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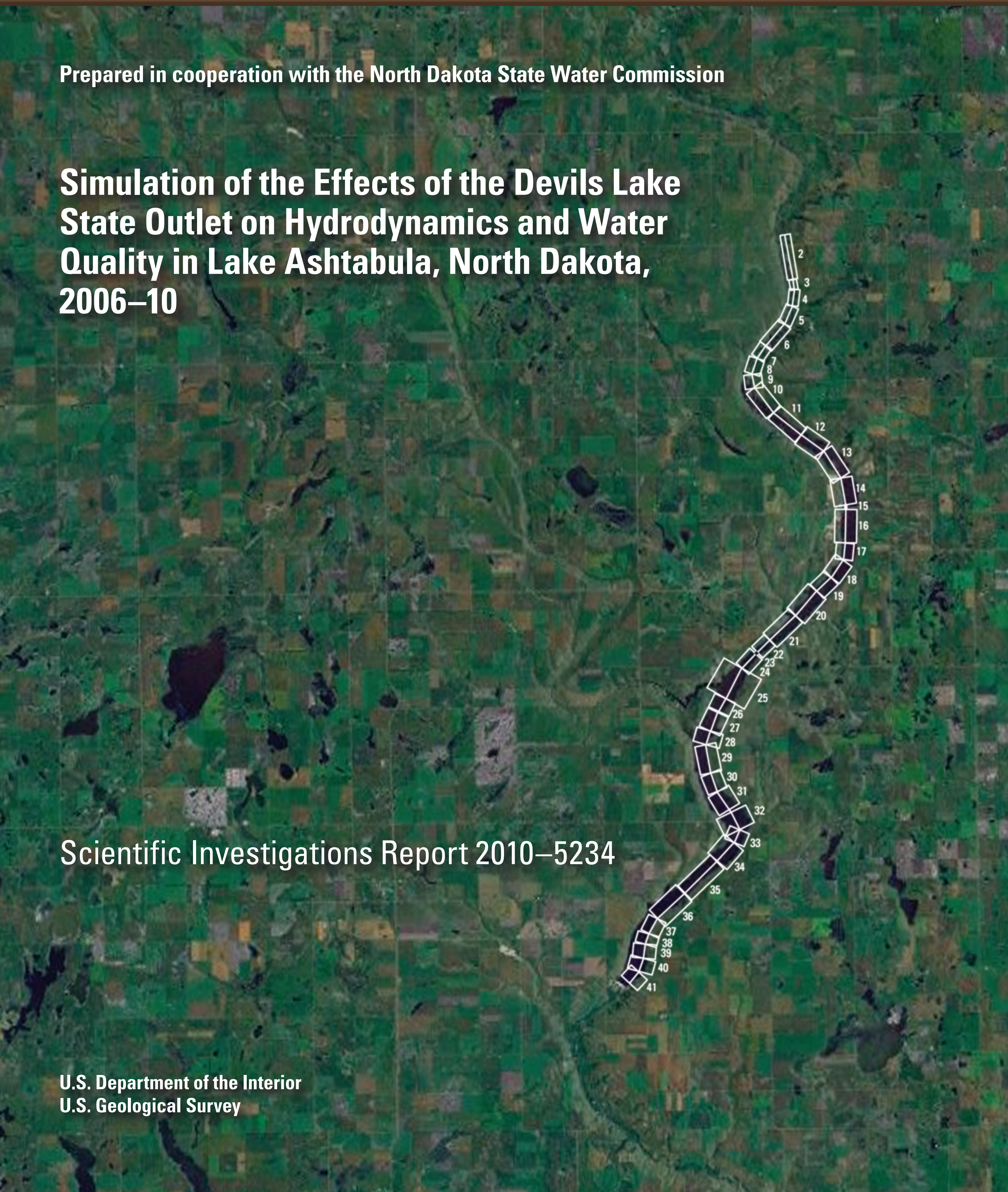
Simulation of the Effects of the Devils Lake State Outlet on Hydrodynamics and Water Quality in Lake Ashtabula, North Dakota, 2006–10

Scientific Investigations Report 2010–5234



U.S. Department of the Interior
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Cover. CE-QUAL-W2 model grid overlain on aerial photography of Lake Ashtabula, North Dakota, and surrounding area. Aerial photography from U.S. Department of Agriculture, Farm Service Agency, 2010.

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U.S. Geological Survey
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The author also thanks Brian Clark and Scott Davidson (USGS Arkansas Water Science Center) for developing scripts used in processing input and output data for the model. In addition, the author would like to thank Tara Gross (USGS North Dakota Water Science Center) for the development and refinement of the illustrations used in this report.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	1,233.5	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°F=(1.8\times°C)+32$$

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

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 either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Water year is the 12-month period of October 1 through September 30 designated by the calendar year in which it ends.

Simulation of the Effects of the Devils Lake State Outlet on Hydrodynamics and Water Quality in Lake Ashtabula, North Dakota, 2006–10

By Joel M. Galloway

Abstract

In 2010, a two-dimensional hydrodynamic and water-quality model (CE-QUAL-W2) of Lake Ashtabula, North Dakota, was developed by the U.S. Geological Survey in cooperation with the North Dakota State Water Commission to understand the dynamics of chemical constituents in the reservoir and to provide a tool for the management and operation of the Devils Lake State Outlet in meeting the water-quality standards downstream from Baldhill Dam. The Lake Ashtabula model was calibrated for hydrodynamics, sulfate concentrations, and total dissolved-solids concentrations to ambient conditions from June 2006 through June 2010. The calibrated model then was used to simulate four scenarios that represent various Devils Lake outlet options that have been considered for reducing the water levels in Devils Lake.

Simulated water temperatures compared well with measured temperatures and differences varied spatially in Lake Ashtabula from June 2006 through June 2010. The absolute mean error ranged from 0.7 degrees Celsius to 1.0 degrees Celsius and the root mean square error ranged from 0.7 degrees Celsius to 1.1 degrees Celsius.

Simulated sulfate concentrations compared well with measured concentrations in Lake Ashtabula. In general, simulated sulfate concentrations were slightly overpredicted with mean differences between simulated and measured sulfate concentrations ranging from -2 milligram per liter to 18 milligrams per liter. Differences between simulated and measured sulfate concentrations varied temporally in Lake Ashtabula from June 2006 through June 2010. In 2006, sulfate concentrations were overpredicted in the lower part of the reservoir and underpredicted in the upper part of the reservoir.

Simulated total dissolved solids generally were greater than measured total dissolved-solids concentrations in Lake Ashtabula from June 2006 through June 2010. The mean difference between simulated and measured total dissolved-solids concentrations ranged from -3 milligrams per liter to 15 milligrams per liter, the absolute mean error ranged from 58 milligrams per liter to 100 milligrams per liter, and the root mean square error ranged from 73 milligrams per liter to 114 milligrams per liter.

Simulated sulfate concentrations from four scenarios were compared to simulated ambient concentrations from June 2006 through June 2009. For scenario 1, the same location, outflow capacity, and sulfate concentration as the current (2010) Devils Lake State Outlet were assumed. The increased flow and sulfate concentration in scenario 1, beginning on May 31 and extending to October 31 each year, resulted in an increase in sulfate concentrations to greater than 450 milligrams per liter in the reservoir at site 7T (approximately the middle of the reservoir), starting July 5 in 2006, July 28 in 2007, and July 15 in 2008. Sulfate concentrations increased to greater than 450 milligrams per liter considerably later at site 1T (near the dam), starting October 8 in 2006, October 29 in 2007, and October 3 in 2008. For scenario 2, the same Devils Lake State Outlet sulfate concentration as scenario 1 was assumed, but the flow through the Devils Lake State Outlet was doubled, which resulted in a more rapid increase in sulfate concentrations in the lower part of the reservoir and slightly greater values at all four sites compared to scenario 1. Sulfate concentrations increased to greater than 450 milligrams per liter 61 days earlier in 2006, 67 days earlier in 2007, and 41 days earlier in 2008 at site 1T.

For scenarios 3 and 4, possible increases in flow and concentration from the current outlet location (from the West Bay of Devils Lake) and from a proposed outlet from East Devils Lake were simulated. Conditions for scenario 3 resulted in a relatively rapid increase in sulfate concentrations in the reservoir, and concentrations were greater than 750 milligrams per liter in most years at all four sites. As expected, scenario 4 resulted in greater sulfate concentrations in the reservoir compared to the other scenarios. Concentrations were greater than 750 milligrams per liter for 139 days in 2006, 214 days in 2007, and 215 days in 2008 at site 1T.

Introduction

Since 1993, Devils Lake, located in northeastern North Dakota (fig. 1), has been experiencing an unprecedented rise (in recorded history) with water levels rising nearly 28 feet (ft) to the current (June 2010) level of 1,452.0 ft above National Geodetic Vertical Datum of 1929 (NGVD 29). The Devils Lake basin is a 3,810 square mile (mi^2) subbasin of the Red River of the North. The basin is closed when Devils Lake water levels are less than 1,446.5 ft above NGVD 29, but spills to West Stump Lake and East Stump Lake at higher levels, and subsequently spills to the Sheyenne River, a tributary of the Red River of the North, at elevations greater than 1,458.0 ft above NGVD 29. Devils Lake began to spill to West Stump Lake and East Stump Lake in 1999 until West Stump Lake, East Stump Lake, and Devils Lake reached the same water level and continued to rise to the current water-level elevation.

In 2002, in an effort to reduce the rate of the water-level rise in Devils Lake, the State of North Dakota began construction of an outlet near Minnewaukan, North Dakota, that diverts water into the Peterson Coulee and subsequently to the Sheyenne River (fig. 1). In 2005, construction was completed and the State of North Dakota began operation of the outlet. Because of strict requirements in the operating permit for the outlet, very little water was released from 2005 through 2008. The operating permit, which is renewed annually, restricts operation based upon requirements of streamflow and sulfate concentrations in the Sheyenne River. From 2005 through June 2009, the permit included a restriction of a maximum sulfate concentration of 450 milligrams per liter (mg/L) and a maximum streamflow of 600 cubic feet per second (ft^3/s) in the Sheyenne River downstream from the Devils Lake State Outlet (North Dakota Department of Health, 2009). In 2006, requirements of the permit were not met, so the outlet could not be used. Between June 2007 and August 2008, a total of 460 acre-feet (acre-ft) of water was released from the outlet. An emergency rule change to the water-quality restriction was imposed in July 2009 that increased the maximum sulfate concentration to 750 mg/L in the Sheyenne River from the headwaters to just downstream from Baldhill Dam (fig. 1), where the standard remained 450 mg/L of sulfate (North Dakota Department of Health, 2009). From the end of May 2009 to the end of October 2009, the Devils Lake State Outlet pumps were operated at near the maximum operating capacity of 100 ft^3/s. Modifications constructed from late 2009 through early 2010 increased the Devils Lake State Outlet capacity to 250 ft^3/s, and pumping began at the higher rate near the end of June 2010.

The recent (2010) increase in the Devils Lake State Outlet capacity to 250 ft^3/s needed to be evaluated to determine the effects on downstream waters in the Sheyenne River, including Lake Ashtabula. In 2010, a two-dimensional hydrodynamic and water-quality model of Lake Ashtabula was developed by the U.S. Geological Survey (USGS) in cooperation with the North Dakota State Water Commission (NDSWC) to understand the dynamics of chemical constituents in Lake Ashtabula and to provide a tool for the management and operation of the Devils Lake State Outlet in meeting the water-quality standards downstream from Baldhill Dam.

Purpose and Scope

The purpose of this report is to describe the simulation of hydrodynamics and water quality in Lake Ashtabula and to provide a better understanding of how discharge from the Devils Lake State Outlet located upstream in the Sheyenne River would effect the hydrology and water quality in Lake Ashtabula. Hydrodynamics and water-quality characteristics in Lake Ashtabula were simulated using the U.S. Army Corps of Engineers (USACE) CE-QUAL-W2 modeling software, version 3.6 (Cole and Wells, 2003). The laterally averaged, two-dimensional model was calibrated using ambient data collected from June 2006 through June 2010. Scenarios also were conducted using the Lake Ashtabula model to simulate the possible effects of the current Devils Lake State Outlet operation, possible future changes to the outlet, and additional outlets from Devils Lake on the water quality in Lake Ashtabula.

Description of Study Area

Baldhill Dam, which creates the reservoir of Lake Ashtabula, is located on the Sheyenne River approximately 271 river miles (mi) upstream from the confluence with the Red River of the North (fig. 1). Lake Ashtabula is a multipurpose reservoir used for rural and municipal water supply, flood control, municipal pollution abatement, fish and wildlife habitat, and recreation. Construction of Baldhill Dam began in July 1947, and the dam was fully operational in the spring of 1951. Lake Ashtabula has a capacity of approximately 70,600 acre-ft at the conservation pool elevation (1,266 ft above NGVD 29) and a capacity of 101,300 acre-ft at the elevation of the top of the flood pool (1,271 ft above NGVD 29) (U.S. Army Corps of Engineers, 2007). At the conservation pool elevation, Lake Ashtabula has a shoreline length of approximately 78 mi, a pool length of 27 mi, and a maximum depth of approximately 45 ft near the dam.

