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Simulation of the Effects of Devils Lake Outlet Alternatives on Future Lake Levels and Downstream Water Quality in the Sheyenne River and Red River of the North

Scientific Investigations Report 2011–5050

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

Cover photo: Devils Lake engulfing roads and farmland, May, 2007.

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^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)

Lake-level elevations in this report are with respect to the National Geodetic Vertical Datum of 1929 (NGVD 29).

“Water year” is the 12-month period October 1 to September 30. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 2000 is called “water year 2000.”

Simulation of the Effects of Devils Lake Outlet Alternatives on Future Lake Levels and Downstream Water Quality in the Sheyenne River and Red River of the North

By Aldo V. Vecchia

Abstract

Since 1992, Devils Lake in northeastern North Dakota has risen nearly 30 feet, destroying hundreds of homes, inundating thousands of acres of productive farmland, and costing more than $1 billion for road raises, levee construction, and other flood mitigation measures. In 2011, the lake level is expected to rise at least another 2 feet above the historical record set in 2010 (1,452.0 feet above the National Geodetic Vertical Datum of 1929), cresting less than 4 feet from the lake's natural spill elevation to the Sheyenne River (1,458.0 feet). In an effort to slow the rising lake and reduce the chance of an uncontrolled spill, the State of North Dakota is considering options to expand a previously constructed outlet from the west end of Devils Lake or construct a second outlet from East Devils Lake. Future outlet discharges from Devils Lake, when combined with downstream receiving waters, need to be in compliance with applicable Clean Water Act requirements. This study was completed by the U.S. Geological Survey, in cooperation with the North Dakota Department of Health Division of Water Quality, to evaluate the various outlet alternatives with respect to their effect on downstream water quality and their ability to control future lake levels.

A Devils Lake stochastic simulation model developed in previous studies was modified and combined with a downstream stochastic routing model developed for this study to simulate future (2011–30) Devils Lake levels and water quality, and outlet discharges, flows, and water quality (specifically, dissolved sulfate and total dissolved solids concentrations) for key downstream locations. Outlet alternatives include: (1) a 250 cubic feet per second west-end outlet (the current outlet) combined with a 250 cubic feet per second east-end outlet (W250E250); (2) a 350 cubic feet per second west-end outlet combined with a 250 cubic feet per second east-end outlet (W350E250); and (3) a 250 cubic feet per second west-end outlet combined with a 350 cubic feet per second east-end outlet (W250E350). In addition to satisfying current (2011) flow and water-quality requirements for the upper Sheyenne River, each of the outlet options was simulated with a less restrictive downstream sulfate constraint (750 milligrams per liter) and a more restrictive downstream sulfate constraint (650 milligrams per liter) for the outflows from Baldhill Dam. Thus, there were a total of six outlet scenarios (three outlet alternatives, each with the less restrictive and more restrictive downstream sulfate constraint). In addition, a baseline simulation in which there were no outlet discharges was used for comparison with the outlet simulations.

Simulation results indicate all six outlet scenarios substantially reduce, but do not eliminate, the chance of a spill. For the baseline simulation, the chance of a spill would be 0.6 percent this year (2011), about 14 percent by next year (2012), about 28 percent by 2015, and about 45 percent by 2030. The outlet scenarios reduce the chance of a spill to 0.2 percent this year, about 9 percent next year, 14 to 15 percent by 2015, and 17 to 19 percent by 2030. The chances of a spill are slightly less for the larger outlets (W350E250 and W250E350) compared with the smaller outlet (W250E250) and slightly greater for the more restrictive downstream sulfate constraint (650 milligrams per liter) compared with the less restrictive constraint (750 milligrams per liter). All of the outlet scenarios prevent most spills that would have occurred after 2015, but many of the spills that occur before 2015 are not prevented by any of the outlet scenarios.

All of the outlet scenarios are effective for drawing the lake down in future years, but the more restrictive downstream constraint results in slower drawdown compared with the less restrictive constraint. For the baseline condition, the chance the lake would be above 1,450.0 feet is 99 percent in 2015 and 38 percent in 2030. For the outlet scenarios with the 750 milligrams per liter downstream constraint, the chance is 55 to 63 percent in 2015 and about 5 percent in 2030. For the outlet scenarios with the 650 milligrams per liter downstream constraint, the chance is 75 to 80 percent in 2015 and about 6 percent in 2030.

The 90th percentiles of simulated monthly average sulfate and total dissolved solids concentrations for downstream sites were used as a measure of concentrations that may be expected to occur during relatively dry years when Devils Lake water could provide a substantial part of downstream flows. The percentiles were similar among the three

outlet alternatives (W250E250, W350E250, and W250E350). However, the percentiles were sensitive to the downstream sulfate constraint. During periods of declining lake levels and relatively low downstream flows, the 650 milligrams per liter downstream sulfate constraint resulted in reduced outlet discharges and lower downstream concentrations compared with the 750 milligrams per liter constraint. For the 750 milligrams per liter constraint, the 90th percentile concentration for the Red River of the North at Halstad peaked at about 500–550 milligrams per liter of sulfate and 1,200–1,250 milligrams per liter of total dissolved solids during 2013–15 and declined to about 300 milligrams per liter of sulfate and 800 milligrams per liter of total dissolved solids during 2025. The 90th percentile concentration for the Red River of the North at Emerson peaked at about 450–500 milligrams per liter of sulfate and 1,150–1,200 milligrams per liter of total dissolved solids during 2013–15 and declined to about 200–250 milligrams per liter of sulfate and 750 milligrams per liter of total dissolved solids during 2025. For the 650 milligrams per liter constraint, the 90th percentile concentration for the Halstad site peaked at about 400 milligrams per liter of sulfate and 1,000 milligrams per liter of total dissolved solids during 2013–17 and declined to about 300 milligrams per liter of sulfate and 800 milligrams per liter of total dissolved solids during 2025. The 90th percentile concentration for the Emerson site peaked at about 350 milligrams per liter of sulfate and 950 milligrams per liter of total dissolved solids during 2013–17 and declined to about 275 milligrams per liter of sulfate and 750 milligrams per liter of total dissolved solids during 2025.

Introduction

The Devils Lake Basin is a 3,810-square-mile (mi^2) subbasin of the Red River of the North (Red River) Basin (fig. 1). About 3,320 mi^2 of the basin is tributary to Devils Lake and the remainder is tributary to Stump Lake. At an elevation of 1,446.5 feet, Devils Lake begins to spill into Stump Lake, and at an elevation of 1,458.0 feet, the combined Devils Lake and Stump Lake system begins to spill from Stump Lake, through Tolna Coulee, to the Sheyenne River (fig. 2) (North Dakota State Water Commission, 2010).

Data on historical lake levels, surface areas, and volumes of Devils Lake and Stump Lake can be obtained online (U.S. Geological Survey, 2011a). Lake levels of Devils Lake were recorded sporadically from 1867 to 1890, and in 1901 the U.S. Geological Survey (USGS) established a gaging station on Devils Lake (fig. 3). From 1867 through 2010, the lake level fluctuated from a minimum of 1,400.9 feet (nearly dry) in 1940 to a maximum of 1,452.0 feet in 2010. From 1992 to 1999, in response to wet conditions and unusually high inflows, Devils Lake rose more than 25 feet and began spilling to Stump Lake, which in 1999, was at an elevation of about 1,408.0 feet. Wet conditions and high inflows continued and, by 2007, Devils Lake had filled Stump Lake and the two water bodies essentially became one continuous lake with an elevation of about 1,447.5 feet, a combined volume of about 3 million acre-feet, and a combined surface area of about 140,000 acres. From 1992 to 2007, the combined volume of the lakes increased about 5-fold (from about 600,000 to 3 million acre-feet) and the combined surface area nearly tripled (from about 49,000 to 140,000 acres). The lakes have continued to rise since 2007, and in 2010 reached an elevation of 1,452.0 feet, with a combined volume of about 3.7 million acre-feet, and a combined surface area of about 180,000 acres.

The rising water of Devils Lake and Stump Lake has destroyed hundreds of homes, inundated thousands of acres of productive farmland, and forced the raising of roads, bridges, levees, and other infrastructure to mitigate the rising water. Since 1992, more than $1 billion has been spent by federal, state, and local agencies to address the effects of the rising lake (U.S. Army Corps of Engineers, 2010).

If Devils Lake and Stump Lake continue to rise to 1,458.0 feet, water would begin spilling though the natural outlet from Stump Lake (Tolna Coulee) to the Sheyenne River. According to National Weather Service Advanced Hydrologic Prediction System (AHPS) simulations from February 27, 2011 (National Oceanic and Atmospheric Administration, 2011), Devils Lake has a 50-percent chance of rising to 1,454.7 feet in 2011, placing it just 3.3 feet from the spill elevation. Based on geologic evidence from Murphy and others (1997), Devils Lake has spilled to the Sheyenne River at least twice in the past 4,000 years, with the most recent spill estimated to have occurred 800–1,200 years ago. The recent extreme wet period in the Devils Lake Basin appears to be the result of natural, long-term climatic variation rather than "climate change" (Vecchia, 2008; Hoerling and others, 2010). Furthermore, it is likely the wet conditions will continue for a considerable time, perhaps decades, before reverting to more "normal" conditions.

The State of North Dakota has initiated a number of projects in recent years to help slow the rising lake. The Extended Acreage Storage Program , initiated in 1996, is a program for paying landowners to store water that would otherwise contribute to flooding of Devils Lake (North Dakota State Water Commission, 2011). Construction of the west-end outlet from Devils Lake to the Sheyenne River was completed in 2005 (fig. 2). The outlet consists of a series of pump stations, pipelines, and open channel flow and was originally designed to discharge a maximum of 100 cubic feet per second (ft^3/s). In 2010, the outlet capacity was increased to 250 ft^3/s (North Dakota State Water Commission, 2010). Because of the continued rise of the lake and concerns of a natural overflow, construction of a second outlet from East Devils Lake is scheduled to begin in 2011, with a goal of having the east-end outlet operational by April 2012. There are two capacities

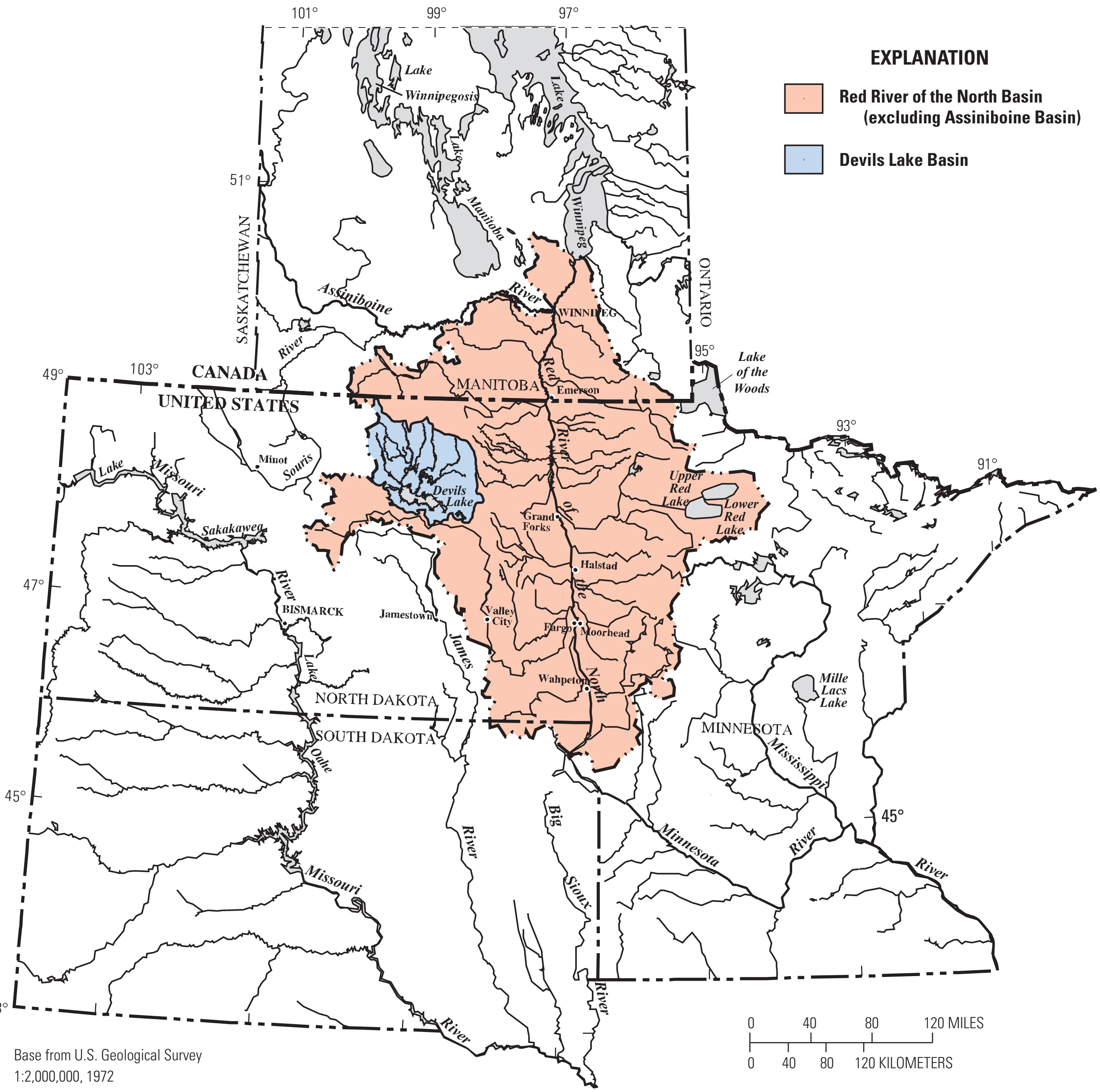

Figure 1. Location of Devils Lake Basin in North Dakota.

being considered for the east-end outlet, 250 and 350 ft^3/s, but the exact alignment and design of the outlet are still being discussed as of the preparation of this report. In addition, an option for increasing the capacity of the existing west-end outlet to 350 ft^3/s is being considered.

The North Dakota Department of Health (NDDH) is responsible for ensuring that future outlet discharges from Devils Lake, when combined with the downstream receiving waters, are in compliance with applicable Clean Water Act requirements. This study was completed by the USGS in cooperation with NDDH Division of Water Quality to evaluate the effects of the various outlet alternatives on downstream water-quality conditions in the Sheyenne River and in the Red River from its confluence with the Sheyenne River to the international border crossing with Manitoba.

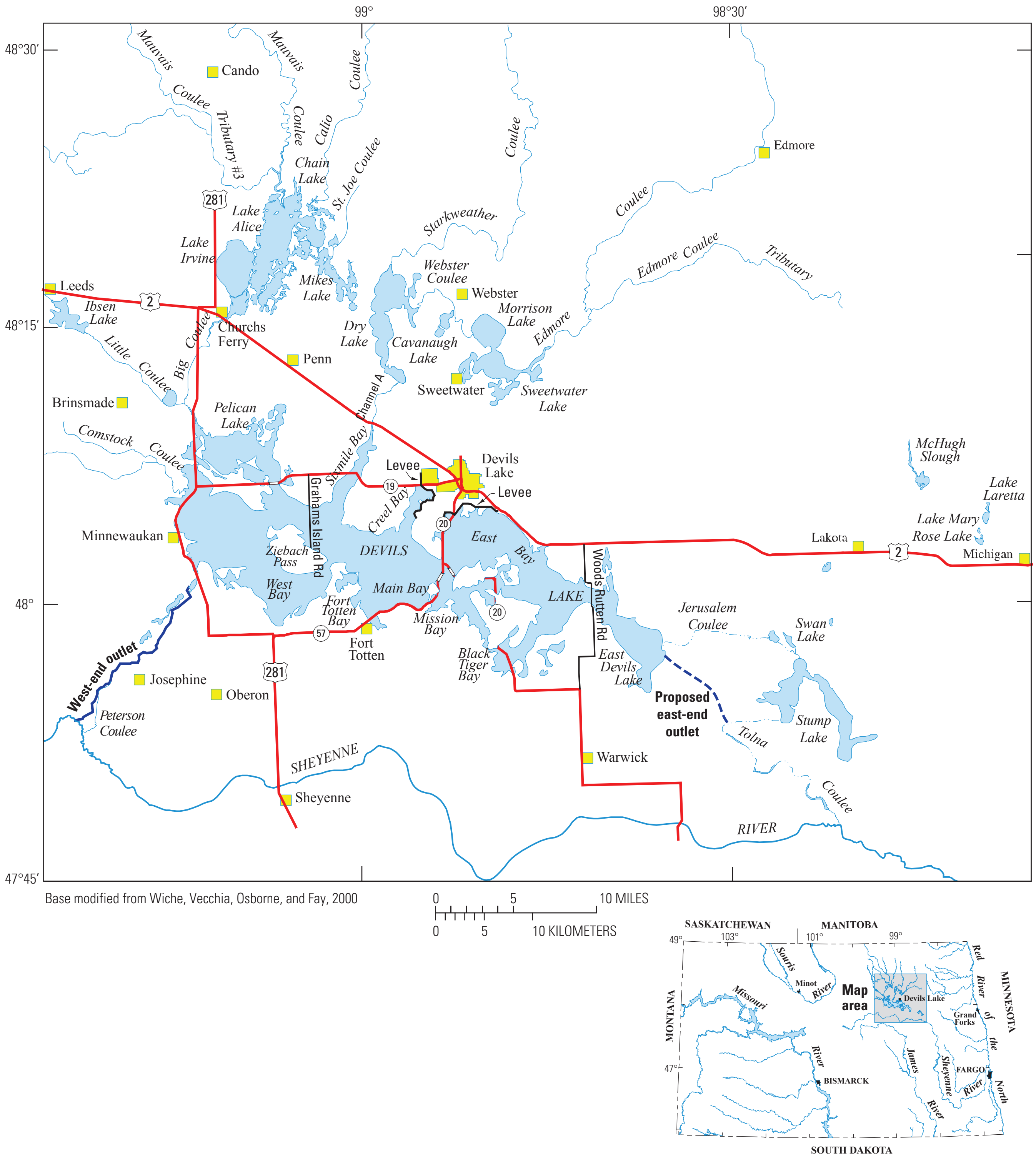

Figure 2. Devils Lake, Stump Lake, and vicinity.

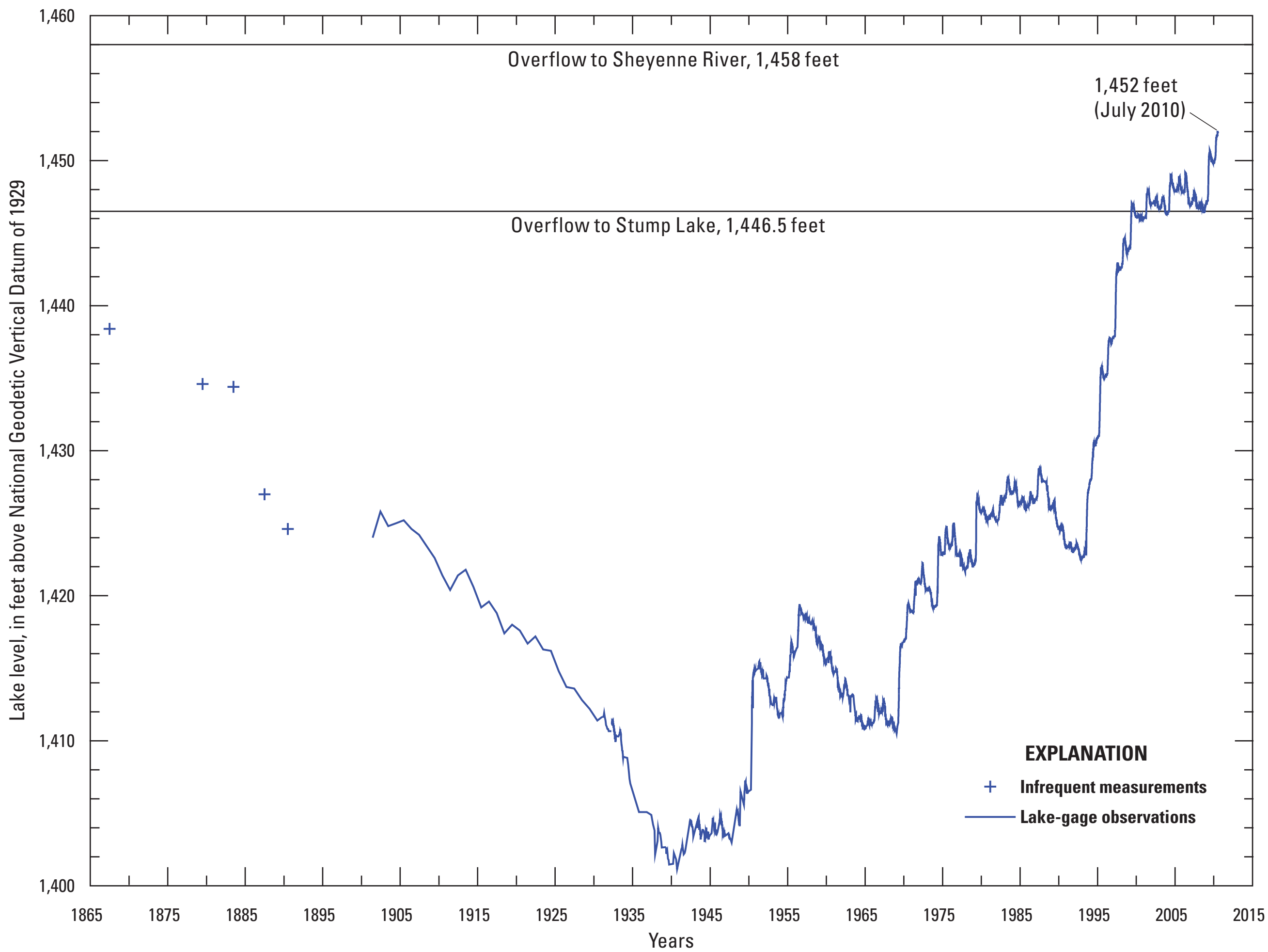

Figure 3. Recorded lake levels of Devils Lake, North Dakota, for 1868–2010.

Purpose and Scope

The purpose of this report is to describe the evaluation of potential effects of several Devils Lake outlet alternatives on flow, sulfate concentrations, and total dissolved solids (TDS) concentrations at key stream sites in the Sheyenne and Red Rivers. The USGS Devils Lake stochastic simulation model developed in previous studies (Vecchia, 2002; Vecchia, 2008) was combined with a downstream stochastic flow, sulfate, and TDS routing model described in this report to simulate future outlet discharges and concentrations and resultant downstream flows and concentrations for a 20-year simulation period (2011–30). None of the outlet alternatives being considered eliminate the possibility of a spill from the natural outlet from Stump Lake in future years. Therefore, the potential downstream effects of a spill also were evaluated.

In addition to evaluating downstream effects, the effectiveness of the various outlet alternatives for controlling future lake levels also was evaluated. Results indicating the effectiveness of the various outlet alternatives relative to their downstream effects can provide useful guidance to water-resource managers for deciding which alternative to carry forward as the preferred option.

Methods

The combined Devils Lake/downstream stochastic simulation model was developed for simulating future realizations, or “traces” of Devils Lake levels and water quality, outlet discharges, and downstream flow and water quality for key locations. This section describes the methods used to develop the downstream routing model, reviews the Devils Lake stochastic simulation model, and describes the methods used to combine the two models.

Downstream Stochastic Routing Model

The downstream stochastic routing model is a statistical model designed to reproduce (as accurately as possible) the joint probability distributions of future downstream flows, sulfate concentrations, and TDS concentrations for a long-term (20-year) simulation period. It is an empirical rather than physical (hydrodynamic) model, and thus, is not intended for “real-time” simulation. A hydrodynamic flow and water-quality model for Lake Ashtabula (located on the Sheyenne River, fig. 4) developed in a previous study (Galloway, 2011) is better suited for real-time simulation of the effects of Devils Lake outlet discharges on water-quality conditions in Lake Ashtabula.

Historical flows, sulfate concentrations, and TDS concentrations for seven USGS streamgaging stations were used for developing the downstream routing model for this study (fig. 4; table 1). Flow data for water years 1981–2009 (U.S. Geological Survey, 2011b) were used to calibrate the model because future climatic conditions for the simulation period (2011–30) are expected to be similar to conditions during 1981–2009 (Vecchia, 2008). The model was calibrated assuming “ambient” conditions (with no Devils Lake outlet). Although the Devils Lake west-end outlet was operational during 2005–09, outlet discharges during those years were negligible compared to flows in the upper Sheyenne River. Measured sulfate and TDS concentrations for 1981–2008, obtained from USGS and NDDH databases, also were used for model calibration (U.S. Geological Survey, 2011b; Wax, 2010).

A simplified schematic of the downstream routing model is shown in figure 5. The Devils Lake stochastic simulation model and the methods used to combine Devils Lake discharges with downstream flows are described in later sections of this report. This section describes the data sets and calibration procedures that were used for developing the ambient downstream stochastic routing model.

The Sheyenne River near Warwick, North Dakota (station 05056000, fig. 4), hereafter referred to as the Warwick site, is important because it serves as the control point for ensuring Devils Lake outlet discharges do not exceed channel capacity and water-quality constraints for the upper Sheyenne River. Historical flows, sulfate concentrations, and TDS concentrations for this site are shown in figure 6. To smooth out variability in the daily values and simplify the routing model, a 5-day time step was used. The top graph shows the 5-day mean flows computed from the daily streamflow record for this site. The next graphs show the measured concentrations along with estimated concentrations for each 5-day period using regression models described in the appendix (one for sulfate and one for TDS) that relate concentration to variables computed from flow and time-of-year. Significant uptrends, unrelated to flow, occurred from 1999–2001 for sulfate (increase of 56 percent) and TDS (increase of 16 percent). Schuh and Hove (2006) determined that increases in sulfate in the upper Sheyenne River after 2000 likely resulted from higher water tables and flushing of evaporative salts from riverbanks and soils bordering drainageways, coulees, and tributaries. The implications of these trends for the downstream simulations will be considered later in this section.

The Sheyenne River near Cooperstown, North Dakota (station 05057000, fig. 4), hereafter referred to as the Cooperstown site, is important because it provides much of the inflow to Lake Ashtabula. Flows and concentrations for this site (fig. 7) (developed for 5-day time steps as described for the previous site) indicate a similar pattern of long-term variability to the previous site, but the estimated concentrations have more high-frequency variability compared to the Warwick site (fig. 6). As for the Warwick site, there were significant uptrends during 1999–2001 for sulfate (32 percent increase) and TDS (21 percent increase).

Baldhill Creek near Dazey, North Dakota (station 05057200, fig. 4), hereafter referred to as the Dazey site, also provides inflow to Lake Ashtabula. Flows and concentrations for this site are shown in figure 8. Unlike the previous sites, there were no trends detected in the concentrations for this site.

The next downstream site is the Sheyenne River below Baldhill Dam (station 05058000, fig. 4), hereafter referred to as the below Baldhill Dam site. Modeling flows and concentrations for this site was the most critical step in the routing model. Historical flows and concentrations for this site could not be used directly for future simulations because Devils Lake water, when routed through Lake Ashtabula, changes the volume and chemical composition of the discharges from Lake Ashtabula in ways that cannot be predicted using simple stream routing. Therefore, a conceptual reservoir simulation model was developed for tracking the movement of water, sulfate, and TDS through Lake Ashtabula. As shown in figure 5 and described in detail in the appendix, the lake is represented as a series of three interconnected reservoir compartments with equal volume. Inflow to the upstream reservoir compartment (RES1) consists of inflow from the Cooperstown site plus estimated ungaged inflow. Inflow to the next downstream reservoir compartment (RES2) consists of inflow from the Dazey site plus estimated ungaged inflow. A numerical algorithm (see appendix) is used to route water between the two upstream reservoir compartments and the downstream reservoir compartment (RES3), account for evaporation, and compute outflow from the downstream reservoir compartment (which is the estimated flow for the below Baldhill Dam site). Ungaged inflow was assumed to be proportional to flow for the Dazey site, and the concentrations of the ungaged inflow were assumed to be proportional to concentrations for the Dazey site. The best fit (see appendix) was obtained using ungaged inflow equal to 84 percent of flow for the Dazey site, sulfate concentration of ungaged inflow equal to 150 percent of the concentration for the Dazey site, and TDS concentration of ungaged inflow equal to 120 percent of the concentration for the Dazey site. The fit was not particularly sensitive to how the ungaged flow was split up, so one-half of the ungaged flow was assumed to enter each of the two upstream reservoirs. The recorded flows for the below Baldhill Dam site and the

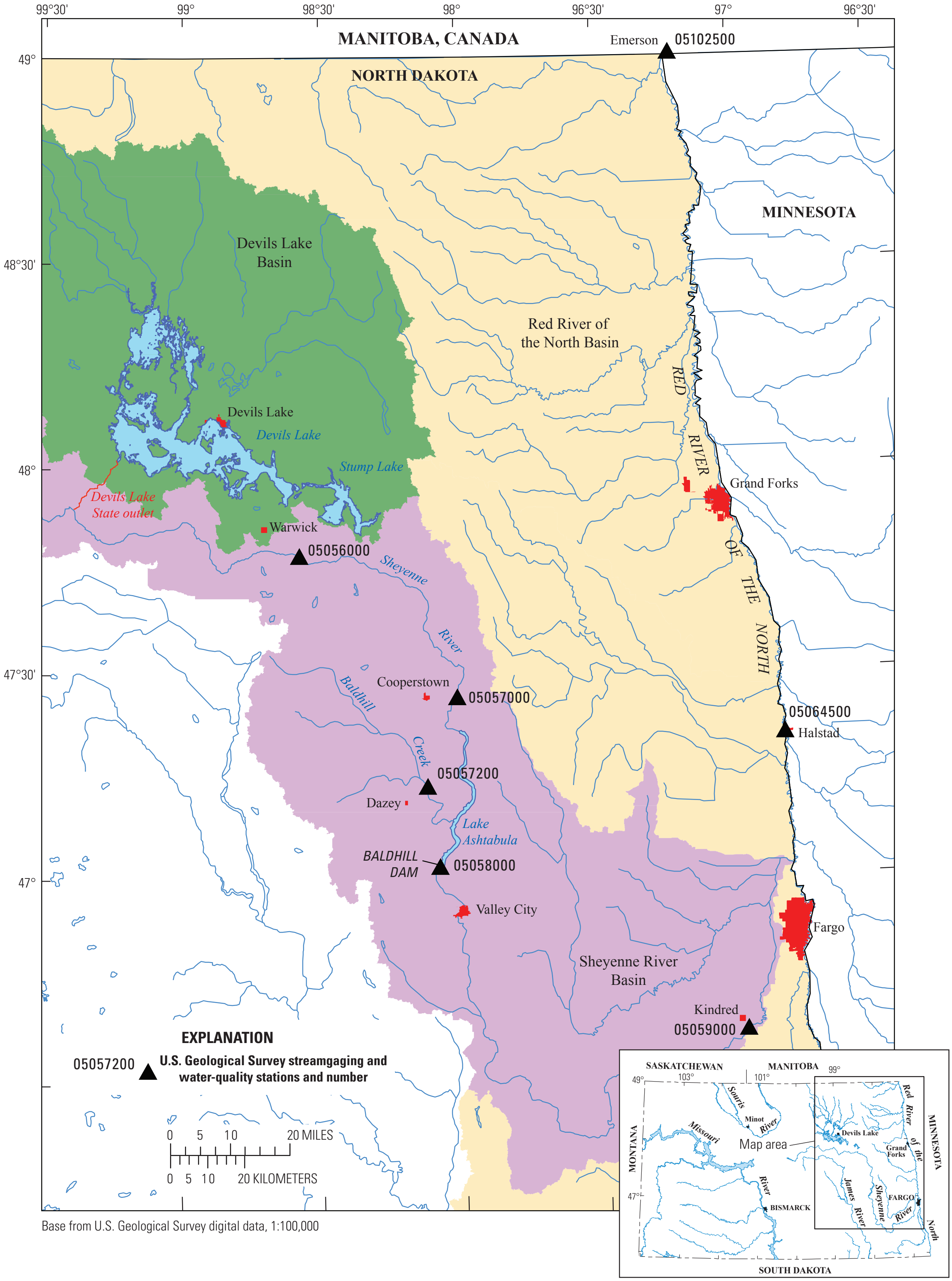

Figure 4. Devils Lake Basin and downstream streamgaging stations used for developing flow, sulfate, and total dissolved solids routing model.

