittsburg (model segment 67) and Lowellville (model segment 155), Ohio. Locations of inflowing tributaries or point sources are noted. Abbreviations: mg/L, milligram per liter; N, nitrogen.

Figures 30–49

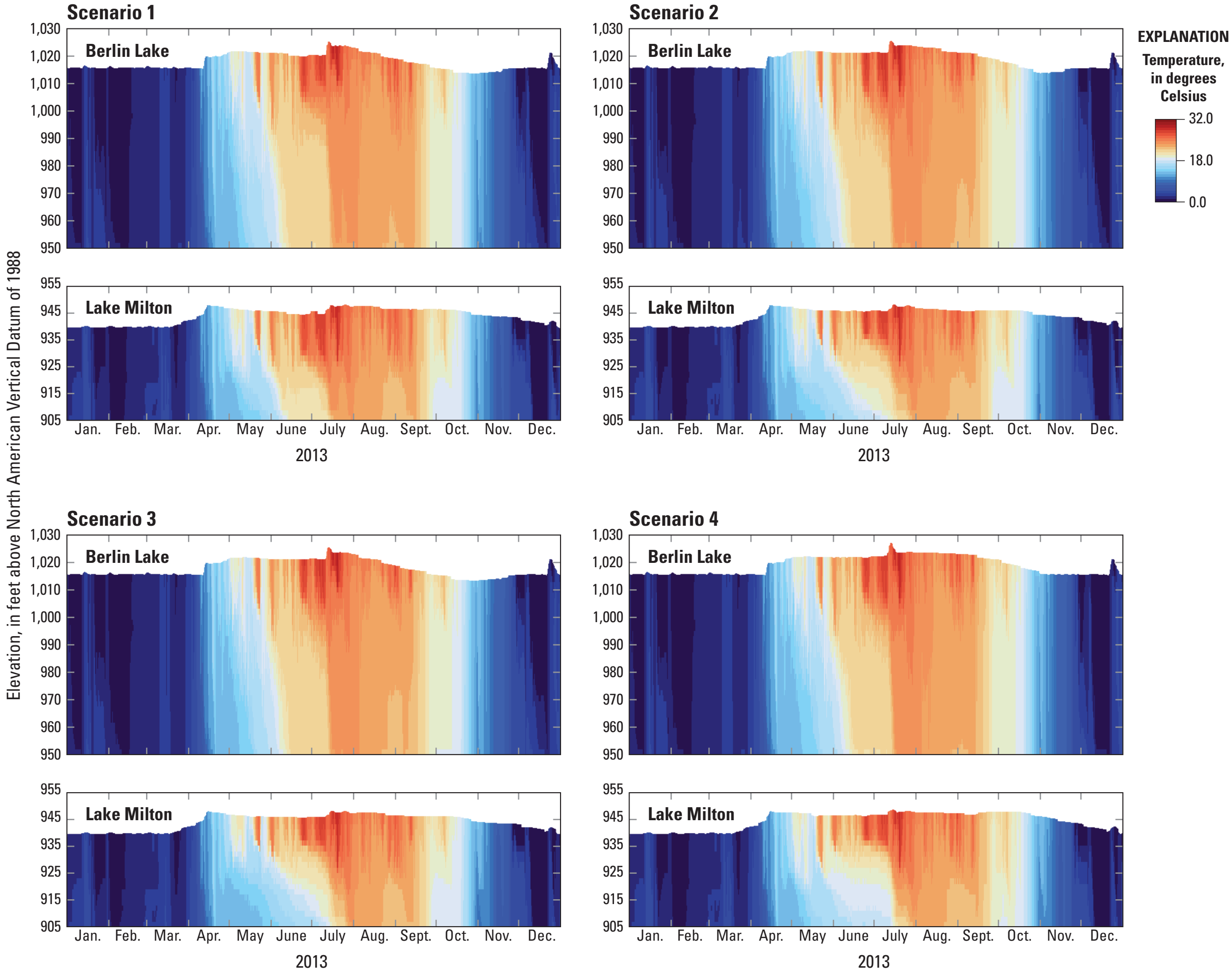

Figure 30. Modeled depth profiles of water temperature for scenarios 1–4 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from the model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Scenarios are described in table 10.

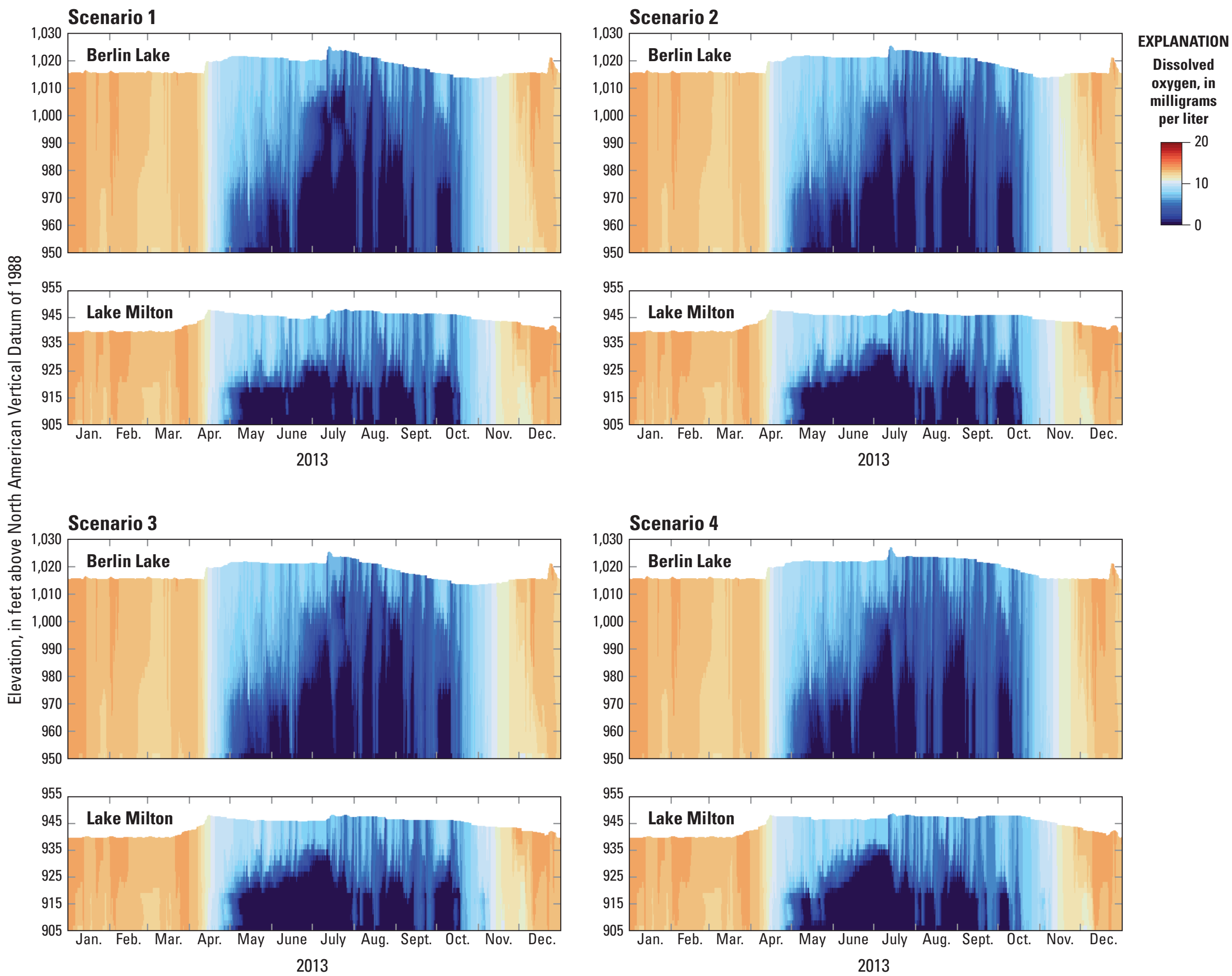

Figure 31. Modeled depth profiles of dissolved oxygen for scenarios 1–4 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are midnight and noon every day through 2013 from one model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Scenarios are described in table 10.