The main inflows into the reservoir are the Sheyenne River and Baldhill Creek (fig. 2). The Sheyenne River upstream from Baldhill Dam has a total drainage area of 3,812 mi^2, of which 462 mi^2 are noncontributing. The mean annual streamflow measured at the Sheyenne River near Cooperstown (05057000; the main inflow into Lake Ashtabula) was 144 ft^3/s for the period of record (1945–2009; *http://waterdata.usgs.gov/nwis/*) (figs. 2 and 3). During the simulation period, June 2006 through June 2010, the annual mean streamflow ranged from 68.5 ft^3/s (water year 2008) to 593 ft^3/s (water year 2009, the greatest annual mean

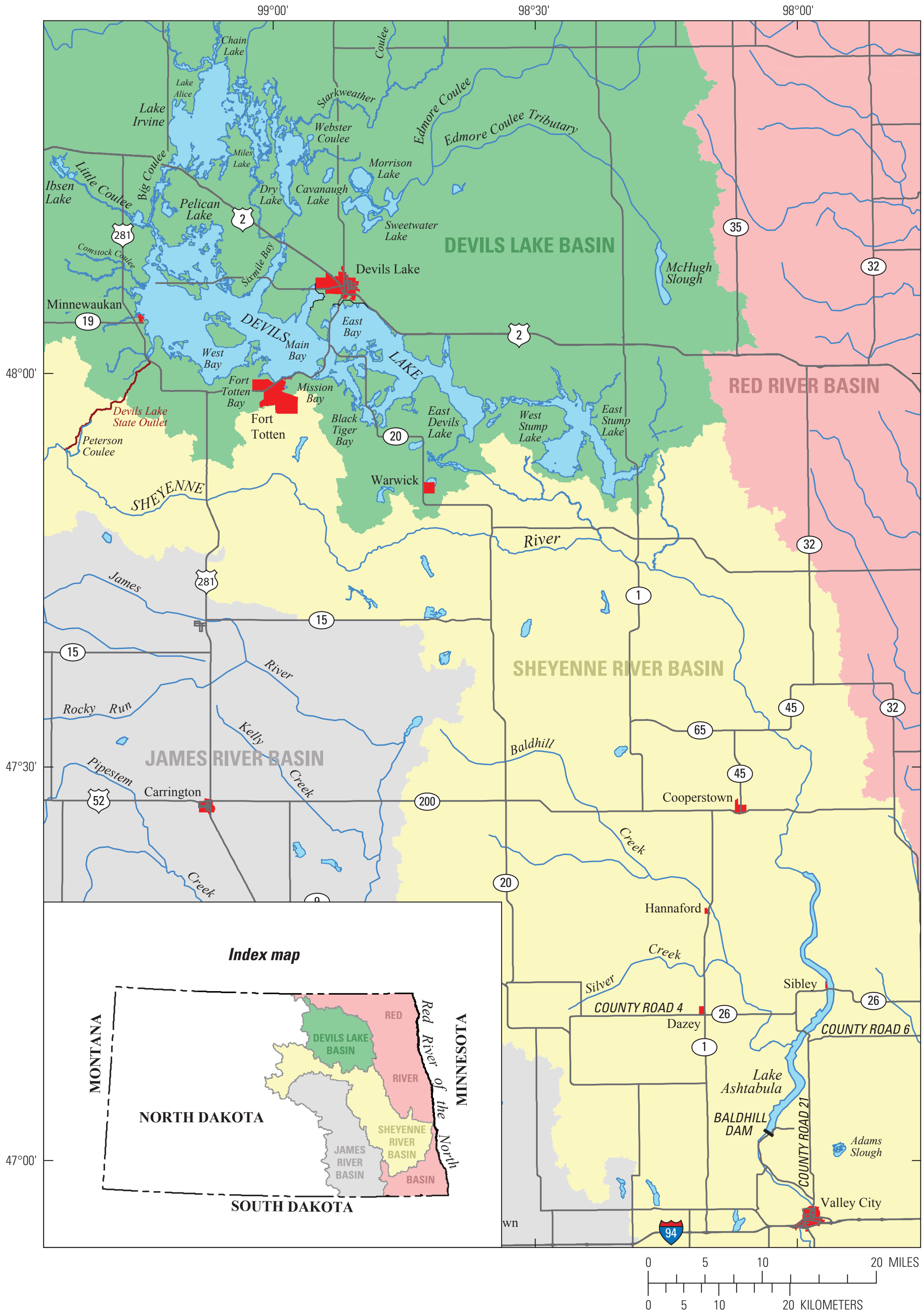

Figure 1. Devils Lake and Lake Ashtabula area, North Dakota.

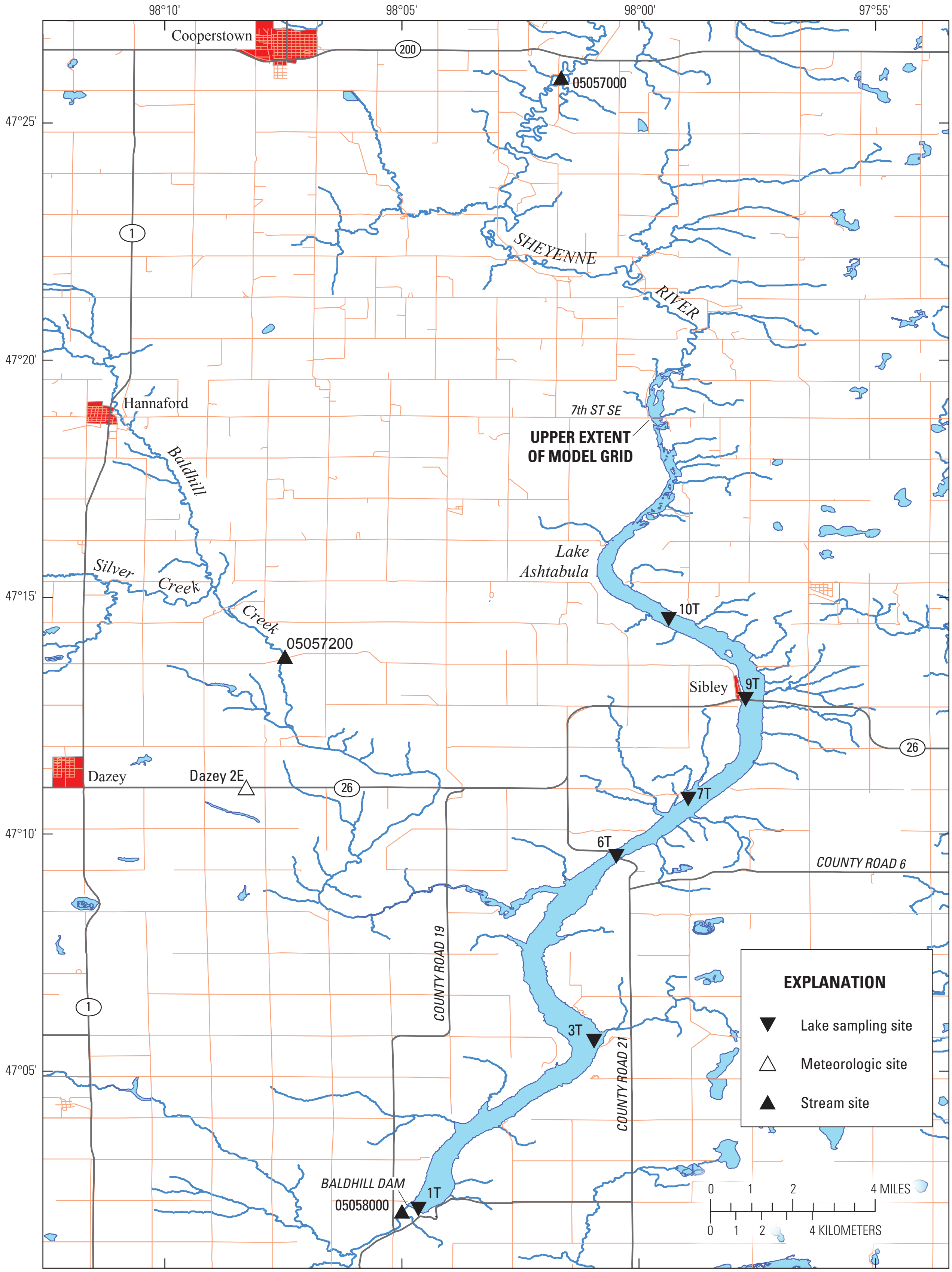

Figure 2. Lake Ashtabula study area, North Dakota, and associated data collection sites.

streamflow for the period of record) (fig. 3). Baldhill Creek (upstream from the USGS streamflow-gaging station near Dazey; 05057200) has a total drainage area of 691 mi², of which 340 mi² are noncontributing. The mean annual streamflow for Baldhill Creek was 28.3 ft³/s for the period of record (1956-2009; *http://waterdata.usgs.gov/nwis/*). During the simulation period, the annual mean streamflow ranged from 9.38 ft³/s (water year 2008) to 142 ft³/s (water year 2009, the greatest annual mean streamflow for the period of record) (fig. 3). Generally, the highest flows occur in the Sheyenne River and Baldhill Creek in the spring (March through May) and lowest flows occur in the winter (November through February) (fig. 3).

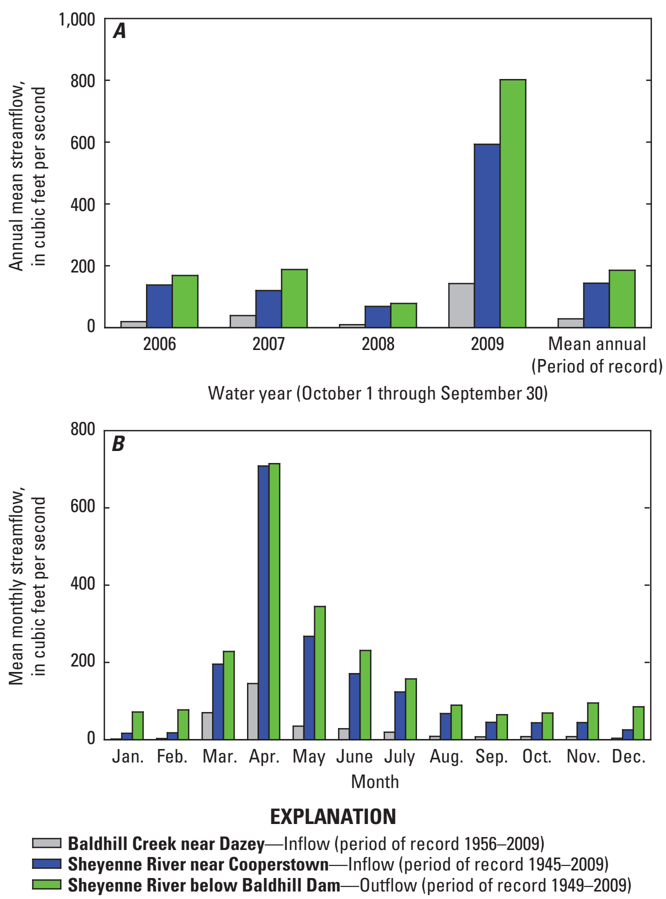

Figure 3. Annual mean (and mean annual) (*A*), and mean monthly (*B*), streamflow for the Sheyenne River near Cooperstown, North Dakota (05057000; inflow to Lake Ashtabula), Baldhill Creek near Dazey, North Dakota (05057200; inflow to Lake Ashtabula), and Sheyenne River below Baldhill Dam, North Dakota (05058000; outflow from Lake Ashtabula).

Methods

Hydrodynamic and water-quality characteristics in Lake Ashtabula were simulated using the USACE CE-QUAL-W2 modeling software, version 3.6 (Cole and Wells, 2003). The laterally averaged, two-dimensional model was developed and calibrated using hydrologic and water-quality data collected from June 2006 through June 2010. The methods used in the collection of data and implementation of the Lake Ashtabula model are described in this section.

Measured Data

Streamflow and water-quality data collected in June 2006 through June 2010 by multiple agencies were used for the development and calibration of the Lake Ashtabula model. Agencies that were involved in data collection during the simulation period included the USGS, the USACE, and the NDSWC.

Streamflow

Stream stage was measured continuously by the USGS at the Sheyenne River near Cooperstown, North Dakota (USGS streamflow-gaging station number 05057000), Baldhill Creek near Dazey, North Dakota (USGS streamflow-gaging station number 05057200), and Sheyenne River below Baldhill Dam (USGS streamflow-gaging station number 05058000) (fig. 2 and table 1; *http://waterdata.usgs.gov/nwis/*). Stage and instantaneous discharge were measured to compute the continuous streamflow from stage-discharge rating curves using methods described in Rantz and others (1982).

