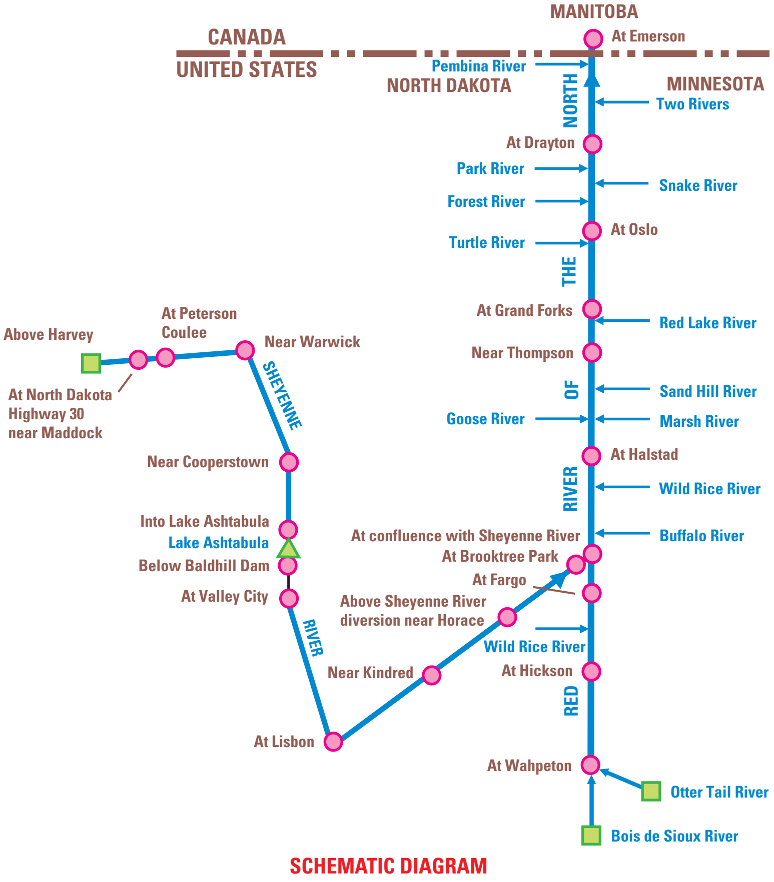
In cooperation with the Bureau of Reclamation

Simulation of Conservative-Constituent Transport in the Red River of the North Basin, North Dakota and Minnesota, 2003-04



Scientific Investigations Report 2005–5273

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

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By Rochelle A. Nustad and Jerad D. Bales

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Mass		
pound per day (lb/d)	0.4536	kilogram per day (kg/d)
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

Simulation of Conservative-Constituent Transport in the Red River of the North Basin, North Dakota and Minnesota, 2003-04

By Rochelle A. Nustad and Jerad D. Bales

Abstract

Population growth along with possible future droughts in the Red River of the North (Red River) Basin will create an increasing need for reliable water supplies. Therefore, as a result of the Dakota Water Resources Act of 2000, the Bureau of Reclamation identified eight water-supply alternatives (including a no-action alternative) to meet future water needs in the basin. Because of concerns about the possible effects of the alternatives on water quality in the Red River and the Sheyenne River and in Lake Winnipeg, Manitoba, the Bureau of Reclamation needs to prepare an environmental impact statement that describes the specific environmental effects of each alternative. To provide information for the environmental impact statement, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, conducted a study to develop and apply a water-quality model, hereinafter referred to as the Red River water-quality model, to part of the Red River and the Sheyenne River to simulate conservative-constituent transport in the Red River Basin. The Red River water-quality model is a one-dimensional, steady-state flow and transport model for selected constituents in the Red River and the Sheyenne River. The model simulates the flow and transport of total dissolved solids, sulfate, and chloride during steady-state conditions. The physical model domain includes the Red River from the confluence of the Bois de Sioux and Otter Tail Rivers to the Red River at Emerson, Manitoba, and the Sheyenne River from above Harvey, N. Dak., to the confluence with the Red River.

The Red River water-quality model was calibrated and tested using data collected at 34 sites from September 15 through 16, 2003, and from May 10 through 13, 2004. Water-quality samples were collected during low, steady-flow conditions from September 15 through 16, 2003, and during medium, unsteady-flow conditions from May 10 through 13, 2004. The simulated total dissolved-solids, sulfate, and chloride concentrations generally were within 5 percent of the measured concentrations.