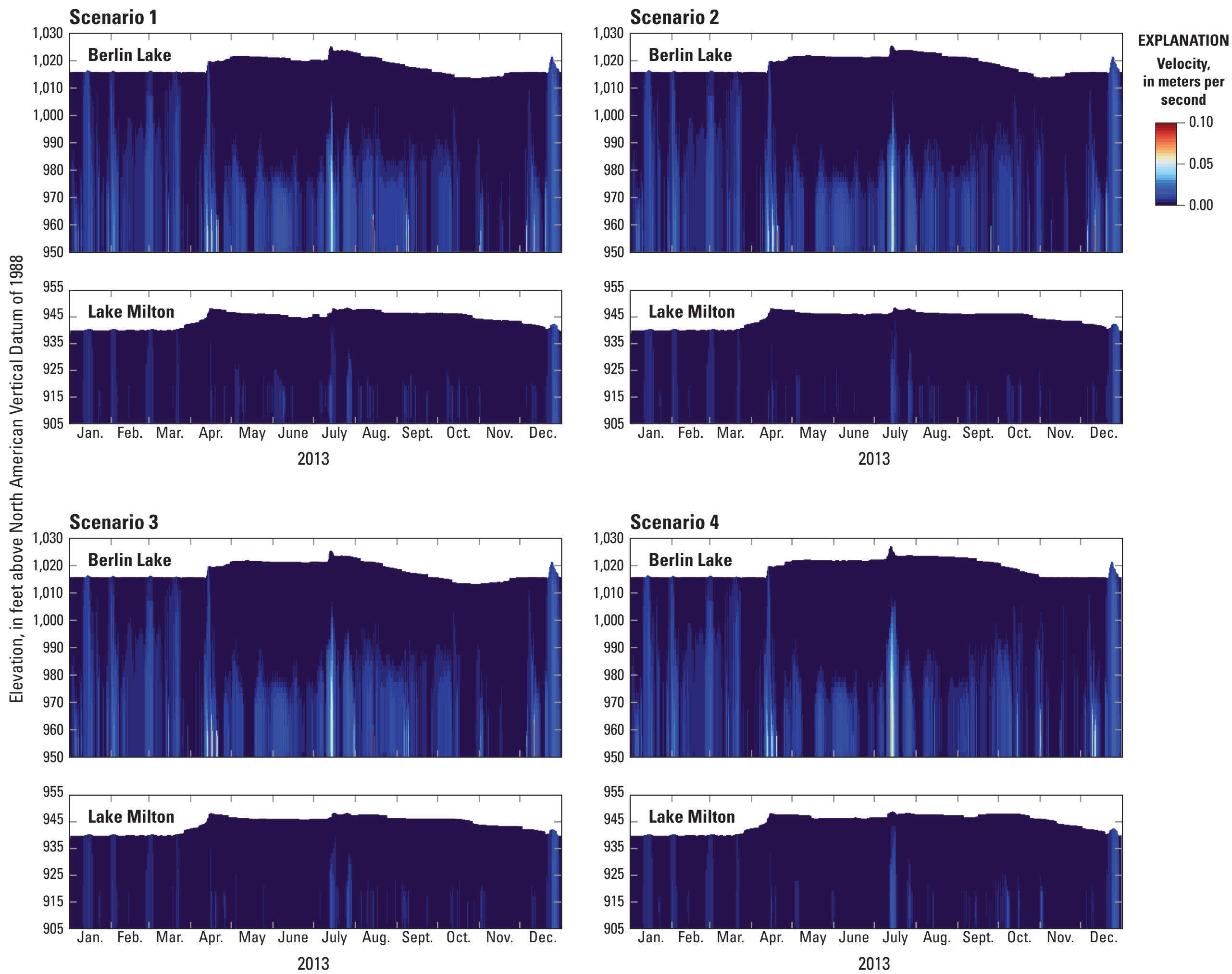

Figure 32. Modeled depth profiles of horizontal velocity for scenarios 1–4, in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from one model segment just upstream from each dam. Scenarios are described in table 10.

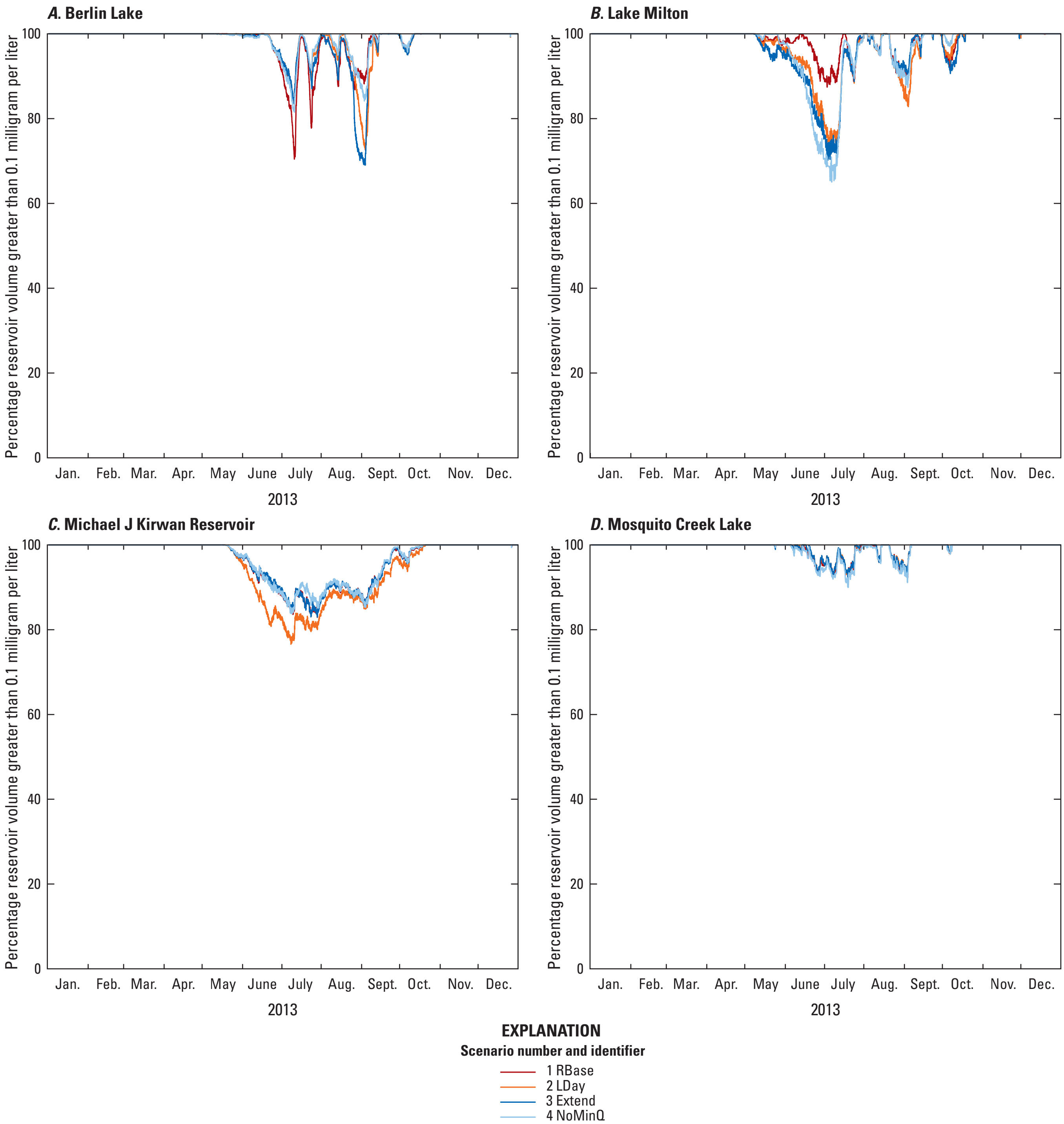

Figure 33. Lake volume with dissolved oxygen concentrations greater than 0.1 mg/L through the year for (*A*) Berlin Lake, (*B*) Lake Milton, (*C*) Michael J Kirwan Reservoir, and (*D*) Mosquito Creek Lake, Ohio, for the model scenarios.