Water Quality

Water-quality samples were collected by the USACE from June 2006 through June 2010 at four fixed sites established along the downstream gradient in Lake Ashtabula (sites 10T, 7T, 3T, and 1T; table 1 and fig. 2). Sample sites in the lake were located along the original stream channel, the deepest location within the lake cross section. Samples were collected at two locations within the vertical profile, one at 3 ft below the water surface (epilimnion) and one at 3 ft above the reservoir bottom (hypolimnion) using a Kemmerer sampler (Lane and others, 2003). Samples generally were collected twice a month during open-water conditions from May through September in 2006, 2008, and 2009. Water-quality samples were not collected in 2007. Samples were analyzed for concentrations of major ions (including sulfate), total dissolved solids (TDS), nutrients (dissolved and total nitrite plus nitrate, total ammonia plus organic nitrogen, dissolved phosphorus, dissolved and total phosphorus), dissolved and total organic carbon, chlorophyll *a*, and selected trace metals. Quality assurance samples such as replicate and blank

Table 1. Water-quality and streamflow sites used for the Lake Ashtabula model.

[USGS, U.S. Geological Survey; USACE, U.S. Army Corps of Engineers; NDSWC, North Dakota State Water Commission]

USGS site number	Site name	Site type	Data collection agency
05057000	Sheyenne River near Cooperstown	Inflow streamflow, water quality	USGS
471432097592200	Lake Ashtabula site 10T	Water quality	USACE, USGS
471249097575100	Lake Ashtabula site at Sibley Crossing Bridge 9T	Water quality	NDSWC, USGS
471044097585800	Lake Ashtabula site 7T	Water quality	USACE, USGS
470932098002800	Lake Ashtabula site at Ashtabula Crossing Bridge 6T	Water quality	NDSWC, USGS
05057200	Baldhill Creek near Dazey	Inflow streamflow, water quality	USGS
470533098012000	Lake Ashtabula site 3T	Water quality	USACE, USGS
470214098044300	Lake Ashtabula site 1T	Water quality	USACE, USGS
05058000	Sheyenne River below Baldhill Dam	Outflow streamflow	USGS

samples were not collected by the USACE from June 2006 through 2010. Field measurements (water temperature, dissolved-oxygen concentration, pH, and specific conductance) were measured at 3-ft vertical intervals from the water surface to the reservoir bottom at each sampling site at the time of sample collection. In 2008, field measurements were not collected when water-quality samples were collected. All sample analyses were conducted at the North Dakota Department of Health Laboratory in Bismarck, North Dakota using methods described in American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995 and 2005), Creed and others (1994), Hautman and Munch (1997), and Martin and others (1994). The laboratory followed protocols from an internal quality control/quality assurance plan (Errol Erickson, North Dakota Department of Health, written commun., 2010) and participated in the USGS lab evaluation program by processing blind reference samples two times a year (*http://qadata.cr.usgs.gov/lep_new/*). Water-quality results are available at *http://www.epa.gov/storet/dw_home.html*.

Water-quality samples were collected by the NDSWC at two bridges (sites 6T and 9T; table 1) that cross Lake Ashtabula from August 2009 through June 2010. Samples were collected every week during open-water conditions and every 2 weeks during ice-cover conditions using a grab-type sampler for collection of a sample from the water-surface and a Van Dorn sampler (Lane and others, 2003) for collection of a sample 3 ft from the reservoir bottom at each site. Water-quality samples were analyzed for sulfate concentration at the North Dakota Department of Health Laboratory in Bismarck, North Dakota using methods described in Hautman and Munch (1997). Water-quality results are available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetCategoryRecord/Map%20and%20Data%20Resources*.

The USGS also collected samples at all six sites (sites 1T, 3T, 6T, 7T, 9T, and 10T) in September 2009, October 2009, and February 2010. Samples were collected using a peristaltic pump and hose to collect samples at 3 ft below the water surface and at 3 ft above the reservoir bottom. Water-quality samples were analyzed for concentrations of major ions (including sulfate), TDS, nutrients, chlorophyll *a,* and selected trace metals. All sample analyses were conducted at North Dakota Department of Health Laboratory in Bismarck, North Dakota using methods described in American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995 and 2005), Creed and others (1994), Hautman and Munch (1997), and Martin and others (1994). Field measurements also were measured at 3 ft vertical intervals from the water surface to the reservoir bottom at each sampling site at the time of sample collection. Water-quality results are stored in the USGS National Water Information System (NWIS) and are available at *http://waterdata.usgs.gov/nwis/*.

Additional depth profiles of water temperature were obtained from an automated profiler operated by USACE at site 1T from May through October 2009 and from May through June 2010. The profiler is pontoon mounted and anchored near the outlet of the dam at the reservoir's deepest location (site 1T). The profiler was programmed to collect water-quality measurements using a multiparameter sonde every 6 hours at 3-ft increments starting at 1 ft below the surface to 1 ft above the bottom of the reservoir. The multiparameter sonde was automatically lowered and raised throughout the water column by a mechanical winch and drive mechanism housed inside the pontoon's weather resistant shell. The water-quality data were then downloaded remotely to a computer using an internet connection and a cellular modem aboard the profiler (James B. Noren, U.S. Army Corps of Engineers, written commun., 2010).

Reservoir Model Implementation

Implementation of the CE-QUAL-W2 model for Lake Ashtabula included development of the computational grid, specification of boundary and initial conditions, and preliminary selection of model parameter values. Model development and associated assumptions in the selection of boundary and initial conditions are described, and model parameters are listed in this section.

Computational Grid

The computational grid is the geometric scheme that numerically represents the space and volume of the reservoir. Bathymetric data and geographic information system (GIS) analysis were used in the development of the computational grid. Bathymetric contours of Lake Ashtabula were obtained from the North Dakota Game and Fish Department (2009). The bathymetric contours had a 20-ft interval up to an elevation of 1,266 ft above NGVD 29. Digital elevation data were used in GIS to extrapolate the bathymetry to slightly below the current dam elevation of 1,278.5 ft above NGVD 29. The computational grid was created from the modified bathymetric data using Aquaveo WMS, version 8.1 software (*http://wmstutorials.aquaveo.com/*), to divide the reservoir into segments and layers.

The resulting model grid extended 23 mi from the upstream boundary (7th Street Southeast bridge across the Sheyenne River east of Hannaford, North Dakota) to Baldhill Dam (figs. 2 and 4). Forty computational segments exist along the mainstem of the Sheyenne River in Lake Ashtabula. Volumes of the smaller embayments not included in the computational grid were added to associated mainstem segments so that reservoir volume was preserved. Each segment was divided vertically into 3.3-ft (1-meter) layers. Boundary segments (segment 1 and segment 42) and layers (layers 1 and 20) allow for the application of input parameters to the computational grid and have no length or width associated with them. One tributary also was included in the model at segment 25 to represent the inflow from Baldhill Creek (fig. 4). Tributaries allow for the application of boundary conditions to the grid without affecting the geometry. Relations between water-surface elevation and volume and surface area in the Lake Ashtabula model were similar to USACE preimpoundment data (U.S. Army Corps of Engineers, 2007) (fig. 5).

Hydraulic and Thermal Boundary Conditions

Daily reservoir inflows used in the model were obtained from USGS streamflow-gaging station data on the two main inflows—the Sheyenne River and Baldhill Creek. The daily mean streamflow recorded for the Sheyenne River near Cooperstown, North Dakota (USGS streamflow-gaging station number 05057000), was used to estimate the inflow from the Sheyenne River and the daily mean streamflow recorded for Baldhill Creek near Dazey, North Dakota (USGS streamflow-gaging station number 05057200; *http://waterdata.usgs.gov/nwis/*), was used to estimate the inflow from Baldhill Creek (fig. 2).

The downstream boundary for the Lake Ashtabula model was the outflow from Baldhill Dam. The outlet structure consists of a 3-ft diameter culvert (intake elevation 1,238 ft above NGVD 29), and three spillway gates that are each 40 ft wide and 20 ft high with the bottom of the spillway at an elevation of 1,252 ft above NGVD 29 (U.S. Army Corps of Engineers, 2007). Daily outflow data were obtained from the USGS streamflow-gaging station at Sheyenne River below Baldhill Dam (USGS streamflow-gaging station number 05058000; *http://waterdata.usgs.gov/nwis/*) (fig. 2). The outflow from the culvert was estimated as 9 ft^3/s (Scott Tichy, U.S. Army Corps of Engineers, personal commun., 2010). The flow from the culvert was subtracted from the total outflow measured at the streamflow-gaging station to obtain the daily outflow from the spillway gates.

Hydraulic boundary conditions at the water surface included evaporation, wind stress, and surface heat exchange. Meteorological data required for these computations were measured at a North Dakota Agricultural Weather Network (NDAWN) station near Dazey, North Dakota (station name Dazey 2E; *http://ndawn.ndsu.nodak.edu/*) (fig. 2) and generally were recorded at hourly intervals.

Daily mean water temperatures for inflow into Lake Ashtabula from the Sheyenne River were obtained from a continuously recording water-quality monitor at the Sheyenne River near Cooperstown, North Dakota (USGS streamflow-gaging station number 05057000; *http://waterdata.usgs.gov/nwis/*). Water temperature data were not available for Baldhill Creek; therefore, values from the Sheyenne River were also used to estimate the daily water temperatures for Baldhill Creek.

Chemical Boundary Conditions

Daily TDS and sulfate concentrations for the inflow from the Sheyenne River were estimated from regression equations developed by Ryberg (2007) relating TDS and sulfate to continuously recorded specific conductance and streamflow measured at the Sheyenne River near Cooperstown, North Dakota (USGS streamflow-gaging station number 05057000; *http://waterdata.usgs.gov/nwis/*). Because continuously recorded specific conductance data was not available for Baldhill Creek, daily sulfate concentrations (SO_4) for Baldhill Creek were estimated as follows:

When daily mean streamflow (Q) was less than or equal to 10 ft^3/s, then SO_4 = 270 mg/L. If daily mean streamflow was greater than 10 ft^3/s, then $SO_4=270/(Q/10)^{0.31}$.

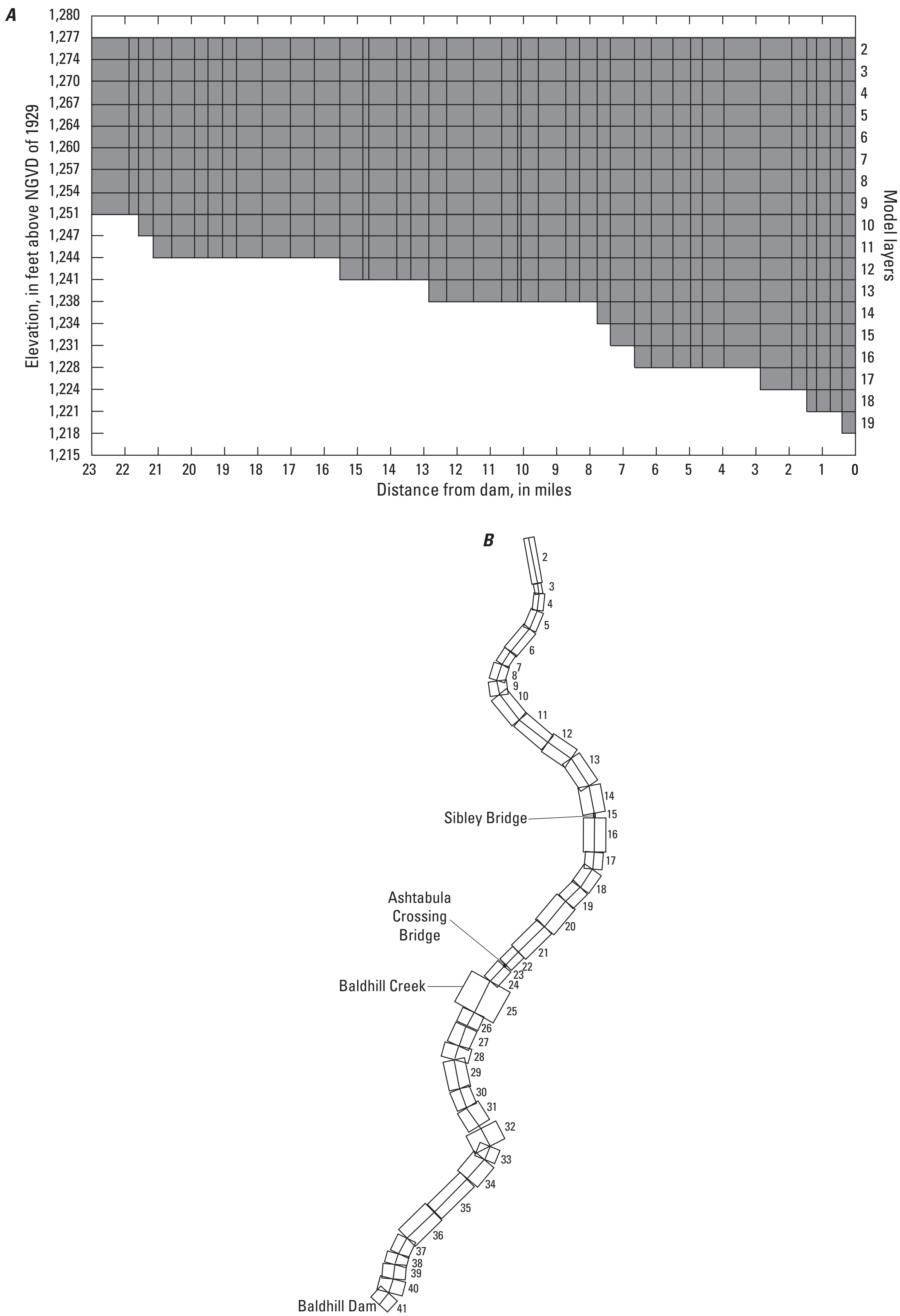

Figure 4. Side view and top view of the computational grid used in the CE-QUAL-W2 model of Lake Ashtabula, North Dakota.