Table 1. U.S. Geological Survey streamgaging stations used for developing downstream routing model.

[streamflow for Emerson site provided by Environment Canada]

Station number (fig. 4)	Station name (short name in bold font)	Approximate contributing drainage area (square miles)
05056000	Sheyenne River near Warwick, N.Dak. **(Warwick)**	1,790
05057000	Sheyenne River near Cooperstown, N.Dak. (**Cooperstown**)	2,600
05057200	Baldhill Creek near Dazey, N.Dak. (**Dazey**)	690
05058000	Sheyenne River below Baldhill Dam (below **Baldhill Dam**)	3,600
05059000	Sheyenne River near Kindred, N.Dak. (**Kindred**)	5,000
05064500	Red River of the North at Halstad, Minn. (**Halstad**)	18,000
05102500	Red River of the North at Emerson, Manitoba (**Emerson**)	36,400

estimated flows using the reservoir algorithm are shown in figure 9, along with the measured concentrations and the concentrations computed using the reservoir algorithm.

The estimated flows (not the actual flows) for the below Baldhill Dam site were routed downstream and used to estimate incremental flows (the flows entering the river between a given site and the nearest upstream site) for the Sheyenne River near Kindred, North Dakota (station 05059000, fig. 4) (referred to as the Kindred site). The best fit resulted by using a 5-day time lag for the flows from below Baldhill Dam to reach Kindred. However, using simple subtraction of the routed flows from the measured flows for the Kindred site to estimate incremental flows resulted in highly variable incremental flows and a large proportion of negative incremental flows in many years. This was expected because of the relatively flat slope of the Sheyenne River in that reach and the fact that the incremental flows often are small compared to flows for below Baldhill Dam. Therefore, to smooth out noise and improve the simulated concentrations, incremental flows, sulfate concentrations, and TDS concentrations for the reach from below Baldhill Dam to Kindred were estimated implicitly and then combined with routed flows as described in the appendix. The resulting estimated flows, sulfate concentrations, and TDS concentrations for the Kindred site are shown in figure 10. Like the Warwick and Cooperstown sites, significant concentration uptrends were determined for Kindred incremental flows. However, the uptrends occurred earlier, during 1994–95, rather than during 1999–2001. In particular, sulfate concentrations for incremental flows increased 56 percent and TDS concentrations increased 11 percent during 1994–95.

Estimated flows and concentrations for the Kindred site then were used along with measured flows and concentrations for the Red River of the North at Halstad, Minnesota (station 05064500, fig. 4) (referred to as the Halstad site) to estimate incremental flows and concentrations for the reach between Kindred and Halstad. A 5-day time lag between Kindred and Halstad resulted in the best fit. Incremental flows for Halstad were determined using straight subtraction of estimated routed flows from Kindred and measured flows at Halstad. This worked well because incremental flows between Kindred and Halstad generally were much larger than routed flows from Kindred. The flows for the Halstad site (which in this case, corresponded with the actual flows) are shown in figure 11 along with the estimated concentrations obtained from the routing procedure. There were no significant trends determined in the sulfate or TDS concentrations for the Halstad incremental flows.

Finally, the procedure just described for routing flows from Kindred to Halstad was repeated to route flows from Halstad to the Red River of the North at Emerson, Manitoba (station 05102500, fig. 4) (referred to as the Emerson site). A 10-day time lag for routing flows from Halstad to Emerson resulted in the best fit. Incremental flows for the reach between Halstad and Emerson were computed using straight subtraction of routed flow from measured flow. The resulting flows and estimated concentrations for the Emerson site are shown in figure 12. Two significant concentration trends were determined for incremental flows between Halstad and Emerson—a steady increase during 1980–2008 of 5.4 percent per year for sulfate and 3.8 percent per year for TDS combined with downtrends of 42 percent for sulfate and 67 percent for TDS during 1995–98.

The ultimate objective of the model was to simulate future conditions for 2011–30, not just reproduce historic conditions. With this goal in mind, the concentration trends described previously become somewhat problematic. In particular, historical concentration increases for several of the sites during various times indicate that ambient concentrations during the later part of the calibration period (2000–09) generally were greater than earlier concentrations. Therefore, it was assumed that future concentrations will be more like the recent period, rather than returning to lower levels. If concentrations eventually do decline, this assumption would result in overestimation of future ambient concentrations and thus provide conservative estimates of downstream water-quality conditions. Of course, it is possible future ambient concentrations could increase still further, but there is no way to know

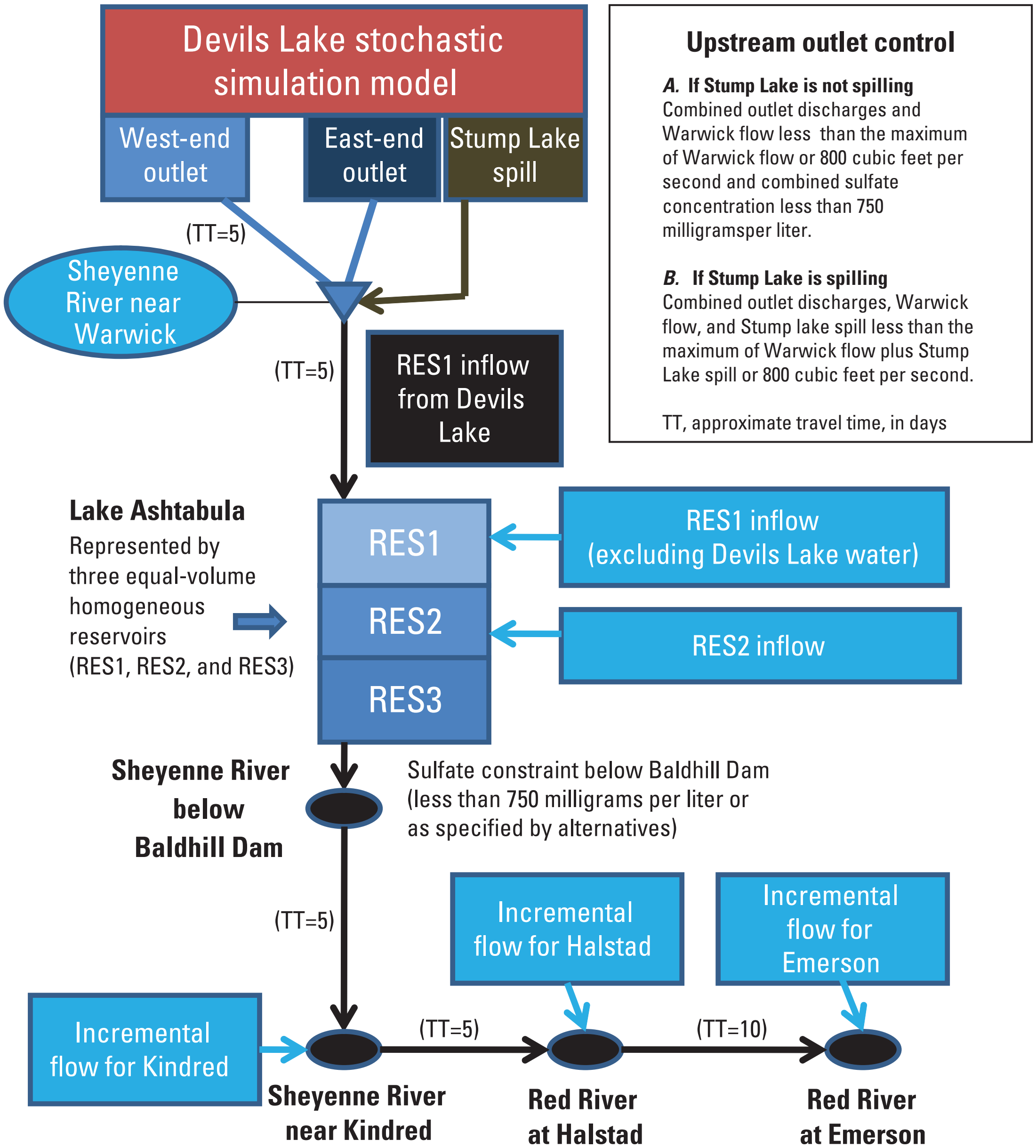

Figure 5. Downstream routing model for Devils Lake, the Sheyenne River, and the Red River of the North.

for sure when or how much; therefore, for use in the future simulations, historical concentrations were adjusted to represent recent conditions. The concentration trends were removed by "reversing" the trends and adding them back in, raising earlier concentrations to comparable levels with the later concentrations. This resulted in a "population" of 29 years of estimated historical record (1981–2009) that could be used to simulate future conditions. These data are shown in figure 13 (flow), figure 14 (sulfate concentration), and figure 15 (TDS concentration).

Seasonal averages of the data shown in figures 13–15 were computed for a particularly dry 5-year period, water years 1987–92 (table 2), and a particularly wet 5-year period, water years 1995–2000 (table 3). The seasons consist of a late fall/winter low-flow season (November–February), the spring runoff season (March–June), and a summer/early fall season (July–October). These seasonal averages can be used to provide some general insight into how the addition of Devils Lake water might affect downstream concentrations during different flow conditions and seasons. The first notable observation is that average concentrations for sulfate and TDS were similar among all three seasons and the dry and wet periods, particularly for the downstream sites (below Baldhill Dam, Kindred, Halstad, and Emerson). Although there was considerable day-to-day variability in the concentrations (figs. 14 and 15), when averaged through the seasons, the concentrations were not

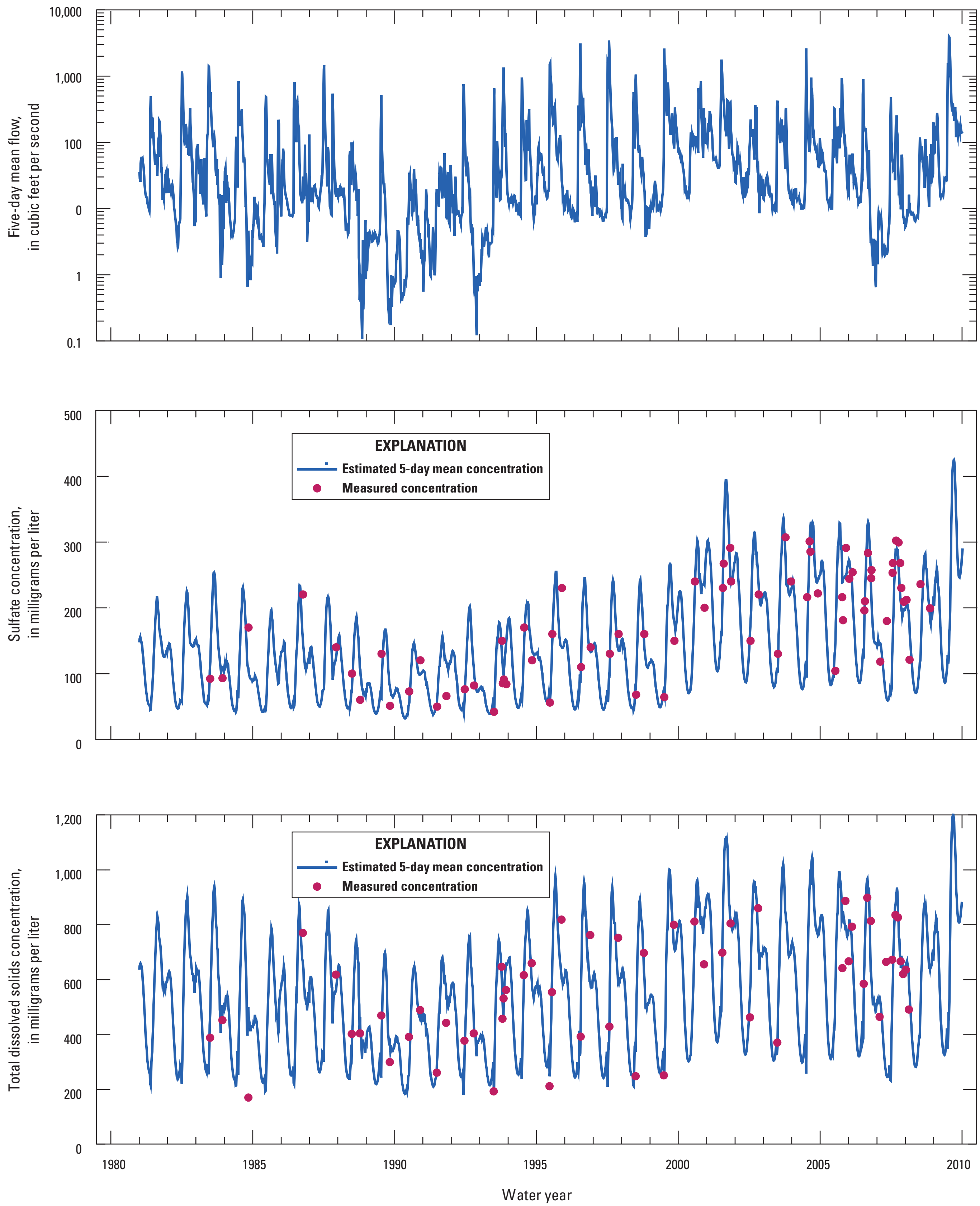

Figure 6. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Sheyenne River near Warwick, North Dakota.

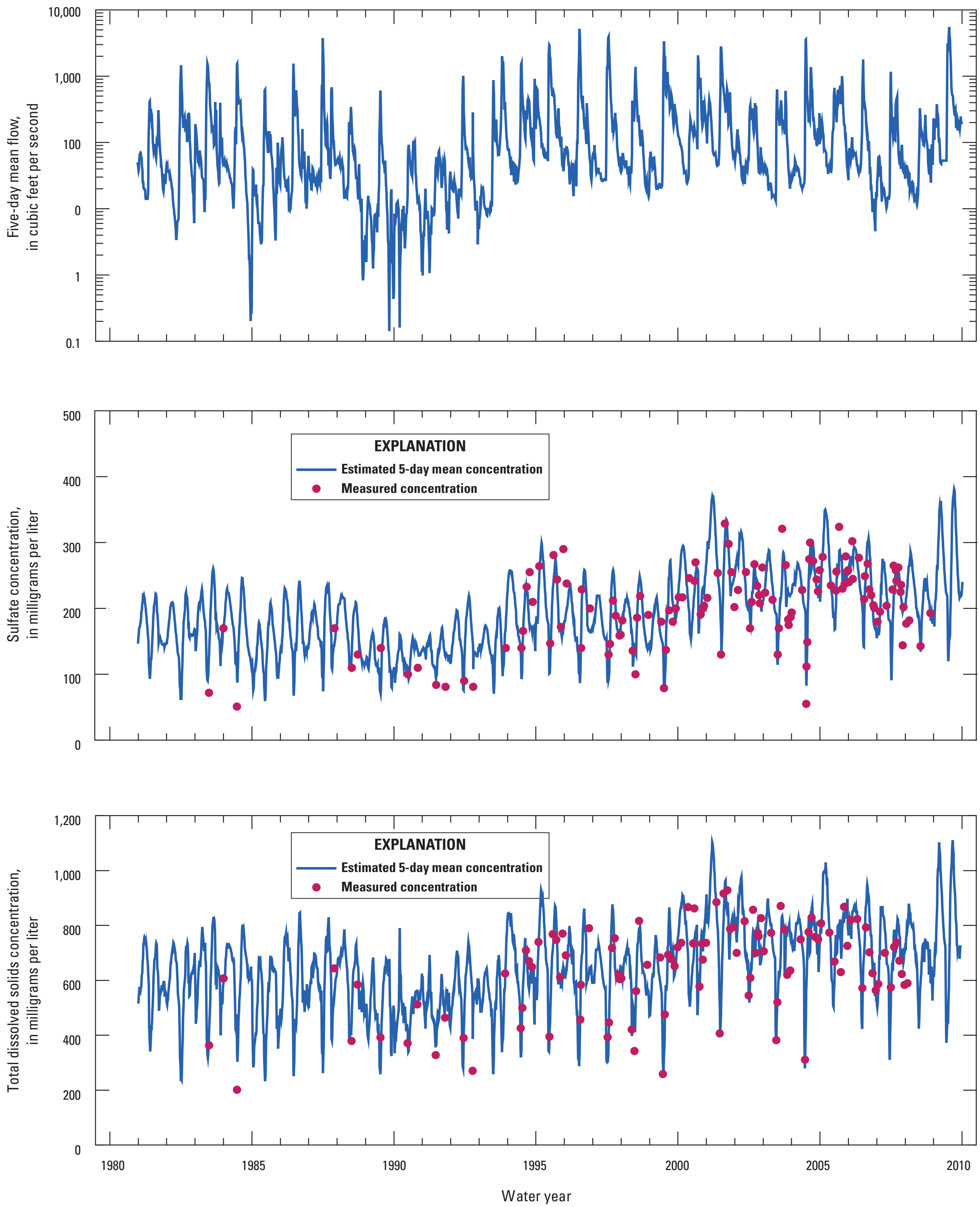

Figure 7. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Sheyenne River near Cooperstown, North Dakota.

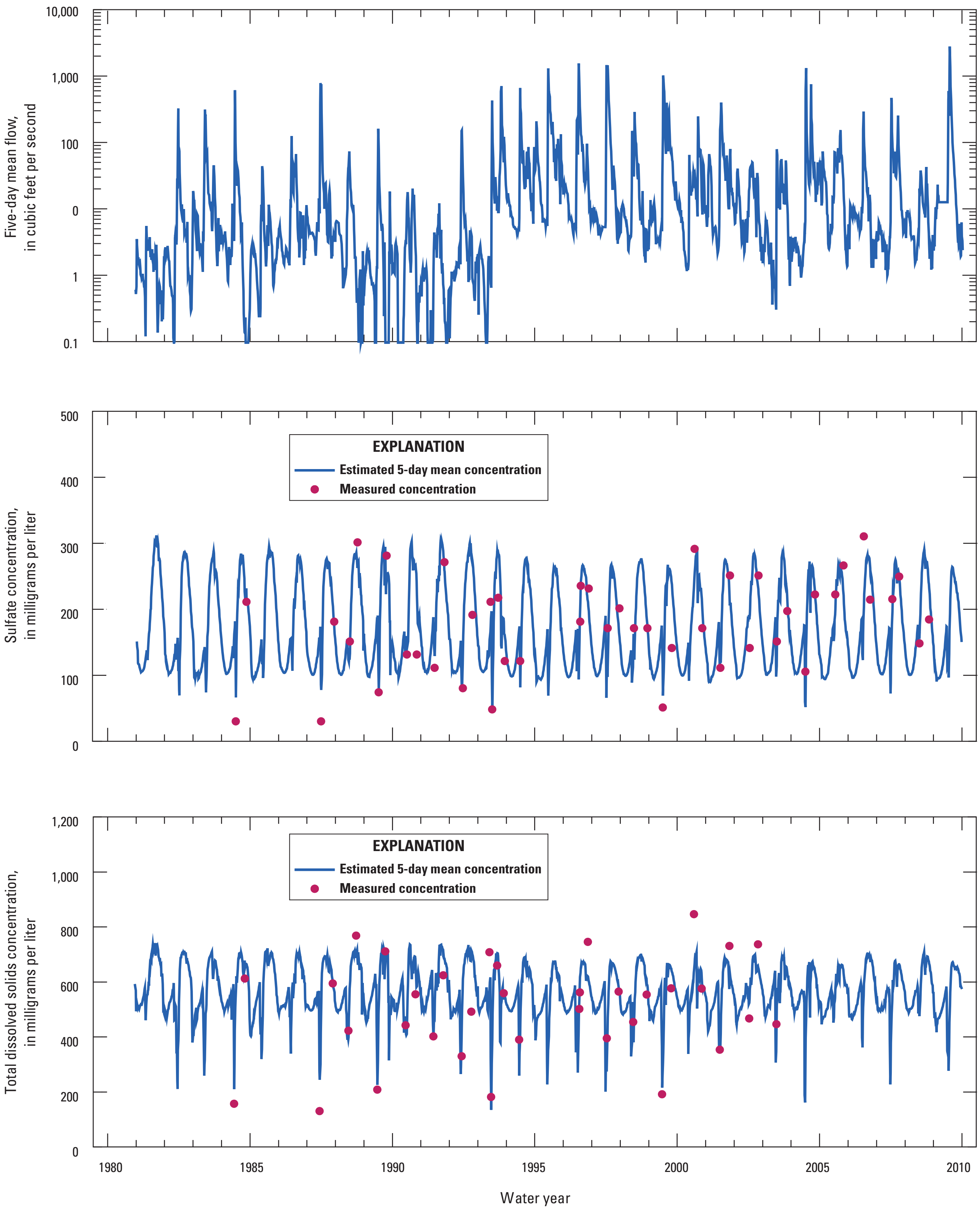

Figure 8. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Baldhill Creek near Dazey, North Dakota.

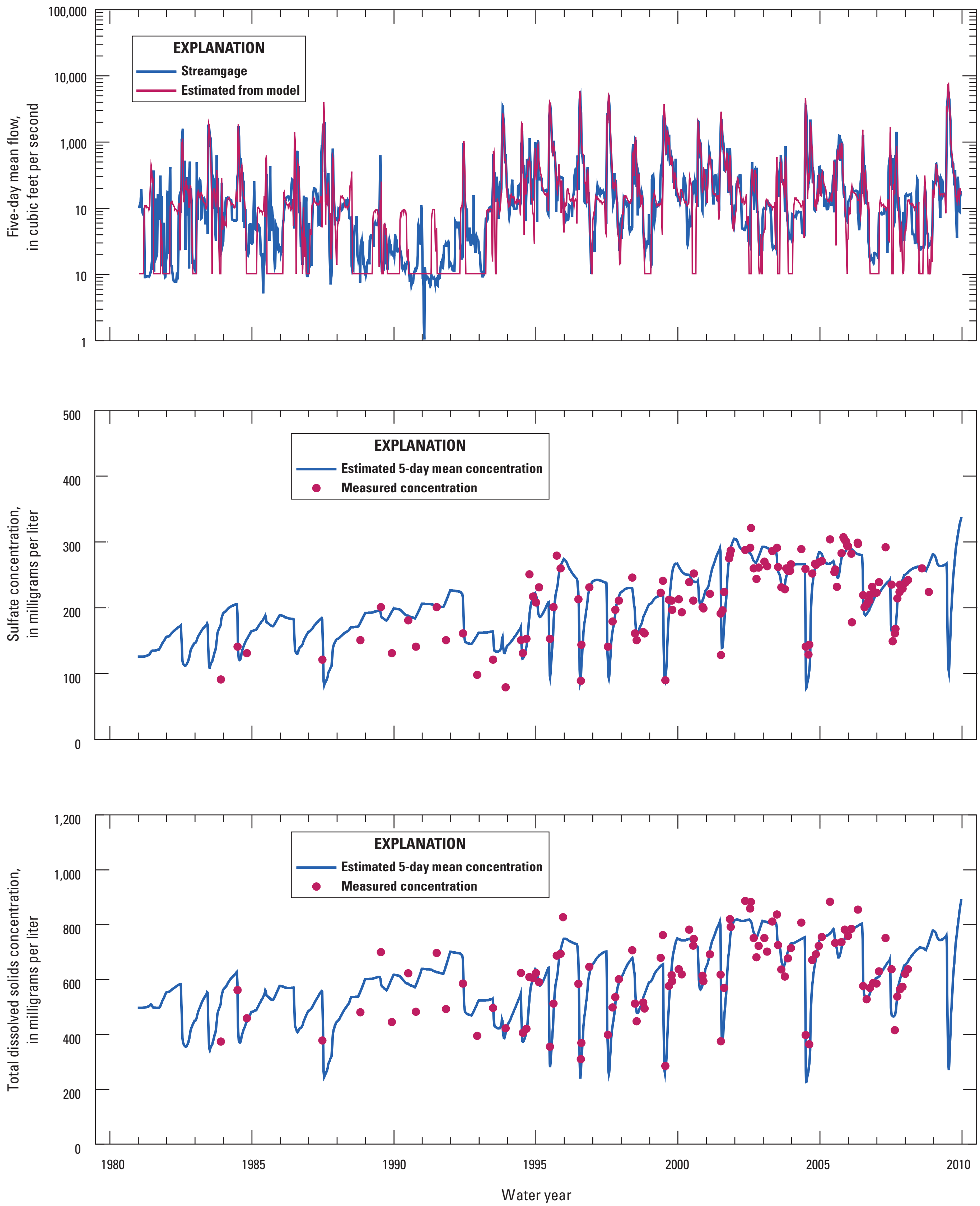

Figure 9. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Sheyenne River below Baldhill Dam in North Dakota.

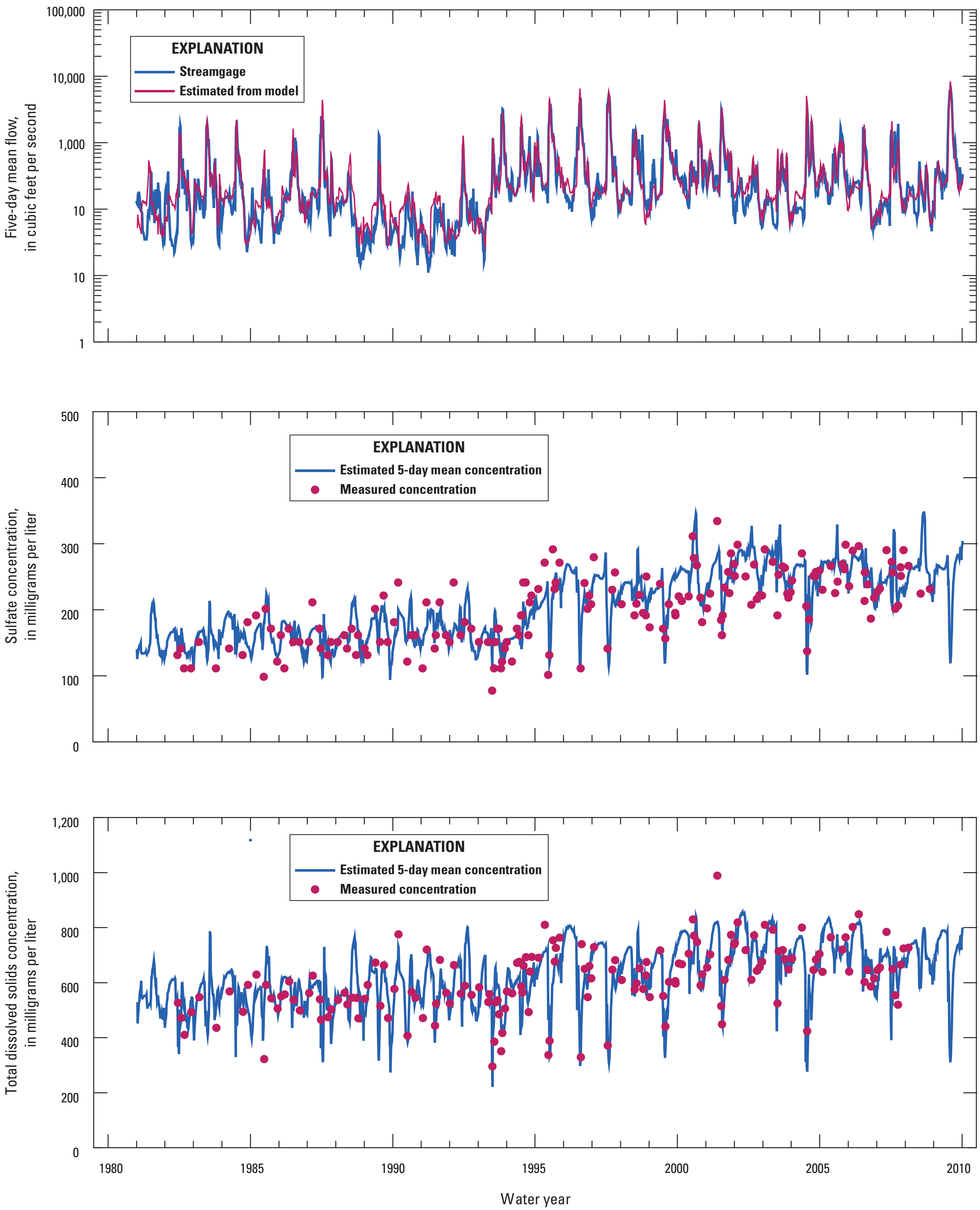

Figure 10. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Sheyenne River near Kindred, North Dakota.