The Red River water-quality model was used to simulate conservative-constituent transport in the Red River and the Sheyenne River for the eight water-supply alternatives identified by the Bureau of Reclamation. For the first set of eight simulations, September 2003 streamflows were used with projected 2050 return flows and withdrawals. For the second set of eight simulations, the September 2003 streamflows were reduced by 25 percent. The simulated concentrations for three of the alternatives generally were lower than for the no-action alternative. Of those alternatives, one would result in a decrease in concentrations for two constituents, one would result in a decrease in concentrations for all three constituents, and one would result in a decrease in concentrations for one constituent and an increase in concentrations for another constituent. For four of the alternatives, the differences between the mean simulated concentrations were less than calibration errors, indicating the effects of those alternatives on water quality in the rivers is uncertain. The effects of reduced streamflow on simulated total dissolved-solids, sulfate, and chloride concentrations were greatest for alternative 2. Reduced streamflow probably has an effect on simulated total dissolved-solids concentrations for alternatives 2, 3, 5, and 7 and on simulated sulfate concentrations for alternatives 2 and 5. Except for alternative 2, reduced streamflow had little effect on simulated chloride concentrations.

Introduction

Population growth along with possible future droughts in the Red River of the North (Red River) Basin (figure 1 at back of report) in North Dakota, Minnesota, and South Dakota will create an increasing need for reliable water supplies. Therefore, the Dakota Water Resources Act passed by the U.S. Congress on December 15, 2000, authorized the Secretary of the Interior to conduct a comprehensive study of the future water needs in the basin in North Dakota and of possible options to meet those water needs. As part of the comprehensive study, the Bureau of Reclamation identified eight water-supply alternatives (including a no-action alternative) for the Red River Valley Water Supply Project (RRVWSP) (U.S. Department of the Interior, Bureau of Reclamation, 2005). Of those alternatives, four include the interbasin transfer of water.

Because many stakeholders have expressed concerns about the possible effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River and in Lake Winnipeg, Manitoba, the Bureau of Reclamation needs to prepare an environmental impact statement (EIS) that describes the specific environmental effects of each alternative. To provide information for the EIS, the U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation, conducted a study to develop and apply a water-quality model to part of the Red River and the Sheyenne River to simulate conservative-constituent transport in the Red River Basin. The numerical HEC-5 and HEC-5Q models used previously by the U.S. Army Corps of Engineers to develop a water-quality model for part of the study area (U.S. Army Corps of Engineers, 1998; Resource Management Associates, 1996a, 1996b) were used to simulate flow and constituent transport for 2003 conditions. In addition, selected water-quality constituents measured during low, steady-flow conditions and during medium, unsteady-flow conditions were characterized and the concentrations for those constituents were compared to historical concentrations.

Purpose and Scope

The purpose of this report is to describe the simulation of conservative-constituent transport in the Red River Basin. Development, calibration, and testing of the water-quality model and model simulations for selected water-supply alternatives are documented. The numerical model, hereinafter referred to as the Red River water-quality model, was developed from the U.S. Army Corps of Engineers (2003) HEC-5Q water-quality model. For this study, the U.S. Army Corps of Engineers model was expanded to include the entire study area and applied to the water-supply alternatives identified by the Bureau of Reclamation to simulate changes in conservative-constituent transport.

The Red River water-quality model is a one-dimensional, steady-state flow and transport model for selected conservative constituents in the Red River and the Sheyenne River. The model was calibrated for the simulation of flow and transport of total dissolved solids, sulfate, and chloride. Data collected from September 15 through 16, 2003, and from May 10 through 13, 2004, were used to develop, calibrate, and test the model. The physical model domain includes the Red River from the confluence of the Bois de Sioux and Otter Tail Rivers to the Red River at Emerson, Manitoba, and the Sheyenne River from above Harvey, N. Dak., to the confluence with the Red River (figure 1 at back of report). Although Lake Ashtabula is in the model domain, water-quality processes for the lake were not included in the model.

Study Area

The study area includes the Red River from the confluence of the Bois de Sioux and Otter Tail Rivers to the Red River at Emerson, Manitoba, the Sheyenne River from above Harvey, N. Dak., to the confluence with the Red River, and selected tributaries to the Red River. The Red River Basin is part of the Hudson Bay drainage system. Parts of North Dakota, Minnesota, and South Dakota in the United States and parts of Saskatchewan and Manitoba in Canada are drained by the Red River, and the North Dakota-Minnesota boundary is formed by the river (figure 1 at back of report). The drainage area of the Red River at Emerson is 40,200 mi^2. Downstream from Emerson, the Red River drains into Lake Winnipeg, Manitoba. The streamflow-gaging station at Emerson is located 0.8 mi downstream from the international boundary.

The Red River is formed by the confluence of the Bois de Sioux and Otter Tail Rivers at Wahpeton, N. Dak. (figure 1 at back of report), and flows northward 394 mi to the international boundary. The slope of the river is extremely flat. The river falls only about 200 ft over the reach between Wahpeton and the international boundary. Between 1990 and 2000, the population in the United States part of the Red River Basin increased 19 percent to 607,000 (Sether and others, 2004). About one-third of the population in the United States part of the basin resides in Fargo, N. Dak., Grand Forks, N. Dak., and Moorhead, Minn. (Stoner and others, 1998). In 1990, total water use in the United States part of the basin was about 196 Mgal/d. Most of the water was used for public supplies and irrigation. Slightly more than one-half of the water was obtained from ground-water sources, but the largest cities (Fargo, Grand Forks, and Moorhead) obtained most of their water from the Red River (Stoner and others, 1993).