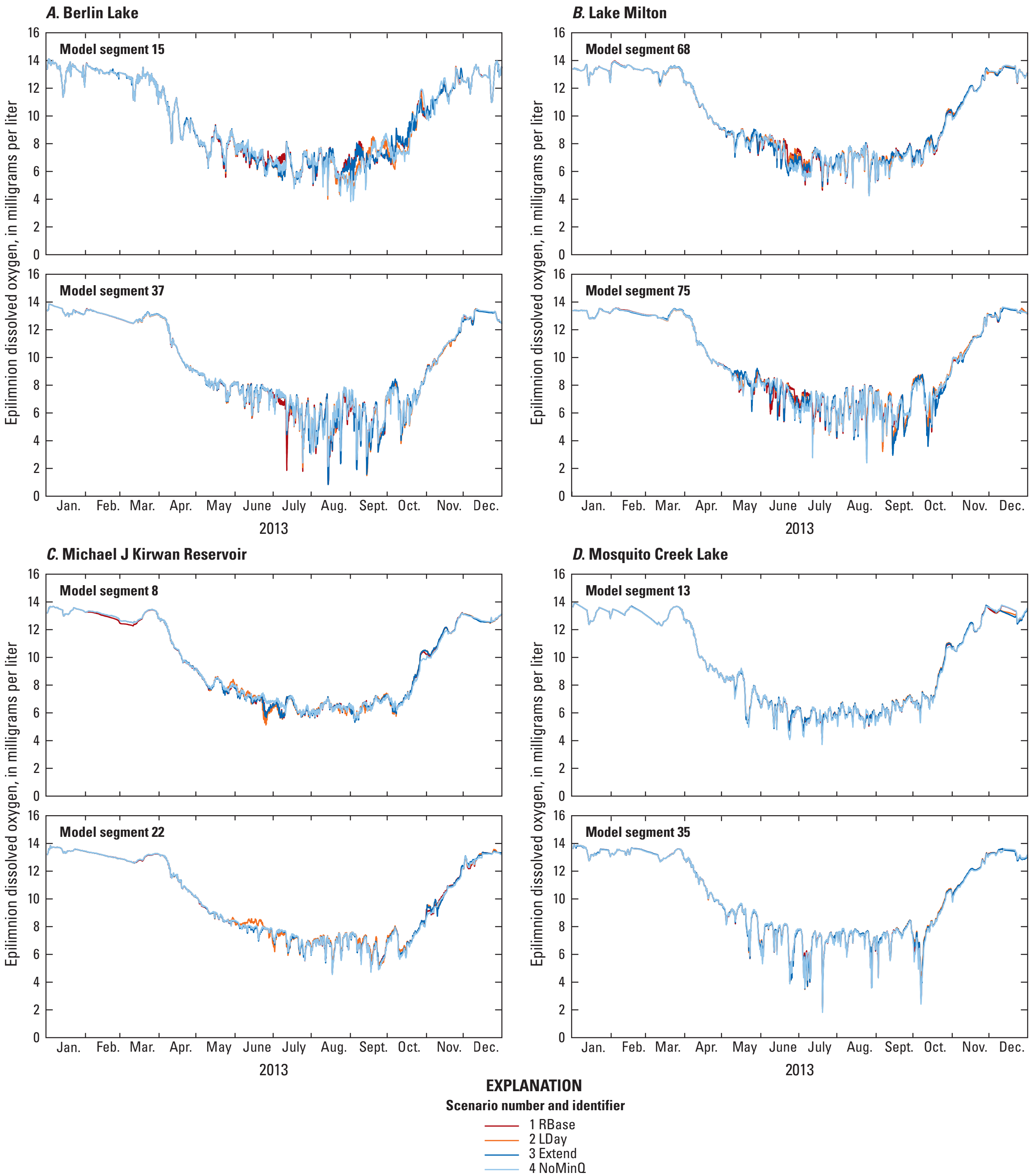

Figure 34. Modeled volume-weighted average lake dissolved oxygen concentration in the epilimnion (near-surface waters) (0–10 foot depth) at select model segments in (*A*) Berlin Lake, (*B*) Lake Milton, (*C*) Michael J Kirwan Reservoir, and (*D*) Mosquito Creek Lake, Ohio. Model segment numbers are shown in figures 2–4. Higher segment numbers are nearer the dams, lower number segments are more upstream.

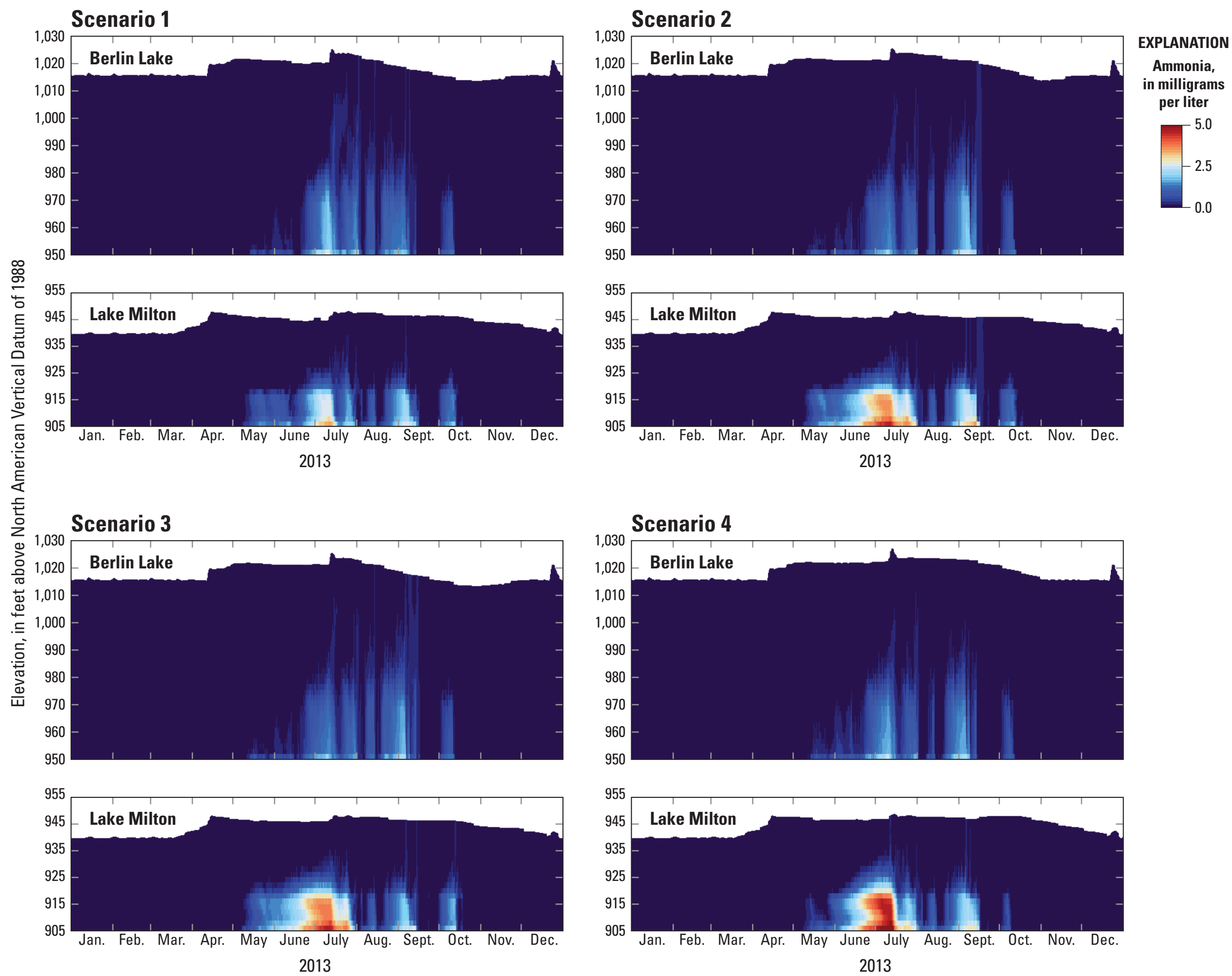

Figure 35. Modeled depth profiles of ammonia for scenarios 1–4 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from one model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Scenarios are described in table 10.

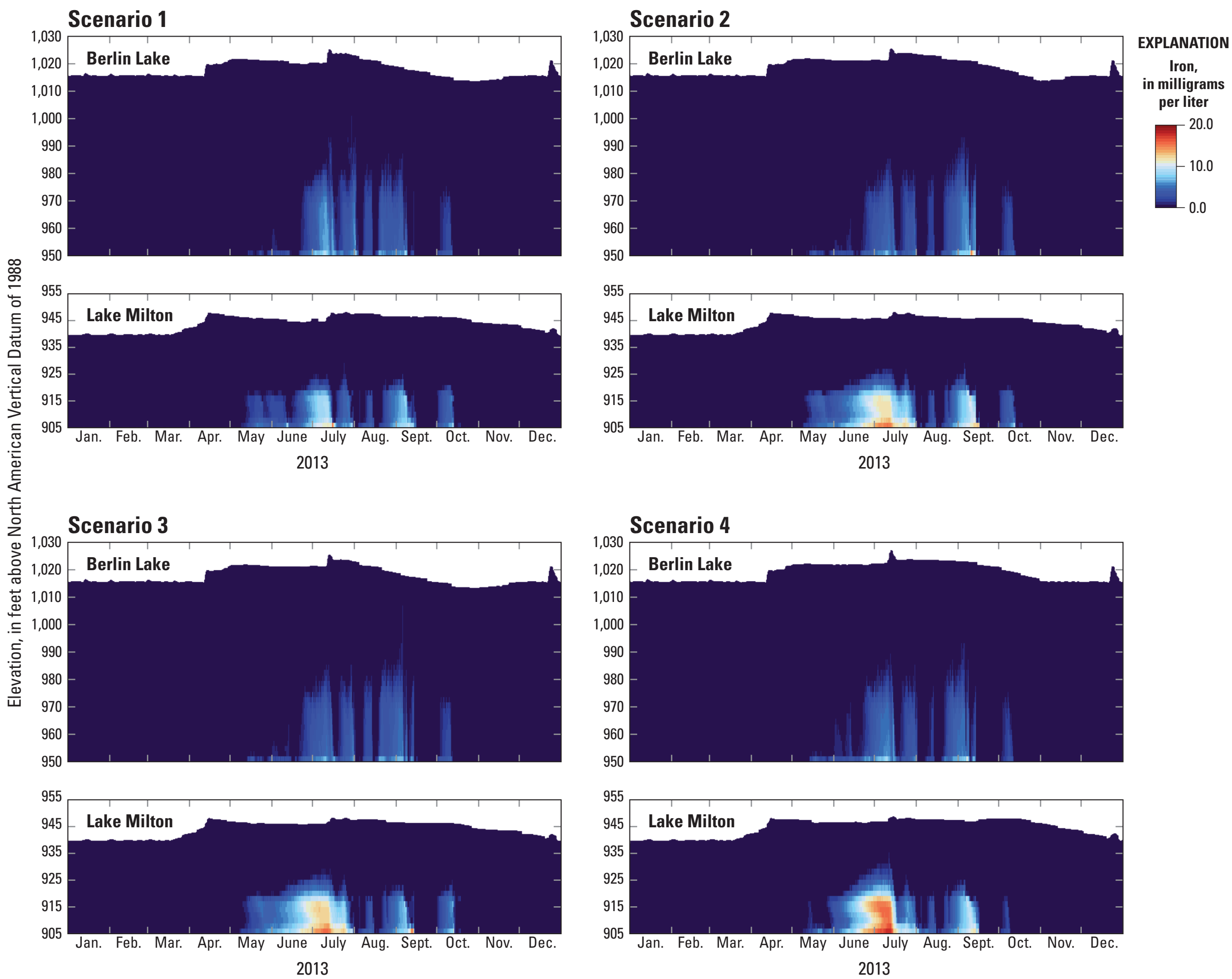

Figure 36. Modeled depth profiles of iron for scenarios 1–4 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from one model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Scenarios are described in table 10.