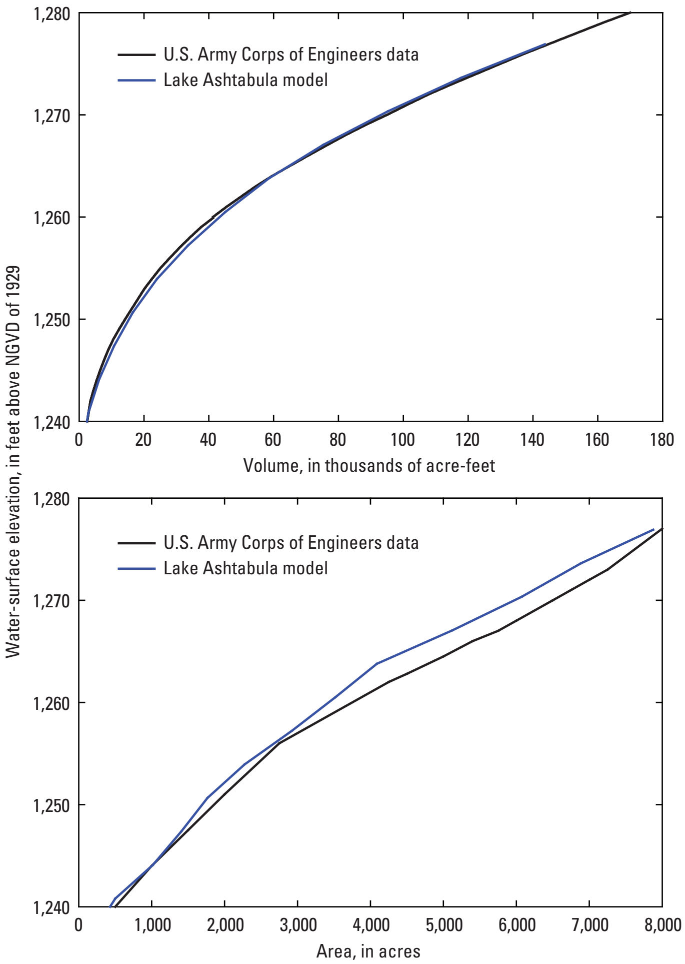

Figure 5. Comparison of the relation between water-surface elevation and volume and water-level elevation and surface area for the Lake Ashtabula model and data from the U.S. Army Corps of Engineers (2007).

Daily TDS concentrations for Baldhill Creek were estimated by multiplying daily estimated SO_4 by 3.38 (Aldo S. Vecchia, U.S. Geological Survey, written commun., 2010).

Initial Conditions

Initial water-surface elevation, water temperature, and constituent concentrations for each model segment were required at the start of the model simulation. Initial water-surface elevations were set to the measured value on June 1, 2006. Because CE-QUAL-W2 only allows a single initial condition to be specified across the model grid, Lake Ashtabula was assumed to be in isothermal conditions throughout the entire reservoir and the water temperature equal to 21.3°C. Initial constituent concentrations also were assumed to be uniform, and concentrations measured at sampling sites 1T, 3T, 7T, and 10T on June 8, 2006, were used to approximate an initial value of 220 mg/L for sulfate and 600 mg/L for TDS.

Model Parameters

Parameters are used to describe the physical and chemical processes that are not explicitly modeled and to provide the chemical kinetic rate information. Many parameters cannot be measured directly and often are adjusted during the model calibration process until simulated values agree with measured observations. Most of the hydrodynamic and thermal processes are modeled internally in CE-QUAL-W2, which results in very few adjustable hydraulic and thermal parameters. Many of the coefficients were based on suggested values given as default values for CE-QUAL-W2, and others were based on other model applications (Haggard and Green, 2002; Galloway and Green, 2002, 2003, 2006; Green and others, 2003; Bales and others, 2001; Sullivan and Rounds, 2005) (table 2).

There are many chemical and biological rate coefficients required for the application of CE-QUAL-W2 that are all temporally constant. However, because the only chemical constituents simulated for Lake Ashtabula were SO_4 and TDS, which were assumed to be conservative in this application, none of the rate coefficients was required. The only rate coefficients in CE-QUAL-W2 that could have been applied to the SO_4 simulation were a decay rate coefficient and settling rate coefficient. These coefficients were not used in this application. There are no rate coefficients applicable to TDS in the CE-QUAL-W2 model.

Table 2. Parameters and values used for the Lake Ashtabula model, June 2006 through June 2010.

[*, default values]

Hydraulic and thermal input parameters	Value
Coefficent of bottom heat exchange, watts/square meter/second	0.7
Sediment temperature, degrees Celsius	10.5
Wind-sheltering coefficient, dimensionless	0.90
Horizontal eddy viscosity, square meters/second	1.0*
Horizontal eddy diffusivity, square meters/second	1.0*
Ice albedo, dimensionless	0.45
Coefficent of water-ice heat exchange, watts/square meter/second	10.0*
Fraction of radiation absorbed by ice, dimensionless	0.6*
Solar radiation extinction coefficient, 1/meter	0.07*
Minimum ice thickness before ice formation, meters	0.03*
Temperature above which ice does not form, degrees Celsius	4.5
Light extinction coefficient for pure water, 1/meter	0.3
Light extinction coefficient for organic solids, 1/meter	0.01
Light extinction coefficient for inorganic solids,1/meter	0.01

Statistics Used for Model Evaluation

Two statistics were used to compare simulated and measured water temperature, sulfate concentrations, and TDS concentrations. The absolute mean error (AME) indicates the average difference between simulated and measured values and is computed by equation 1.

$$AME = \frac{\Sigma \left| \, simulated\ value - measured\ value \, \right|}{number\ of\ observations} \qquad (1)$$

An AME of 0.5°C means that the average difference between simulated temperatures and measured temperature is 0.5°C.

The root mean square error (RMSE) indicates the spread of how far simulated values deviate from the measured values and is computed by equation 2:

$$RMSE = \sqrt{\frac{\Sigma \left(simulated\ value - measured\ value \right)^2}{number\ of\ observations}} \qquad (2)$$

An RMSE of 0.5°C means that the simulated temperatures are within 0.5°C of the measured temperatures about 67 percent of the time (Cole and Wells, 2003).

Reservoir Model Application

Scenarios were simulated using the calibrated Lake Ashtabula model to evaluate the effects of the current (2010) Devils Lake State Outlet operation, possible future changes to the outlet, and an additional outlet from Devils Lake on the water quality in Lake Ashtabula. Four scenarios were selected for evaluation using the model, in which streamflow and sulfate concentrations were adjusted for the Sheyenne River for June 1, 2006 through June 1, 2009. The scenarios were not evaluated subsequent to June 1, 2009, because the outlet was operating near full capacity during that period, and the effects of the increases in sulfate concentrations would have been difficult to isolate from the ambient conditions in Lake Ashtabula. For each scenario, assumed outflow from the Devils Lake State Outlet was added to the ambient inflow to Lake Ashtabula. Scenario 1 assumed the outflow from the Devils Lake State Outlet was at the current (2010) location and capacity of 250 ft^3/s and the SO_4 concentration was 575 mg/L, based on current (2010) measurements in the West Bay of Devils Lake (fig. 1; *http://www.epa.gov/storet/dw_home.html*). For scenario 2, the capacity of the current outlet was increased to 500 ft^3/s with the same SO_4 concentration (575 mg/L) as scenario 1. Scenarios 3 and 4 were conducted to evaluate the possibility of an additional outlet from East Devils Lake (fig. 1), which has a higher SO_4 concentration (1,025 mg/L; *http://www.epa.gov/storet/dw_home.html*). For scenario 3, it was assumed that the flow from the current outlet was 250 ft^3/s and that the outflow from East Devils Lake was 250 ft^3/s for a combined flow of 500 ft^3/s with a blended SO_4 concentration of 800 mg/L. For scenario 4, the same flow of 500 ft^3/s was assumed, but the SO_4 concentration was increased to 1,000 mg/L. For all four scenarios, it was assumed that the outlets were pumping during open-water conditions from May 31 to October 31, with none of the current constraints for the operation of the Devils Lake State Outlet (maximum streamflow of 600 ft^3/s in the Sheyenne River, maximum sulfate concentration of 750 mg/L upstream from Baldhill Dam and 450 mg/L downstream from Baldhill Dam). For each scenario, daily inflow concentrations of SO_4 and TDS for the Sheyenne River were computed using the following equation:

$$C_{SC}\left(t\right) = \frac{Q_s\left(t\right)C_s\left(t\right) + Q_O\left(t\right)C_O\left(t\right)}{Q_s(t) + Q_O\left(t\right)} \qquad (3)$$

where

$C_{SC}(t)$ is the daily concentration for the Sheyenne River for a given scenario, in milligrams per liter, for day t;

$Q_S(t)$ is the daily ambient streamflow for the Sheyenne River, in cubic feet per second, for day t;

$C_S(t)$ is the daily ambient constituent concentration for the Sheyenne River, in milligrams per liter, for day t;

$Q_O(t)$ is the daily simulated streamflow for the Devils Lake State Outlet (or outlets) for a given scenario, in cubic feet per second, for day t and;

$C_O(t)$ is the daily simulated constituent concentration for the Devils Lake State Outlet (or outlets) for a given scenario, in milligrams per liter, for day t.

The outflow also was adjusted to accommodate the increased inflow and to maintain the ambient water-surface elevations in Lake Ashtabula.

Simulation of Hydrodynamics and Water Quality in Lake Ashtabula

The Lake Ashtabula model was calibrated for hydrodynamics, sulfate concentrations, and TDS concentrations to ambient conditions from June 2006 through June 2010. The calibrated model then was used to simulate four different scenarios that represent various Devils Lake outlet options that have been considered for reducing the water levels in Devils Lake.

Model Calibration for Ambient Conditions

Successful model application requires model calibration that includes comparing simulated results with measured reservoir conditions. The Lake Ashtabula model calibration was completed by adjusting parameters for the 4-year period from June 2006 through June 2010. Calibration was achieved generally by first calibrating the water balance and thermodynamics, including ice cover, then calibrating the water-quality conditions (TDS and sulfate). This section describes the simulation of the ambient hydrologic and water-quality conditions in Lake Ashtabula from June 2006 through June 2010. The simulated values were compared to measured data collected at four sites from June 2006 through June 2010 (sites 1T, 3T, 7T, and 10T), and two sites that had measured data from August 2009 through June 2010 (6T and 9T) (fig. 2).

Hydrodynamics

Simulated water-surface elevations in Lake Ashtabula were adjusted to the measured water surface for the simulation period of June 2006 through June 2010 (fig. 6). Measured water-surface elevations were obtained from the USACE for the simulation period (*http://www.mvp-wc.usace.army.mil/projects/Baldhill.shtml*). The water-surface elevations were corrected to the measured values by adjusting the unmeasured inflow into the lake, which was distributed to all the segments within the model grid. The distributed inflow was added or subtracted so that the simulated water-surface elevation reflected the measured water-surface elevation, therefore, accounting for unmeasured inflow and groundwater interaction in Lake Ashtabula. By adjusting the distributed inflow, the temperature and water quality could be calibrated without the added uncertainty incurred with having differences between simulated and measured water-surface elevations.

Simulated water temperatures in Lake Ashtabula were compared to 41 depth profiles of temperature measured at sites 1T, 3T, 7T, and 10T on Lake Ashtabula (figs. 7 and 8). Temperatures were calibrated to the measured values for the simulation period of June 2006 through June 2010.