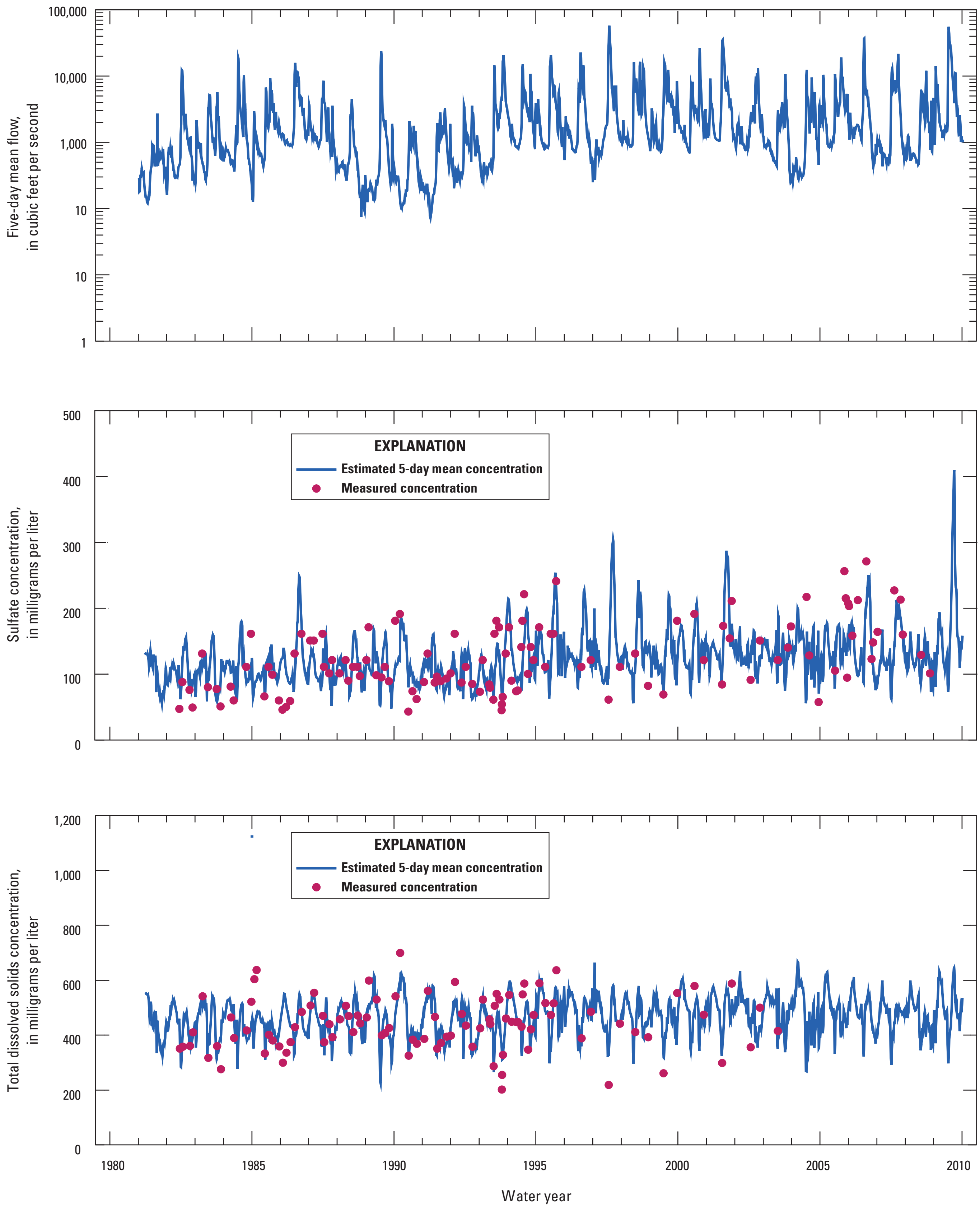

Figure 11. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Red River of the North at Halstad, Minnesota.

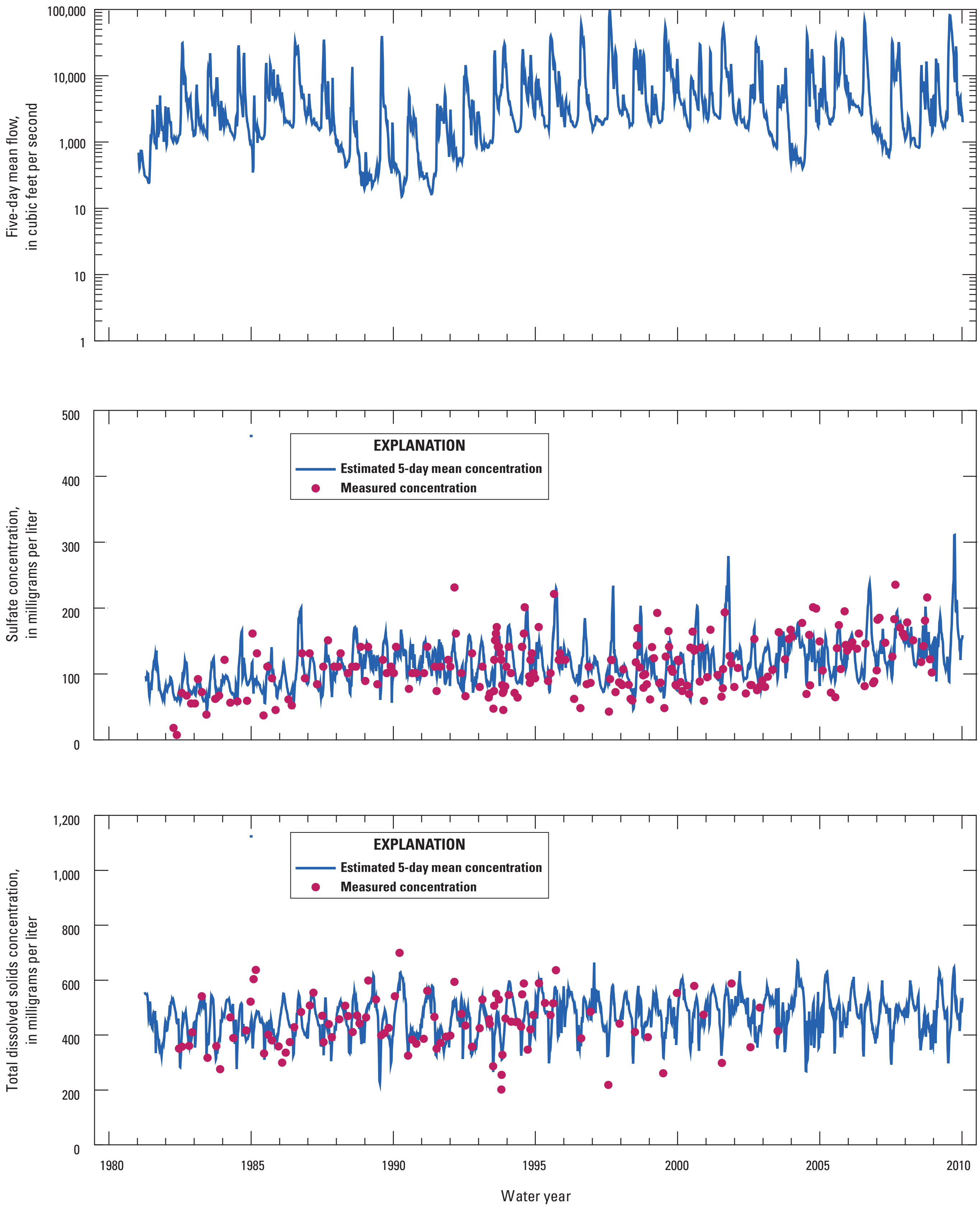

Figure 12. Flow, sulfate concentration, and total dissolved solids concentration for water years 1981–2009 for Red River of the North at Emerson, Manitoba.

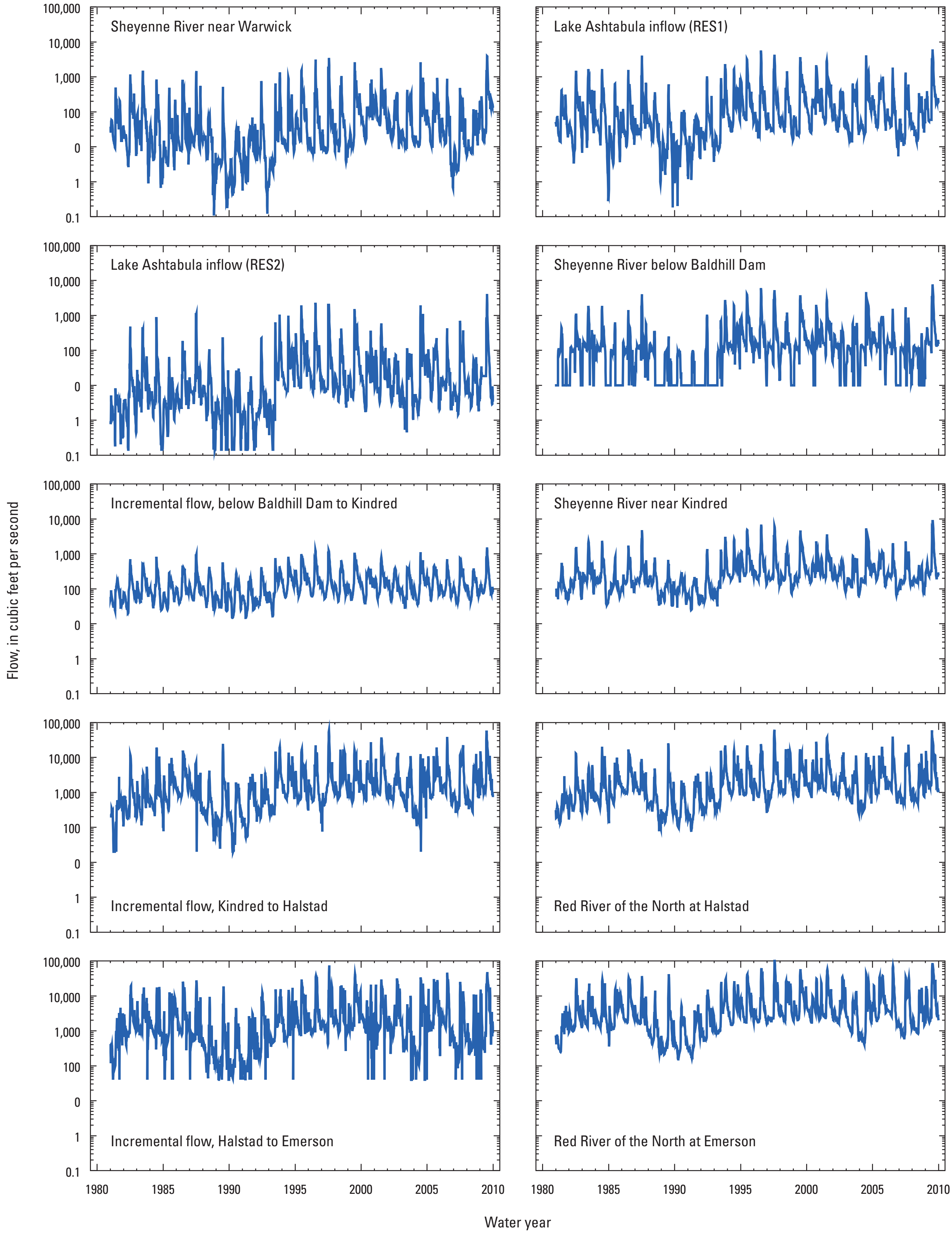

Figure 13. Five-day mean flows for water years 1981–2009 used for downstream stochastic simulation model.

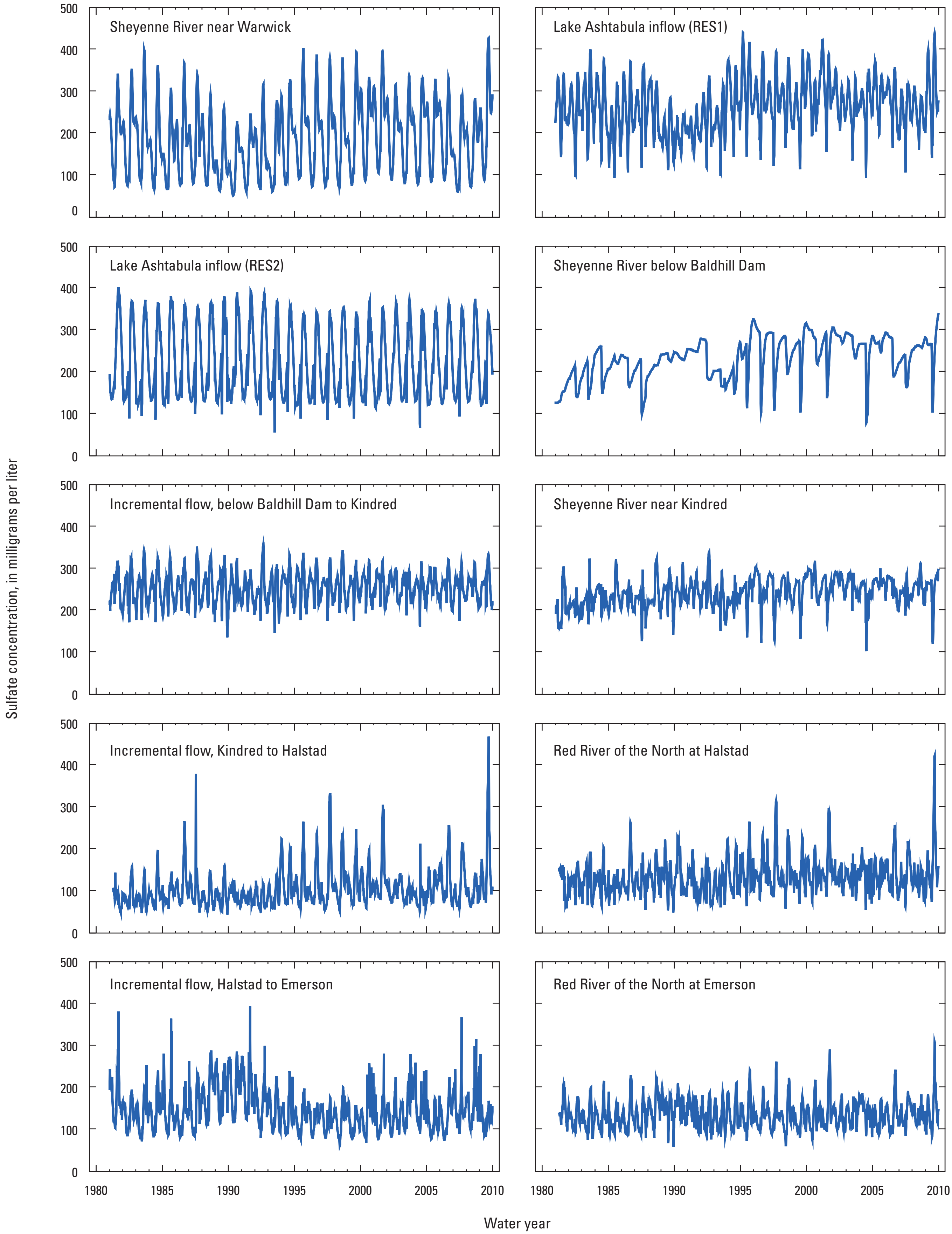

Figure 14. Trend-adjusted 5-day mean sulfate concentrations for water years 1981–2009 used for downstream stochastic simulation model.

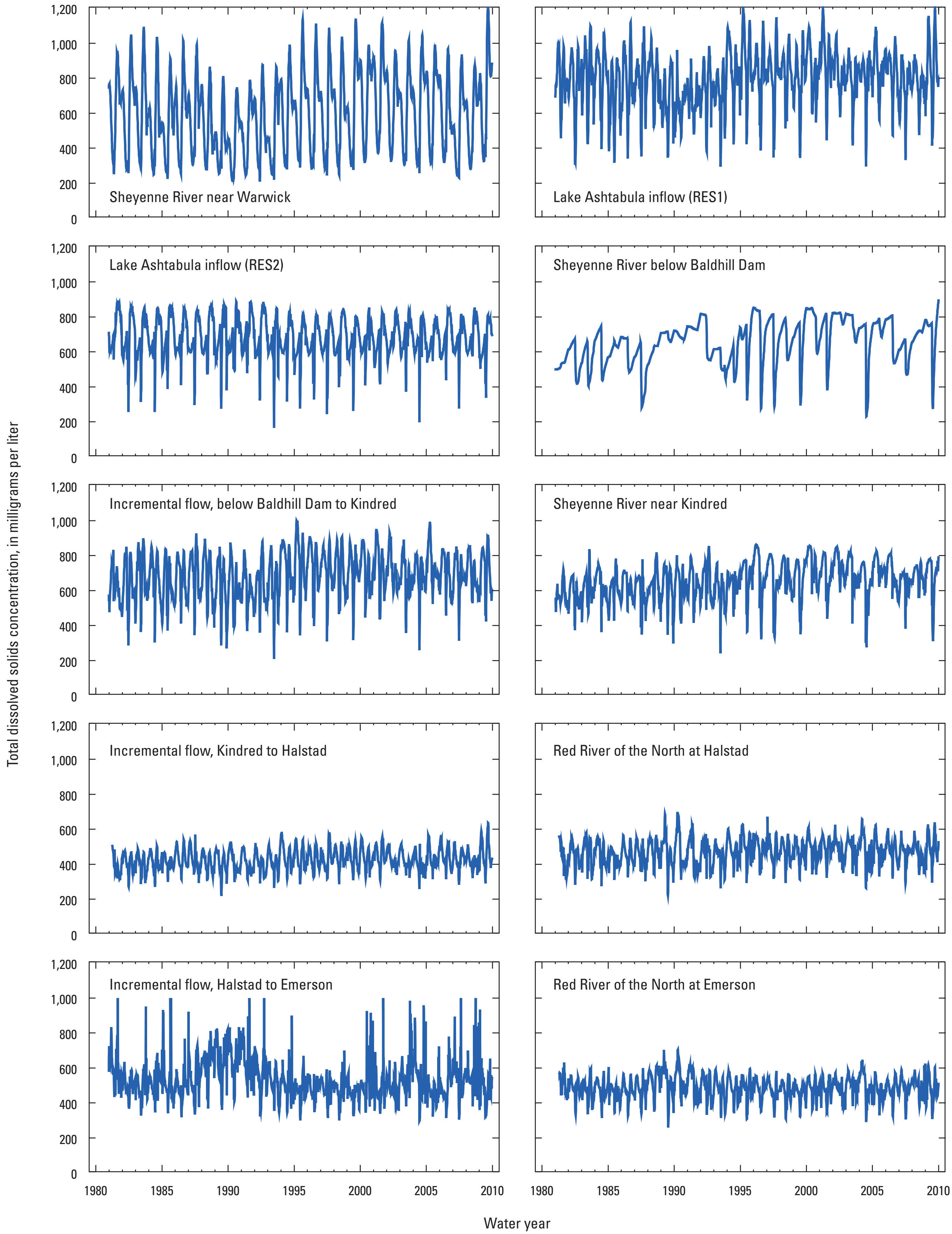

Figure 15. Trend-adjusted 5-day mean total dissolved solids concentrations for water years 1981–2009 used for downstream stochastic simulation model.

particularly dependent on flow conditions or season. Thus, the relative effect on downstream water quality of adding Devils Lake water to the downstream flows probably would be driven largely by the amount of flow that comes from Devils Lake relative to downstream ambient flows. Unlike concentrations, flows were dependent on season and variable among wet and dry periods. For example, flows during the wet period (table 3) generally averaged about 4 times more than flows during the dry period (table 2). Using 600 ft^3/s as a benchmark flow (the maximum amount that could be discharged from the Devils Lake outlet for any of the scenarios being considered), and comparing that benchmark to ambient flows for below Baldhill Dam, it is evident that Devils Lake water could provide a large part, if not most, of the flow for that site during wet or dry years and for all three seasons. During dry years, Devils Lake water could provide much, if not most, of the flow for Kindred, Halstad, and Emerson during November–February, Kindred during March–June, and Kindred and Halstad during July–October. During wet years, Devils Lake water could provide much, if not most, of the flow for Kindred and Halstad during November–February, Kindred during March–June, and Kindred during July–October.

Table 2. Seasonal averages of estimated flow, sulfate concentration, and total dissolved solids concentration for data used in the downstream routing model for water years 1987–92.

[conc., concentration; TDS, total dissolved solids; ft^3/s, cubic feet per second; mg/L, milligrams per liter; RES1 and RES2, Lake Ashtabula reservoir compartments (see fig. 5); downstream gages in **bold font**]

Site or reservoir compartment	November–February			March–June			July–October		
	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)
Warwick	8	98	374	74	194	604	32	149	504
RES1	16	233	755	183	235	701	79	225	723
RES2	3	150	632	51	285	711	19	228	694
Below Baldhill Dam	**61**	**237**	**695**	**174**	**209**	**617**	**88**	**223**	**657**
Kindred incremental	44	259	729	204	271	634	102	250	638
Kindred	**102**	**244**	**692**	**382**	**254**	**621**	**190**	**238**	**625**
Halstad incremental	236	84	457	1,843	98	389	875	86	410
Halstad	**334**	**141**	**541**	**2,224**	**127**	**432**	**1,064**	**124**	**464**
Emerson incremental	231	163	634	2,903	187	578	1,219	182	617
Emerson	**563**	**147**	**570**	**5,047**	**147**	**480**	**2,280**	**143**	**512**

Table 3. Seasonal averages of estimated flow, sulfate concentration, and total dissolved solids concentration for data used in the downstream routing model for water years 1995–2000.

[conc., concentration; TDS, total dissolved solids; ft^3/s, cubic feet per second; mg/L, milligrams per liter; RES1 and RES2, Lake Ashtabula reservoir compartments (see fig. 5); downstream gages in **bold font**]

Site or reservoir compartment	November–February			March–June			July–October		
	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)	Flow (ft^3/s)	Sulfate conc. (mg/L)	TDS conc. (mg/L)
Warwick	30	128	461	382	245	724	164	205	652
RES1	68	306	915	791	276	765	343	286	838
RES2	15	141	611	282	260	666	110	212	664
Below Baldhill Dam	**165**	**282**	**783**	**986**	**215**	**595**	**443**	**255**	**696**
Kindred incremental	80	269	820	428	274	691	217	257	724
Kindred	**241**	**276**	**789**	**1,404**	**232**	**610**	**660**	**251**	**691**
Halstad incremental	1,107	87	452	7,156	152	432	3,438	117	435
Halstad	**1,346**	**126**	**522**	**8,543**	**161**	**454**	**4,098**	**142**	**483**
Emerson incremental	1,697	108	486	11,213	136	468	5,311	127	486
Emerson	**3,046**	**116**	**500**	**19,201**	**142**	**447**	**9,399**	**131**	**474**

Devils Lake Stochastic Simulation Model

Accurate simulation of future downstream conditions with the Devils Lake outlet depends on accurate simulation of downstream ambient flows and concentrations and accurate simulation of Devils Lake levels and concentrations. Fortunately, a Devils Lake stochastic simulation model described in previous USGS studies in cooperation with the U.S. Army Corps of Engineers (Vecchia, 2002) and Federal Emergency Management Agency (Vecchia, 2008) could be used with minor modifications in this study. This section provides a brief overview of the stochastic simulation model and the modifications that were made for this study. Similar to the downstream stochastic routing model, the Devils Lake stochastic simulation model is designed for long-term simulation and is not a real-time hydrodynamic model. A detailed hydrodynamic model for Devils Lake developed in a separate study (Nustad and others, 2011) is better suited for engineering applications such as designing levees, roads, or bridges.

The Devils Lake stochastic simulation model simulates the movement of water and dissolved sulfate though the Devils Lake/Stump Lake system in response to precipitation, evaporation, and inflow, exchange of water and sulfate between the major bays, and flux of sulfate between bottom sediments and lake water. The model consists of six interconnected lake "boxes" (fig. 16). The first box consists of the part of Devils Lake north of Highway 19 that drains into West Bay. At lake levels below 1,430.0 the first box has zero volume.

Data from U.S. Geological Survey, Earth Resources Observation and Science (EROS) Center
Sioux Falls, South Dakota

Figure 16. Landsat image of Devils Lake, North Dakota, from 1999 showing six lake "boxes" included in the water and sulfate mass-balance model.

Above 1,430.0, West Bay backs up into Pelican Lake (part of the first box) and above 1,445.0, water from West Bay backs up all the way to lakes Alice and Irvine, which then also become part of the first box. The remaining boxes consist of West Bay, Main Bay, East Bay, East Devils Lake, and Stump Lake (fig. 16). Most of the runoff from the Devils Lake Basin enters through the upstream chain of lakes (Alice, Irvine, Dry, Sweetwater, and Morrison Lakes) and makes its way into Devils Lake through Big Coulee and Channel A, which was constructed in 1979 to drain water from Dry Lake into Main Bay (fig. 2). Both Big Coulee and Channel A currently (2011) are in backwater from Devils Lake. The lake boxes are separated by various bridge openings, culverts, or natural constrictions that limit the flow of water from west to east during periods of high inflow and limit wind- or density-driven mixing of sulfate during periods of stable or declining lake levels.

The stochastic simulation model uses a monthly time step, and the algorithms used to compute monthly inflows (and sulfate loads) to lake boxes, precipitation and evaporation, flow between lake boxes, mixing between lake boxes, flux of sulfate between bottom sediments and lake boxes, and potential outlet discharges are described in detail by Vecchia (2002). Simulated monthly water-balance variables (precipitation, evaporation, and inflow) are generated using a time series model described by Vecchia (2002) and updated as described by Vecchia (2008). The only modifications to the model that were made for this study involve the calculation of sulfate loads for inflows, estimation of TDS concentrations based on dissolved sulfate, and the calculation of flow rates from Tolna Coulee in the event of a natural spill from Stump Lake to the Sheyenne River.

The time series model for simulating climatic inputs (precipitation and evaporation) and inflows was updated recently (Vecchia, 2008). However, the algorithms for simulating sulfate concentrations for the lake boxes are based on calibration data through 1999 and were not updated. Because Devils Lake has risen considerably since 1999 (fig. 3), filling Stump Lake, and considering the importance that sulfate concentrations will have on potential outlet discharges, data from 2000–10 were used to verify the sulfate calculations and see if any changes were warranted based on the more recent data. The simulation model was started with initial conditions on Oct. 1, 1999 (beginning of water-year 2000) and used to simulate lake levels and sulfate concentrations for 2000–10 for comparison with measured data. Because the goal of this exercise was to verify the algorithms for simulating sulfate concentrations, estimated precipitation, evaporation, and inflow for 2000–10 (not values generated randomly from the time series model) were used in this analysis. The simulated sulfate concentrations for West Bay and Pelican Lake, when using the original calibration from Vecchia (2002), were considerably lower in 2010 than measured concentrations (by almost 40 percent). It was determined that the probable cause for this underestimation was that sulfate concentrations (and hence loads) for inflows into Pelican Lake and West Bay were considerably higher than estimated using the data through 1999. Such an increase is consistent with the upward trends in sulfate concentration during 1999–2001 described in the previous section for the Warwick and Cooperstown sites. Therefore, simulated sulfate concentrations for inflows to the first box were increased by 80 percent from the earlier calibration. The simulated and measured monthly lake levels for Devils Lake (Main Bay) and Stump Lake are shown in figure 17, and the simulated sulfate concentrations (after incorporating the increased sulfate loads) and measured sulfate concentrations for the lake boxes are shown in figure 18. The measured sulfate concentrations for Pelican Lake, West Bay, Main Bay, East Bay, and East Devils Lake are from NDDH (Wax, 2010) and the measured concentrations for Stump Lake are from the USGS National Water Information System (U.S. Geological Survey, 2011b).

The simulated flow from East Devils Lake into Stump Lake was somewhat less than the actual flow during 2005–08, with Devils Lake and Stump Lake equalizing about a year later than actually occurred (fig. 17). However, given the relatively small volume of Stump Lake in relation to Devils Lake, this was considered a minor discrepancy. Sulfate concentrations for Main Bay, East Bay, East Devils Lake, and Stump Lake were overestimated slightly by the model for 2005–08 (fig. 18), which is consistent with the underestimation of flow into Stump Lake (and hence through Main Bay, East Bay and East Devils Lake) during that time. Again, this was considered a minor discrepancy.

The Devils Lake stochastic simulation model originally was not developed to simulate TDS concentration, so TDS concentrations for the lake boxes were estimated based on sulfate concentrations. Comparison of measured sulfate and TDS concentrations for 2000–10 for the various lake boxes (fig. 19) indicated a single equation could be used for all the lake boxes to closely estimate TDS concentrations based on sulfate concentrations:

$$CTDS = 5.25\,[CSO_4]^{0.87},$$

where

$CTDS$ is TDS concentration, in milligrams per liter, and

CSO_4 is sulfate concentration, in milligrams per liter.

TDS concentrations for Stump Lake for 2008–10 were somewhat below the fitted regression line, but seem to be rebounding toward the line as concentrations decline (fig. 19).

The final change to the simulation model involved calculation of flow rates from Tolna Coulee in the event of a spill. Control structures are currently (2011) being designed by the U.S. Army Corps of Engineers (USACE) and North Dakota State Water Commission to prevent catastrophic flows from discharging through Tolna Coulee in the event of a spill and subsequent down-cutting of the outlet (B. Engelhardt, North Dakota State Water Commission, oral commun., 2011). These structures would not prevent natural erosion of the outlet channel, but would prevent outflows from exceeding a prescribed

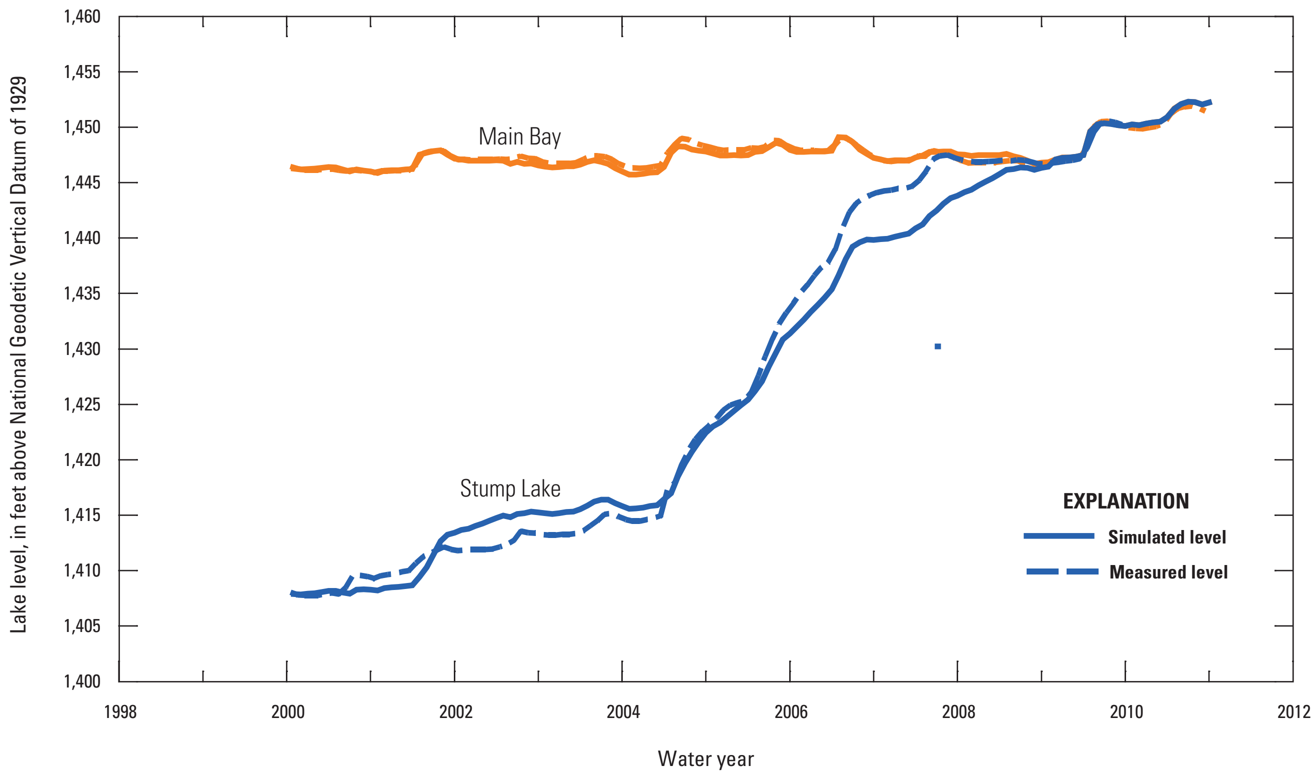

Figure 17. Model-simulated and measured monthly lake levels for Main Bay of Devils Lake and Stump Lake, North Dakota, for water years 2000–10.

maximum level, thus reducing the peak (and extending the duration) of the outflow hydrograph. Although these structures are planned to be operational by the end of 2011, they are still in the design phase and additional analyses are being done to determine the type of soil materials of the outlet channel and refine estimated erosion rates and outflow rating curves (the amount of water that flows out at a given lake level and given state of erosion). The outflow rating curves and erosion rates used for this study were the same as the rough initial estimates described in Vecchia (2002), with two modifications. The first modification involves the initial spill elevation. At the time of the 2002 study, the initial (with no erosion) spill elevation was 1,459.0 feet. In 2009, a berm was removed from the outlet channel by the City of Devils Lake (B. Engelhardt, North Dakota State Water Commission, oral commun., 2011), lowering the spill elevation to 1,458.0 feet. Therefore, the initial outflow rating curve from the previous study was shifted down by 1.0 foot, to 1,458.0 feet. The remaining parameters (the rate of erosion and subsequent downcutting, shifts in the rating curves because of the erosion, and the ultimate minimum spill elevation/maximum flow rating) remained the same. The second modification to the previous model was that the flow rating from the Tolna Coulee outlet under eroded conditions (after down-cutting begins) was set at a maximum of 1,500 ft^3/s. This is the maximum currently (2011) being considered in the design phase (B. Engelhardt, North Dakota State Water Commission, oral commun., 2011). Until downcutting begins, the outflow rating is unchanged, and thus could exceed 1,500 ft^3/s under certain circumstances.