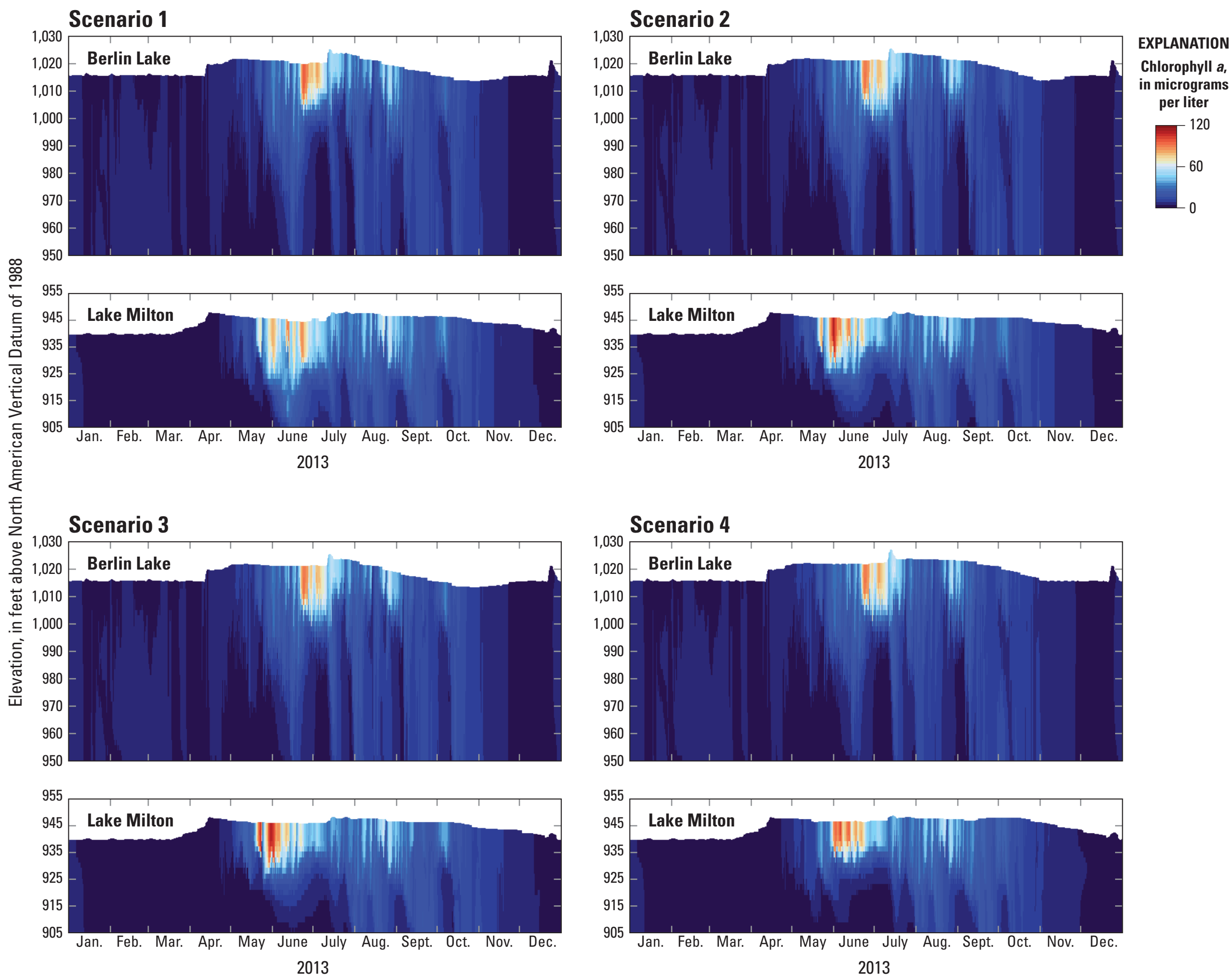

Figure 37. Modeled depth profiles of chlorophyll *a* for scenarios 1–4 in Berlin Lake and Lake Milton, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from one model segment just upstream from each dam (segment 37 for Berlin Lake, 75 for Lake Milton). Scenarios are described in table 10.

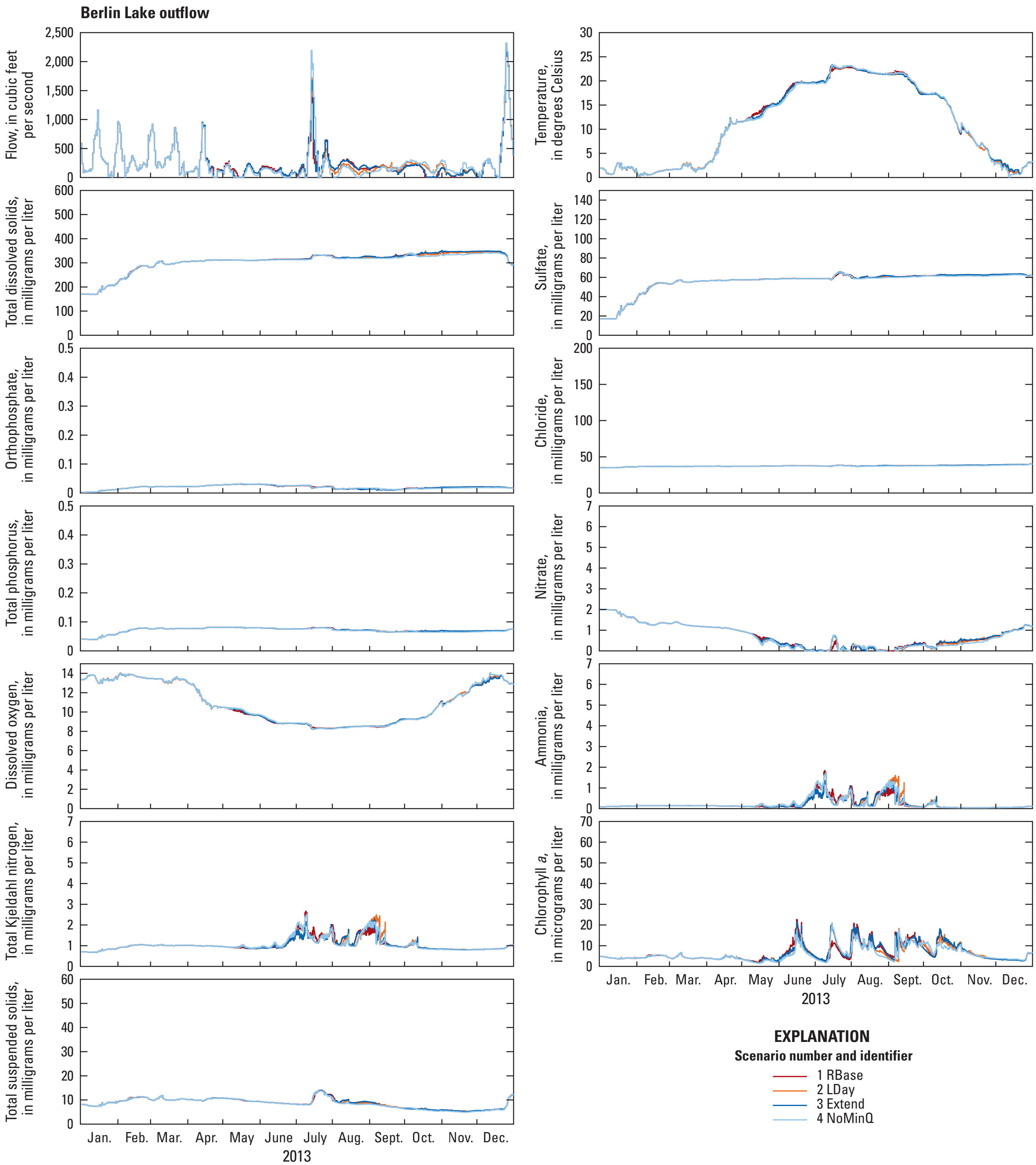

Figure 38. Model scenario flow, water temperature, and water quality in Berlin Lake dam outflow, Ohio, 2013.