Simulated temperatures compared reasonably well with measured temperatures and differences varied spatially in Lake Ashtabula for June 2006 through June 2010. Differences in temperature between simulated and measured values were the greatest at sites 3T and 10T and the least at sites 1T and 7T. The AME ranged from 0.7°C at site 7T to 1.0°C at sites 3T and 10T, and the RMSE ranged from 0.7°C at site 7T to 1.1°C at site 3T from June 2006 through June 2010 (figs. 7 and 8; table 3). The greatest differences between measured and simulated data occurred during a period when the reservoir was partly stratified at the beginning of the simulation in 2006 and during the fall of 2009 (October). In June and July 2006, the lower part of the reservoir was slightly stratified where site 1T and 3T were located. Because the initial conditions were applied assuming isothermal conditions, the model did not properly simulate the stratified conditions at the beginning of the simulation period in the lower part of the reservoir resulting in an AME ranging from 1.2 to 2.0°C at site 1T and from 0.5 to 2.9°C at site 3T in June and July 2006 (figs. 7 and 8). The RMSE ranged from 1.2 to 2.7°C at site 1T and from 0.6 to 3.1°C at site 3T during the same period. During October 2009, the simulated temperature was less than the measured water temperature with the AME ranging from 1.2°C to 2.0°C (site 1T) and RMSE ranging from 1.2°C to 2.1°C (site 1T) (figs. 7 and 8).

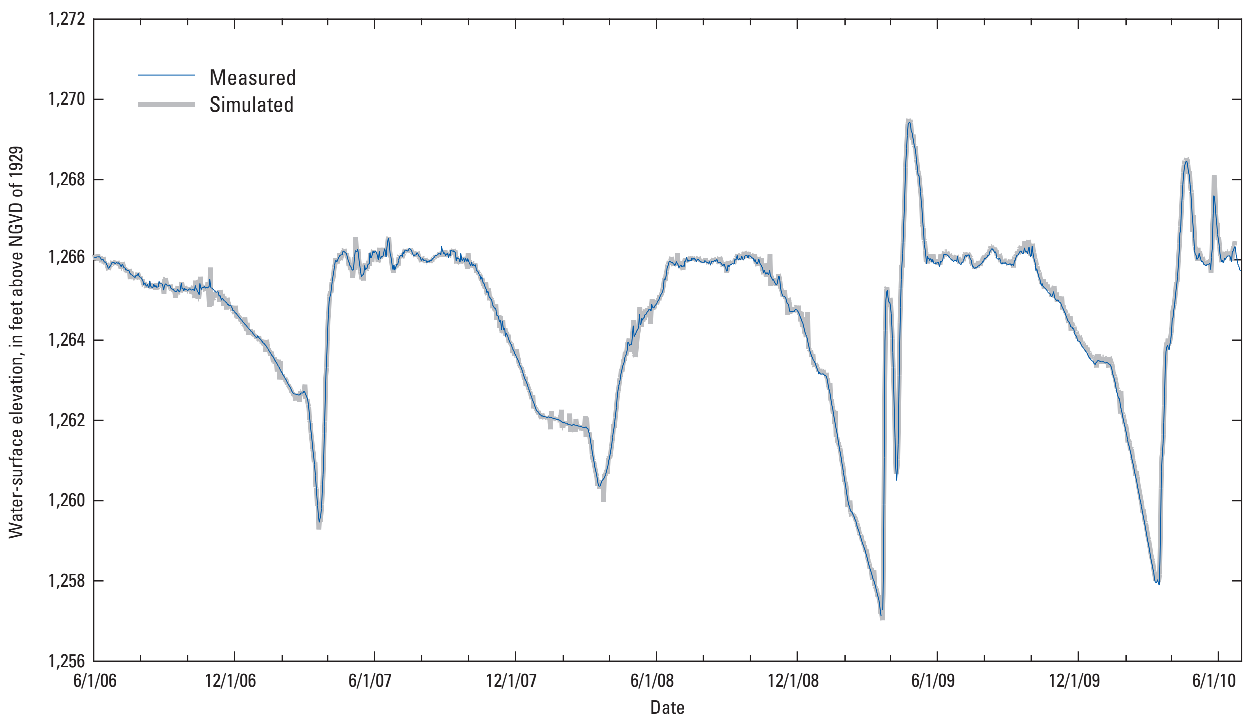

Figure 6. Simulated and measured water-level elevations for Lake Ashtabula, North Dakota, June 2006 through June 2010.

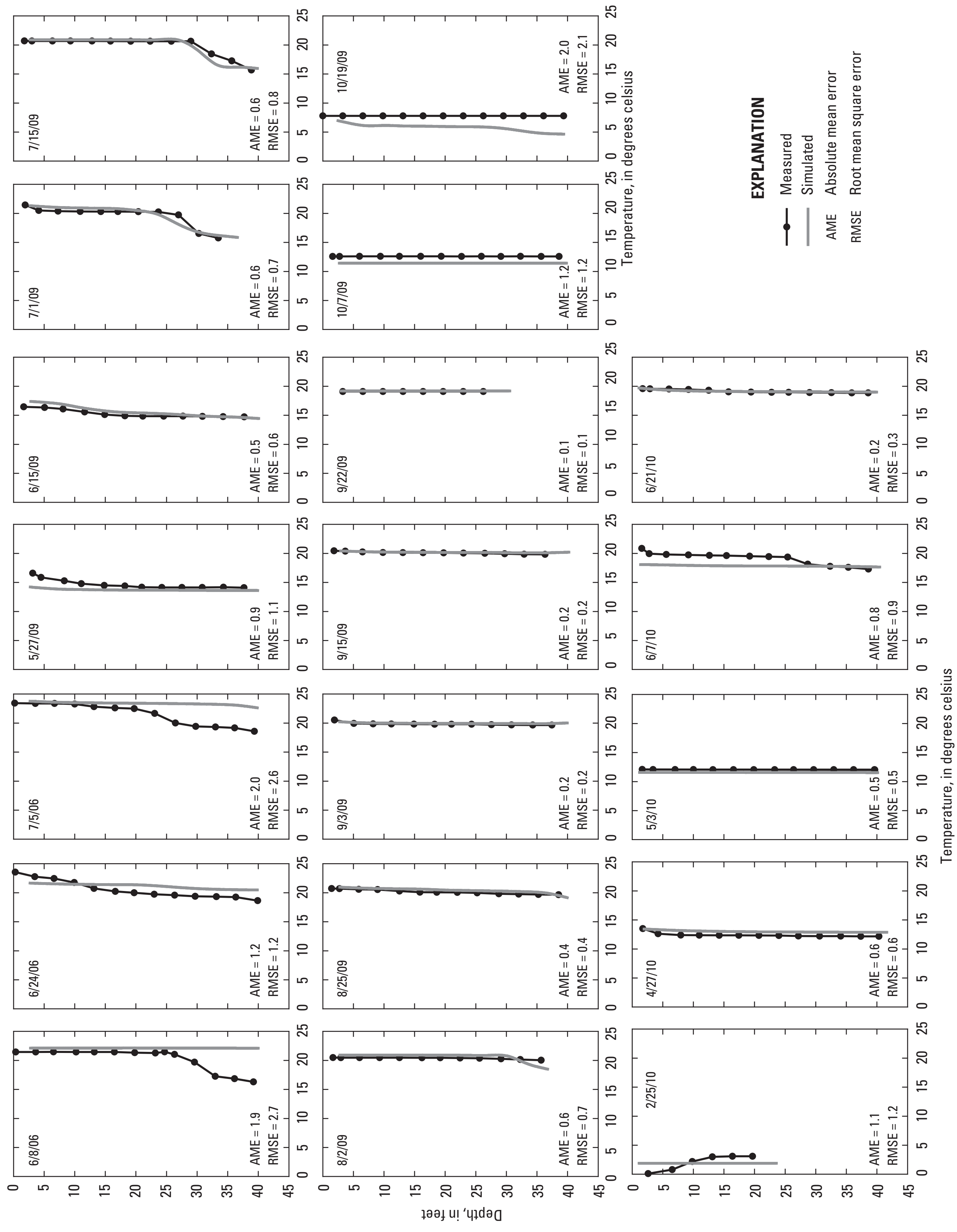

Figure 7. Simulated and measured water-temperature profiles for Lake Ashtabula, North Dakota, at site 1T (near Baldhill Dam), June 2006 through June 2010.

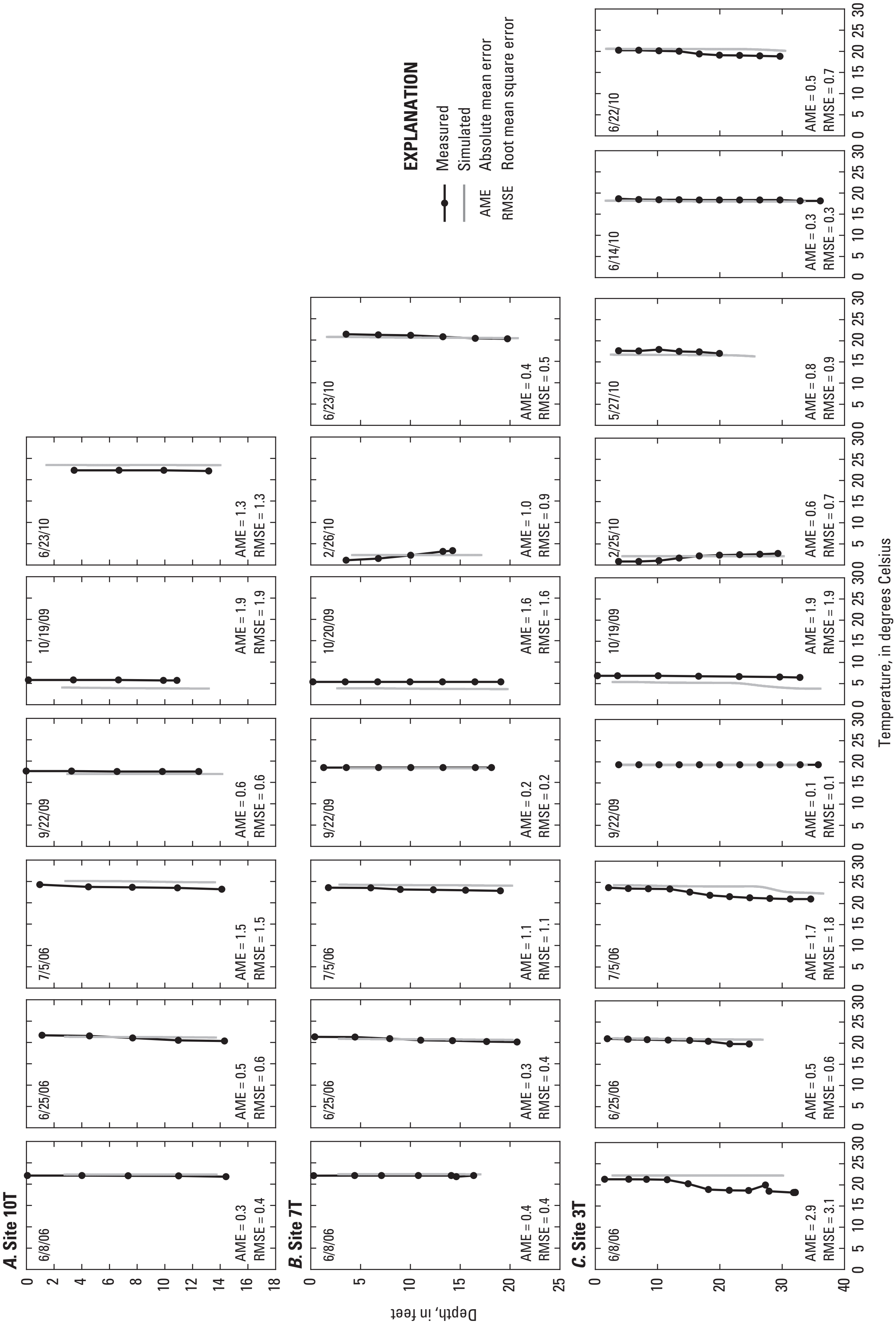

Figure 8. Simulated and measured water-temperature profiles for Lake Ashtabula, North Dakota, at sites 3T, 7T, and 10T, June 2006 through June 2010.

Table 3. Comparative statistics of simulated and measured water temperature and constituent concentrations at six sites in Lake Ashtabula, North Dakota, June 2006 through June 2010.

[--, not available]

Site identification number	Number of compared data	Mean difference (simulated minus measured)	Maximum difference (simulated minus measured)	Minimum difference (simulated minus measured)	Absolute mean error	Root mean square error
			Temperature, in degrees Celsius			
10T	24	0.2	1.6	-1.9	1.0	1.0
9T	--	--	--	--	--	--
7T	41	.0	1.2	-1.7	.7	.7
6T	--	--	--	--	--	--
3T	83	.5	4.0	-2.6	1.0	1.1
1T	216	.1	5.8	-3.2	.8	.9
			Sulfate, in milligrams per liter as sulfate			
10T	18	1	42	-98	20	29
9T	34	-2	72	-78	29	36
7T	20	2	61	-96	38	44
6T	34	13	90	-67	32	42
3T	33	18	73	-57	28	33
1T	43	14	68	-43	22	27
			Total dissolved solids, in milligrams per liter			
10T	18	6	139	-250	60	85
9T	--	--	--	--	--	--
7T	20	-3	152	-278	100	114
6T	--	--	--	--	--	--
3T	33	15	182	-223	58	77
1T	43	5	245	-164	59	73

A limitation to the simulation of the hydrodynamics in Lake Ashtabula is the lack of measured data in all of 2007 and during ice-cover periods. Based on comparisons of simulated ice thickness to measured ice thickness data collected weekly by the USACE near site 1T during winter months (November through March), the model appeared to simulate ice cover fairly well (fig. 9). However, because few measured water-temperature data were available under ice-cover conditions, it was difficult to assess how well the model simulated the thermodynamics under ice-cover conditions. Three water- temperature profiles were collected at sites 1T, 3T, and 7T on February 25 and 26, 2010, by the USGS and compared to simulated data (figs. 7 and 8). The measured data showed slightly stratified conditions at site 1T that was not indicated by the simulated water temperatures. However, the AME and RMSE were 1.1 and 1.2°C or less, respectively, at all three sites.