Combined Devils Lake/Downstream Stochastic Simulation Model

The models described in the previous sections were combined and used to simulate future potential realizations, or traces, of Devils Lake levels and water quality, and downstream flows and water quality for 2011–30 for various outlet scenarios. Results of these simulations are described in the next section. The methods used to simulate the future traces are described in the following algorithm (see fig. 5):

1. The time series model was used to randomly generate future monthly sequences of precipitation, evaporation, and inflow for Devils Lake and flow for the Warwick site for water years 2011–30. These sequences depend on initial conditions for 2010 and (as described later) forecast information for 2011 from the National Weather Service.

2. The generated flows for Warwick from step 1 were used to select historical years from 1981–2009 that match up as closely as possible to the generated Warwick flows. If $GFW_{n,j}$ is the generated flow for Warwick for simulation year (n) and month (j) and $HFW_{m,j}$ is the historical flow for Warwick for historical year (m) and month (j), then

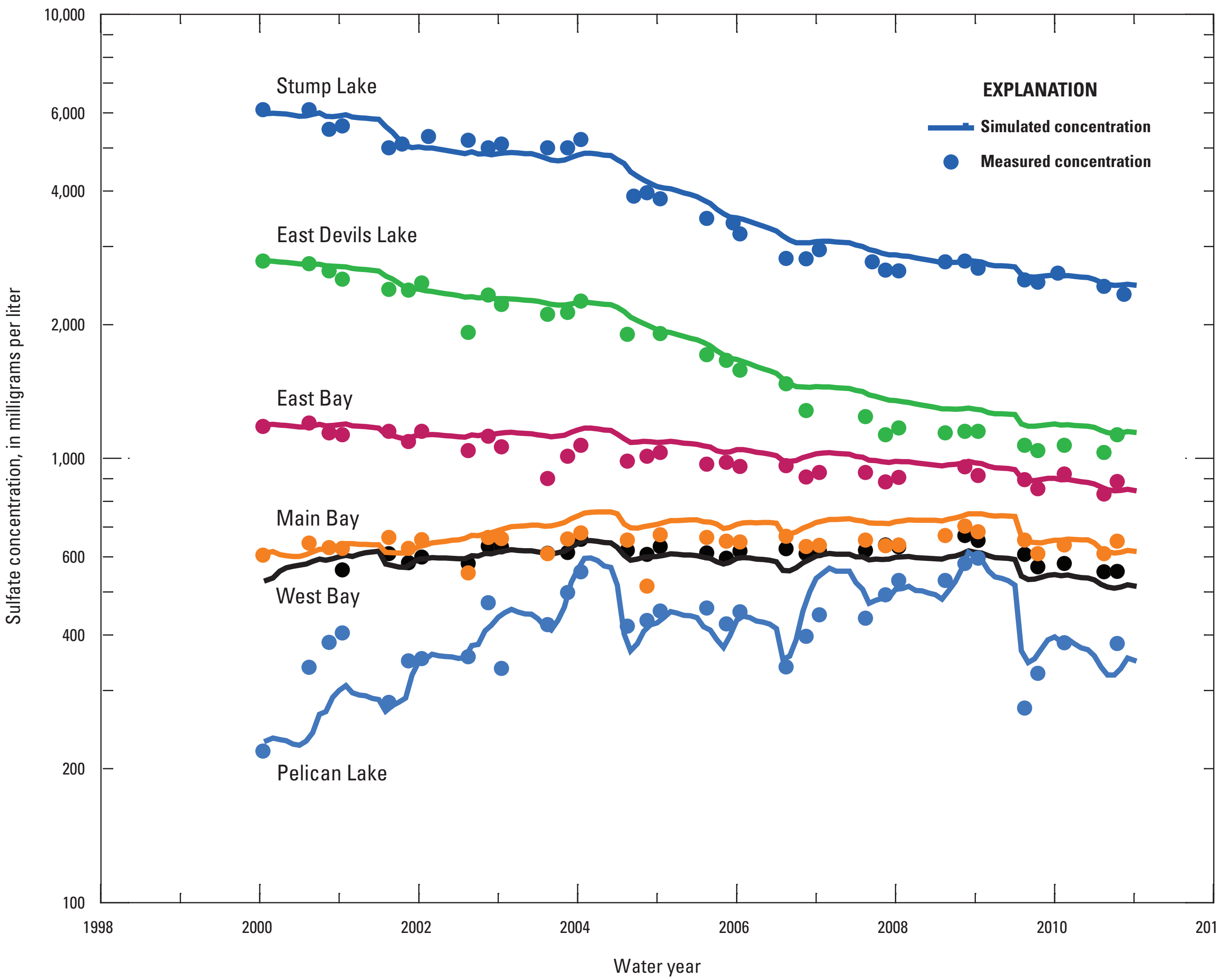

Figure 18. Model-simulated and measured sulfate concentrations for six lake "boxes" in the Devils Lake model for water years 2000–10.

m was selected such that the sum through all months of $|GFW_{n,j}–HFW_{m,j}|$ was minimized. Once the historical year corresponding with each simulation year was fixed, that historical year was used for computing ambient downstream flows for Warwick (the original generated values are replaced by the historical values), inflow to reservoir compartments RES1 and RES2, and incremental flows for Kindred, Halstad, and Emerson.

3. For a given monthly time step (and starting conditions from the previous time step), simulated Devils Lakes precipitation, evaporation, and inflow from step 1 were used to compute lake levels, sulfate concentrations, TDS concentrations (by relation with sulfate concentrations), and Stump Lake spills (if any) for the current time step.

4. If the west-end or east-end outlets were operating for the current month, outlet discharges were computed so that the total discharge for the west-end outlet (lagged 5 days) and the east-end outlet satisfied certain constraints. If Stump Lake was not spilling, then the total outlet discharges were constrained so that the combined Warwick flow and outlet discharge did not exceed the maximum of Warwick flow or 800 ft^3/s and the combined sulfate concentration did not exceed 750 mg/L. These were the assumed flow and water-quality constraints for the simulation period for the upper Sheyenne River (B. Engelhardt, North Dakota State Water Commission, oral commun., 2011). If Stump Lake was spilling, then the combined Warwick flows, Stump Lake spills, and outlet discharges could not exceed the maximum of Warwick flow plus the Stump Lake spill, or 800 ft^3/s. In addition, another sulfate constraint was that the outlet discharges could not cause sulfate concentration below Baldhill Dam to exceed 750 mg/L. This constraint was never active

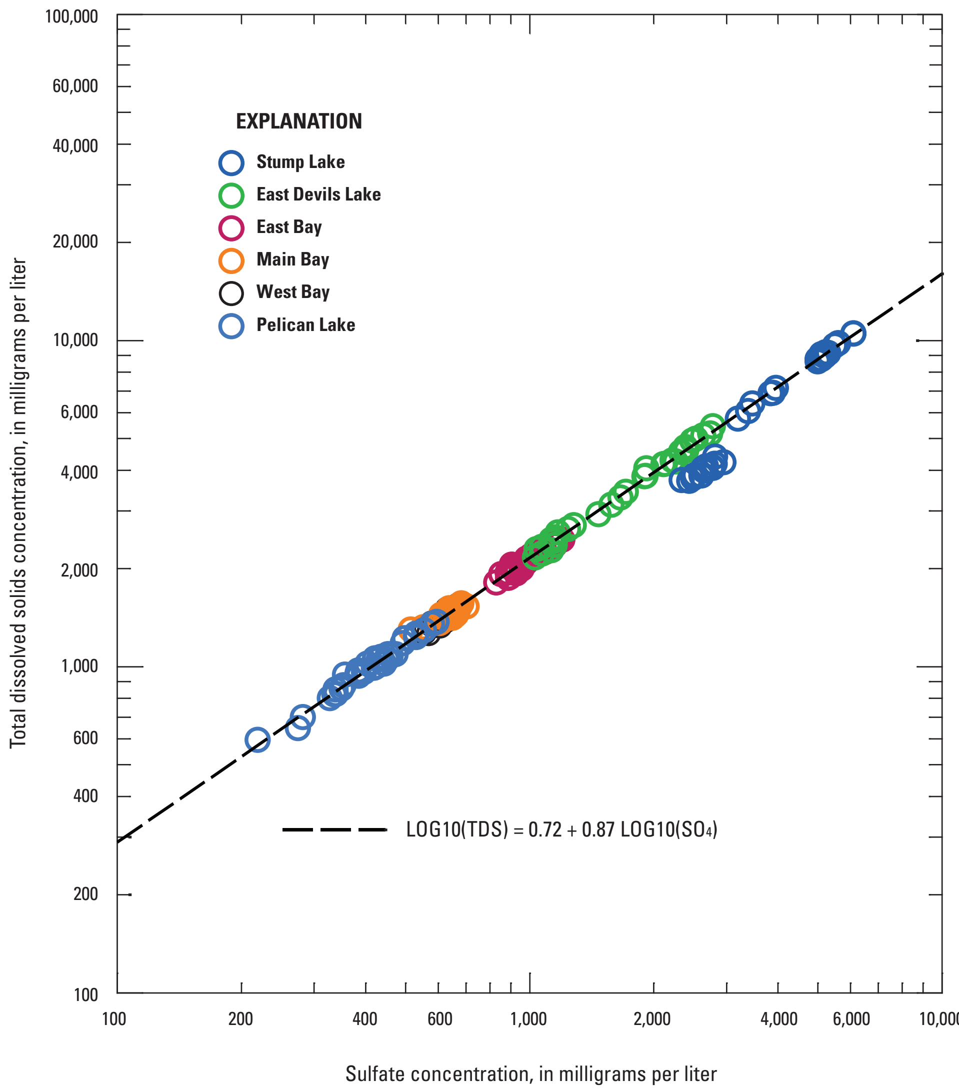

Figure 19. Measured sulfate (SO_4) concentration and total dissolved solids (TDS) concentration for six lake "boxes" for the Devils Lake model for water years 2000–10.

given the upstream constraint of 750 mg/L. However, in some alternatives described later, a lower constraint was specified to better control downstream water-quality conditions.

5. The downstream stochastic routing model was used with the data from steps 2 and 4 to compute downstream flows and concentrations for the current time step. Discharges from the west-end outlet (lagged by 10 days), the east-end outlet (lagged by 5 days), and from Stump Lake (lagged by 5 days) were added to the input for the upstream reservoir compartment (RES1). Inflow to the remaining reservoir compartments and downstream incremental flows remained the same.

6. Steps 3–5 were repeated for each month of the simulation period and the whole process (steps 1–5) was repeated for each new trace with a new set of generated values in step 1.

Simulation of the Effects of Devils Lake Outlet Alternatives

Results of the outlet simulations are described in this section. The different assumptions and outlet scenarios used for this report are given in tables 4 and 5. As indicated in table 4, the west-end and east-end outlets were assumed to operate only when Devils Lake was above 1,446.0 feet, and only during April 1 to November 30. Outlet discharges were constrained as described earlier to meet the upper Sheyenne River flow and sulfate concentration constraints of 800 ft³/s and 750 mg/L, respectively. If spills from Stump Lake began

Table 4. Assumptions used in the Devils Lake and downstream stochastic simulation model for all Devils Lake outlet scenarios for 2011–30.

[Lake levels relative to National Geodetic Vertical Datum of 1929]

Minimum lake level for outlet operation (west-end and east-end outlets)	1,446.0 feet
Upper Sheyenne River channel capacity constraint	800 cubic feet per second
Upper Sheyenne River sulfate concentration constraint	750 milligrams per liter
Window for outlet operation (west-end and east-end outlets)	April 1 to November 30
Maximum flow for Stump Lake (Tolna Coulee) spills under eroded conditions	1,500 cubic feet per second
99-percent-chance exceedance level of Devils Lake on July 1, 2011*	1,453.7 feet
90-percent-chance exceedance level of Devils Lake on July 1, 2011*	1,454.0 feet
50-percent-chance exceedance level of Devils Lake on July 1, 2011*	1,454.7 feet
10-percent-chance exceedance level of Devils Lake on July 1, 2011*	1,455.5 feet
1-percent-chance exceedance level of Devils Lake on July 1, 2011*	1,456.3 feet

* Time-series model-generated precipitation, evaporation, and inflow for first 9 months of simulation period (October 1, 2010 through June 30, 2011) conditioned based on National Weather Service, Advanced Hydrologic Prediction System (AHPS) simulations from Februrary 27, 2011 (National Oceanic and Atmospheric Administration, 2011).

Table 5. Devils Lake outlet scenarios analyzed for this study.

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

Outlet alternative	Outlet capacities	Sulfate constraint below Baldhill Dam
W250E250	West Bay: 250 ft^3/s (existing outlet) East Devils Lake: 250 ft^3/s beginning April 1, 2012	A. 750 mg/L B. 650 mg/L
W350E250	West Bay: 250 ft^3/s until April 1, 2013; 350 ft^3/s beginning April 1, 2013 East Devils Lake: 250 ft^3/s beginning April 1, 2012	A. 750 mg/L B. 650 mg/L
W250E350	West Bay: 250 ft^3/s (existing outlet) East Devils Lake: 350 ft^3/s beginning April 1, 2012	A. 750 mg/L B. 650 mg/L
Baseline	No outlet discharges (for comparison with other scenarios)	Not applicable

to erode the natural outlet, Tolna Coulee discharges were held to a maximum of 1,500 ft^3/s. In April 2011, it was known that Devils Lake would rise substantially the first year (2011), but there was still considerable uncertainty about exactly how much it would rise. Therefore, the model-generated water-balance variables for Devils Lake (monthly precipitation, evaporation, and inflow) for the first 9 months of the simulation period (October 2010 through June 2011) were adjusted so that the chances the simulated lake levels on July 1, 2011 exceeded various values were as close as possible to those provided by the National Weather Service, Advanced Hydrologic Predictions System, simulations dated Feb. 27, 2011 (National Oceanic and Atmospheric Administration, 2011). An exact match could not be made because the two models run on different time scales and use different inputs. Of the simulations generated for this report (based on 5,000 future traces), 99 percent exceeded 1,453.7 feet, 50 percent exceeded 1,454.7 feet, and 1 percent exceeded 1,456.3 feet on July 1, 2011.

The outlet scenarios given in table 5 were selected as the most feasible scenarios based on consultation with NDDH and NDSWC personnel. The scenarios consisted of combinations of the existing west-end outlet (250 ft^3/s capacity), two proposed east-end outlet capacities (250 ft^3/s or 350 ft^3/s), and a proposed expansion of the west-end outlet to a capacity of 350 ft^3/s. The east-end outlet was assumed to be operational April 1, 2012 and the west-end outlet expansion was assumed to be operational April 1, 2013. All three of the outlet alternatives were run with two separate sulfate concentration constraints for flow below Baldhill Dam—750 and 650 mg/L—to explore how sensitive the outlet discharges and downstream water-quality conditions were to this constraint. Thus, there were a total of six outlet scenarios, with three alternatives for the outlet capacities and locations and 2 alternatives for the downstream sulfate constraint. In addition, for comparison purposes, a hypothetical baseline condition was simulated in which there was assumed to be no outlet discharges. Although the downstream model simulations were done using a 5-day time step, for presenting the subsequent results the data were aggregated to an approximately monthly time step.

Example Traces

Before providing statistical summaries and discussion of the overall findings, three example traces will be shown to provide some context for the subsequent discussion. All three of these traces are for the W250E350 outlet (table 5), with the less restrictive sulfate constraint for the below Baldhill Dam site (W250E350A; 750 mg/L) and with the more restrictive sulfate constraint (W250E350B; 650 mg/L). In the first example (trace 17; figs. 20*A*–*C*), the baseline lake level rises to about 1,456 feet before stabilizing and then declining through 2016, after which it rises again to just above 1,458.0 feet and trickles out of Stump Lake during 2019–20, causing minimal erosion of the natural outlet (fig. 20*A*). Both outlet scenarios drew the lake down much faster than the baseline condition and reduced the second peak by about 6 feet. However, lake levels for the more restrictive outlet (W250E350B) were somewhat higher (about 1.5 to 2.0 feet) compared with the less restrictive outlet (W250E350A) during 2016–23. West Bay and East Devils Lake sulfate concentrations (which were the concentrations of the west-end and east-end outlet discharges, respectively) rose during the initial lake decline, reaching about 1,100 mg/L in East Devils Lake and 600 mg/L in West Bay during 2016. Concentrations subsequently fell as the lake level increased rapidly, reaching about 900 mg/L (East Devils Lake) and 500 mg/L (West Bay) during 2020. For this trace, the outlet had a minor effect on concentrations in the lake, with concentrations at the end of the period (2025) somewhat lower with the outlet than for the baseline condition. The mean monthly outlet discharges indicated the outlet was running at or near full capacity for most of the period. However, during the initial period of lake level decline, discharges were reduced for the more restrictive downstream constraint during the end of the pumping periods in 2013–14 and for longer intervals during 2015–16. In 2023 the less restrictive outlet did not operate because the lake level for that case was below 1,446.0 feet, but the more restrictive outlet was still discharging.

Downstream sulfate concentrations for trace 17 (fig. 20*B*) indicated that concentrations for below Baldhill Dam for the less restrictive outlet never reached 750 mg/L, and so the less restrictive constraint was never active. However, the more restrictive constraint was active during 2014–17, and again during 2022–23. The reduction in pump discharges (and subsequent reduction in below Baldhill Dam outflow volumes) during those years resulted in reduced sulfate concentration for the Kindred, Halstad, and Emerson sites. The five highest sulfate concentration peaks for the Halstad and Emerson sites for the less restrictive outlet were reduced considerably with the more restrictive outlet. For the baseline condition, although only small spills from Stump Lake occurred during 2019–20 (fig. 20*A*, bottom graph), baseline concentrations for below Baldhill Dam and Kindred still were elevated during those years.

Downstream flows for trace 17 (fig. 20*C*) were mostly consistent with the Devils Lake fluctuations, with relatively low flows during periods of lake-level declines and relatively high flows during periods of lake-level rises. As discussed in the "Downstream Stochastic Routing Model" section, variability in the downstream flows between seasons and between wet and dry years was expected to be a primary factor affecting sensitivity of downstream sulfate concentrations to Devils Lake discharges. Devils Lake flows provided a substantial part of downstream flows for Halstad and Emerson during July–December of dry years, especially for the less restrictive outlet option.

For the next example, trace 39 (figs. 21*A*–*C*), the baseline condition lake level rose steadily and Stump Lake started spilling in 2016 (fig. 21*A*). The spill was severe enough to trigger erosion of the outlet, and Stump Lake spills rose quickly to the maximum of 1,500 ft^3/s, staying at that level for about 8 months and continuing at lower levels for several more years. The Stump Lake outlet eventually eroded to a base level of about 1,451.0 feet and Stump Lake finally stopped spilling in 2023. Devils Lake declined rapidly along with Stump Lake after the spills began. Both outlet scenarios prevented the lake from rising above 1,456.0 feet, preventing the spill and subsequent erosion. Devils Lake sulfate concentrations remained relatively stable for both outlet scenarios, but baseline concentrations in East Devils Lake (and in Stump Lake, not shown) declined rapidly as a result of the spill. Outlet discharges for both outlet scenarios were at full capacity for most of the time, except during 2017, when the more restrictive outlet discharges needed to be reduced, and during 2023–25, when the lake levels were below the minimum pumping elevation of 1,446.0 for much of the time.

For trace 39 (fig. 21*B*), downstream sulfate concentrations for the baseline condition were many times greater than normal during the initial stages of the spill, peaking at about 1,800 mg/L in 2017 for all of the downstream sites. This was because of the large discharge (1,500 ft^3/s) and high sulfate concentration (initially about 2,000 mg/L) of the Stump Lake spills. Downstream sulfate concentrations for the outlet scenarios were similar to the previous example (trace 17), except that the more restrictive downstream sulfate constraint was much less active for this trace.

Downstream flows for trace 39 for the baseline condition (fig. 21*C*) indicated that the year when Stump Lake spills were highest (2017) happened to be an unusually dry year downstream. This was fortunate in terms of downstream flooding potential, but unfortunate in terms of downstream water quality. It was the low ambient downstream flows in 2017 that resulted in reduction in the outlet discharges during those years for the more restrictive outlet.

The last example is trace 12 (figs. 22*A*–*C*), where the ambient lake level rose too quickly and severely for a spill to be prevented by the outlet discharges (fig. 22*A*). The lake

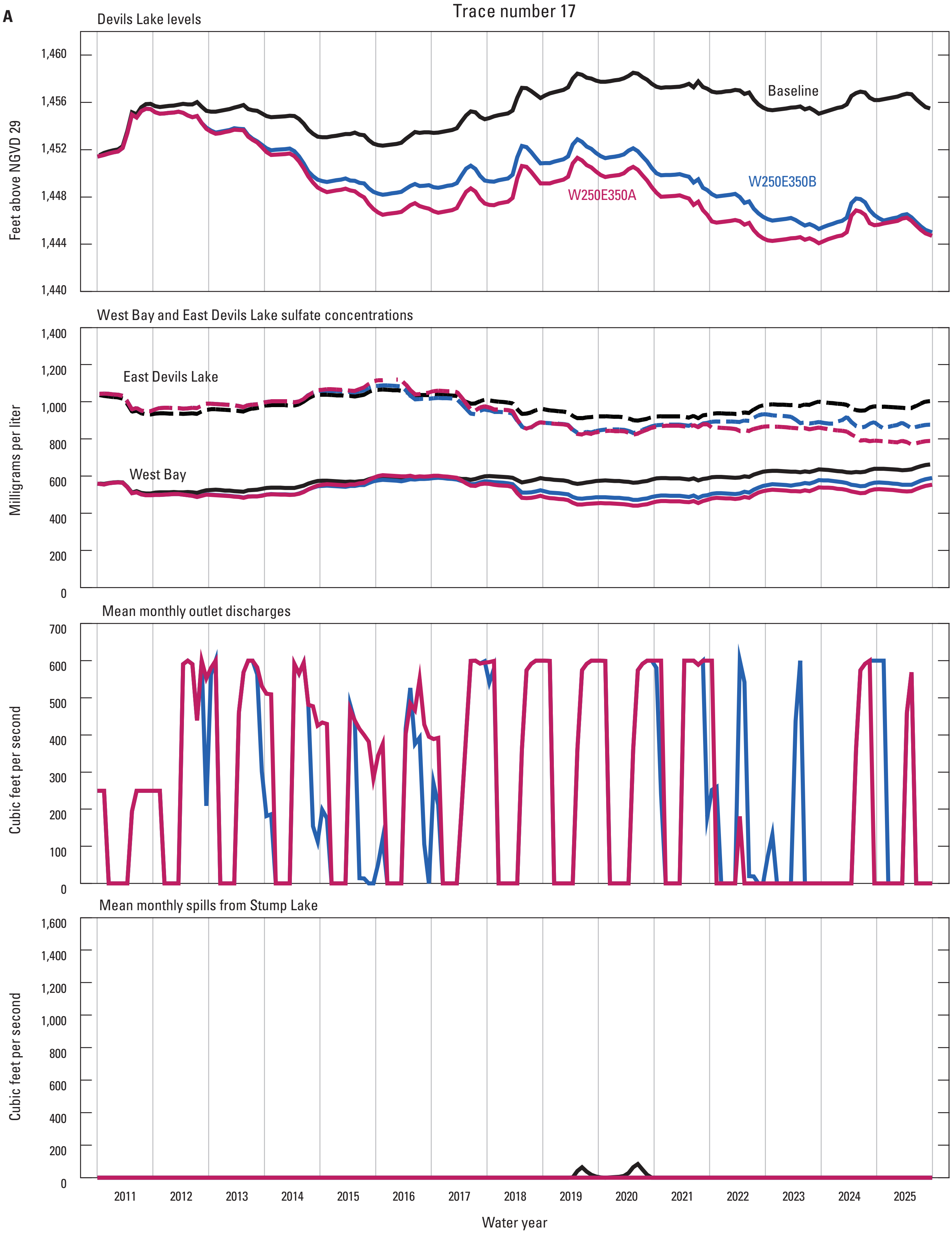

Figure 20. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 17: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.

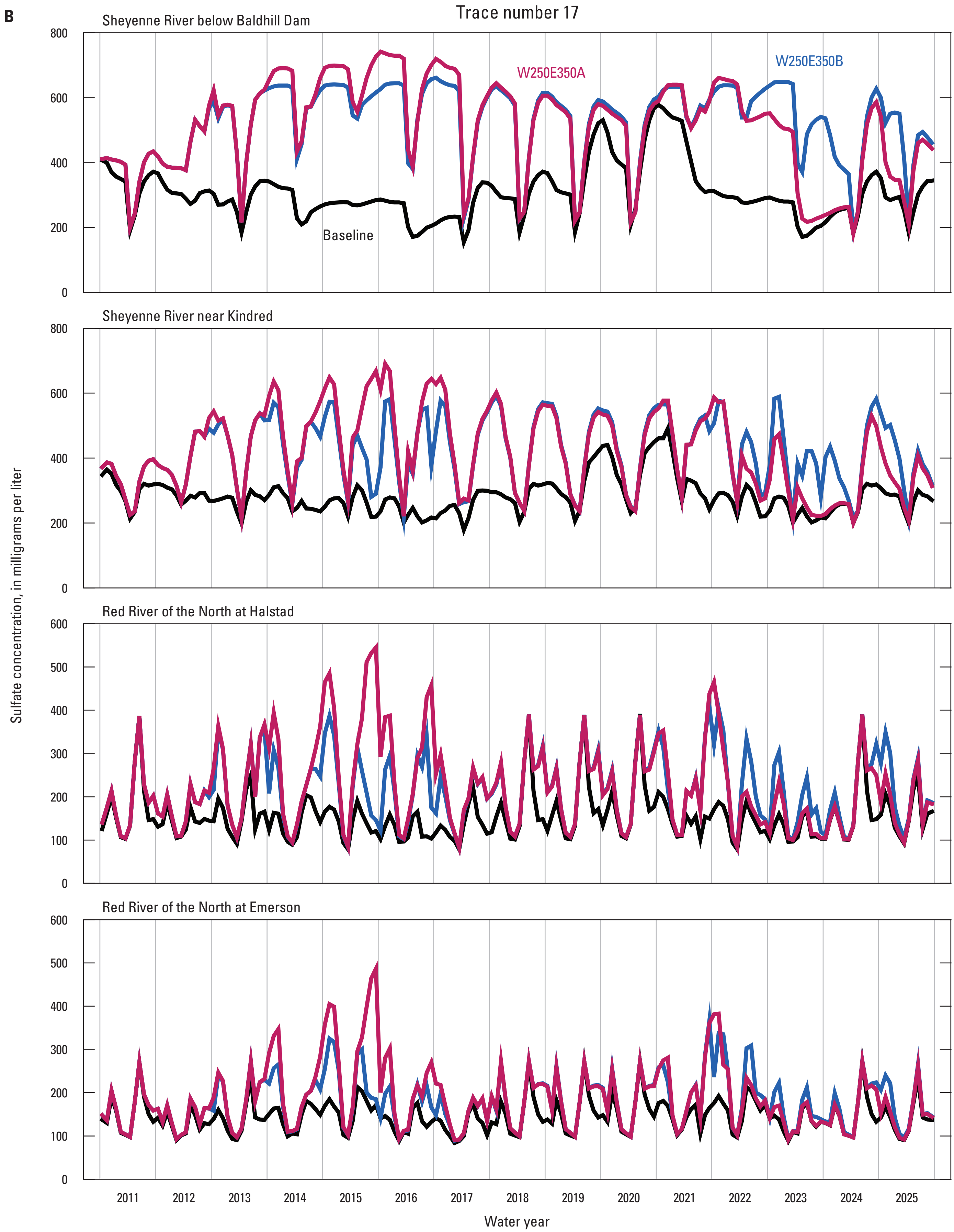

Figure 20. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 17: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