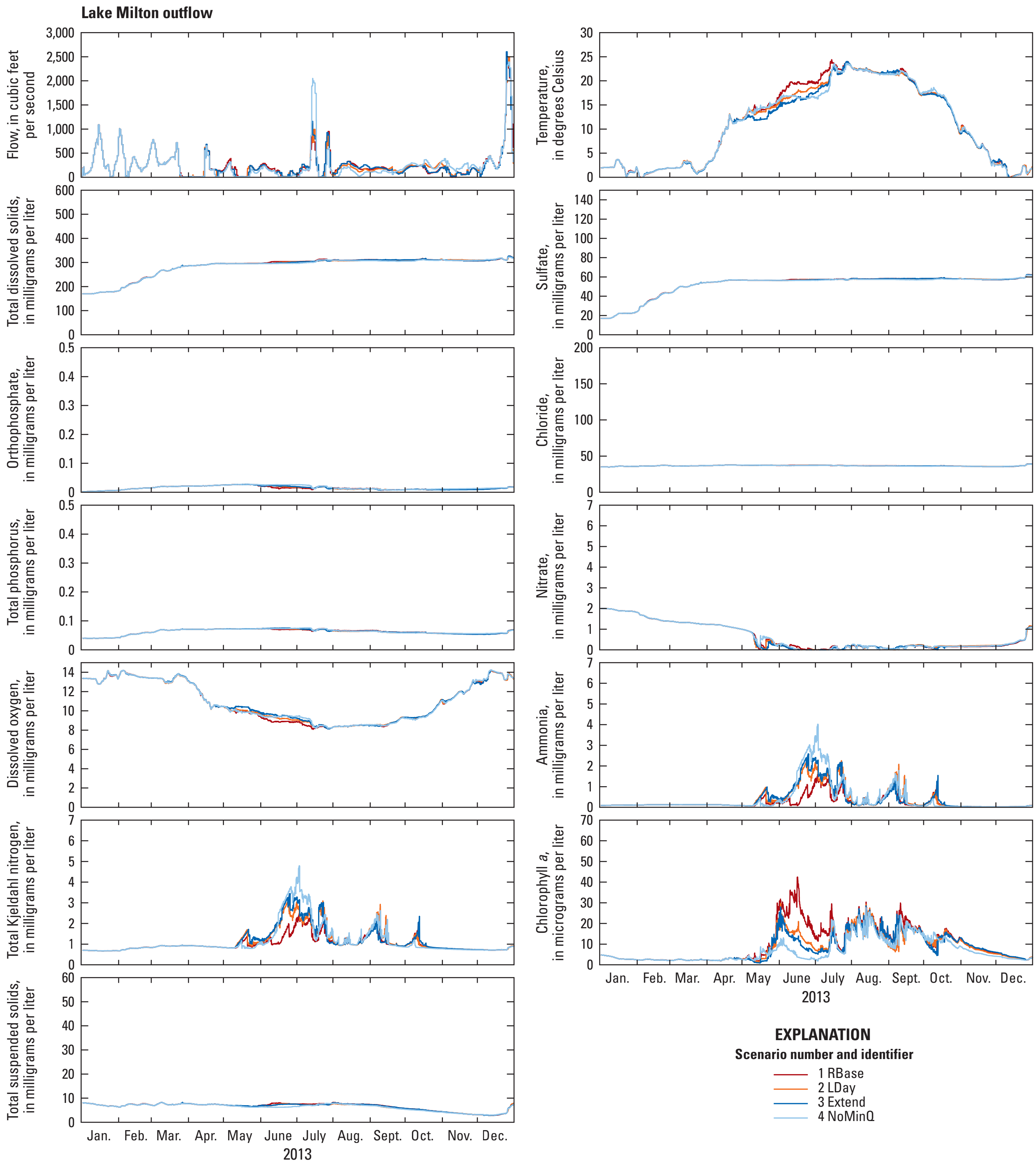

Figure 39. Model scenario flow, water temperature, and water quality in Lake Milton dam outflow, Ohio, 2013.

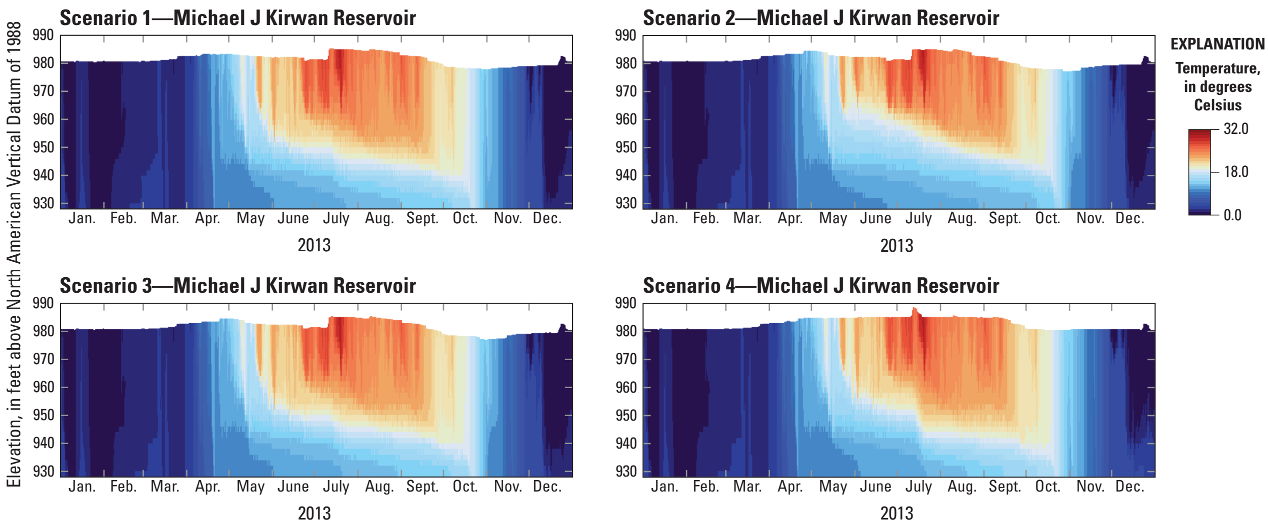

Figure 40. Modeled depth profiles of water temperature for scenarios 1–4 in Michael J Kirwan Reservoir, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from model segment 22, just upstream from the dam. Scenarios are described in table 10.

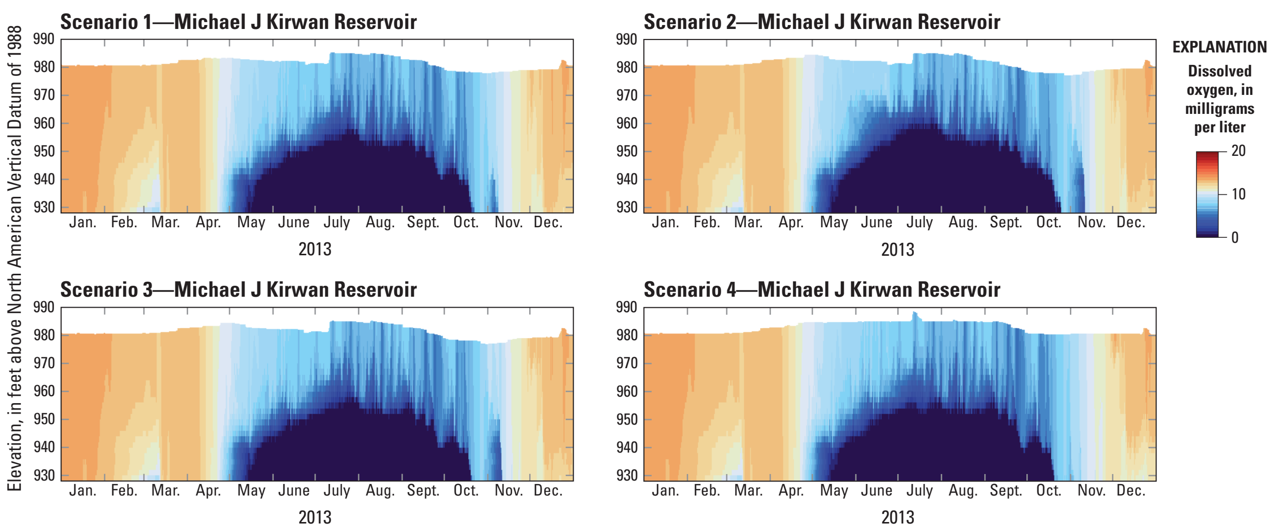

Figure 41. Modeled depth profiles of dissolved oxygen for scenarios 1–4 in Michael J Kirwan Reservoir, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from model segment 22, just upstream from Michael J Kirwan Reservoir dam. Scenarios are described in table 10.