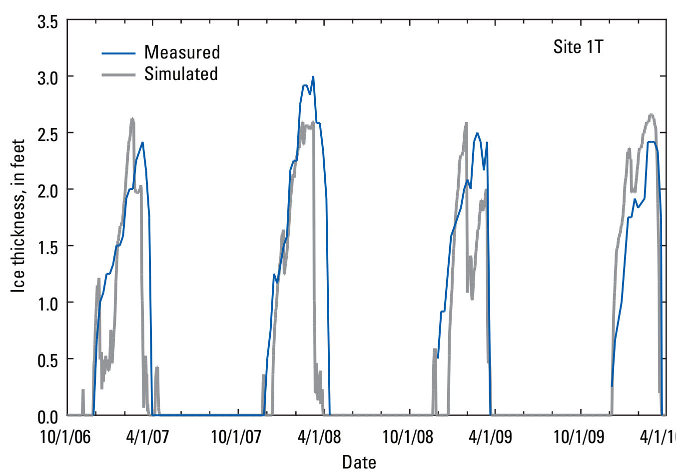

Figure 9. Simulated and measured ice thickness for Lake Ashtabula, North Dakota, site 1T, 2006 through 2010.

Sulfate

Simulated sulfate concentrations compared well to measured concentrations in Lake Ashtabula. Simulated concentrations were compared to 182 measured concentrations at sites 1T, 3T, 6T, 7T, 9T, and 10T for the period of June 2006 through June 2010 (figs. 10 and 11, table 3). Simulated sulfate concentrations were compared to measured data in the epilimnion (near the water surface) and hypolimnion (near the reservoir bottom) at each site. In general, simulated sulfate concentrations were overpredicted with mean differences between simulated and measured sulfate concentrations ranging from 1 mg/L (site 10T) to 18 mg/L (site 3T) (table 3). However, at site 9T (bridge near Sibley, North Dakota), which was only measured from August 2009 through June 2010, the sulfate concentrations generally were underpredicted with mean differences of -2 mg/L. The AME between simulated and measured data ranged from 20 mg/L (site 10T) to 38 mg/L (site 7T), and the RMSE ranged from 27 mg/L (site 1T) to 44 mg/L (site 7T). Site 7T may have had the greatest error because the model may not have simulated mixing properly between the channel constrictions from two bridge crossings over Lake Ashtabula upstream (site 9T) and downstream (site 6T) from where site 7T is located (fig. 2). However, it appears that the model does adequately simulate the mixing downstream from both bridges, because the AME and RMSE for site 3T (28 and 33 mg/L, respectively) and 1T (22 and 27 mg/L, respectively) were relatively less compared to site 7T.

Differences between simulated and measured sulfate concentrations varied temporally in Lake Ashtabula from June 2006 through June 2010. In 2006, sulfate concentrations were overpredicted at sites 1T and 3T and underpredicted at sites 7T and 10T, mainly because the initial conditions set for the model assumed that the reservoir was well mixed when there actually was a concentration gradient from upstream to downstream in Lake Ashtabula (fig. 10). There was no sulfate concentration data collected in 2007 for comparison with simulated concentrations. In 2008 and in most of 2009, sulfate concentrations were overpredicted at all four sites that had measured sulfate concentration data. Data collected at sites 6T and 9T indicated that the simulated concentrations generally were lower than measured data at both sites during the winter months of 2009 and 2010 (November 2009 through March 2010) (fig. 11 and table 3). In general, measured data from all six sites in the spring through the end of the simulation period (April through June 2010) indicated that simulated concentrations were slightly underpredicted compared to measured data.

Simulation of the sulfate concentrations in Lake Ashtabula was limited by the lack of measured data in 2007 and during ice-cover periods. The only ice-cover period where measured data were available was at sites 6T and 9T during the winter of November 2008 through March 2010, with one sample collected at sites 1T, 3T, and 7T in February 2009.

Total Dissolved Solids

Simulated TDS generally were greater than measured TDS concentrations in Lake Ashtabula from June 2006 through June 2010. Simulated TDS were compared to 114 measured concentrations in the epilimnion and hypolimnion at four sites in the reservoir (fig. 12 and table 3). The mean difference between simulated and measured data at sites ranged from -3 mg/L at site 7T to 15 mg/L at site 3T (table 3). The AME between simulated and measured TDS concentrations ranged from 58 mg/L (site 3T) to 100 mg/L (site 7T) and the RMSE ranged from 73 mg/L (site 1T) to 114 mg/L (site 7T). Similar to the simulation of sulfate, site 7T may have had the greatest error because the model may not have simulated mixing properly between the two bridge crossings over Lake Ashtabula upstream and downstream from where site 7T is located (fig. 2). However, it appears that the model does adequately simulate the mixing downstream from both bridges, because the AME and RMSE for sites 3Tand 1T were relatively less compared to site 7T (table 3).

Throughout the simulation period, differences between simulated and measured TDS followed the same temporal patterns as the sulfate concentrations in Lake Ashtabula from June 2006 through June 2010 (fig. 12). In 2006, TDS concentrations were overpredicted at sites 1T and 3T and underpredicted at site 7T, mainly because the initial conditions set for the model assumed that the reservoir was well mixed when there was a concentration gradient from upstream to downstream in Lake Ashtabula (fig. 12). There was no TDS concentration data collected in 2007 for comparison with simulated concentrations. In 2008, TDS concentrations were overpredicted at all four sites. In 2009, TDS concentrations were underpredicted at sites 1T and 10T and overpredicted at sites 3T and 7T (fig. 12).

Model Limitations

An understanding of model limitations is essential for effective use of reservoir models. The accuracy of the Lake Ashtabula model is limited by the simplification of complexities of the water quality and hydrodynamics within the reservoir, by spatial and temporal discretization effects, and by assumptions made in the formulation of the governing equations. Model accuracy is limited by segment size, boundary conditions, accuracy of calibration, and parameter sensitivity. Model accuracy also is limited by the availability of data and by the interpolations and extrapolations that are inherent in using data in a model. Although a model might be calibrated, calibration parameter values are not necessarily unique in yielding acceptable values for the selected water-quality constituents.

Another limitation of the Lake Ashtabula model is that it is a two-dimensional representation of a three-dimensional waterbody. The governing equations are laterally averaged within layers. Although the model may accurately represent vertical and longitudinal processes within the reservoir,

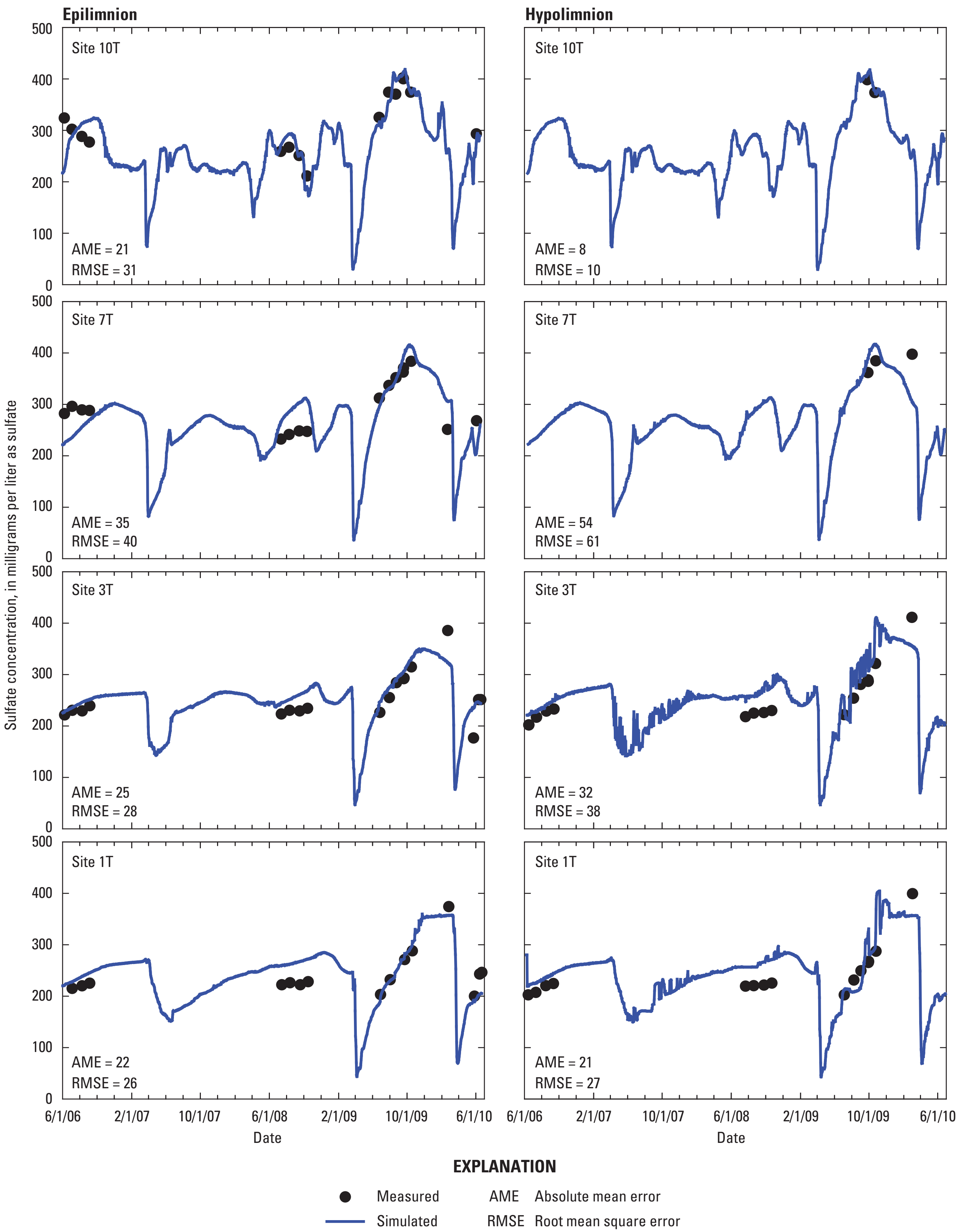

Figure 10. Simulated daily and measured sulfate concentrations at four sites in Lake Ashtabula, North Dakota, June 2006 through June 2010.

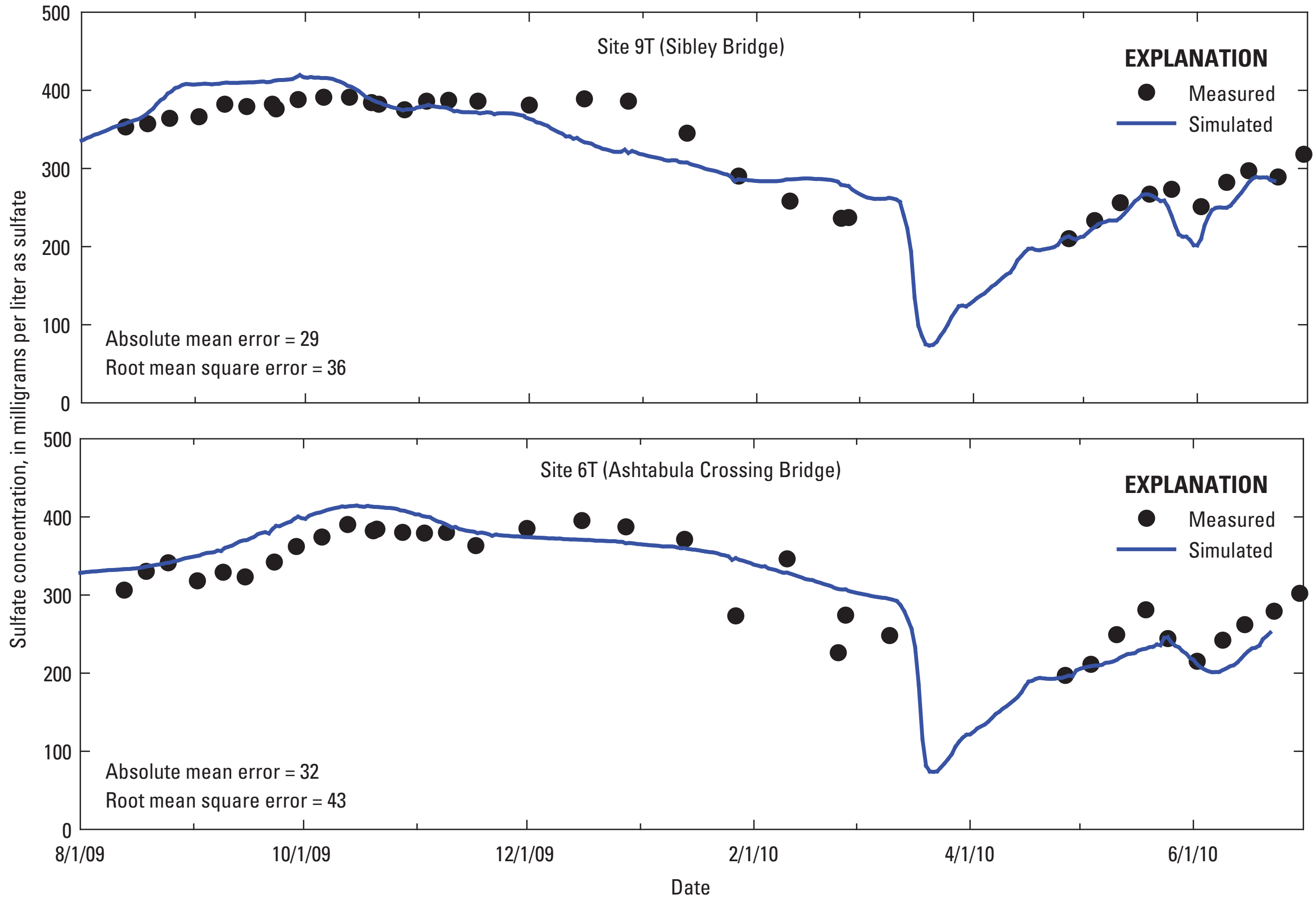

Figure 11. Simulated daily and measured sulfate concentrations at sites 6T and 9T in Lake Ashtabula, North Dakota, August 2009 through June 2010.