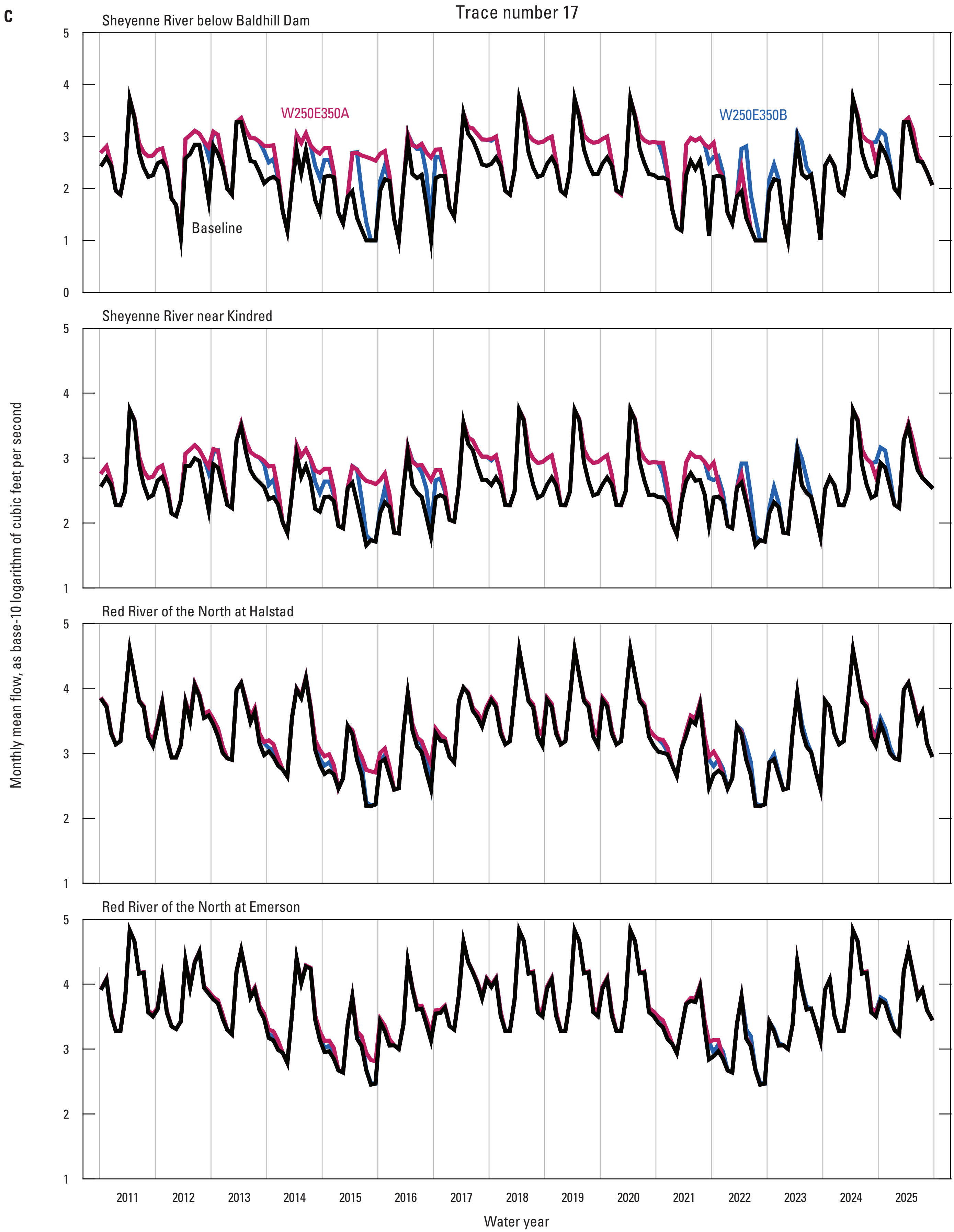

Figure 20. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 17: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

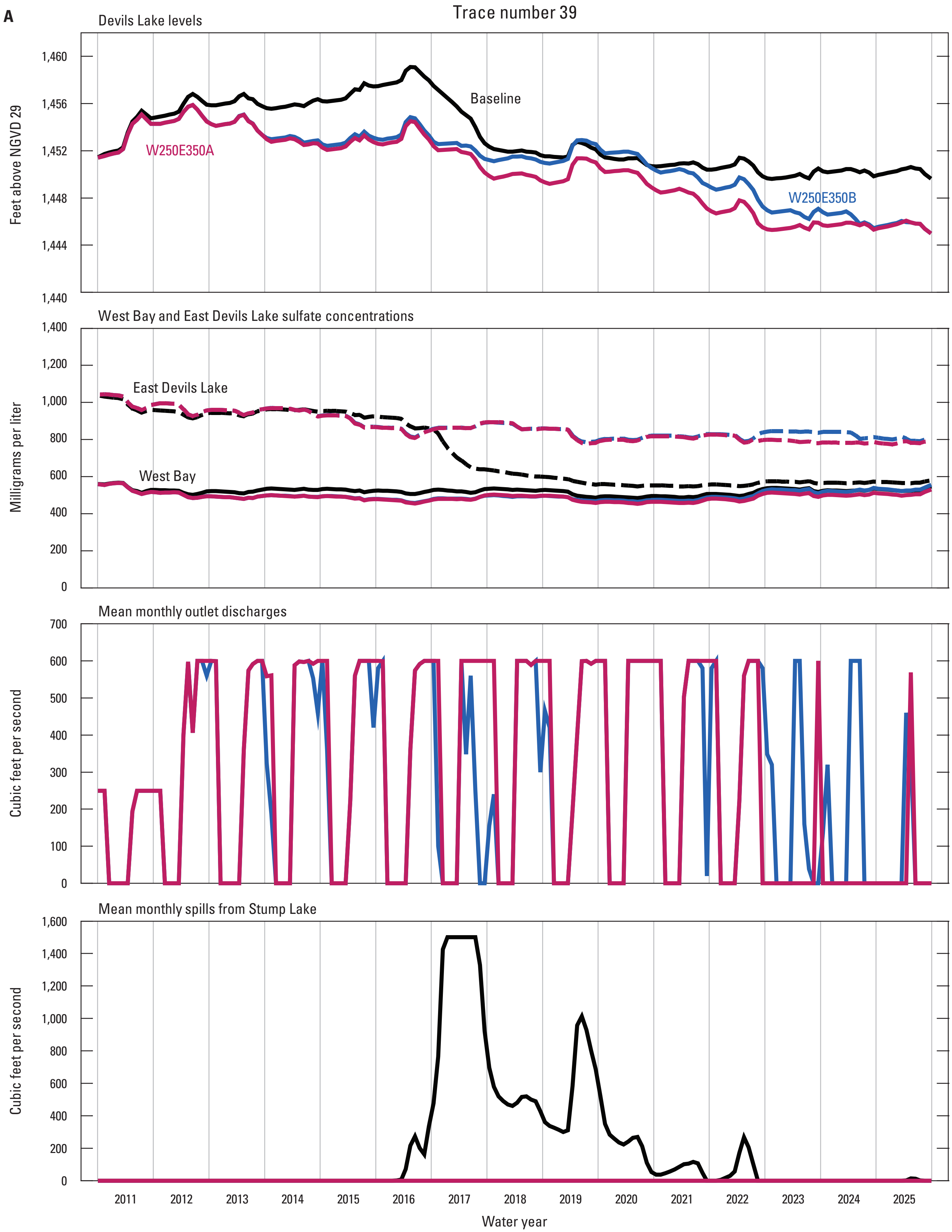

Figure 21. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 39: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.

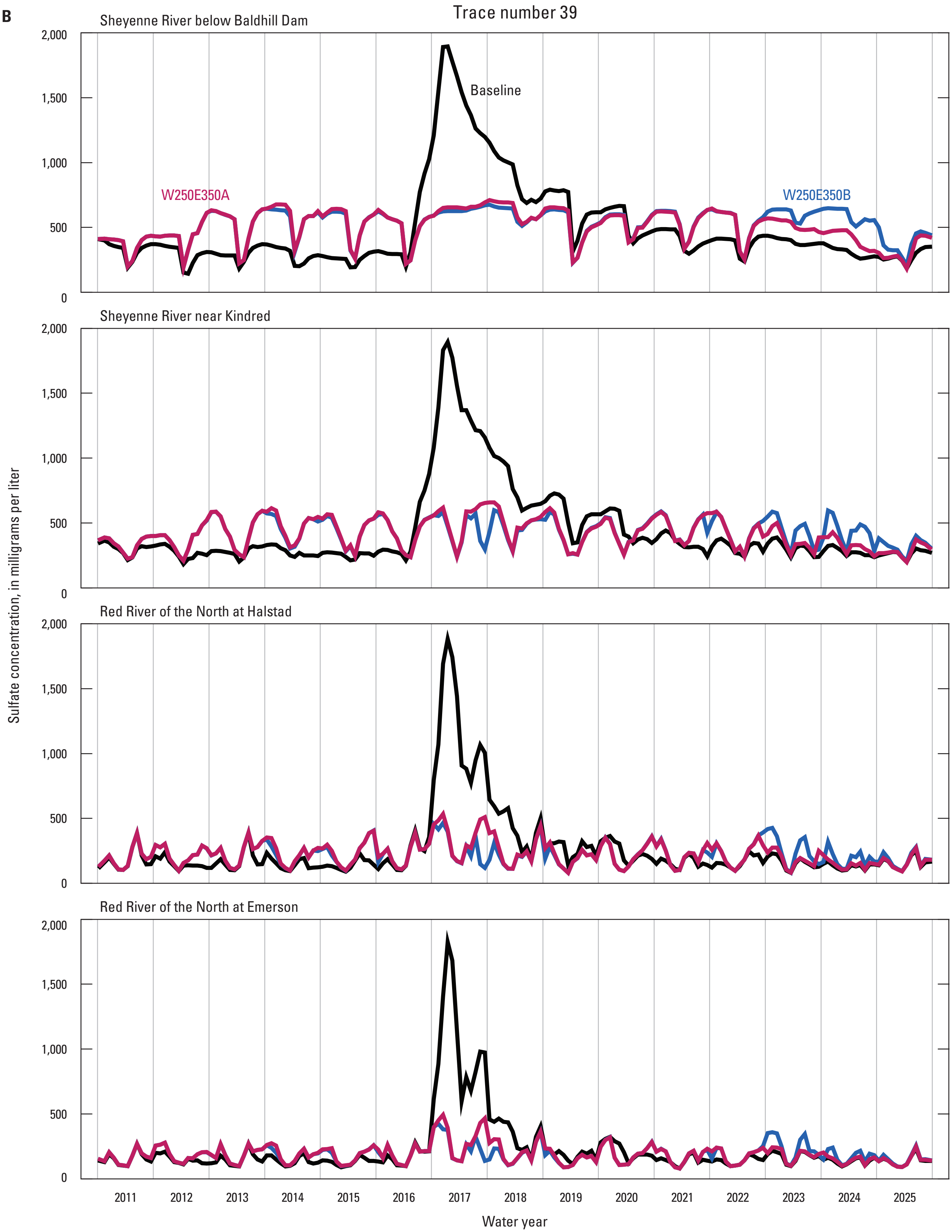

Figure 21. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 39: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

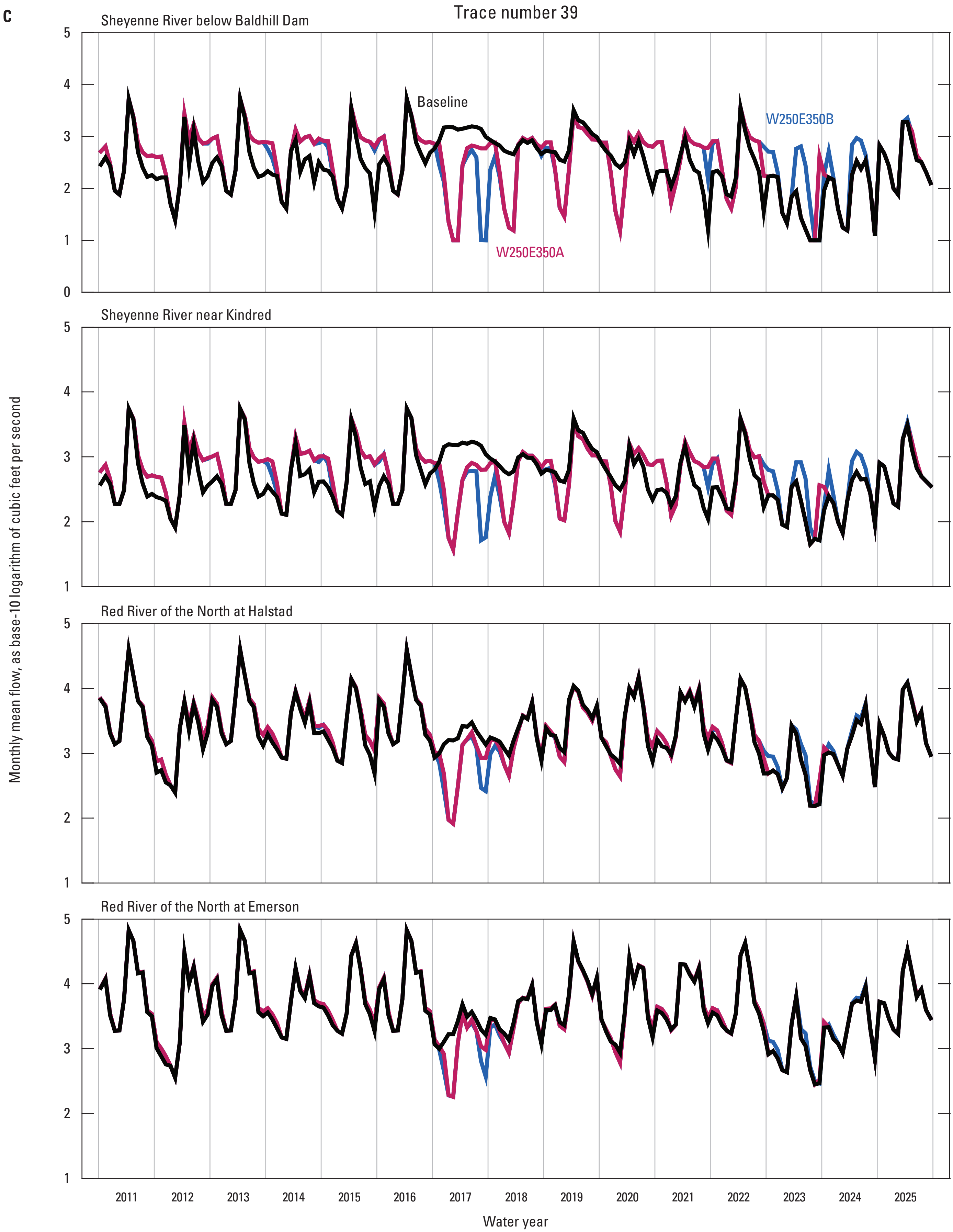

Figure 21. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 39: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and spills from Stump Lake; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

level increased steadily from about 1,455.0 feet in 2011 to about 1,460.0 feet in 2013–14. Even with the outlet, Stump Lake began spilling in 2013, the spills increased rapidly to 1,500 ft^3/s and remained there for more than 2 years, and the Stump Lake outlet eroded down to the base of about 1,451.0 feet. Stump Lake (and as a result, Devils Lake) declined to about 1,451 feet in 2016. Devils Lake sulfate concentrations in the east part of the lake (and in Stump Lake, not shown) declined to about 500 mg/L in 2016 as a result of the spill. Outlet discharges were curtailed during the spill, but began again late in 2016. After that, both outlet scenarios caused the lake to decline below the then 1,451-foot spill elevation but the lake level for the baseline scenario rose above the new spill elevation during 2019–22.

The downstream sulfate concentrations for trace 12 (fig. 22*B*) rose to more than 1,500 mg/L for the below Baldhill Dam and Kindred sites, more than 1,000 mg/L for the Halstad site, and more than 600 mg/L for the Emerson site during the initial stages of the spill. The downstream flows (fig. 22*C*) were elevated as a result of the spill, especially for the below Baldhill Dam and Kindred sites. Flows for Halstad and Emerson during 2013–15 were high, but the peak flows for those years were not particularly high in relation to ambient peak flows for several other years. There happened to be moderate downstream ambient flows during 2013–15, which was fortunate in terms of downstream flooding potential and downstream water-quality effects (compare sulfate concentrations for Halstad and Emerson for figs. 21*B* and 22*B*).

Outlet Effectiveness for Reducing Devils Lake Levels

In this section, the effectiveness of the various outlet alternatives for slowing or preventing lake level rises and for speeding lake drawdown is discussed. The first issue (slowing lake level rise) is best discussed using cumulative exceedance probabilities. The cumulative exceedance probability for a given future year and specified lake level is the percent chance the specified lake level will be exceeded anytime between now and the given future year. The cumulative percent chance exceedance is computed as the percentage of all the generated future traces (5,000 traces in all) that exceed the specified level on or before the given year. The cumulative percent chance of Devils Lake exceeding 1,456.0 feet for the different outlet scenarios is given in table 6. With no outlet (baseline condition), there would be a 16.3 percent chance of exceeding 1,456.0 feet this year (2011). All of the outlet scenarios were the same this year (the existing west-end outlet) and all reduced the chance to 9.5 percent. The baseline condition indicated a 44.1 percent chance of exceeding 1,456.0 feet by the end of next year (2012), compared to about a 28–29 percent chance for the outlet scenarios. The W250E250 and W350E250 outlet scenarios were the same in 2012 because the west-end expansion did not begin operation until 2013, but the W250E350 outlet resulted in a minimal reduction in the chance of exceedance compared to the other scenarios because of the extra 100 ft^3/s from the east-end outlet beginning that year. For subsequent years, the cumulative chances of exceeding 1,456.0 increased, but the increase was relatively modest for all of the outlet scenarios. Furthermore, all of the outlet scenarios resulted in similar exceedance chances. For example, by 2015 there was about a 34–36 percent chance of exceeding 1,456.0 feet for all six of the outlet scenarios, with W250E350A having the least chance (34.2 percent) and W250E250B the greatest (36.1 percent). By 2030, the chances for the outlet scenarios ranged from 37.7 percent for W250E350A to 41.2 percent for W250E250B.

The cumulative percent chance of Devils Lake exceeding 1,458.0 feet (the spill elevation) are given in table 7. For the baseline condition, the chance of a spill was 0.6 percent this year (2011), 14.2 percent by 2012, 27.8 percent by 2015, and 44.7 percent by 2030. For all of the outlet scenarios, the chance of a spill was 0.2 percent this year (2011), about 8.8 percent by 2012, 14.4 to 15.0 percent by 2015, and 16.9 to 18.9 percent by 2030. As for the previous results, there were only modest differences in the exceedance probabilities among the six outlet scenarios, with W250E350A having the least chances and W250E250B the greatest chances. All of the outlet scenarios prevented most baseline spills that occurred after 2015 (for example, trace 39, fig. 21*A*), but many of the baseline spills that occurred before 2015 could not be prevented by any of the scenarios (for example, trace 12, fig. 22*A*).

The other measure of outlet effectiveness is lake drawdown. The faster the lake level can be lowered, the sooner flooded farmland and other property around the lake can be reclaimed, and the more pressure is reduced on roads, levees, and other infrastructure. For discussing drawdown, it is best to use annual exceedance probabilities. The annual percent chance of exceedance for a specified lake level and a given year is the percent chance of exceeding the specified lake level sometime during the given year. The annual percent chance of Devils Lake exceeding 1,458.0 feet (the spill elevation) is given in table 8. For the baseline condition, the chance of a spill was 0.6 percent the first year, peaked at 17.9 percent in 2013, and then declined to 1.4 percent in 2030. For all six outlet scenarios, the results were similar. The chance of a spill was 0.2 percent in 2011, peaked at about 10 percent in 2013, and declined to 0.1 to 0.2 percent in 2030.

The annual percent chance of Devils Lake exceeding 1,454.0 feet (table 9) indicated that for the baseline condition, the chance was 98.9 percent in 2011, 57 percent in 2015, and 10.8 percent in 2030. For all six outlet scenarios, the chance was 94.2 percent in 2011, 16.7 to 22.9 percent in 2015, and 1.1 to 1.6 percent in 2030. All of the outlet scenarios were effective in drawing the lake down compared with the baseline condition. However, the more restrictive sulfate constraint resulted in somewhat slower drawdown than the less restrictive constraint. For example, in 2015, 16.7 percent (W250E350A) to 19.8 percent (W250E250A) of the traces were above 1,454.0 feet for the less restrictive sulfate

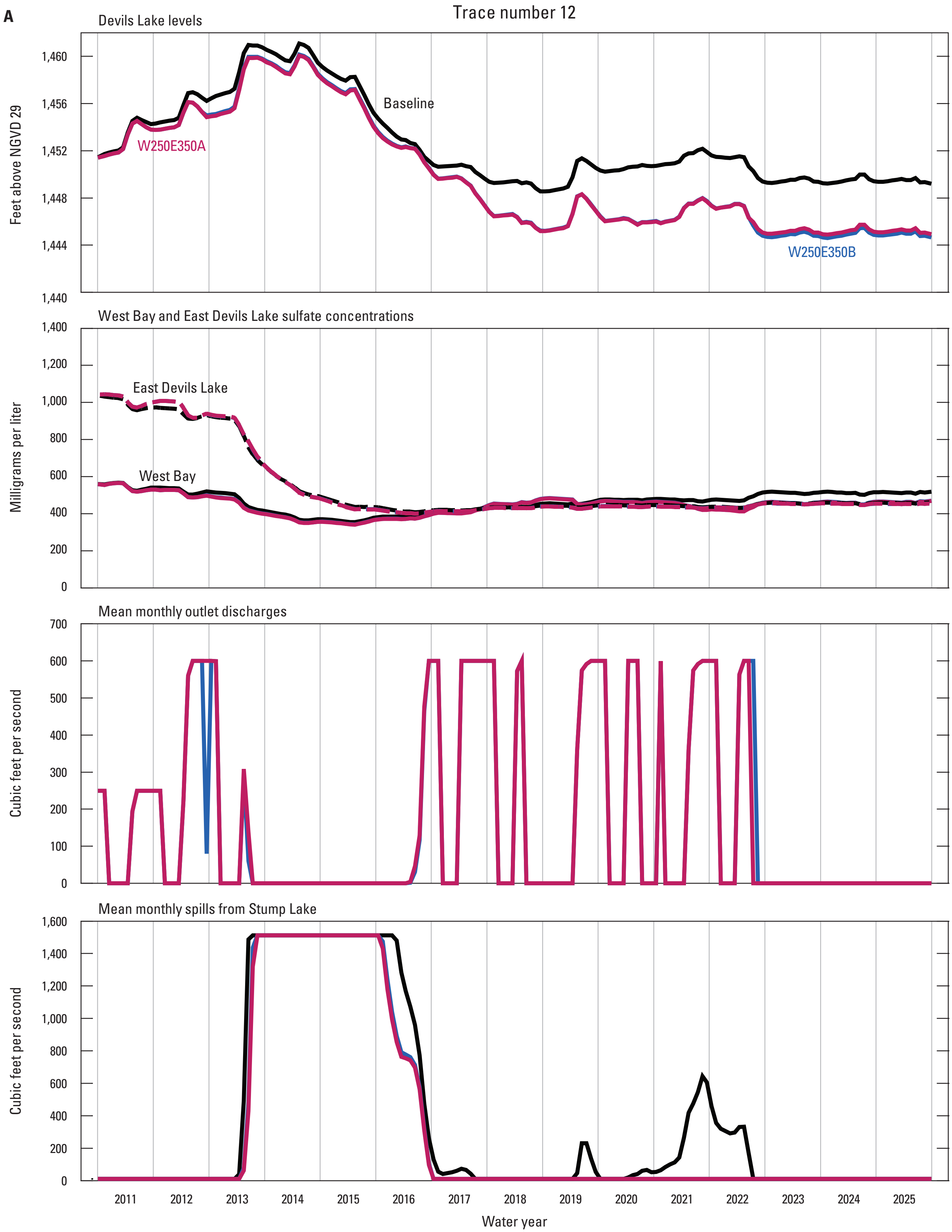

Figure 22. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 12: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and Stump Lake spills; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.

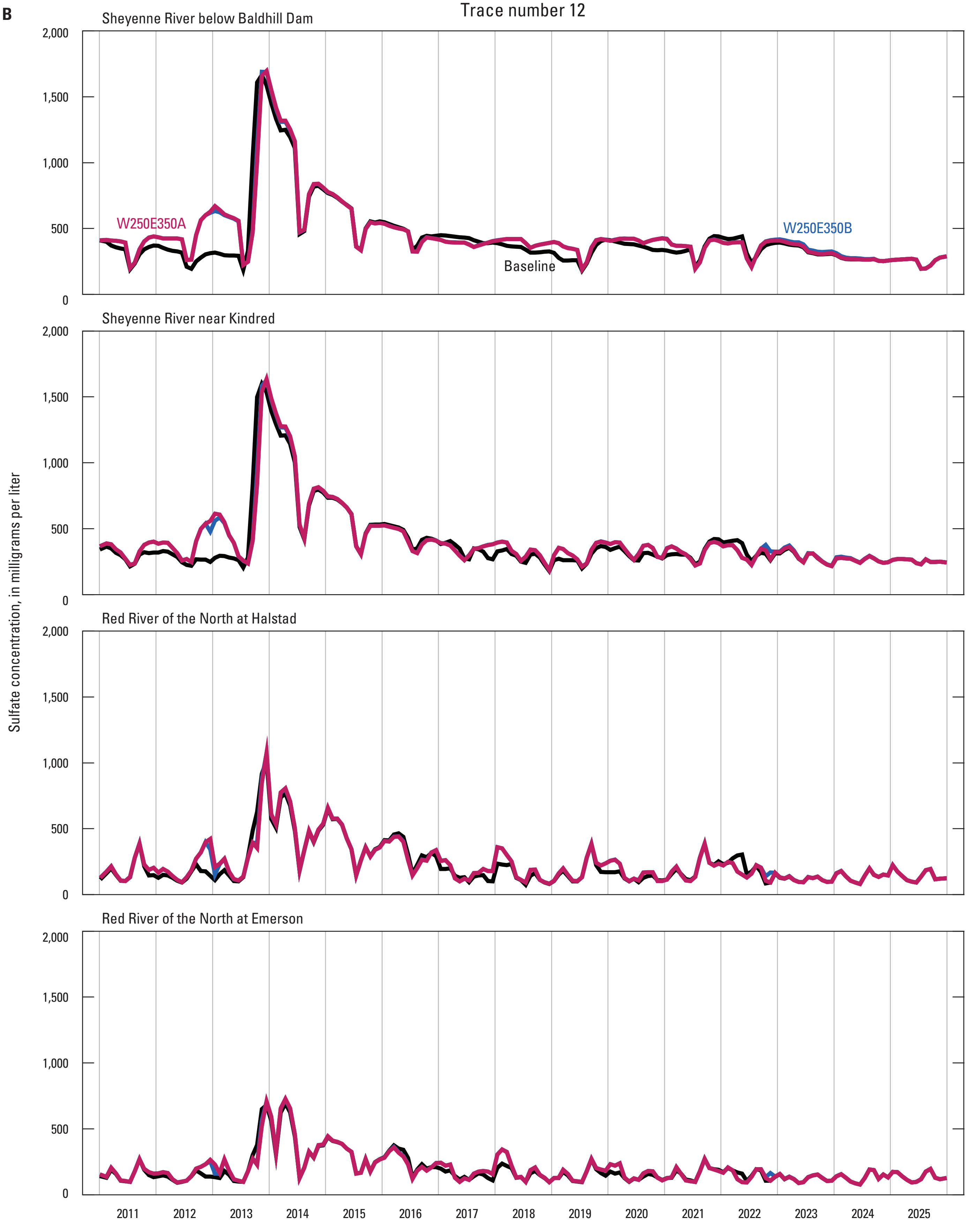

Figure 22. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 12: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and Stump Lake spills; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

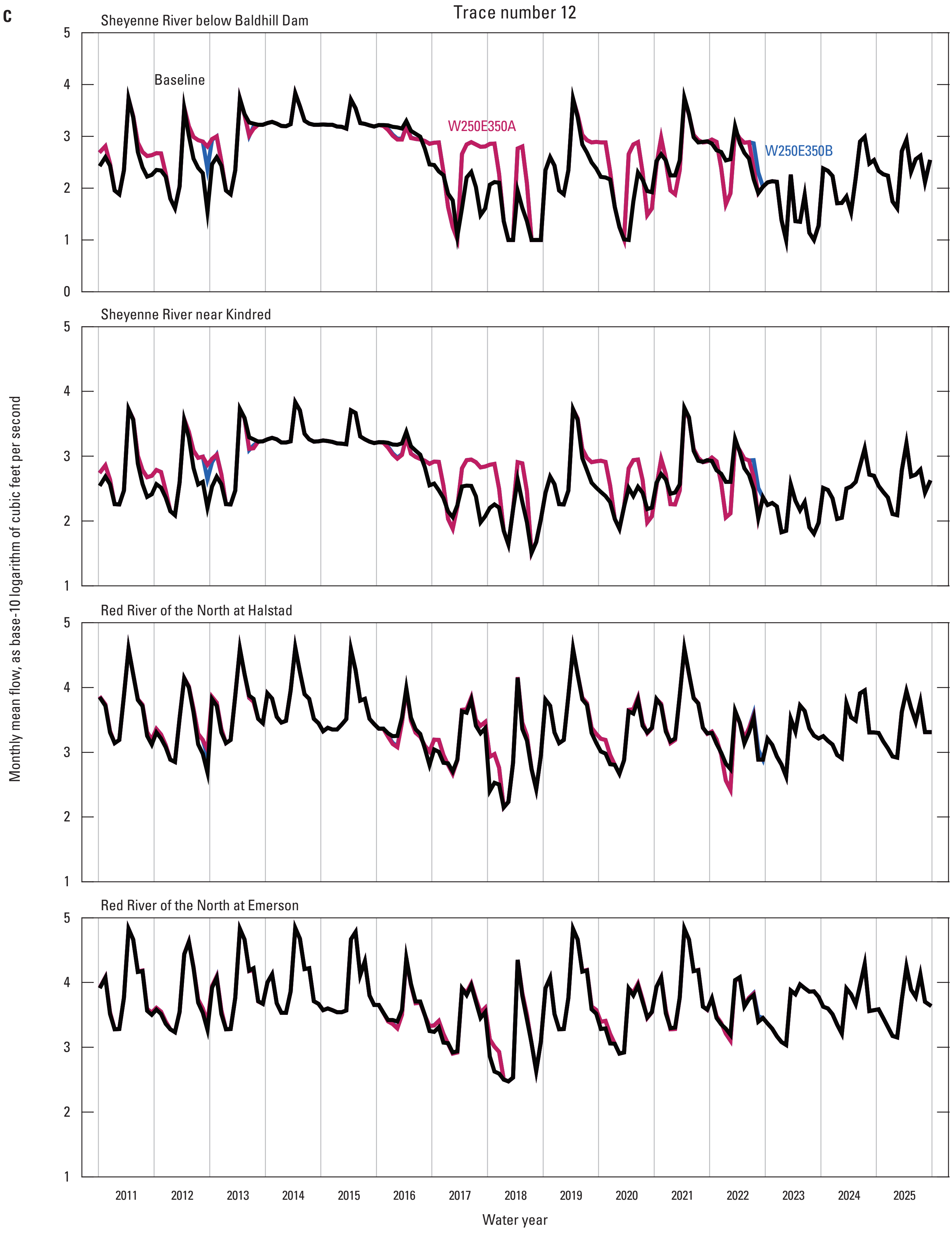

Figure 22. Simulation results for water years 2011–25 for baseline, W250E350A, and W250E350B outlet options for trace 12: *A*) monthly Devils Lake levels and sulfate concentrations, outlet discharges, and Stump Lake spills; *B*) monthly sulfate concentrations for downstream sites; *C*) monthly flows for downstream sites.—Continued

constraint compared with 19.3 percent (W350E250B) to 22.9 percent (W250E250B) for the more restrictive constraint.