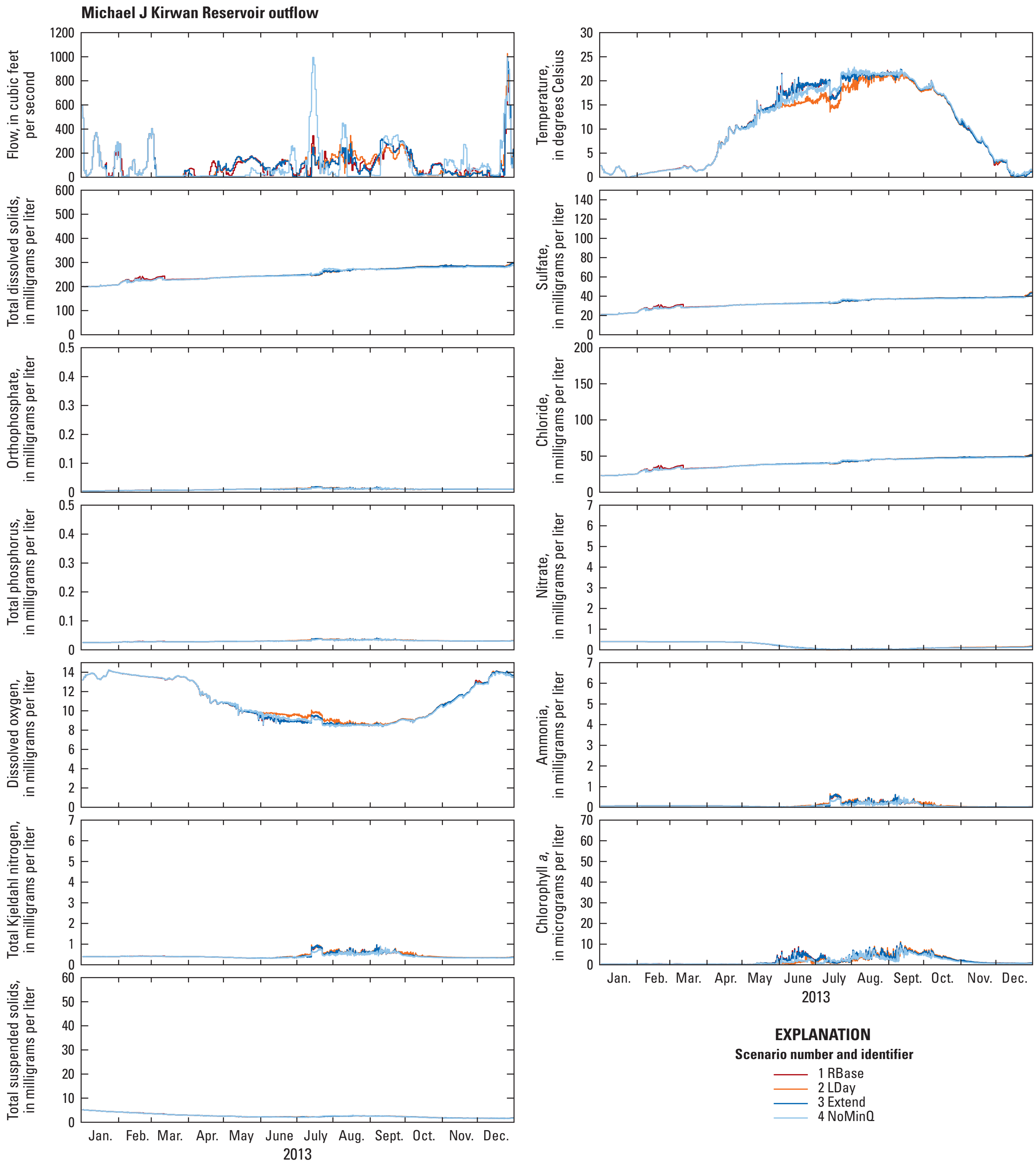

Figure 42. Model scenario flow, water temperature, and water quality in Michael J Kirwan Reservoir dam outflow, Ohio, 2013.

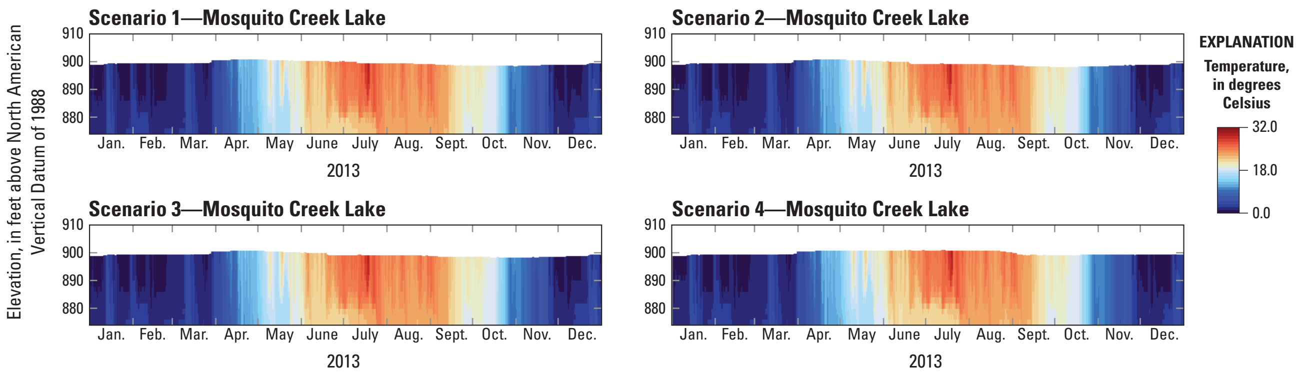

Figure 43. Modeled depth profiles of water temperature in Mosquito Creek Lake, Ohio, through 2013, for scenarios 1–4. The depth profiles are for midnight and noon every day through 2013 from model segment 35, just upstream from the dam. Scenarios are described in table 10.

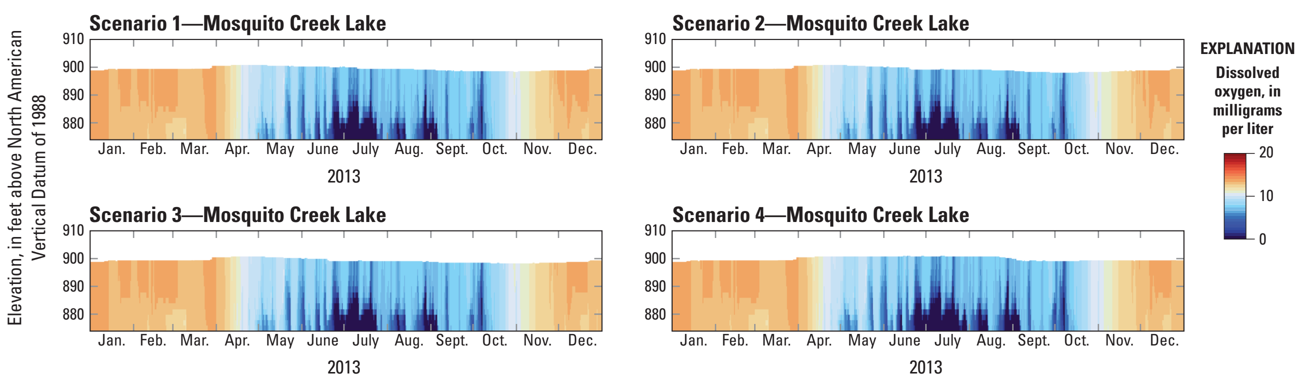

Figure 44. Modeled depth profiles of dissolved oxygen for scenarios 1–4 in Mosquito Creek Lake, Ohio, 2013. The depth profiles are for midnight and noon every day through 2013 from model segment 35, just upstream from the dam. Scenarios are described in table 10.