processes that occur laterally, or from shoreline to shoreline perpendicular to the downstream axis, may not be properly represented.

Eddy coefficients are used to model turbulence in a reservoir in which vertical turbulence equations are written in the conservative form using the Boussinesq and hydrostatic approximations (Cole and Wells, 2003). Because vertical momentum is not included, the model may give inaccurate results where there is substantial vertical acceleration.

A specific limitation for the Lake Ashtabula model is the lack of measured vertical profiles of temperature, TDS data, and sulfate data in all of 2007 and during ice-cover periods. Although the model appears to simulate ice thickness fairly well compared to measured ice thickness data, there were few measured data available for comparison to determine how well the model simulated thermodynamics and water-quality conditions under ice cover.

Devils Lake Outlet Scenarios

Simulated sulfate concentrations from four scenarios were compared to simulated ambient concentrations at sites 1T, 3T, 7T, and 10T at 3 ft below the water surface (epilimnion) and 3 ft above the bottom of the reservoir (hypolimnion) at each site from June 2006 through June 2009 (fig. 13). The maximum simulated ambient sulfate concentrations in the epilimion for 2006, 2007, and 2008 were 264 mg/L, 271 mg/L, and 285 mg/L, respectively, at site 1T; 270 mg/L, 280 mg/L, and 290 mg/L, respectively, at site 3T; 301 mg/L, 295 mg/L, and 311 mg/L, respectively, at site 7T; and 327 mg/L, 273 mg/L, and 321 mg/L, respectively, at site 10T. Results of the four scenarios are mainly discussed in the following section in reference to sulfate concentrations in the epilimion because most of the outflow from Baldhill Dam occurred through the spillway gates compared to the culvert located at

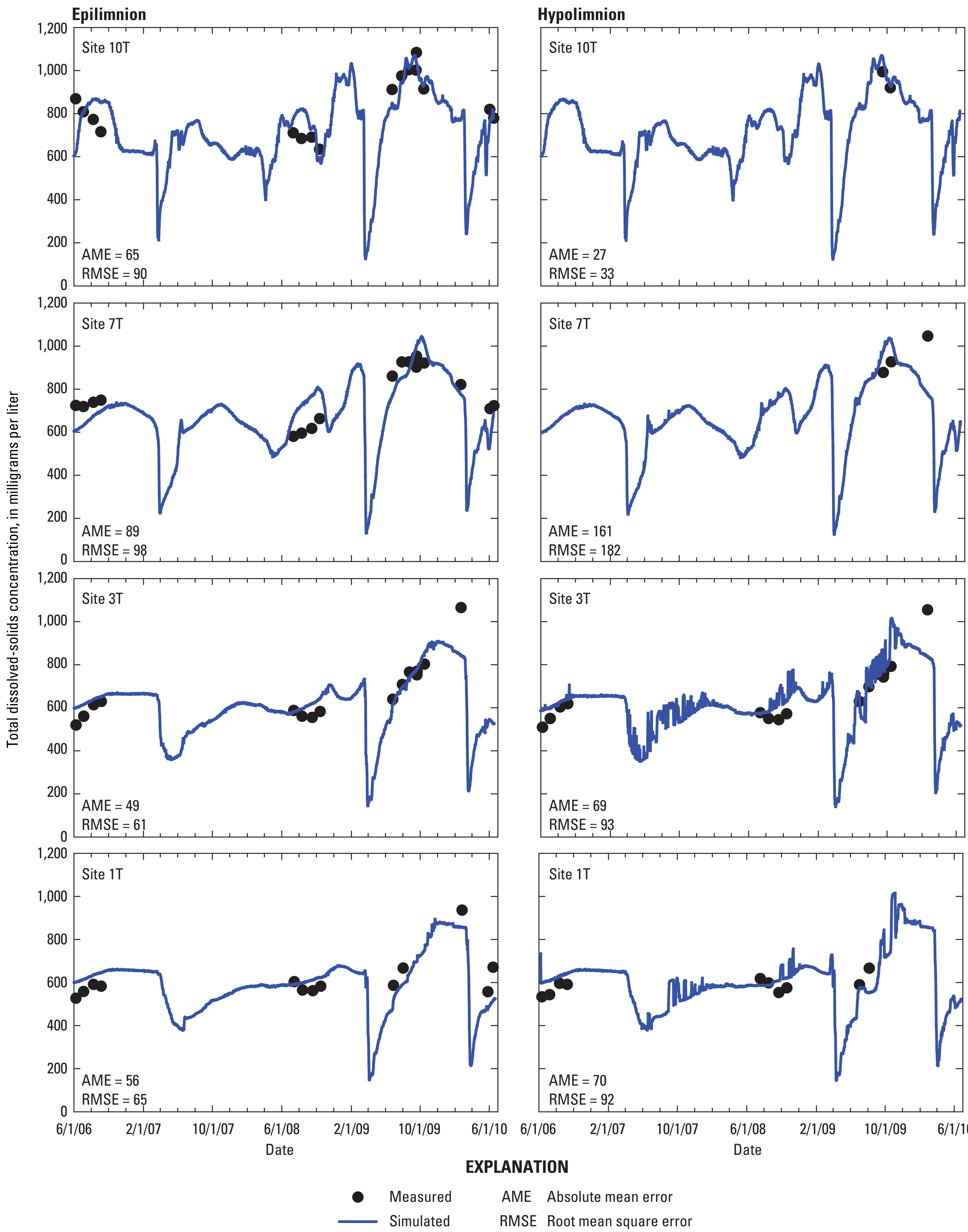

Figure 12. Simulated daily and measured total dissolved-solids concentrations at four sites in Lake Ashtabula, North Dakota, June 2006 through June 2010.

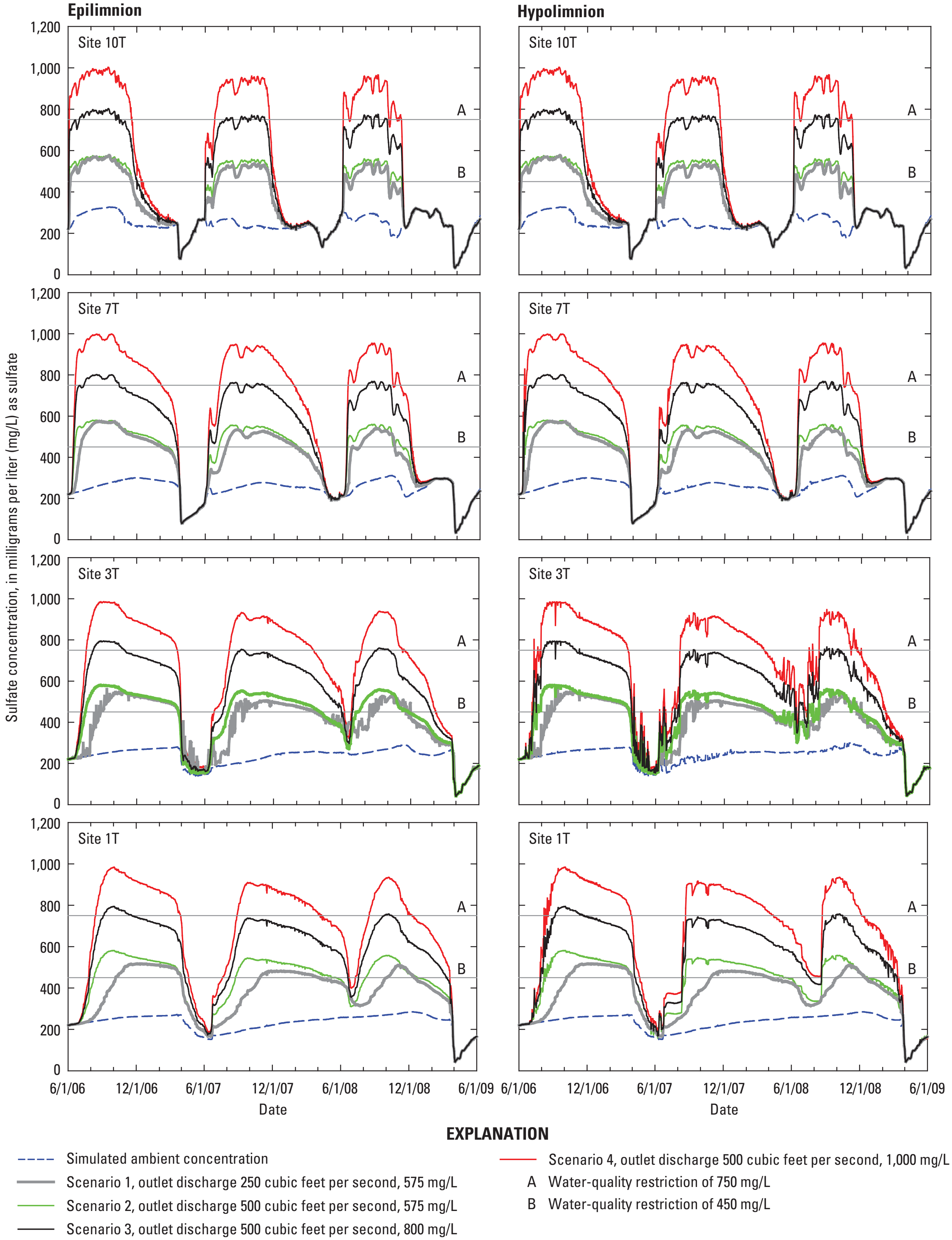

Figure 13. Simulated daily sulfate concentrations at four sites in Lake Ashtabula, North Dakota, for ambient conditions and four scenarios, June 2006 through June 2009.

greater depth. The spillway outflow draws water mainly from the upper portion of the water column, which, therefore, would have a greater effect on the outflow sulfate concentrations downstream from the dam during the simulation period.

For scenario 1, the same location, outflow capacity, and sulfate concentration as the current (2010) Devils Lake State Outlet (250 ft^3/s of flow and 575 mg/L of sulfate) were assumed. The increased flow and sulfate concentration in scenario 1, beginning on May 31 and extending to October 31 each year, resulted in an increase in sulfate concentrations to greater than 450 mg/L in Lake Ashtabula at site 7T (approximately the middle of the reservoir) starting July 5 in 2006, July 28 in 2007, and July 15 in 2008 (fig. 13). Sulfate concentrations increased to greater than 450 mg/L considerably later at site 1T (near the dam), starting October 8 in 2006, October 29 in 2007, and October 3 in 2008 (fig. 13). At site 1T, concentrations remained greater than 450 mg/L for 85 days in 2006, 154 days in 2007, and 170 days in 2008 (table 4). The peak concentrations at site 1T occurred on December 3 in 2006, December 13 in 2007, and November 6 in 2008, although the simulated Devils Lake State Outlet pumping ceased on October 31 each year (table 4). The peak (maximum) concentrations ranged from 533 mg/L (2007) to 575 (2006) at site 7T and from 510 mg/L (2008) to 517 mg/L (2006) at site 1T (table 4). The concentrations and timing of concentration changes were similar in the epilimnion and hypolimnion at all four sites.