The annual percent chance of Devils Lake exceeding 1,450.0 feet (table 10), as with the previous tables, indicated all of the outlet scenarios were effective in drawing the lake down compared with the baseline condition. However, there were substantial differences between the exceedance chances for the less restrictive and more restrictive sulfate constraints. For the baseline condition, the chance the lake would be above 1,450.0 feet is 99 percent in 2015 and 38 percent in 2030. For the outlet scenarios with the 750 milligrams per liter downstream constraint, the chance is 55 to 63 percent in 2015 and about 5 percent in 2030. For the outlet scenarios with the 650 milligrams per liter downstream constraint, the chance is 75 to 80 percent in 2015 and about 6 percent in 2030. In 2015, the best alternative for the less restrictive sulfate constraint was W350E250A, which had a 55.4 percent chance of exceeding 1,450.0 feet. The best alternative for the more restrictive constraint was W350E250B, which had a 75.5 percent chance of exceeding 1,450.0 feet in 2015.

Another more indirect measure of outlet effectiveness is the amount of water that can be discharged relative to the capacity of the outlet. Average April–November outlet discharges for the 5,000 simulated traces were used to compute percentiles of the simulated discharges. The 50th percentile outlet discharge (table 11) is the average April–November outlet discharge below which 50 percent of the traces were observed (or, equivalently, above which 50 percent of

Table 6. Cumulative percent chance of Devils Lake exceeding 1,456.0 feet during 2011–30 for various outlet scenarios.

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	16.3	9.5	9.5	9.5	9.5	9.5	9.5
2012	44.1	29.1	29.1	28.5	29.1	29.1	28.6
2013	51.0	32.9	32.8	31.9	33.2	33.1	32.5
2014	54.9	34.3	34.0	33.2	34.8	34.5	34.1
2015	57.6	35.5	35.0	34.2	36.1	35.7	35.4
2020	64.9	37.7	36.7	36.0	39.1	38.0	38.0
2025	68.8	38.9	37.7	37.0	40.4	39.0	39.1
2030	70.5	39.7	38.3	37.7	41.2	39.7	39.9

Table 7. Cumulative percent chance of Devils Lake exceeding 1,458.0 feet during 2011–30 for various outlet scenarios.

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	0.6	0.2	0.2	0.2	0.2	0.2	0.2
2012	14.2	8.8	8.8	8.7	8.8	8.8	8.7
2013	21.1	12.6	12.5	12.2	12.6	12.6	12.3
2014	24.9	13.9	13.7	13.5	14.0	13.8	13.7
2015	27.8	14.9	14.7	14.4	15.0	14.8	14.7
2020	36.9	16.7	16.0	15.7	17.4	16.6	16.7
2025	41.8	17.4	16.6	16.4	18.3	17.4	17.5
2030	44.7	18.0	17.1	16.9	18.9	17.8	18.0

the traces were observed). In 2011, for all outlet scenarios, 50 percent of the traces averaged at least 212 ft^3/s, compared to the 250 ft^3/s capacity. The reduction from full capacity was primarily because of flow constraints in the upper Sheyenne River. From 2013 to 2015, when all outlets were fully operational and most traces were above the minimum operation level (1,446.0 feet), there were some interesting contrasts between the two sulfate constraints. For the 750 mg/L constraint, the larger outlets (W350E250A and W250E350A) were able to release substantially more water than the smaller outlet (W250E250A). The W350E250A outlet was particularly efficient, releasing essentially the full excess 100 ft^3/s capacity more than the W250E250A outlet. However, for the 650 mg/L sulfate constraint, the median discharge for the larger W250E350B outlet was essentially the same as for the smaller W250E250B outlet, and the W350E250B outlet only averaged about 60 ft^3/s more discharge than the smaller outlet. Later in the simulations, more than 50 percent of the traces were below 1,446.0 feet in any given year, and therefore the 50th percentile discharges were zero for those years.

The 90th percentile discharge (table 12) is the average April–November outlet discharge below which 90 percent of the traces were observed (or, equivalently, above which 10 percent of the traces were observed). The 90th percentile discharges can be used to compare discharges for the wetter traces where the lake level either rises or remains high for longer periods of time. For the 750 mg/L sulfate constraint all of the outlet options had at least 10 percent of the traces where

Table 8. Annual percent chance of Devils Lake exceeding 1,458.0 feet during 2011–30 for various outlet scenarios.

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	0.6	0.2	0.2	0.2	0.2	0.2	0.2
2012	14.2	8.8	8.8	8.7	8.8	8.8	8.7
2013	17.9	9.9	9.8	9.5	10.1	10.1	9.8
2014	12.5	5.5	5.1	5.1	5.7	5.4	5.4
2015	9.1	3.5	3.2	3.1	3.7	3.4	3.5
2020	3.9	.7	.5	.5	.8	.6	.8
2025	2.5	.3	.2	.2	.3	.2	.2
2030	1.4	.2	.1	.2	.2	.1	.2

Table 9. Annual percent chance of Devils Lake exceeding 1,454.0 feet during 2011–30 for various outlet scenarios.

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	98.9	94.2	94.2	94.2	94.2	94.2	94.2
2012	90.2	72.7	72.7	72.3	72.7	72.7	72.4
2013	79.5	46.8	46.5	44.4	50.6	50.4	50.3
2014	69.1	31.1	29.4	28.1	35.4	32.2	34.8
2015	57.0	19.8	17.3	16.7	22.9	19.3	22.3
2020	27.9	4.0	3.0	3.2	4.9	3.7	4.2
2025	17.6	1.9	1.6	1.6	2.3	1.7	2.0
2030	10.8	1.4	1.1	1.1	1.6	1.2	1.2

Table 10. Annual percent chance of Devils Lake exceeding 1,450.0 feet during 2011–30 for various outlet scenarios.

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2012	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2013	100.0	99.5	99.5	99.4	99.9	99.9	99.9
2014	99.9	86.1	81.6	84.8	94.7	93.9	94.6
2015	98.9	63.4	55.4	59.2	79.5	75.5	78.7
2020	73.9	14.3	10.8	11.1	20.0	14.2	17.7
2025	53.6	7.6	6.1	6.1	8.8	7.1	7.8
2030	38.3	5.6	4.7	4.8	6.1	5.1	5.6

Table 11. 50th percentile (for 5,000 simulated traces) of average April–November Devils Lake outlet discharges during 2011–30 for various outlet scenarios.

[discharges in cubic feet per second]

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	0	212	212	212	212	212	212
2012	0	394	394	426	355	355	368
2013	0	448	523	490	336	399	334
2014	0	436	542	486	320	389	318
2015	0	426	523	472	316	374	318
2020	0	0	0	0	167	117	161
2025	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0

Table 12. 90th percentile (for 5,000 simulated traces) of average April–November Devils Lake outlet discharges during 2011–30 for various outlet scenarios.

[discharges in cubic feet per second]

Simulation year	Baseline	A. 750 milligrams per liter sulfate constraint below Baldhill Dam			B. 650 milligrams per liter sulfate constraint below Baldhill Dam		
		W250E250A	W350E250A	W250E350A	W250E250B	W350E250B	W250E350B
2011	0	235	235	235	235	235	235
2012	0	429	429	483	412	412	436
2013	0	498	571	579	458	529	490
2014	0	496	597	579	454	553	489
2015	0	497	596	583	458	551	501
2020	0	486	526	526	434	510	490
2025	0	418	445	445	415	430	429
2030	0	332	341	341	320	338	332

the outlet was operating at near full capacity during 2013–20. For the 650 mg/L constraint, the smaller W250E250B and the larger W350E250B options also operated near capacity for at least 10 percent of the traces during 2013–20. However, the 90th percentiles for the larger W250E350B outlet were considerably smaller than the 600 ft^3/s capacity during 2013–20.

Downstream Water-Quality Effects of Outlet Scenarios

The simulated future traces also were used to evaluate potential future sulfate and TDS concentrations that could be expected to occur downstream as a result of the outlet scenarios from table 5. The 5,000 traces were aggregated to an approximately monthly time scale and the average monthly concentrations were used to compute percentiles for the downstream concentrations. The 50th and 90th percentiles were selected to represent concentrations that could be expected to occur under “normal” conditions and under more extreme conditions, such as relatively dry years when Devils Lake water could provide a substantial part of downstream flows. The percentiles were similar among the three outlet alternatives (W250E250, W350E250, and W250E350). However, the percentiles were sensitive to the downstream sulfate constraint. During periods of declining lake levels and relatively low downstream flows, the 650 milligrams per liter downstream sulfate constraint resulted in reduced outlet discharges and lower downstream concentrations compared with the 750 milligrams per liter constraint.

For the Kindred site and the less restrictive, 750 mg/L, sulfate constraint for below Baldhill Dam (fig. 23), the concentration percentiles were similar among the three outlet alternatives (W250E250A, W350E250A and W250E350A). The 50th percentile concentrations during 2013–15 peaked in November at about 650 mg/L for sulfate and 1,400 mg/L for TDS and then steadily declined after that to about 300 mg/L for sulfate and 800 mg/L for TDS by 2022. The 90th percentile concentrations during 2013–15 peaked in November at about 700 mg/L for sulfate and 1,550 mg/L for TDS and then steadily declined to about 550 mg/L for sulfate and 1,300 mg/L for TDS by 2025.

The concentration percentiles for Kindred for the more restrictive, 650 mg/L, sulfate constraint below Baldhill Dam (fig. 24), again, were similar among the outlet alternatives. Compared to the less restrictive constraint (fig. 23), the percentiles were considerably lower during the early years of the simulation period and more slowly declined during the later years. The 50th percentile concentrations peaked at about 550 mg/L for sulfate and 1,300 mg/L for TDS during 2013–17 before declining to about 300 mg/L for sulfate and 800 mg/L for TDS in 2025. The 90th percentile concentrations peaked at about 600 mg/L for sulfate and 1,350 mg/L for TDS during 2013–17 before declining to about 550 mg/L for sulfate and 1,300 mg/L for TDS in 2025.

For the Halstad site and both downstream constraints (figs. 25 and 26), the concentration percentiles again were similar among the three outlet alternatives (W250E250, W350E250 and W250E350). For the 750 mg/L downstream sulfate constraint (fig. 25), the 50th percentile concentrations during 2013–15 peaked in November at about 350 mg/L for sulfate and 950 mg/L for TDS and then steadily declined after that to about 200 mg/L for sulfate and 600 mg/L for TDS by 2022. The 90th percentile concentrations during 2013–15 peaked in September to November at about 500–550 mg/L for sulfate and 1,200–1,250 mg/L for TDS and then steadily declined to about 300 mg/L for sulfate and 800 mg/L for TDS by 2025.

The concentration percentiles for Halstad for the 650 mg/L downstream sulfate constraint (fig. 26), compared to the 750 mg/L downstream constraint (fig. 25), were considerably lower during the early years of the simulation period and declined more slowly during the later years. The 50th percentile concentrations peaked at about 300 mg/L for sulfate and 800 mg/L for TDS during 2013–15 before slowly declining to about 200 mg/L for sulfate and 600 mg/L for TDS in 2025. The 90th percentile concentrations peaked at about 400 mg/L for sulfate and 1,000 mg/L for TDS during 2013–15 before slowly declining to about 300 mg/L for sulfate and 800 mg/L for TDS in 2025.

For the Emerson site and both downstream constraints (figs. 27 and 28), as for the previous sites, the concentration percentiles were similar among the three outlet alternatives (W250E250, W350E250 and W250E350). For the 750 mg/L downstream sulfate constraint (fig. 27), the 50th percentile concentrations during 2013–15 peaked in December at about 250 mg/L for sulfate and 800 mg/L for TDS and then steadily declined after that to about 200 mg/L for sulfate and 600 mg/L for TDS by 2022. The 90th percentile concentrations during 2013–15 peaked in October to December at about 450–500 mg/L for sulfate and 1,150–1,200 mg/L for TDS and then steadily declined to about 200–250 mg/L for sulfate and 750 mg/L for TDS by 2025.

The concentration percentiles for Emerson for the 650 mg/L downstream sulfate constraint (fig. 28), compared to the 750 mg/L downstream constraint (fig. 27), were considerably lower during the early years of the simulation period and declined more slowly during the later years. The 50th percentile concentrations peaked at about 250 mg/L for sulfate and 800 mg/L for TDS during 2013–15 before slowly declining to about 200 mg/L for sulfate and 600 mg/L for TDS in 2025. The 90th percentile concentrations peaked at about 350 mg/L for sulfate and 950 mg/L for TDS during 2013–15 before slowly declining to about 275 mg/L for sulfate and 750 mg/L for TDS in 2025.

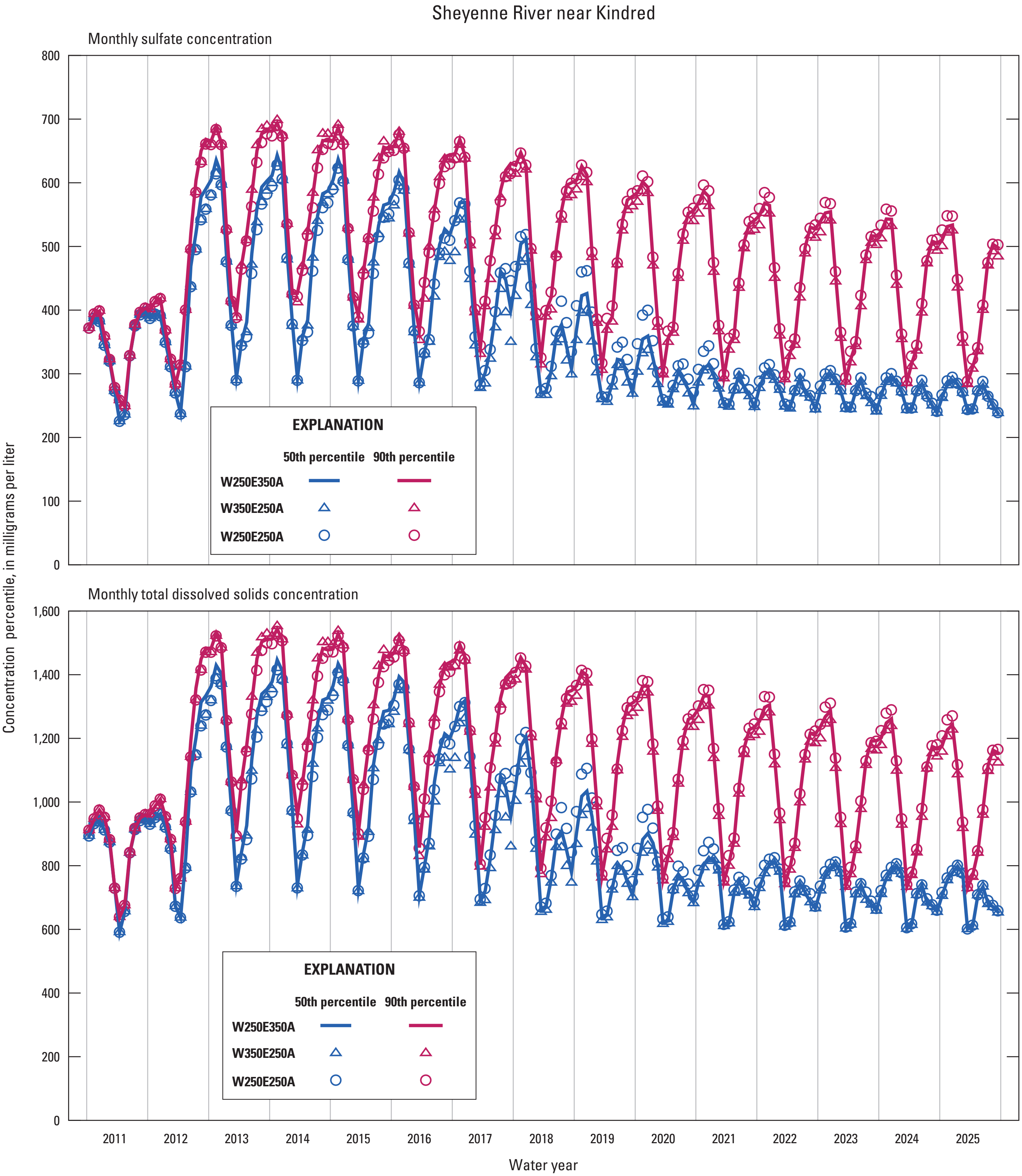

Figure 23. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Sheyenne River near Kindred, North Dakota, for outlet options with 750 milligrams per liter sulfate constraint below Baldhill Dam.

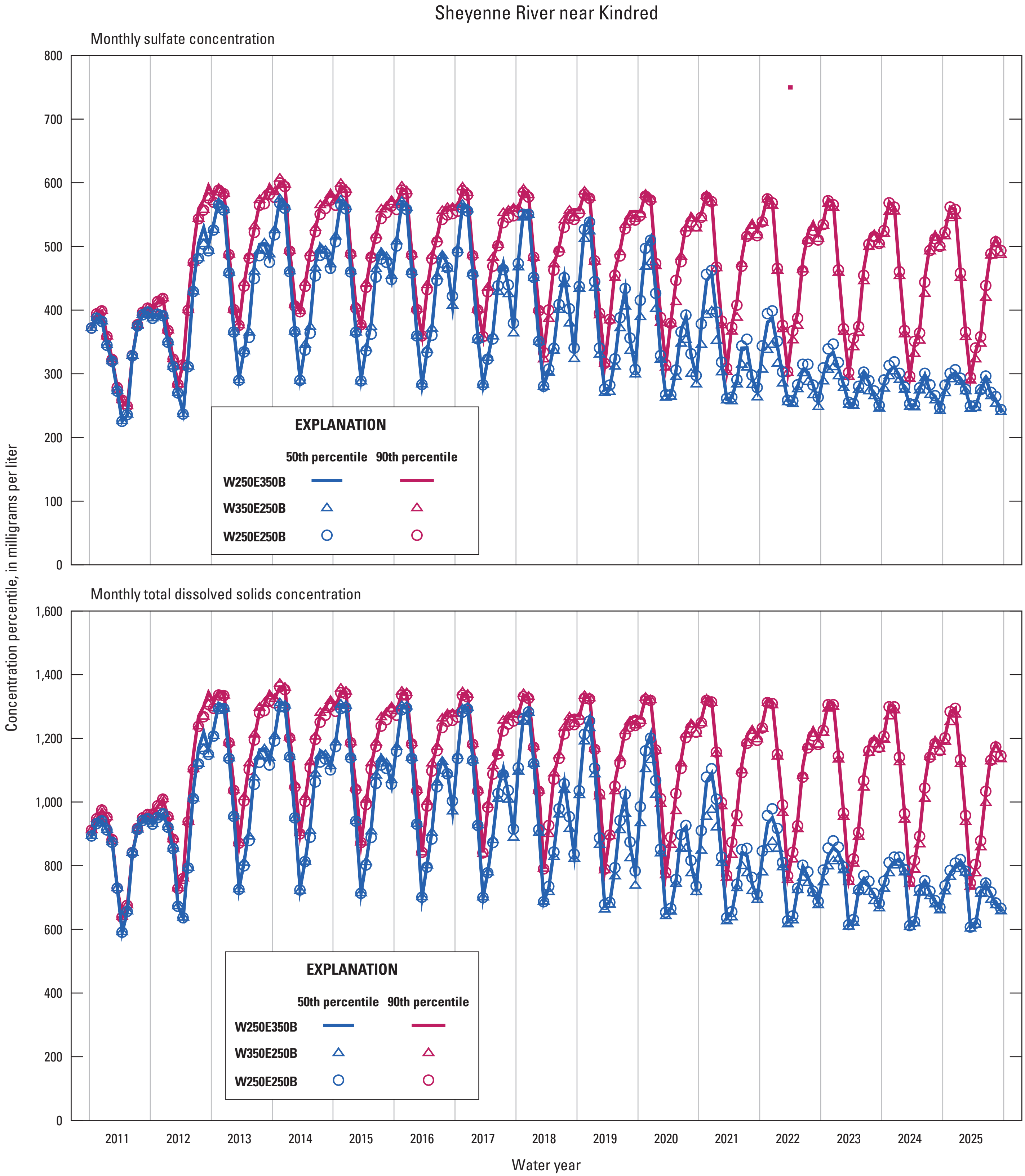

Figure 24. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Sheyenne River near Kindred, North Dakota, for outlet options with 650 milligrams per liter sulfate constraint below Baldhill Dam.

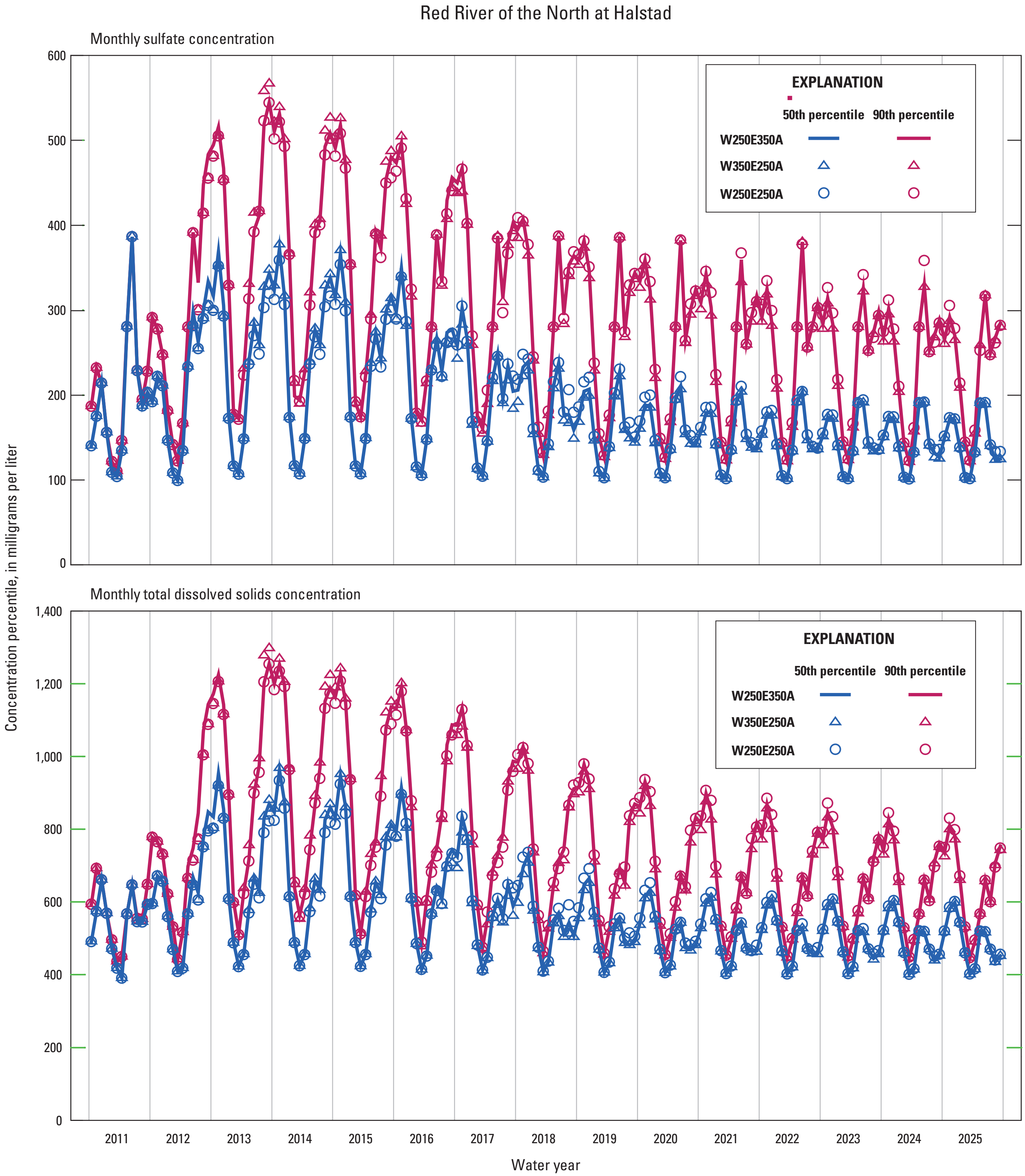

Figure 25. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Red River of the North at Halstad, Minnesota, for outlet options with 750 milligrams per liter sulfate constraint below Baldhill Dam.

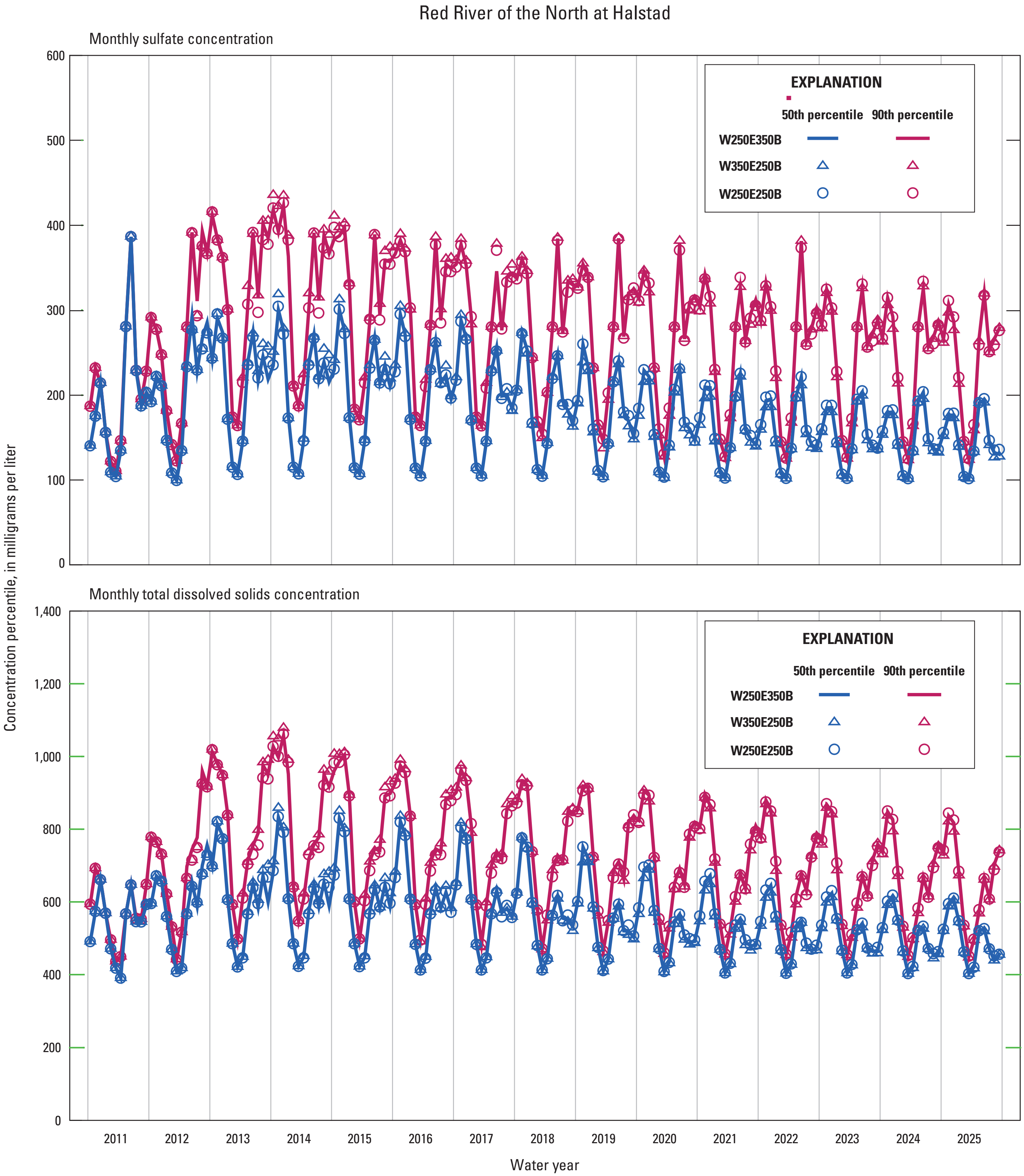

Figure 26. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Red River of the North at Halstad, Minnesota, for outlet options with 650 milligrams per liter sulfate constraint below Baldhill Dam.

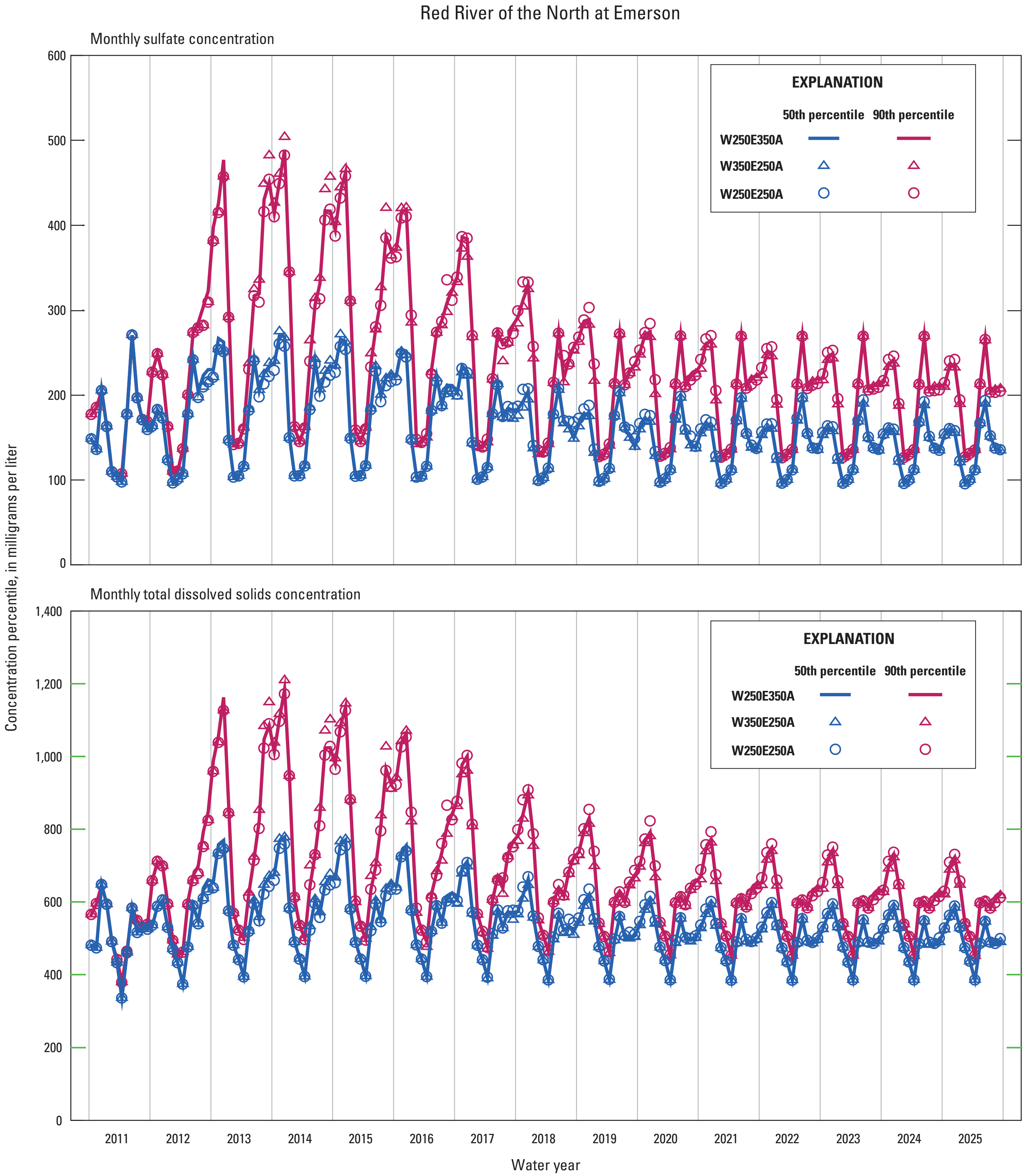

Figure 27. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Red River of the North at Emerson, Manitoba, for outlet options with 750 milligrams per liter sulfate constraint below Baldhill Dam.