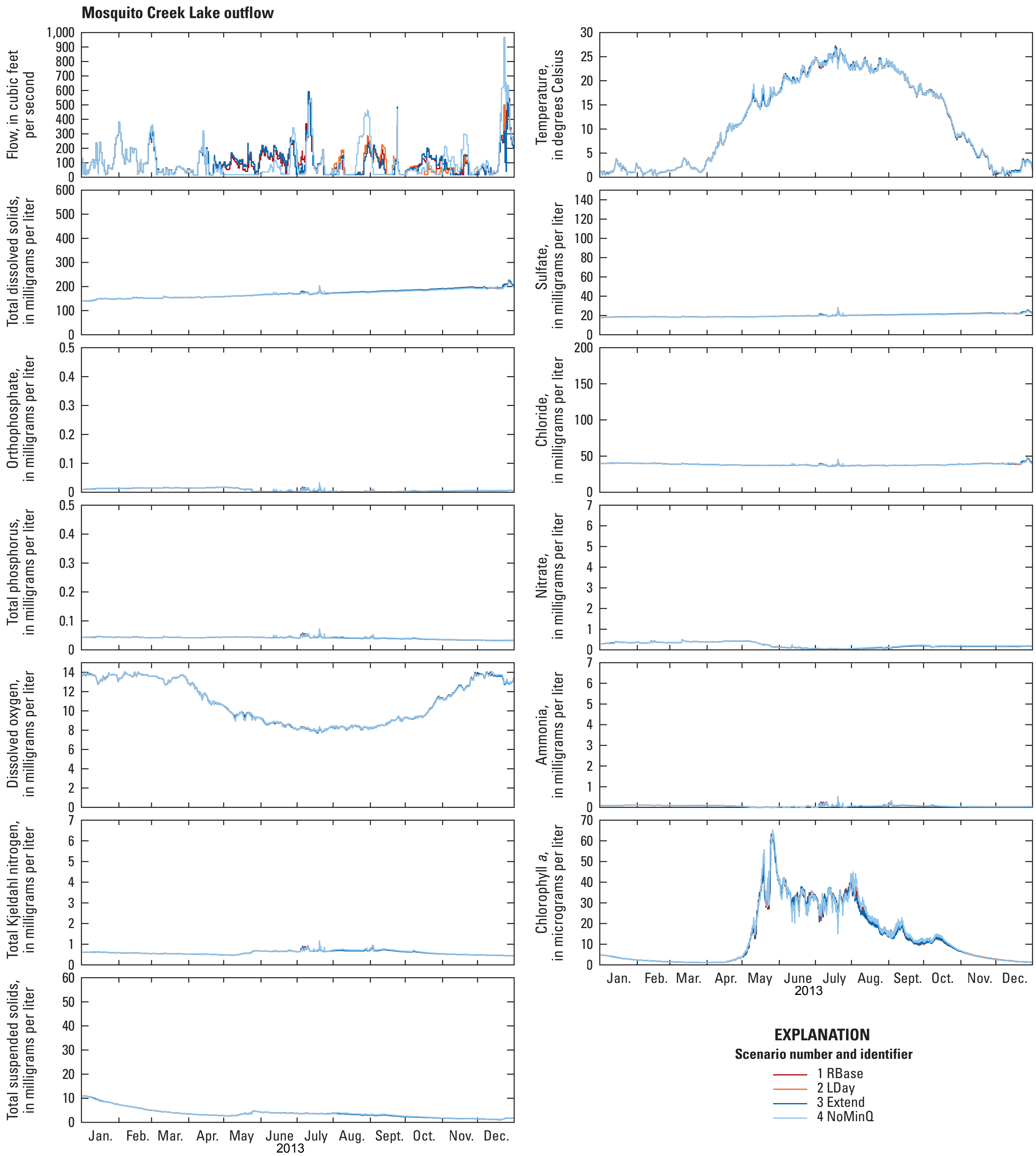

Figure 45. Model scenario flow, water temperature, and water quality for Mosquito Creek Lake, Ohio, outflow at the dam. Scenarios are defined in table 10.

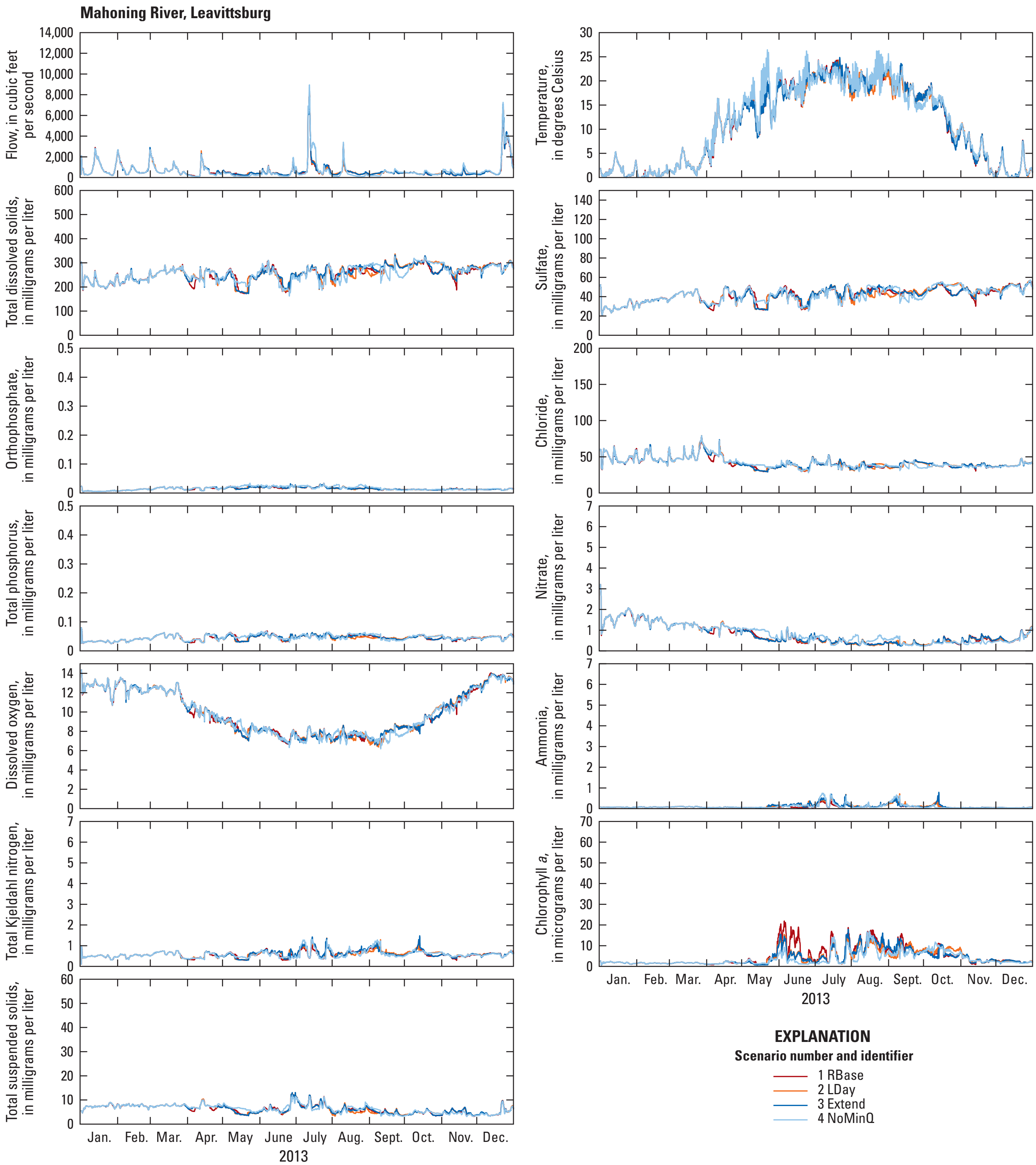

Figure 46. Model scenario flow, water temperature, and water quality in the Mahoning River at Leavittsburg, Ohio, 2013. Scenarios are defined in table 10.

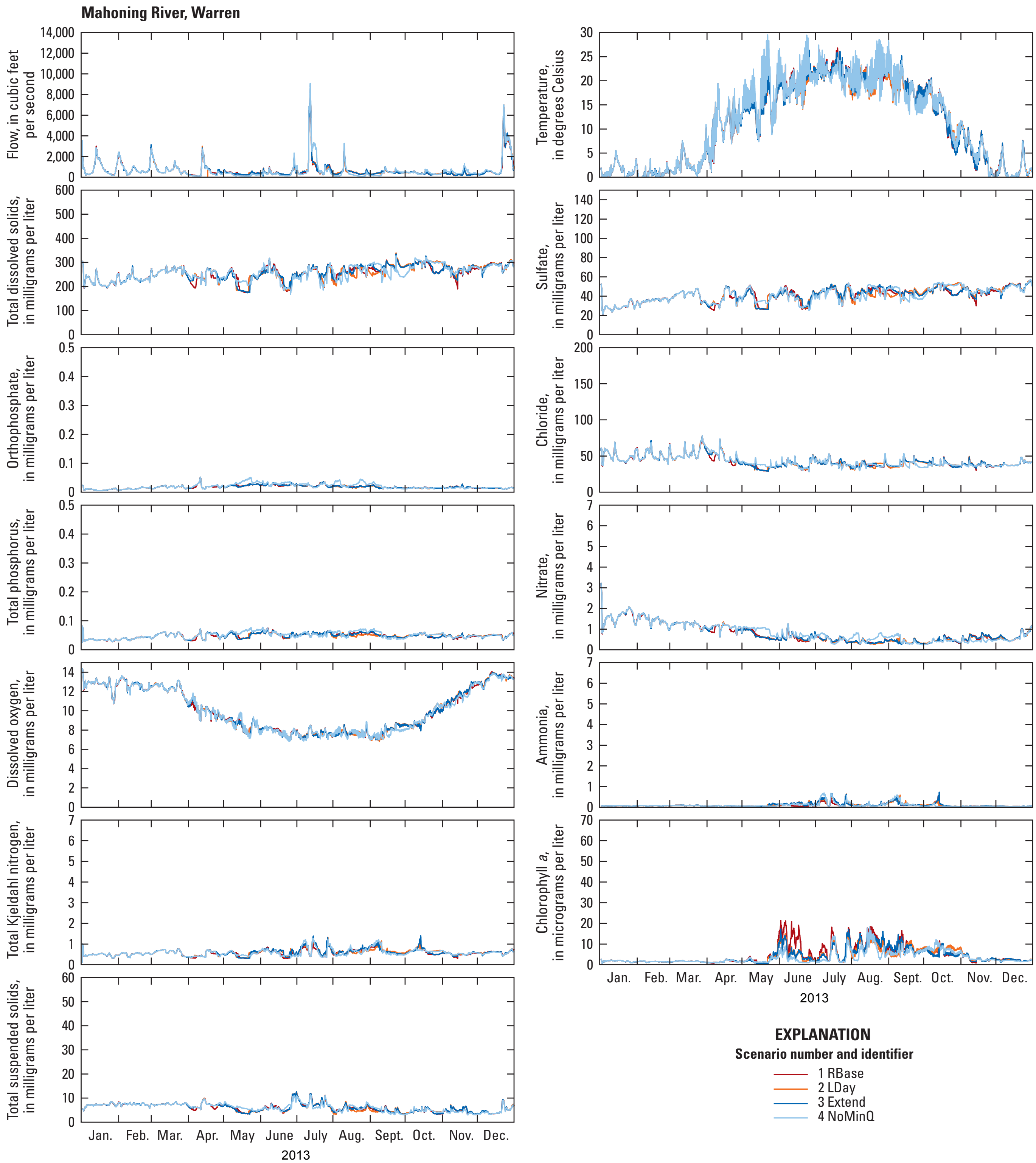

Figure 47. Model scenario flow, water temperature, and water quality in the Mahoning River at Warren, Ohio, 2013. Scenarios are defined in table 10.