For scenario 2, the same Devils Lake State Outlet sulfate concentration as scenario 1 was assumed, but the flow through the Devils Lake State Outlet was doubled (500 ft^3/s), which resulted in a more rapid increase in sulfate concentrations in the lower part of the reservoir and slightly greater values at all four sites compared to scenario 1. Sulfate concentrations for scenario 2 increased to greater than 450 mg/L 20 days earlier in 2006 and 2007 and 31 days earlier in 2008 at site 7T compared to scenario 1 (fig. 13). Sulfate concentrations increased to greater than 450 mg/L 61 days earlier in 2006, 67 days earlier in 2007, and 41 days earlier in 2008 at site 1T. Concentrations at site 1T remained greater than 450 mg/L for 144 days in 2006, 221 days in 2007, and 278 days in 2008 (table 4). The peak concentrations also occurred earlier at site 1T, occurring 61 days earlier in 2006, 78 days earlier in 2007, and 28 days earlier in 2008 compared to scenario 1. The peak concentrations ranged from 555 mg/L (2007) to 580 mg/L (2006) at site 7T and from 546 mg/L (2007) to 581 mg/L (2006) at site 1T (table 4).

For scenarios 3 and 4, possible increases in flow and concentration from the current outlet location (from the West Bay of Devils Lake) and from a proposed outlet from East Devils Lake (fig. 1) were simulated. Flows of 500 ft^3/s from the two outlets combined were assumed in both scenarios and sulfate concentrations were assumed to be 800 mg/L for scenario 3 and 1,000 mg/L for scenario 4. Conditions for scenario 3 resulted in a relatively rapid increase in sulfate concentrations in the reservoir, and concentrations were greater than 750 mg/L in most years at all four sites. For scenario 3, sulfate concentrations increased to greater than 450 mg/L at site 7T in nearly the same time as scenario 2, except for 2007, where concentrations increased to greater than 450 mg/L nearly a month earlier (fig. 13). Sulfate concentrations were greater than 750 mg/L periodically at site 7T throughout the simulation period (June 2006 through June 2009). Concentrations were greater than 750 mg/L at site 7T for 94 days in 2006, 53 days in 2007, and 35 days in 2008. At site 1T, simulated sulfate concentrations increased to greater than 450 mg/L for scenario 3 in nearly the same time as scenario 2 for all 3 years and increased to greater than 750 mg/L for fewer days than was observed at site 7T (table 4) for scenario 3. Concentrations were greater than 750 mg/L for 76 days in 2006, no days in 2007, and 20 days in 2008. The peak concentrations ranged from 763 mg/L (2007) to 801 mg/L (2006) at site 7T and from 737 mg/L (2007) to 794 mg/L (2006) at site 1T (table 4). As expected, scenario 4 resulted in greater sulfate concentrations in the reservoir compared to the other scenarios. Concentrations were greater than 750 mg/L for 194 days in 2006, 209 days in 2007, and 157 days in 2008 at site 7T and 139 days in 2006, 214 days in 2007, and 215 days in 2008 at site 1T. Peak concentrations ranged from 949 mg/L (2007) to 998 mg/L (2006) at site 7T and from 909 mg/L (2007) to 984 mg/L (2006) at site 1T (table 4). Similar to the results of scenarios 1 and 2, the concentrations and timing of concentration changes for scenarios 3 and 4 were similar in the epilimnion and hypolimnion at all four sites.

Summary

Lake Ashtabula is located on the Sheyenne River approximately 271 river miles upstream from the confluence with the Red River of the North. Lake Ashtabula is a multipurpose reservoir used for rural and municipal water supply, flood control, municipal pollution abatement, fish and wildlife habitat, and recreation. In 2010, a two-dimensional hydrodynamic and water-quality model (CE-QUAL-W2) of Lake Ashtabula was developed by the U.S. Geological Survey in cooperation with the North Dakota State Water Commission to understand the dynamics of chemical constituents in Lake Ashtabula, and to provide a tool for the management and operation of the Devils Lake State Outlet in meeting the water-quality standards downstream from Baldhill Dam. The Lake Ashtabula model was calibrated for hydrodynamics, sulfate concentrations, and total dissolved-solids concentrations to ambient conditions from June 2006 through June 2010. The calibrated model then was used to simulate four scenarios that represent various Devils Lake outlet options that have been considered for reducing the water levels in Devils Lake.

During calibration, simulated water-surface elevations in Lake Ashtabula were adjusted to the measured water surface for the simulation period of June 2006 through June 2010. The water-surface elevations were corrected to the measured

Table 4. Results of scenarios simulating the possible effects of changes in inflow streamflow and sulfate concentrations from the current Devils Lake State Outlet or an additional outlet to Lake Ashtabula, North Dakota, June 2006 through June 2009.

[ft, feet; >, greater than; mg/L, milligrams per liter; ft^3/s, cubic feet per second]

Site identification number	Calendar year	Epilimnion (3 ft below the water surface)			Hypolimnion (3 ft above the reservoir bottom)		
		Maximum sulfate concentration	Number of days with sulfate concentrations >450 mg/L	Number of days with sulfate concentrations >750 mg/L	Maximum sulfate concentration	Number of days with sulfate concentrations >450 mg/L	Number of days with sulfate concentrations >750 mg/L
Ambient conditions							
10T	2006	327	0	0	327	0	0
	2007	273	0	0	273	0	0
	2008	321	0	0	321	0	0
7T	2006	301	0	0	301	0	0
	2007	295	0	0	295	0	0
	2008	311	0	0	311	0	0
3T	2006	270	0	0	273	0	0
	2007	280	0	0	280	0	0
	2008	290	0	0	300	0	0
1T	2006	264	0	0	264	0	0
	2007	271	0	0	271	0	0
	2008	285	0	0	285	0	0
Scenario 1 - Devils Lake State Outlet flow of 250 ft^3/s and sulfate concentration of 575 mg/L							
10T	2006	576	163	0	576	163	0
	2007	536	140	0	536	140	0
	2008	543	105	0	543	105	0
7T	2006	575	179	0	575	180	0
	2007	533	193	0	533	193	0
	2008	541	125	0	541	126	0
3T	2006	561	128	0	561	128	0
	2007	515	207	0	515	207	0
	2008	526	178	0	526	178	0
1T	2006	517	85	0	517	85	0
	2007	514	154	0	514	154	0
	2008	510	170	0	510	170	0
Scenario 2 - Devils Lake State Outlet flow of 500 ft^3/s and sulfate concentration of 575 mg/L							
10T	2006	577	169	0	577	169	0
	2007	558	148	0	558	149	0
	2008	560	152	0	560	152	0
7T	2006	580	195	0	580	197	0
	2007	555	230	0	555	230	0
	2008	560	179	0	559	180	0
3T	2006	580	166	0	580	168	0
	2007	552	233	0	551	231	0
	2008	558	231	0	560	223	0
1T	2006	581	144	0	581	145	0
	2007	546	221	0	546	224	0
	2008	557	278	0	557	257	0

Table 4. Results of scenarios simulating the possible effects of changes in inflow streamflow and sulfate concentrations from the current Devils Lake State Outlet or an additional outlet to Lake Ashtabula, North Dakota, June 2006 through June 2009.—Continued

[ft, feet; >, greater than; mg/L, milligrams per liter; ft^3/s, cubic feet per second]

Site identification number	Calendar year	Epilimnion (3 ft below the water surface)			Hypolimnion (3 ft above the reservoir bottom)		
		Maximum sulfate concentration	Number of days with sulfate concentrations >450 mg/L	Number of days with sulfate concentrations >750 mg/L	Maximum sulfate concentration	Number of days with sulfate concentrations >450 mg/L	Number of days with sulfate concentrations >750 mg/L
Scenario 3 - Devils Lake outlets combined flow of 500 ft^3/s and sulfate concentration of 800 mg/L							
10T	2006	802	182	105	802	182	105
	2007	771	179	65	771	179	65
	2008	775	159	42	775	159	42
7T	2006	801	198	94	801	200	94
	2007	763	281	53	763	282	53
	2008	768	244	35	768	245	33
3T	2006	795	176	83	793	174	86
	2007	754	252	9	752	244	3
	2008	760	338	32	765	347	15
1T	2006	794	156	76	794	154	78
	2007	737	247	0	742	241	0
	2008	757	338	20	757	324	20
Scenario 4 - Devils Lake outlets combined flow of 500 ft^3/s and sulfate concentration of 1,000 mg/L							
10T	2006	1,002	194	167	1,002	193	167
	2007	960	186	146	960	186	146
	2008	965	160	144	966	160	144
7T	2006	998	199	194	998	200	195
	2007	949	285	209	948	286	211
	2008	954	259	157	954	261	157
3T	2006	985	178	164	984	178	157
	2007	932	277	227	931	269	227
	2008	938	348	189	947	357	180
1T	2006	984	158	139	984	156	139
	2007	909	274	214	916	253	220
	2008	935	349	215	935	366	211

values by adjusting the unmeasured inflow into the lake that was distributed to all the segments within the model grid.

Simulated temperatures compared well with measured temperatures and differences varied spatially in Lake Ashtabula for June 2006 through June 2010. Differences in temperature between simulated and measured values were the greatest at sites 3T and 10T and the least at sites 1T and 7T. The absolute mean error ranged from 0.7 degrees Celsius at site 7T to 1.0 degrees Celsius at sites 3T and 10T, and the root mean square error ranged from 0.7 degrees Celsius at site 7T to 1.1 degrees Celsius at site 3T from June 2006 through June 2010.

Simulated sulfate concentrations compared well to measured concentrations in Lake Ashtabula for the period of June 2006 through June 2010. In general, simulated sulfate concentrations were overpredicted with mean differences between simulated and measured sulfate concentrations ranging from -2 milligram per liter (site 9T) to 18 milligrams per liter (site 3T). Differences between simulated and measured sulfate concentrations varied temporally in Lake Ashtabula from June 2006 through June 2010. In 2006, sulfate concentrations were overpredicted at sites 1T and 3T and underpredicted at sites 7T and 10T, mainly because the initial conditions set for the model assumed that the reservoir was well mixed when there actually was a concentration gradient from upstream to downstream in Lake Ashtabula. Simulation of the sulfate concentrations in Lake Ashtabula was limited by the lack of measured data in all of 2007 and during ice-cover periods.

Simulated total dissolved solids generally were greater than measured total dissolved-solids concentrations in Lake Ashtabula from June 2006 through June 2010. The mean difference between simulated and measured data ranged from -3 milligrams per liter at site 7T to 15 milligrams per liter at site 3T. The absolute mean error between simulated and measured total dissolved-solids concentrations ranged from 58 milligrams per liter (site 3T) to 100 milligrams per liter (site 7T), and the root mean square error ranged from 73 milligrams per liter (site 1T) to 114 milligrams per liter (site 7T).

Simulated sulfate concentrations from four scenarios were compared to simulated ambient concentrations at sites 1T, 3T, 7T, and 10T from June 2006 through June 2009. For scenario 1, the same location, outflow capacity, and sulfate concentration as the current (2010) Devils Lake State Outlet (250 cubic feet per second of flow and 575 milligrams per liter of sulfate) were assumed. The increased flow and sulfate concentration in scenario 1, beginning on May 31 and extending to October 31 each year, resulted in an increase in sulfate concentrations to greater than 450 milligrams per liter in Lake Ashtabula at site 7T (approximately the middle of the reservoir) starting July 5 in 2006, July 28 in 2007, and July 15 in 2008. Sulfate concentrations increased to greater than 450 milligrams per liter considerably later at site 1T (near the dam), starting October 8 in 2006, October 29 in 2007, and October 3 in 2008. For scenario 2, the same Devils Lake State Outlet sulfate concentration as scenario 1 was assumed, but flow through the Devils Lake State Outlet was doubled (500 cubic feet per second), which resulted in a more rapid increase in sulfate concentrations in the lower part of the reservoir and slightly greater values at all four sites compared to scenario 1. Compared to scenario 1, sulfate concentrations reached concentrations greater than 450 milligrams per liter 20 days earlier in 2006 and 2007 and 31 days earlier in 2008 at site 7T. Sulfate concentrations increased to greater than 450 milligrams per liter 61 days earlier in 2006, 67 days earlier in 2007, and 41 days earlier in 2008 at site 1T.

For scenarios 3 and 4, possible increases in flow and concentration from the current outlet location (from the West Bay of Devils Lake) and from a proposed outlet from East Devils Lake were simulated. Flows of 500 cubic feet per second from the two outlets combined were assumed in both scenarios and sulfate concentrations were assumed to be 800 milligrams per liter for scenario 3 and 1,000 milligrams per liter for scenario 4. Conditions for scenario 3 resulted in a relatively rapid increase in sulfate concentrations in the reservoir, and concentrations were greater than 750 milligrams per liter in most years at all four sites. As expected, scenario 4 resulted in greater sulfate concentrations in the reservoir compared to the other scenarios. Concentrations were greater than 750 milligrams per liter for 194 days in 2006, 209 days in 2007, and 157 days in 2008 at site 7T and 139 days in 2006, 214 days in 2007, and 215 days in 2008 at site 1T.

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