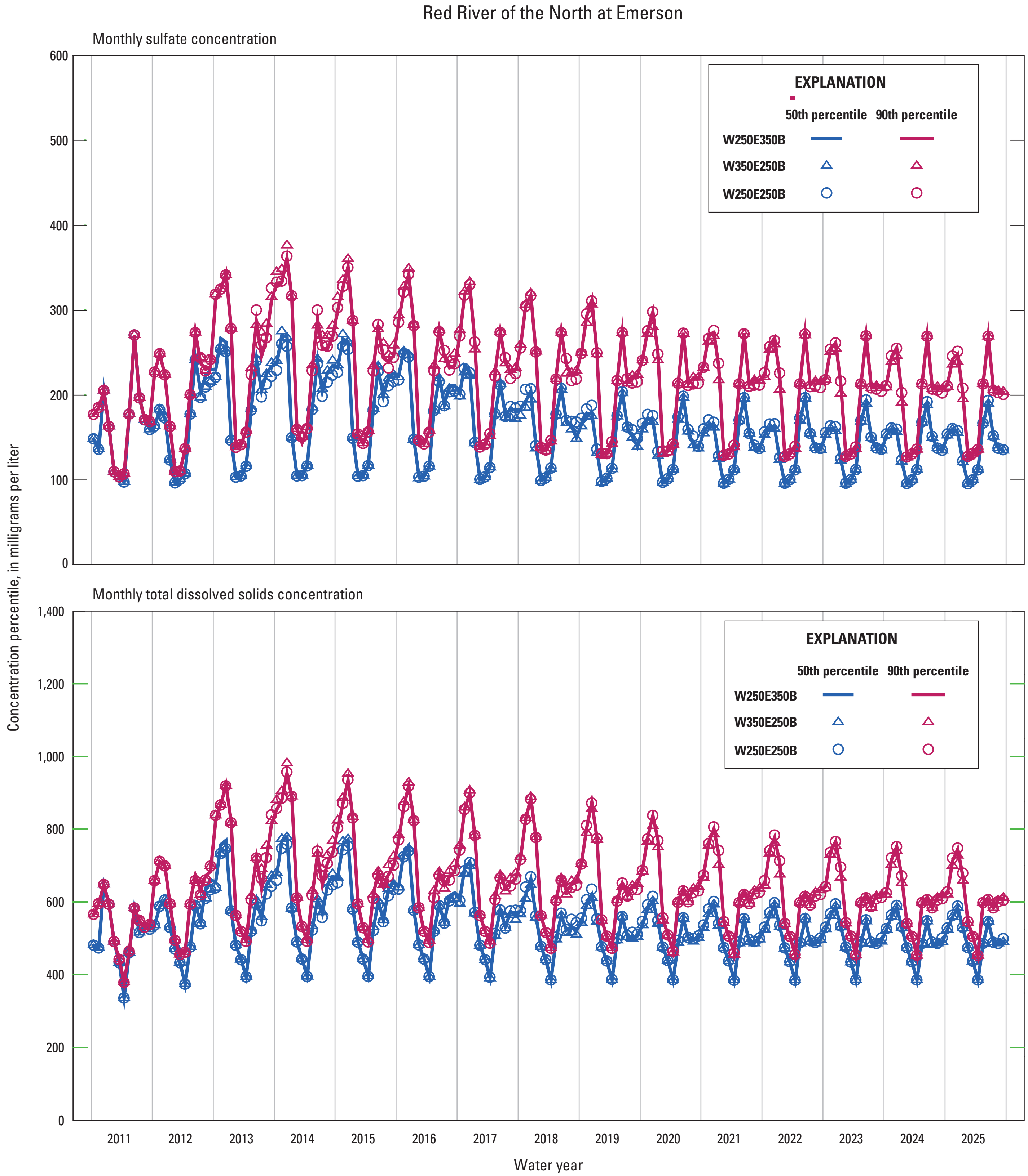

Figure 28. Percentiles of simulated monthly sulfate and total dissolved solids concentrations for water years 2011–25 for the Red River of the North at Emerson, Manitoba, for outlet options with 650 milligrams per liter sulfate constraint below Baldhill Dam.

Summary

The Devils Lake Basin is a 3,810-square-mile subbasin of the Red River of the North (Red River) Basin. At an elevation of 1,446.5 feet, Devils Lake begins to spill into Stump Lake, and at an elevation of 1,458.0 feet, the combined Devils Lake and Stump Lake system begins to spill from Stump Lake, through Tolna Coulee, to the Sheyenne River. In 2007, Devils Lake had filled Stump Lake and the two water bodies essentially became one continuous lake with an elevation of about 1,447.5 feet, a combined volume of about 3 million acre-feet, and a combined surface area of about 140,000 acres. The lakes have continued to rise since 2007, and in 2010 reached an elevation of 1,452.0 feet, with a combined volume of about 3.7 million acre-feet, and a combined surface area of about 180,000 acres. According to National Weather Service predictions from February, 2011, the lake level in 2011 is expected to rise at least 2.5 feet higher than the record level set in 2010, placing it less than 4 feet from the natural spill elevation.

The rising water of Devils Lake and Stump Lake has destroyed hundreds of homes, inundated thousands of acres of productive farmland, and forced the raising of roads, bridges, levees, and other infrastructure to mitigate the rising water. Since 1992, more than $1 billion has been spent by federal, state, and local agencies to address the effects of the rising lake.

The State of North Dakota constructed an outlet from the west end of Devils Lake to the Sheyenne River in 2005, and construction of a second outlet from East Devils Lake is scheduled to begin in 2011. The North Dakota Department of Health (NDDH) is responsible for ensuring that future outlet discharges from Devils Lake, when combined with the downstream receiving waters, are in compliance with applicable Clean Water Act requirements. This study was completed by the USGS in cooperation with NDDH Division of Water Quality to evaluate the effects of various outlet alternatives being considered on downstream water-quality conditions in the Sheyenne River and in the Red River from its confluence with the Sheyenne River to the international border crossing with Manitoba. The USGS Devils Lake stochastic simulation model developed in previous studies was combined with a downstream stochastic flow, sulfate, and TDS (total dissolved solids) routing model described in this report to simulate future outlet discharges and concentrations and resultant downstream flows and concentrations for a 20-year simulation period (2011–30).

Historical flows, sulfate concentrations, and TDS concentrations for seven USGS streamgaging stations were used for developing the downstream stochastic routing model for this study. Flow data for water years 1981–2009 were used to calibrate the model because future climatic conditions for the simulation period (2011–30) are expected to be similar to conditions during 1981–2009. The model was calibrated assuming "ambient" conditions (with no Devils Lake outlet). A numerical reservoir simulation model was developed for tracking the movement of water, sulfate, and TDS through Lake Ashtabula. Historical concentration increases for several of the sites during various times indicate that ambient concentrations during the later part of the calibration period (2000–09) generally were greater than earlier concentrations. Therefore, it was assumed that future concentrations will be more like the recent period, rather than returning to lower levels. After adjusting concentrations by removing historical trends, the downstream routing model calibration resulted in a "population" of 29 years of estimated historical (1981–2009) flow, sulfate concentration, and TDS concentration that could be used to simulate future conditions.

The Devils Lake stochastic simulation model simulates the movement of water and dissolved sulfate though the Devils Lake/Stump Lake system in response to precipitation, evaporation, and inflow, exchange of water and sulfate between the major bays, and flux of sulfate between bottom sediments and lake water. Simulated monthly water-balance variables (precipitation, evaporation, and inflow) for future years are generated using a time series model. The only modifications to the model that were made for this study involve the calculation of sulfate loads for inflows, estimation of TDS concentrations based on dissolved sulfate, and the calculation of flow rates from Tolna Coulee in the event of a spill from Stump Lake. Sulfate loads for inflows were increased by 80 percent over loads estimated using earlier (through 1999) calibration data, an equation for estimating TDS concentration on the basis of simulated sulfate concentrations was developed, and potential spills from Stump Lake were simulated with a proposed control structure to prevent catastrophic outflows in the event of a spill.

The Devils Lake stochastic simulation model and downstream stochastic routing model were combined and used to simulate future conditions for six outlet scenarios being considered, including three alternatives for outlet capacity and location and two alternatives for downstream sulfate concentration constraints. The three alternatives for outlet capacities and locations were: the existing west-end outlet (250 cubic feet per second capacity) combined with a 250-cubic-feet-per-second east-end outlet, the existing west-end outlet combined with a larger 350-cubic-feet-per-second east-end outlet, and a larger 350-cubic-feet-per-second west-end outlet combined with a 250-cubic-feet-per-second east-end outlet. The east-end outlet was assumed to be operational April 1, 2012 and the west-end outlet expansion was assumed to be operational April 1, 2013. Each of the alternatives for the different outlet capacities and locations were run with two separate sulfate concentration constraints for flow below Baldhill Dam—750 and 650 milligrams per liter—to explore how sensitive the outlet discharges and downstream water-quality conditions were to this constraint. In addition, for comparison purposes, a hypothetical baseline condition was simulated in which there was assumed to be no outlet discharges.

The effectiveness of the outlet scenarios for reducing future lake level rises was discussed using cumulative exceedance probabilities. The cumulative exceedance probability for a given future year and specified lake level is the percent

chance the specified lake level will be exceeded anytime between now and the given future year. All of the outlet scenarios resulted in similar reduction in cumulative exceedance probabilities compared with the baseline (no outlet) condition. For the baseline condition, the cumulative percent chance of Devils Lake exceeding 1,458.0 feet (the spill elevation) was 0.6 percent this year (2011), 14.2 percent by 2012, 27.8 percent by 2015, and 44.7 percent by 2030. For all of the outlet scenarios, the chance of a spill was 0.2 percent this year (2011), about 8.8 percent by 2012, 14.4 to 15.0 percent by 2015, and 16.9 to 18.9 percent by 2030. All of the outlet scenarios prevented most baseline spills that occurred after 2015, but many of the baseline spills that occurred before 2015 could not be prevented by any of the scenarios.

The effectiveness of the outlet scenarios for drawing the lake down in future years was discussed using annual exceedance probabilities. The annual percent chance of exceedance for a specified lake level and a given year is the percent chance of exceeding the specified lake level sometime during the given year. All of the outlet scenarios were effective for drawing the lake down compared with the baseline condition. The annual percent chance of Devils Lake exceeding 1,454.0 for the baseline condition was 98.9 percent in 2011, 57 percent in 2015, and 10.8 percent in 2030. For all of the outlet scenarios, the chance was 94.2 percent in 2011, 16.7 to 22.9 percent in 2015, and 1.1 to 1.6 percent in 2030. Although all of the outlet scenarios were effective in drawing the lake down compared with the baseline condition, the more restrictive sulfate constraint for flows below Baldhill Dam (650 milligrams per liter) resulted in somewhat slower drawdown than the less restrictive constraint (750 milligrams per liter). For example, in 2015, for the various outlet capacities and locations, 16.7 percent to 19.8 percent of the traces were above 1,454.0 feet for the less restrictive sulfate constraint compared with 19.3 percent to 22.9 percent for the more restrictive constraint.

The simulated traces also were used to evaluate potential future sulfate and TDS concentrations that could be expected to occur downstream as a result of the outlet scenarios. The simulated concentrations were averaged to an approximately monthly time scale and the average monthly concentrations were used to compute percentiles for the downstream concentrations. The 50th and 90th percentiles were selected to represent concentrations that could be expected to occur under "normal" conditions and under more extreme conditions.

Simulated concentration percentiles were similar among the different outlet capacities and locations, but differed depending on the downstream sulfate constraint for flows below Baldhill Dam. The percentiles were considerably lower during the early years of the simulation period for the more restrictive sulfate constraint (650 milligrams per liter) compared to the less restrictive sulfate constraint (750 milligrams per liter). For the Red River at Halstad, Minnesota, site and the less restrictive sulfate constraint, the 90th percentile concentrations during 2013–15 peaked in September to November at about 500–550 mg/L for sulfate and 1,200–1,250 mg/L for TDS and then steadily declined to about 300 mg/L for sulfate and 800 mg/L for TDS by 2025. The 90th percentile concentrations for the Halstad site for the more restrictive constraint peaked at about 400 mg/L for sulfate and 1,000 mg/L for TDS during 2013–15 before slowly declining to about 300 mg/L for sulfate and 800 mg/L for TDS in 2025. For the Red River at Emerson, Manitoba, site and the less restrictive sulfate constraint, the 90th percentile concentrations during 2013–15 peaked in October to December at about 450–500 mg/L for sulfate and 1,150–1,200 mg/L for TDS and then steadily declined to about 200–250 mg/L for sulfate and 750 mg/L for TDS by 2025. The 90th percentile concentrations for the Emerson site for the more restrictive constraint peaked at about 350 mg/L for sulfate and 950 mg/L for TDS during 2013–17 before declining to about 275 mg/L for sulfate and 750 mg/L for TDS in 2025.

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Appendix. Regression Equations for Downstream Sulfate and Total Dissolved Solids Concentrations

For the downstream stochastic routing model, sulfate and total dissolved solids concentrations needed to be simulated for each 5-day time interval, whereas the available measured concentrations consisted of point samples for intermittent and much sparser sampling intervals. Therefore, regression models (Helsel and Hirsch, 1992) were used to estimate concentration based on flow and time of year. When residuals from the regression models indicated significant time trends that were not accounted for by the explanatory variables based on flow and time of year, trend variables were included as necessary.

Most 5-day intervals had no measured concentrations and the rest generally had a single measured concentration. In rare cases when more than one measured concentration was available for an interval, the concentration value nearest to the midpoint of the interval was used. Based on graphical analysis of the measured concentrations compared to various explanatory variables, the following regression model was selected to represent log-transformed concentration:

$$\hat{E}\{Log(C)\} = b_0 + b_1\,COS1 + b_2\,SIN1 + b_3\,COS2 + b_4\,SIN2 + b_5\,FREV1 + b_6\,FREV1^2 + b_7\,FREV2 + b_8\,FREV2^2 + TREND \qquad \text{(A–1)}$$

where

- *Log(C)* is the base-10 logarithm of sulfate or total dissolved solids concentration, in milligrams per liter (mg/L);
- $\hat{E}\{.\}$ denotes the estimated value of the term within the braces;
- *COS1* is the cosine of $2\pi s$;
- π is the number pi;
- s is the decimal season (s=0 corresponds to Jan. 1 and s=1 to Dec. 31);
- *SIN1* is the sine of $2\pi s$;
- *COS2* is the cosine of $4\pi s$;
- *SIN2* is the sine of $4\pi s$;
- *FREV1* and *FREV2* are flow-related explanatory variables defined later;
- *TREND* is a trend term defined later; and
- $b_0, \ldots, b_8$ are regression coefficients.

The cosine and sine terms with periods of one year (*COS1* and *SIN1*) and one-half year (*COS2* and *SIN2*) were included to model seasonal variability. For the Dazey site, only *COS1* and *SIN1* were included because the seasonal coverage of measured concentrations was too sparse to fit the terms for *COS2* and *SIN2*. The flow-related explanatory variables are dimensionless variables computed using the 5-day mean flows for the specified streamgage site or intervening reach:

$$FREV1 = AVE_{90}\{Log(Q)–M\}$$

where

- *FREV1* is flow-related explanatory variable number 1 (dimensionless);
- *Log(Q)* is the base-10 logarithm of 5-day mean flow, in cubic feet per second (ft^3/s);
- *M* is the mean of *Log(Q)* for 1981–2009; and
- $AVE_{90}\{.\}$ is the average of the deviations of *Log(Q)* from *M* for 90 days (eighteen 5-day intervals) up to and including the current time step; and

$$FREV2 = Log(Q)–M–FREV1$$

where

- *FREV2* is flow-related explanatory variable number 2 (dimensionless).

Using two flow-related explanatory variables, one representing seasonal variability (*FREV1*) and the other short-term deviations from seasonal variability (*FREV2*), resulted in a better fit than just using *Log(Q)–M*, which is the variable that is often used in a regression of concentration on flow. The squared terms ($FREV1^2$ or $FREV2^2$) were included only if the individual p-value (attained significance level) for the respective term was less than 0.10. The form of the trend term depended on individual sites as discussed later.

The fitted regression coefficients are given in tables A1 (sulfate) and A2 (total dissolved solids). For the upstream sites (Warwick, Cooperstown, and Dazey), the flow-related explanatory variables were computed using gaged flows for each site, and ordinary least-squares regression (Helsel and Hirsch, 1992) was used to fit the model (A–1) to measured concentrations for each site. The trend term for both the Warwick and Cooperstown sites consisted of a linear trend from the beginning of 1999 to the end of 2000:

$$TREND = \gamma\{0.5(t–1999)\,I[1999 < t < 2001] + I[t \geq 2001]\} \qquad \text{(A–2)}$$

where

- γ is the trend coefficient;
- t is decimal year (expressed in calendar years); and
- I[.] is the indicator function that equals 1 if t in in the given interval, 0 otherwise.

The fitted trend coefficients and p-values indicated significant uptrends for sulfate for the Warwick and Cooperstown sites, and total dissolved solids for the Cooperstown site. The trends in log-units can be converted to percent change using *PC*(1999–2000)=100(10^{γ}–1) where *PC*(1999–2000) is the percent change in concentration from the beginning of 1999 to the end of 2000. For example, estimated sulfate concentration for Warwick increased 100($10^{0.194}$–1)=56 percent. Fitted log-transformed concentrations from the model were untransformed and multiplied by the bias correction factors (BCFs) shown in tables A1 and A2 to obtain estimated concentrations. The BCF is the mean of the measured concentrations divided by the mean of the untransformed fitted concentrations. Scatterplots of the estimated compared to measured concentrations are shown in figure A1. The coefficient of determination (RSQ in tables A–1 and A–2, expressed in terms of untransformed concentrations) ranged from 66 to 81 percent for the three upstream sites.

Measured incremental flows and concentrations for the downstream intervening reaches were not available, so a sequential procedure for obtaining estimated incremental flows and concentrations was used. Estimated flow and concentration for the below Baldhill Dam site were computed using the Lake Ashtabula simulation model described in the next section. Incremental flow for the intervening reach from below Baldhill Dam to Kindred was estimated using the following equation:

$$\hat{E}\{Log(Q_K)\} = Log(\hat{E}\{Q_{BBH(-5)}\} + \hat{E}\{Q_{KI}\}) \qquad \text{(A–3)}$$

where

Q_K is flow for the Kindred site;

$Q_{BBH(-5)}$ is flow for below Baldhill Dam (lagged 5 days); and

Q_{KI} is incremental flow for the Kindred site.

Nonlinear least-squares regression was used to obtain the best fit between $Log(Q_K)$ and the estimated values from (A–3), with $\hat{E}\{Q_{KI}\}$ expressed in terms of flows for the Dazey site and time of year, resulting in the following estimate for the incremental flows:

$$\hat{E}(Q_{KI}) = (1.16)\ 10^{1.60-0.117\ COS1\ +0.102\ SIN1-0.146\ COS2-0.047\ SIN2+0.33\ Log(Q_D)} \qquad \text{(A–4)}$$

where

Q_D is flow for the Dazey site.

The multiplier (1.16) in equation (A–4) was selected so that the untransformed estimated flows for Kindred (obtained by exponentiating the estimates from eq. A–3) had the same mean as the measured flows for Kindred. Estimated compared to measured flows for the Kindred site are shown in fig. A2.

Next, concentrations for Kindred incremental flows were estimated using the following equation:

$$\hat{E}\{Log(C_K)\} = Log([\hat{E}\{C_{BBH(-5)}\}\hat{E}\{Q_{BBH(-5)}\} + \hat{E}\{C_{KI}\}\hat{E}\{Q_{KI}\}]/[\hat{E}\{Q_{BBH(-5)}\} + \hat{E}\{Q_{KI}\}]) \qquad \text{(A–5)}$$

where

C_K is concentration for the Kindred site;

$C_{BBH(-5)}$ is concentration for the below Baldhill Dam site (lagged 5 days); and

C_{KI} is concentration for Kindred incremental flows.

Nonlinear least-squares was used to obtain the best fit between $Log(C_K)$ and the estimated values from (A–5), with $\hat{E}\{C_{KI}\}$ determined using eq. (A–1) to compute fitted values for log-transformed incremental concentration (estimated coefficients are given in tables A1 and A2; flow-related explanatory variables were computed using $\hat{E}\{Q_{KI}\}$), untransforming the fitted values, and applying a bias correction factor. The trend in concentration for the Kindred incremental flows consisted of a linear trend from the beginning to the end of 1994:

$$TREND = \gamma\ \{(t\text{–}1994)\ \mathrm{I}[1994< t < 1995] + \mathrm{I}[t \geq 1995]\}, \qquad \text{(A–6)}$$

and the fitted coefficient indicated a significant uptrend for sulfate and a nonsignificant uptrend for total dissolved solids. Estimated compared to measured concentrations for the Kindred site are shown in figure A3. The coefficient of determination was 65 percent for sulfate and 60 percent for dissolved solids.

Incremental flow for the intervening reach between the Kindred and Halstad sites was estimated using straight subtraction of the routed flow from Kindred and the flow for Halstad:

$$\hat{E}\{Q_{HI}\} = Q_H – \hat{E}\{Q_{K(-5)}\} \qquad \text{(A–7)}$$

where

Q_{HI} is incremental flow for the Halstad site;

Q_H is flow for the Halstad site; and

$Q_{K(-5)}$ is flow for the Kindred site (lagged 5 days).

Concentration for incremental Halstad flow was estimated in a similar manner to the previous intervening reach:

$$\hat{E}\{Log(C_H)\} = Log([\hat{E}\{C_{K(-5)}\}\hat{E}\{Q_{K(-5)}\} + \hat{E}\{C_{HI}\}\ \hat{E}\{Q_{HI}\}]/[\hat{E}\{Q_{K(-5)}\} + \hat{E}\{Q_{HI}\}]) \qquad \text{(A–8)}$$

where

C_H is concentration for the Halstad site;

$C_{K(-5)}$ is concentration for the Kindred site (lagged 5 days); and

C_{HI} is concentration for Halstad incremental flows.

The estimated compared to measured concentrations are shown in figure A4. The coefficient of determination was 43 percent for sulfate and 45 percent for dissolved solids. There were no trends detected in sulfate or dissolved solids concentration for Halstad incremental flow.

Table A1. Fitted regression coefficients for log-transformed dissolved sulfate concentration for streamgage sites and intervening reaches.

[COS1, cosine of 2πs; SIN1, sine of 2πs; COS2, cosine of 4πs; SIN2, sine of 4πs; FREV1, flow-related explanatory variable; FREV2, flow-related explanatory variable; RSQ, coefficient of determination; BCF, bias-correction factor; %, percent; --, coefficient not included; <, less than]

Streamgage site or intervening reach	Coefficient (and p-value) for specified explanatory variables*										RSQ	BCF
	Intercept	COS1	SIN1	COS2	SIN2	FREV1	FREV1^2	FREV2	FREV2^2	TREND**		
Warwick	2.021 (<.001)	-0.146 (.066)	-0.064 (.112)	-0.051 (.213)	-0.137 (.001)	0.162 (<.001)	--	-0.039 (.279)	--	(a) 0.194 (<.001)	79%	1.030
Cooperstown	2.229 (<.001)	.069 (.003)	.021 (.229)	.021 (.248)	-.060 (<.001)	.147 (<.001)	--	-.103 (.002)	-.055 (.016)	(a) .122 (<.001)	73%	1.020
Dazey	2.208 (<.001)	-.224 (.076)	.081 (.102)	--	--	-.036 (.443)	--	-.054 (.463)	-.074 (.005)	--	66%	1.046
Below Baldhill Dam to Kindred	2.185 (<.001)	.026 (.447)	.088 (.001)	-.034 (.309)	-.033 (.155)	.045 (.628)	--	-.227 (.023)	--	(b) .194 (<.001)	65%	1.062
Kindred to Halstad	1.892 (<.001)	.013 (.730)	.056 (.168)	-.046 (.161)	-.134 (<.001)	.248 (<.001)	.237 (.010)	-.208 (.011)	--	--	43%	1.098
Halstad to Emerson	2.050 (<.001)	-.138 (<.001)	-.036 (.206)	.000 (.999)	-.135 (<.001)	-.183 (<.001)	--	-.143 (.006)	--	(c) -.239 (.002) (d) .023 (<.001)	39%	1.143

* Regression equation and explanatory variables defined in eq. (A–1).

** Trend variables defined in (a) eq. (A–2); (b) eq. (A–6); (c) eq. (A–11); (d) eq. (A–12).

Table A2. Fitted regression coefficients for log-transformed total dissolved solids concentration for streamgage sites and intervening reaches.

[COS1, cosine of 2πs; SIN1, sine of 2πs; COS2, cosine of 4πs; SIN2, sine of 4πs; FREV1, flow-related explanatory variable; FREV2, flow-related explanatory variable; RSQ, coefficient of determination; BCF, bias-correction factor; %, percent; --, coefficient not included; <, less than]

Streamgage site or intervening reach	Coefficient (and p-value) for specified explanatory variables*										RSQ	BCF
	Intercept	COS1	SIN1	COS2	SIN2	FREV1	FREV1^2	FREV2	FREV2^2	TREND**		
Warwick	2.686 (<.001)	-0.123 (.134)	-0.074 (.075)	-0.017 (.707)	-0.108 (.034)	0.127 (.002)	--	-0.005 (.907)	-0.060 (.039)	(a) 0.066 (.141)	73%	1.024
Cooperstown	2.774 (<.001)	.054 (.001)	.021 (.086)	.018 (.166)	-.029 (.007)	.093 (<.001)	--	-.150 (<.001)	--	(a) .082 (<.001)	81%	1.009
Dazey	2.760 (<.001)	-.074 (.379)	.027 (.438)	--	--	-.024 (.457)	--	-.069 (.178)	-.064 (.001)	--	79%	1.019
Below Baldhill Dam to Kindred	2.800 (<.001)	.094 (.002)	.086 (<.001)	-.046 (.115)	-.002 (.914)	.169 (.039)	--	-.303 (.001)	-.167 (.043)	(b) .045 (.152)	60%	1.040
Kindred to Halstad	2.602 (<.001)	.048 (.016)	.009 (.620)	-.003 (.871)	-.056 (<.001)	.063 (.045)	.069 (.092)	-.098 (.023)	--	--	45%	1.024
Halstad to Emerson	2.729 (<.001)	-.041 (.046)	-.002 (.909)	.005 (.789)	-.052 (.001)	-.122 (<.001)	--	-.161 (<.001)	--	(c) -.224 (<.001) (d) .016 (<.001)	52%	1.052

* Regression equation and explanatory variables defined in eq. (A–1).

** Trend variables defined in (a) eq. (A–2); (b) eq. (A–6); (c) eq. (A–11); (d) eq. (A–12).

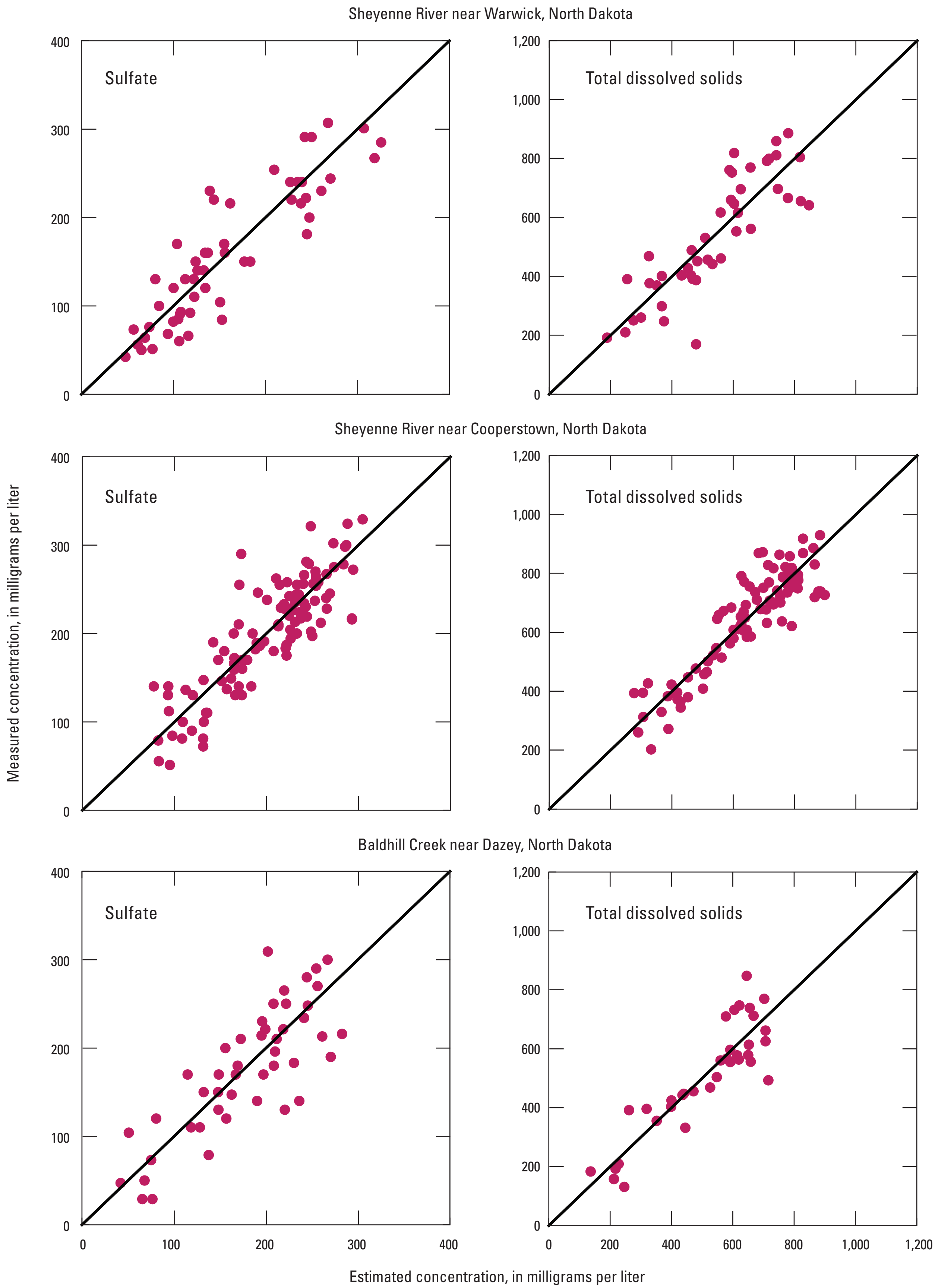

Figure A1. Estimated compared to measured sulfate and total dissolved solids concentrations for the Sheyenne River near Warwick, Sheyenne River near Cooperstown, and Baldhill Creek near Dazey, North Dakota, sites.