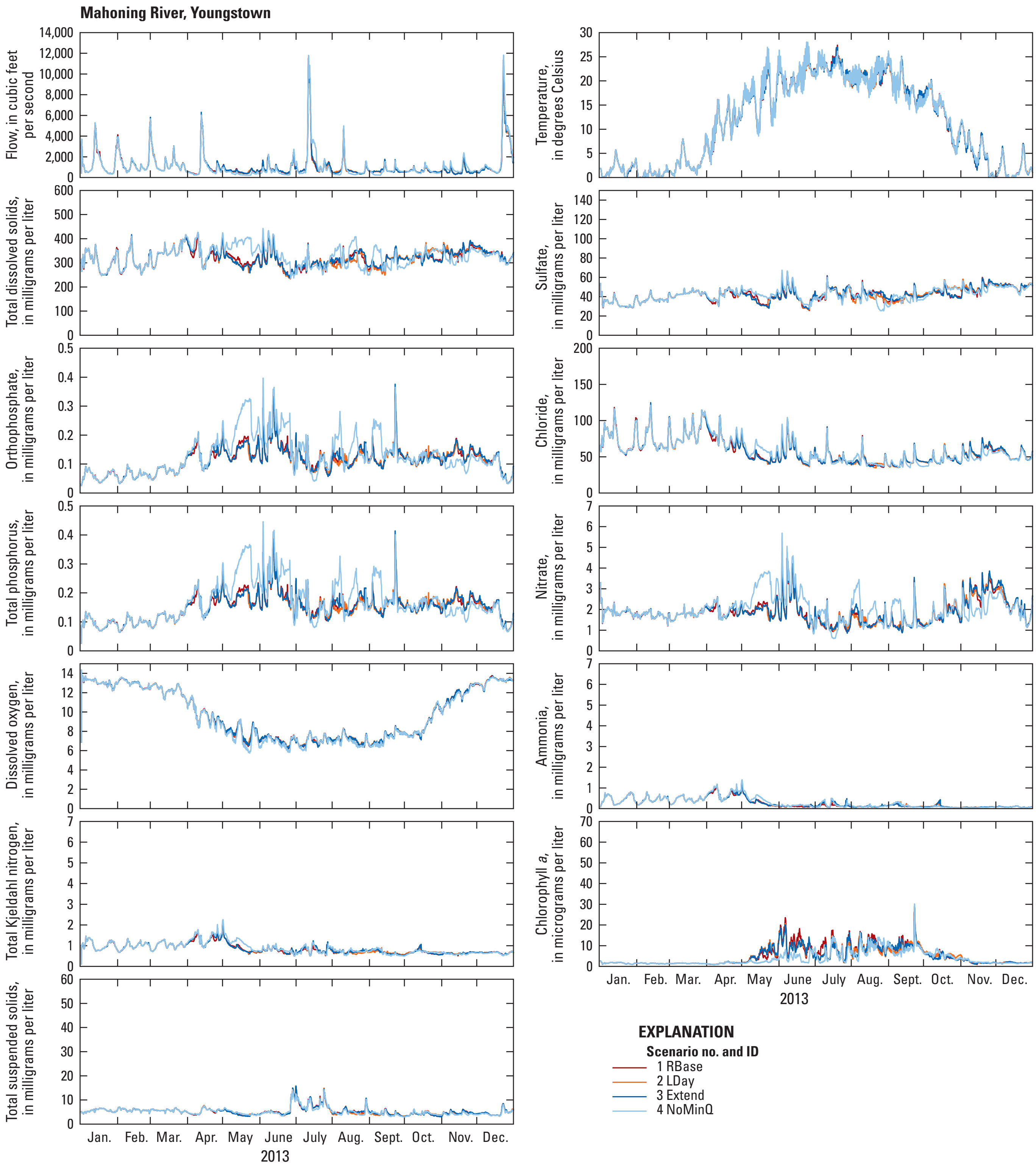

Figure 48. Model scenario flow, water temperature, and water quality of the Mahoning River at Youngstown, Ohio, 2013. Scenarios are defined in table 10.

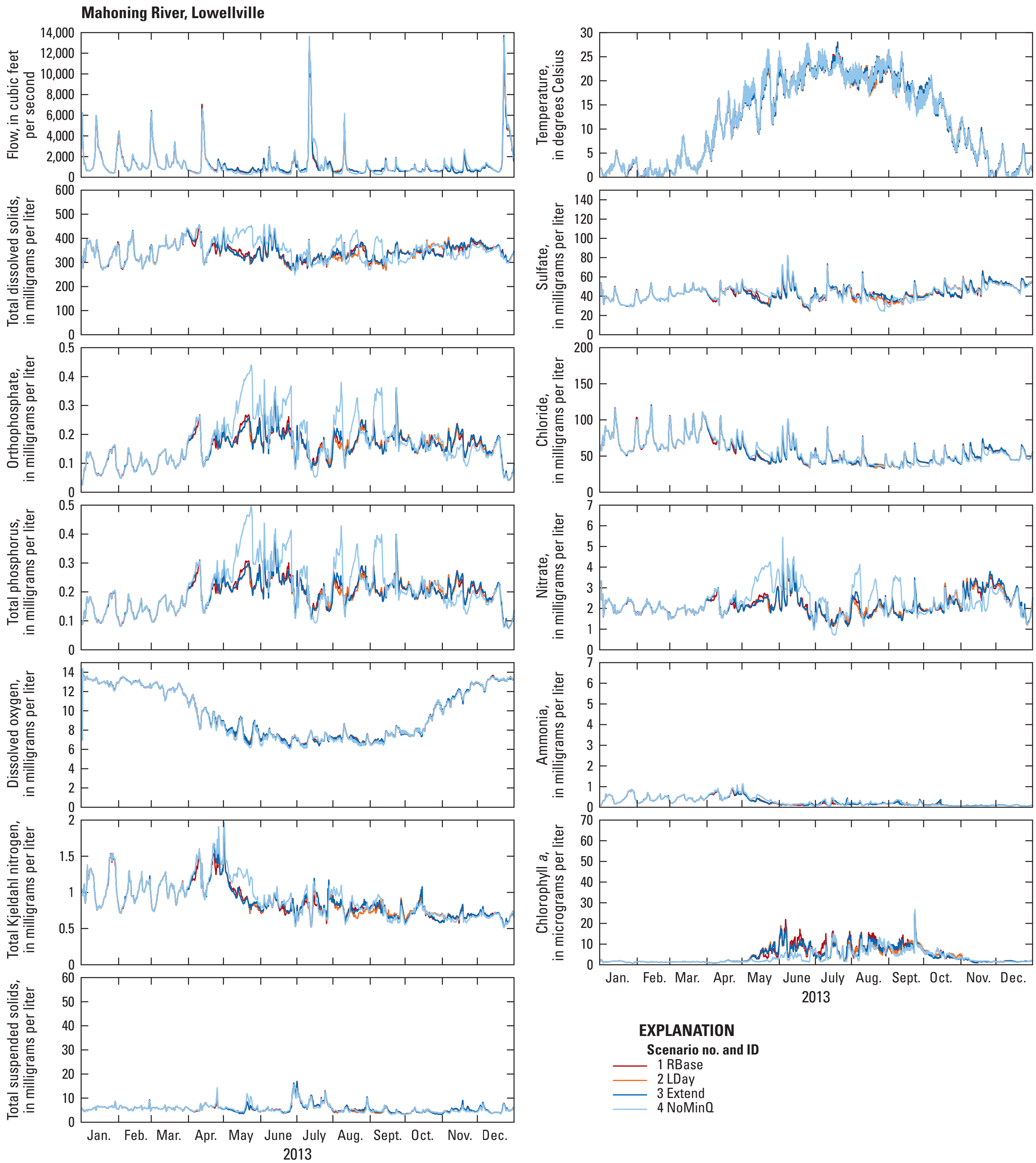

Figure 49. Model scenario flow, water temperature, and water quality of the Mahoning River at Lowellville, Ohio, 2013. Scenarios are defined in table 10.

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