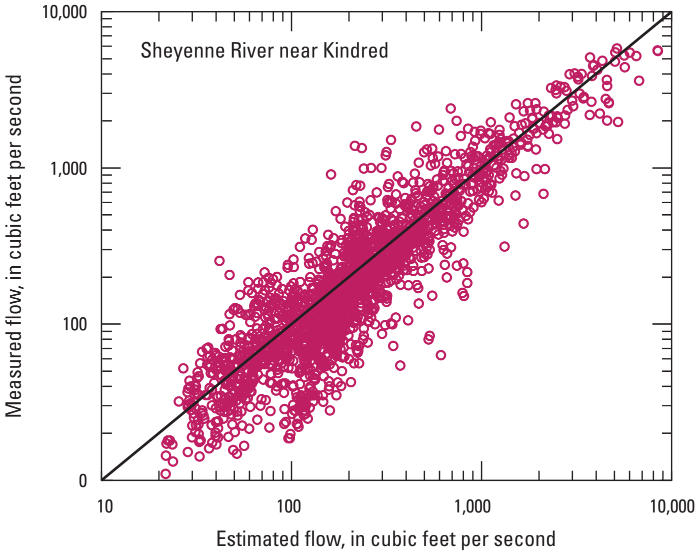

Figure A2. Estimated compared to measured 5-day mean flows for the Sheyenne River near Kindred, North Dakota.

Incremental flow for the intervening reach between the Halstad and Emerson sites was estimated using straight subtraction of the routed flow from Halstad and the flow for Emerson:

$$\hat{E}\{Q_{EI}\} = Q_E - Q_{H(-10)} \tag{A–9}$$

where

Q_{EI} is incremental flow for the Emerson site;
Q_E is flow for the Emerson site ; and
$Q_{H(-10)}$ is flow for the Halstad site (lagged 10 days).

Concentration for Emerson incremental flow was estimated in a similar manner to the previous reaches:

$$\hat{E}\{Log(C_E)\} = Log([\hat{E}\{C_{H(-10)}\}Q_{H(-10)} + \hat{E}\{C_{EI}\}\hat{E}\{Q_{EI}\}]/[Q_{H(-10)} + \hat{E}\{Q_{EI}\}]) \tag{A–10}$$

where

C_E is concentration for the Emerson site;
$C_{H(-10)}$ is concentration for the Halstad site (lagged 10 days); and
C_{EI} is concentration for Emerson incremental flow.

There were two concentration trends detected for Emerson incremental flow—a linear trend from the beginning of 1995 to the end of 1997:

$$TREND1 = \gamma_1\{(1/3)\,(t\text{–}1995)\ I[1995 < t < 1998] + I[t \geq 1998]\}, \tag{A–11}$$

and a linear trend for 1980–2008:

$$TREND2 = \gamma_2\ \{(t\text{–}1994)\ I[1980 < t < 2009] + I[t \geq 2009]\}. \tag{A–12}$$

The fitted trend coefficients (tables A1 and A2) indicated significant downtrends for sulfate and dissolved solids for 1995–98 combined with significant uptrends for both constituents during 1980–2008. The long-term trend coefficient (A–12) is expressed as a change (in log units) per year, whereas the other coefficient (A–11) is expressed as a change (in log units) for the 3-year interval. For example, the estimated percent change in sulfate concentration during 1995–98 is $100(10^{-0.239}-1) = -42$ percent, and the estimated percent change during 1980–2008 is $100(10^{0.023}-1)=5.4$ percent per year. The net effect of the two trends is an increase of $100(10^{-0.239+28(0.023)}-1)=66$ percent from 1980 to 2008. The estimated compared to measured concentrations are shown in figure A4. The coefficient of determination was 39 percent for sulfate and 52 percent for dissolved solids.

Lake Ashtabula Simulation Model

Baldhill Dam, which creates Lake Ashtabula, is located on the Sheyenne River approximately 271 river miles upstream from the confluence with the Red River of the North (fig. 4). Lake Ashtabula has a capacity of approximately 70,600 acre-feet (acre-ft) at the conservation pool elevation (1,266 ft above NGVD 1929) and a capacity of 101,300 acre-ft at the elevation of the top of the flood pool (1,271 ft above NGVD 1929) (U.S. Army Corps of Engineers, 2007). Most of the inflow to the reservoir comes from the Sheyenne River and Baldhill Creek.

From the end of the spring runoff season (generally about June 1) through about October 31, the outflow is maintained to hold the lake level close to the conservation pool elevation. From about November 1 to December 31, the lake is drawn down to about 1,262 feet (volume of about 50,000 acre-ft) to provide flood-control storage for the following spring. Depending on snowpack conditions and flood forecasts for the spring runoff season, the lake may be drawn down further (usually during March) to provide more flood control storage. During years with normal to low spring runoff conditions, the lake is gradually brought up to the conservation elevation (usually from mid-March or early April to the end of May). During years with substantial spring runoff, the lake may be raised above the conservation elevation and slowly lowered to conservation elevation as downstream flooding subsides.

The Lake Ashtabula simulation model is a simple storage model consisting of three equal-volume reservoir compartments used to estimate inflows, storage volumes and concentrations (sulfate and dissolved solids), net evaporation, and outflows. The model will be expressed in terms of a numerical

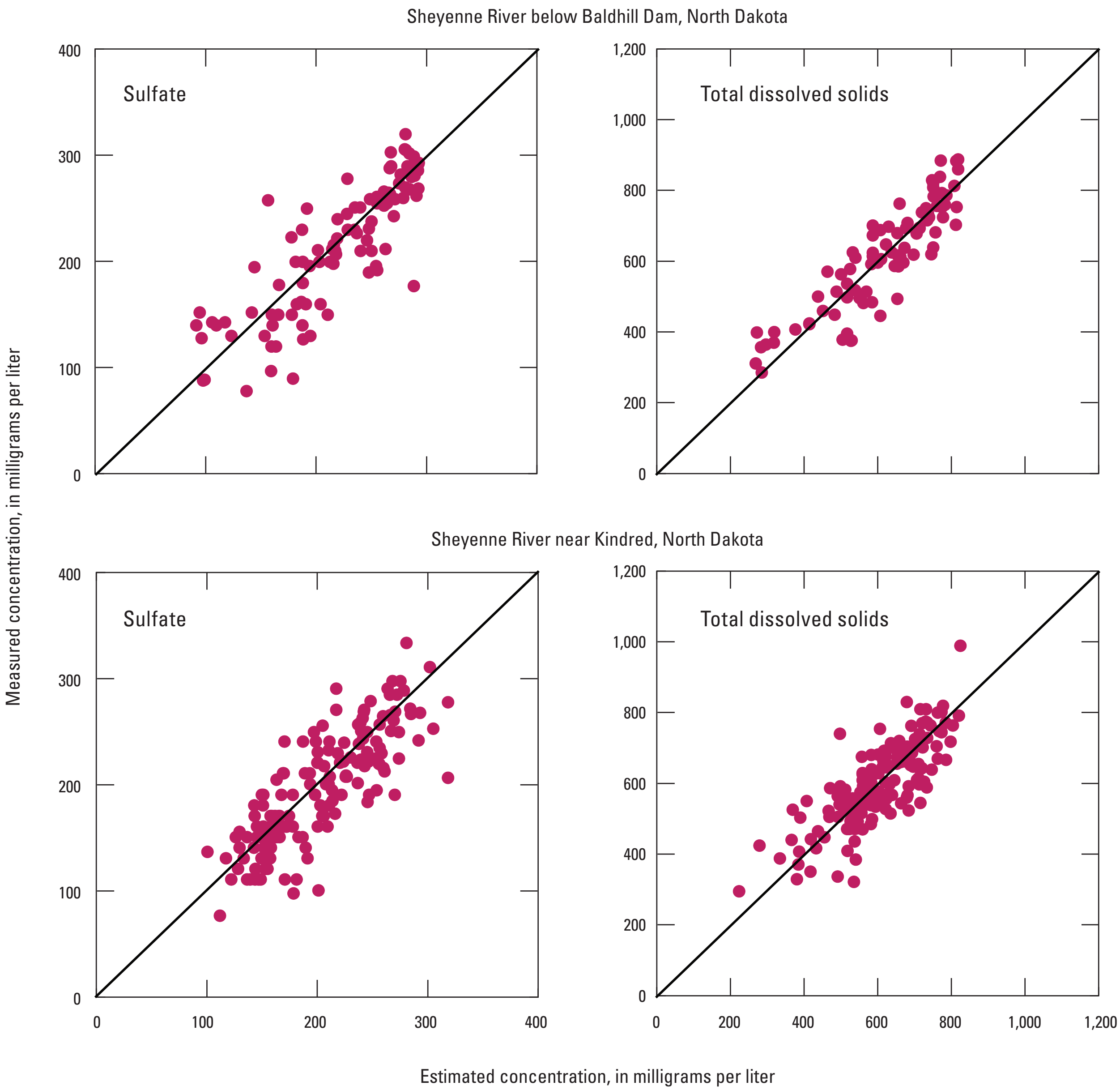

Figure A3. Estimated compared to measured sulfate and total dissolved solids concentrations for the Sheyenne River below Baldhill Dam and near Kindred, North Dakota, sites.

algorithm. The following definitions will be used for describing the algorithm:

- *VJ* is the volume of water stored in the *J*th reservoir compartment (RES1, RES2, or RES3; fig. 5) at the end of the current time step, in acre-feet;
- *RV* is a fixed "reference" volume (defined below) for the current time step, in acre-feet;
- *CJ* is the concentration (either sulfate or dissolved solids) of the *J*th compartment at the end of the current time step, in milligrams per liter;
- *IJ* is inflow to the *J*th compartment for the current time step, in acre-feet;
- *CIJ* is concentration of inflow to the *J*th compartment, in milligrams per liter;
- *NE* is net evaporation (precipitation minus evaporation) for the *J*th compartment for the current time step, in acre-feet;
- *VO* is outflow volume (below Baldhill Dam) for the current time step, in acre-feet;
- *CO* is the outflow concentration for the current time step, in milligrams per liter.

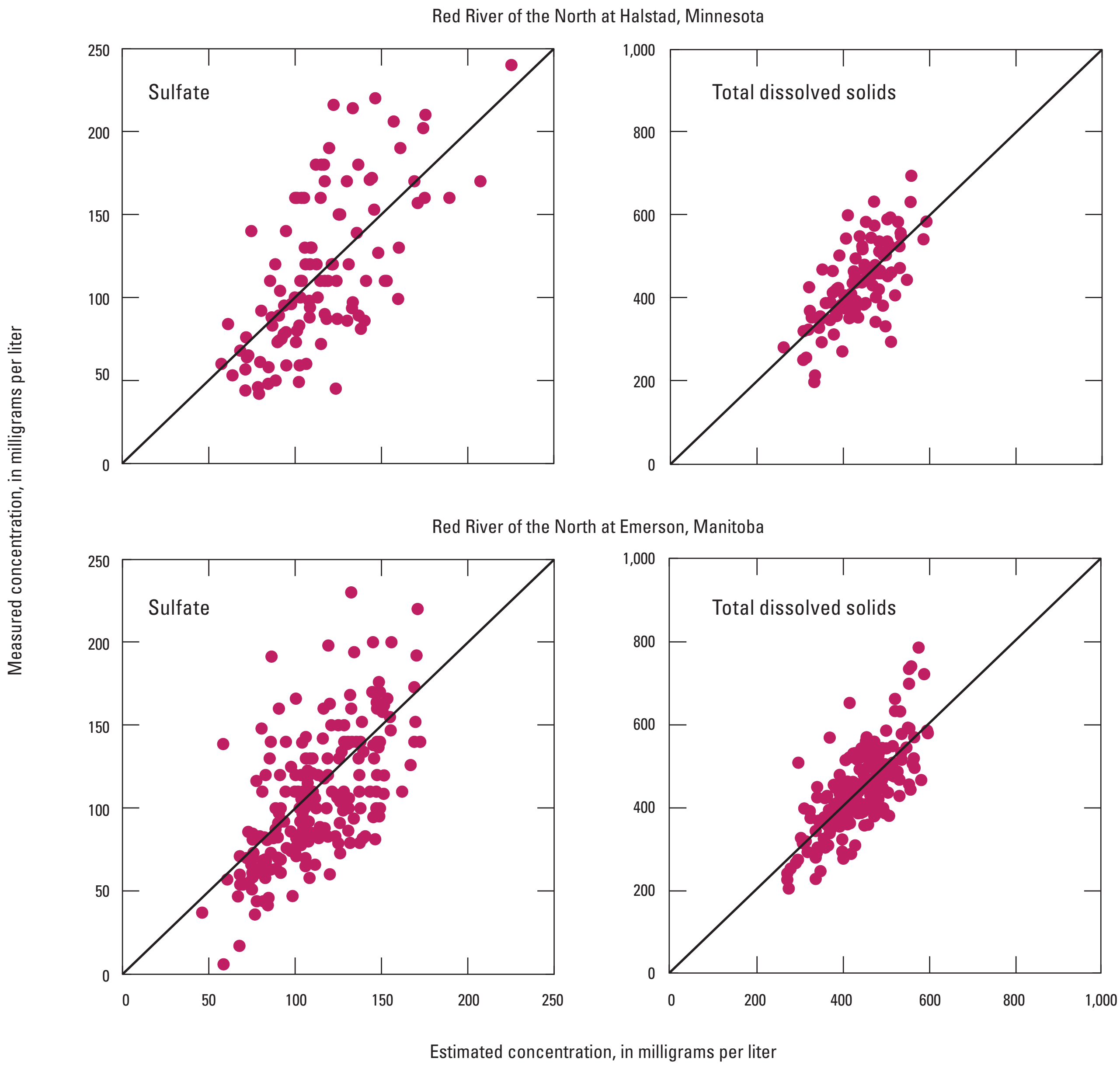

Figure A4. Estimated versus measured sulfate and total dissolved solids concentrations for the Red River of the North at Halstad, Minnesota, and at Emerson, Manitoba, sites.

The reference volume is the same for each compartment, but changes depending on the time of year to reflect the volume at which the compartment is considered to be “full”:

RV = 24,000, during May 1 to October 31;

RV = 24,000–7,000 (d/92), if the time step is within d=1 to d=92 days after October 31;

RV = 17,000, during February 1 to March 31;

RV = 17,000 + 7,000(d/30), if the time step is within d=1 to d=30 days after March 31.

The volume at which the reservoir, consisting of the three equal compartments, is considered full is 72,000 (3 times 24,000) acre-ft during May 1 to October 31, decreases to 51,000 acre-ft from November 1 to January 31, remains at 51,000 acre-ft from February 1 to March 31, and increases to 72,000 acre-ft from April 1 to April 30. The actual volume may be less than the full volume during dry years when there is not enough inflow to fill the reservoir, and it may be more than the full volume in wet years (particularly during the spring flood season). A 5-day time step is used, and inflow volumes and concentrations for each time step and reservoir compartment are computed using flows and concentrations for the Cooperstown and Dazey sites and potential flows and concentrations from Devils Lake (either from constructed outlet or from Tolna Coulee spills). Inflow for the first compartment is

$$I1 = F_C + 0.42\, F_D + F_{WO(-10)} + F_{EO(-5)} + F_{TC(-5)}$$

where F_C is flow for the Cooperstown site, F_D is flow for the Dazey site, $F_{WO(-10)}$ is flow from the west-end outlet (lagged 10 days), $F_{EO(-5)}$ is flow from the east-end outlet (lagged 5 days), and $F_{TC(-5)}$ is flow from Tolna Coulee (lagged 5 days). All flows on the right-hand side are expressed in acre-ft. The multiplier (0.42) for Dazey flows was determined by trial and error so that the outflows computed from the reservoir algorithm for the calibration period (1980–2009) had the same mean as the measured flows for the streamgage below Baldhill Dam. Concentration of inflow for the first compartment is the flow-weighted average of concentrations for the various inflow components,

$$CI1 = [C_C F_C + 0.42\,(BC) C_D F_D + C_{WO(-10)} F_{WO(-10)} + C_{EO(-5)} F_{EO(-5)} + C_{TC(-5)} F_{TC(-5)}]/I1$$

where C_C and C_D are concentrations for the Cooperstown and Dazey sites (either the estimated concentrations described in the previous section for the calibration period or simulated future concentrations), and concentrations for the Devils Lake flows are computed using the Devils Lake simulation model. The bias-correction (BC) for the Dazey site was determined by trial and error so that the outflow concentrations using the reservoir simulation model had the same mean as the measured concentrations below Baldhill Dam. The value was BC=1.5 for sulfate and BC=1.2 for dissolved solids. Inflow and concentration for the second reservoir compartment were

$$I2 = 1.42\, F_D$$

and

$$CI2 = [C_D F_D + 0.42(BC) C_D F_D]/I2$$

and there was no inflow ($I3=0$) for the third compartment. Net evaporation for each compartment was NE=100 acre-ft for time steps during July 1 to September 30 and NE=0 during October 1 to May 31. This corresponds to a total of 5,400 acre-ft per year of net evaporative loss for all three compartments, or about 12 inches per year for the approximately 5,000-acre lake.

The reservoir algorithm was used to recursively compute values of the storage variables for each time step, given initial values from the previous time step. Here are the steps for the algorithm:

1. Given initial values for VJ_0 *and* CJ_0 from the previous time step, compute temporary updated lake volumes (VJ) and concentrations (CJ) to reflect inflows for the first compartment (equations computed recursively, in order from left to right and row to row):

$$C1 = [C1_0\, V1_0 + CI1\, I1]/[V1_0 + I1]\ ;\ V1 = V1_0 + (1/3)I1;$$

$$C2 = [C2_0\, V2_0 + (2/3)\, C1\, I1]/[V2_0 + (2/3)\, I1];\ V2 = V2_0 + (1/3)\, I1;$$

$$C3 = [C3_0\, V3_0 + (1/3)\, C2\, I1]/[V3_0 + (1/3)\, I1];\ V3 = V3_0 + (1/3)\, I1;$$

2. Continue computing temporary lake volumes and concentrations to reflect inflows for the second compartment:

$$C2 = [C2\, V2 + CI2\, I2]/[V2 + I2]\ ;\ V2 = V2 + (1/3)I2;$$

$$C1 = [C1 V1 + (1/3)\, C2\, I2]/[V1 + (1/3)\, I2];\ V1 = V1 + (1/3)\, I2;$$

$$C3 = [C3\, V3 + (1/3)\, C2\, I2]/[V3 + (1/3)\, I2];\ V3 = V3 + (1/3)\, I2.$$

3. Remove net evaporation from each compartment

$$V1 = V1 – NE\ ;\ V2 = V2 – NE\ ;\ V3 = V3 – NE$$

4. Compute initial discharge from the third lake compartment, assumed to be 100 acre-ft, or about 10 ft³/s for the 5-day time step (this is the minimum flow for below Baldhill Dam). Adjust lake volumes and concentrations accordingly.

$$VO = 100;\ CO = C3\ ;\ V3 = V3 – VO;$$

$$C3 = [C3\, V3 + (2/3)\, C2\, VO]/[V3 + (2/3)\, VO];\ V3 = V3 + (2/3)\, VO;$$

$$C2 = [C2\, V2 – (2/3)\, C2\, VO]/[V2 – (2/3)\, VO];\ V2 = V2 – (2/3)\, VO;$$

$$C2 = [C2\, V2 + (1/3)\, C1\, VO]/[V2 + (1/3)\, VO];\ V2 = V2 + (1/3)\, VO;$$

$$V1 = V1 – (1/3) VO$$

5. If the updated volumes for each compartment are less than *RV*, then the only outflow is the initial discharge (computed in step 4). Set the initial values of the storage variables for the next time step equal to the updated values ($VJ_0=VJ$, $CJ_0=CJ$, and so on), go back to step 1, and repeat for the next time step. If the updated volumes are greater than *RV*, then proceed to the next step.

6. Compute additional discharge from the third compartment and adjust volumes and concentrations accordingly:

$$CO = [CO\ VO + C3\ (V3–RV)]/[VO + V3–RV];\ VO = VO + V3–RV;\ V3 = RV;$$

$$C3 = [C3\ V3 + (2/3)\ C2\ (V3–RV)]/[V3 + (2/3)(V3–RV)];\ V3 = V3 + (2/3)(V3–RV);$$

$$C2 = [C2\ V2–(2/3)\ C2\ (V3–RV)]/[V2–(2/3)(V3–RV)];\ V2 = V2–(2/3)(V3–RV);$$

$$C2 = [C2\ V2 + (1/3)\ C1\ (V3–RV)]/[V2 + (1/3)(V3–RV)];\ V2 = V2 + (1/3)(V3–RV);$$

$$V1 = V1–(1/3)(V3–RV)$$

Repeat these equations 2 additional times (3 total). The resulting values for *VO* and *CO* are the total outflow volume and outflow concentration for the current time step. Set the initial values of the storage variables for the next time step equal to the updated values ($VJ_0 = VJ$, $CJ_0 = CJ$, and so on), go back to step 1, and repeat for the next time step.

The need to repeat step 6 three times was determined by trial and error. Repeating it only once resulted in larger volumes of water than desired remaining in the lake at the end of time steps during high spring inflow events. Repeating it a large number of times resulted in volumes essentially equal to *RV* at the end of the time step, so no excess storage is held back. The total Lake Ashtabula volumes (sum of the 3 compartments) are shown in figure A5 for the model calibration period. During the dought years of 1988–92, there was not enough inflow to fill the lake to full capacity. During wet years such as 1996–97 and 2009, the lake rose well above the

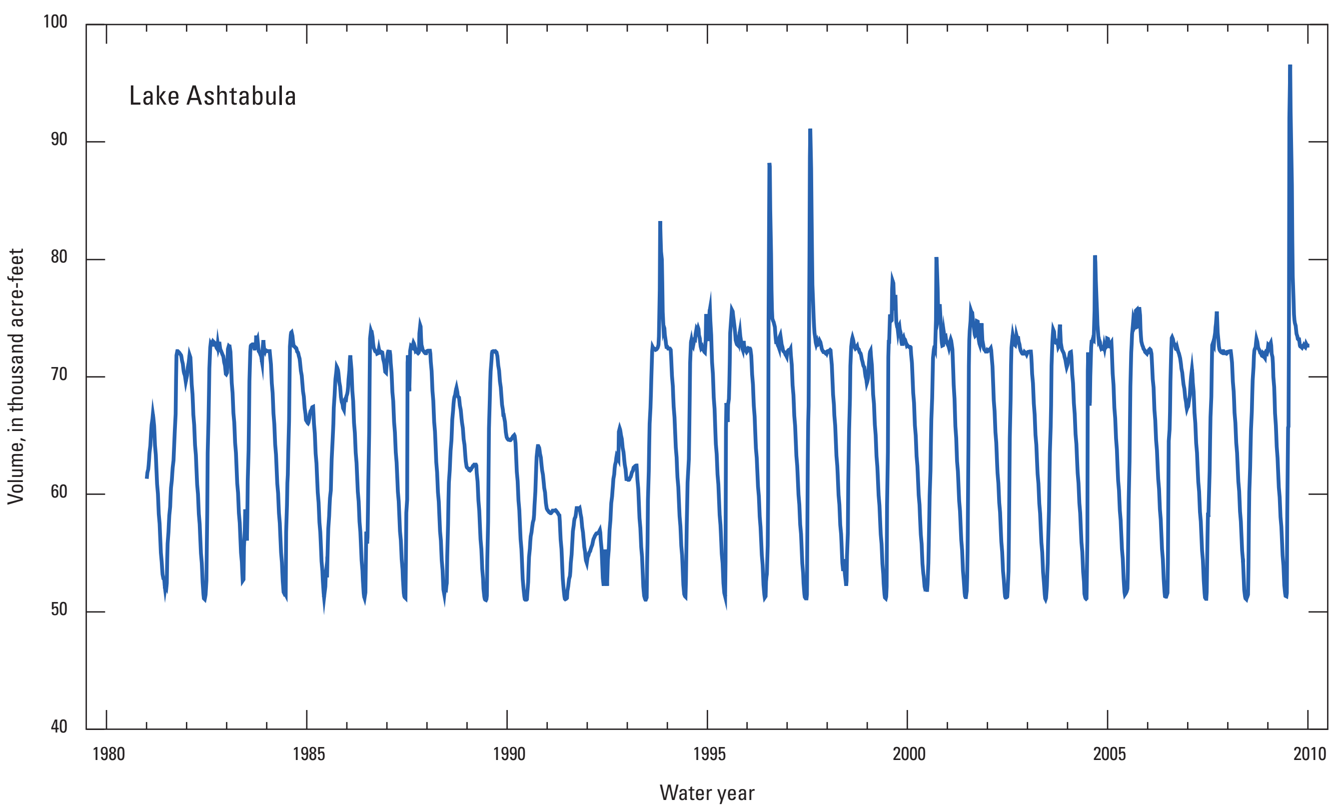

Figure A5. Modeled Lake Ashtabula volumes for model calibration period.

conservation pool during the spring runoff period. A scatterplot of the estimated compared to measured flows for the below Baldhill Dam site for the calibration period are shown in figure A6 (see also fig. 9). The estimated compared to measured concentrations for the below Baldhill Dam site for the calibration period are shown in figure A3.

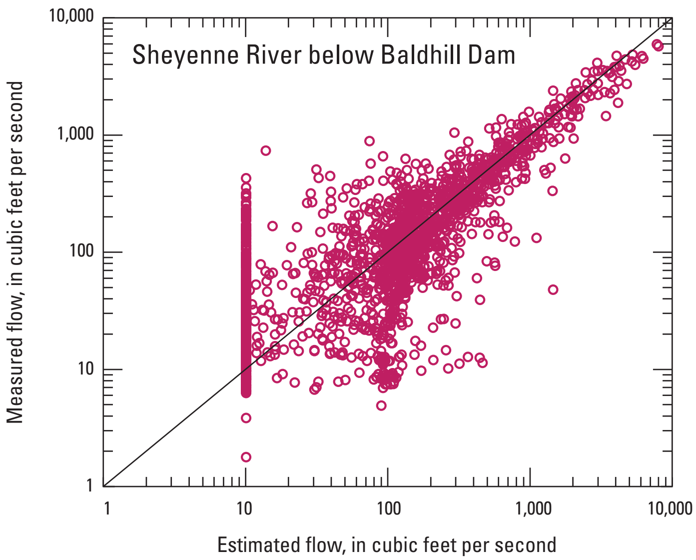

Figure A6. Estimated compared to measured flows for the Sheyenne River below Baldhill Dam, North Dakota.

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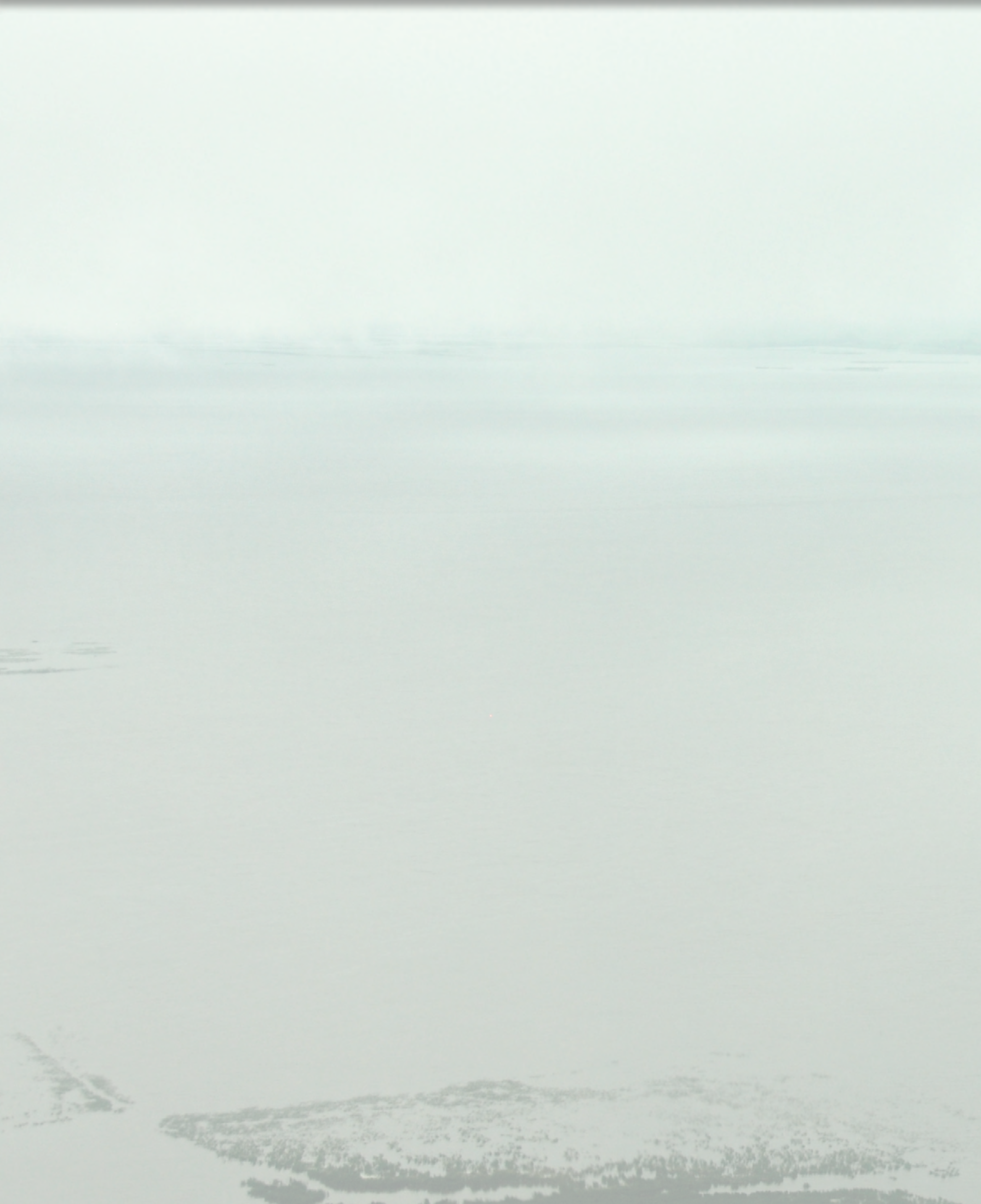

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