Streamflow in the Otter Tail River has been regulated by Orwell Dam since 1953. Orwell Reservoir provides 13,100 acre-ft of storage for multiple uses. Numerous other controlled lakes and ponds and several powerplants affect streamflow in the Otter Tail River.

Lake Traverse and Mud Lake are natural lakes near the headwaters of the Bois de Sioux River. In 1942, Reservation Dam on Lake Traverse and White Rock Dam on Mud Lake were completed. The combined flood storage capacity for the two lakes is 153,700 acre-ft at an elevation of 981 ft.

The Sheyenne River, one of the major tributaries to the Red River, has a drainage area of about 6,910 mi^2 (not including the closed Devils Lake Basin) and is about 500 mi long. The average slope of the river ranges from 1.0 to 1.5 ft/mi. During the 1950s, zero streamflow was recorded along the Sheyenne River from above Harvey, N. Dak., to Lisbon, N. Dak. Flow in the lower reaches of the river is regulated partly by releases from Baldhill Dam, which was completed in 1949. Lake Ashtabula, which is formed by Baldhill Dam, has a capacity of 69,100 acre-ft between the invert of the outlet conduit and the normal pool elevation and a capacity of 157,500 acre-ft at maximum pool elevation (U.S. Army Corps of Engineers, 2003). Lake Ashtabula is operated for flood control, municipal water supply, recreation, and stream-pollution abatement.

Ground water in the Red River Basin is primarily in sand and gravel aquifers near land surface or in buried glacial deposits throughout the basin. Ground water moves toward the Red River through a regional system of bedrock and glacial-drift aquifers (Sether and others, 2004). Saline ground-water discharge from the bedrock aquifers is known to collect in wetlands that drain into tributaries of the Red River (Strobel and Haffield, 1995). The Turtle, Forest, and Park Rivers are the major contributors of salinity to the Red River.

Methods

The Red River water-quality model requires streamflow, water-quality, withdrawal and return-flow, and channel-geometry data. Methods used to collect or compile the data are summarized in this section. The data-collection network, which included locations where water-quality samples were collected and streamflow measurements were made, is presented, and methods used to collect water-quality samples are described. Withdrawal and return-flow data used for the model and methods used to estimate channel-geometry data are described. Finally, a brief overview is given of the HEC-5 and HEC-5Q models, which were used to simulate streamflow and constituent transport, respectively, in the study area.

Data-Collection Network

The data-collection network consisted of 34 sites (11 Red River sites, 8 Sheyenne River sites, and 15 other tributary sites) (table 1, figure 1 at back of report). Of the 34 sites, 23 were co-located with active USGS streamflow-gaging stations. Of the remaining sites, three were located on the main stem of the Red River, and one was located on the main stem of the Sheyenne River. Ungaged tributaries to the Red River (other than the Sheyenne River) were sampled at either the downstream-most gaging station or at ungaged sites near the mouth of the tributary.

Water-Quality Sample Collection and Analysis

Water-quality samples were collected during low, steady-flow conditions from September 15 through 16, 2003, and during medium, unsteady-flow conditions from May 10 through 13, 2004. Streamflow measurements were made at the ungaged sites at the time of sample collection. The field measurements were made and the samples were collected according to methods described by the U.S. Geological Survey (variously dated). The samples were analyzed by the North Dakota Department of Health Laboratory for an extensive set of water-quality properties and constituents (table 2), and the water-quality data are given by Robinson and others (2004, 2005).

Although wastewater is discharged continuously from the Fargo, N. Dak., and Moorhead, Minn., wastewater-treatment facilities, the wastewater is not routinely analyzed for total dissolved solids, sulfate, and chloride. Therefore, because concentrations for those constituents were required for model calibration, water-quality samples were collected from the Red River immediately upstream and immediately downstream from both facilities during the September 2003 sampling period. Loads and concentrations then were determined by mass balance, and the differences between the upstream and downstream concentrations were attributed to the wastewater discharges.

Withdrawal and Return-Flow Data

Withdrawals are made from the Red River and the Sheyenne River primarily for municipal and industrial water supplies and for irrigation. Return flows generally are municipal and industrial wastewater discharges. Only withdrawals and return flows that were large in relation to flow in the river were included in the water-quality model (table 3). Withdrawal data were obtained from the water-treatment facility for each of the major cities (Ron Hendrickson, Fargo Water Treatment Facility, oral commun., 2004; Hazel Sletten, Grand Forks Water Treatment Facility, oral commun., 2004; and Troy Hall, Moorhead Water Treatment Facility, oral commun., 2004). Return-flow data for Fargo, N. Dak., and Grand Forks, N. Dak., were obtained from the North Dakota Department of Health (Gary Bracht, North Dakota Department of Health, written commun., 2004) and the city of Moorhead, Minn. (Bob Zimmerman, Moorhead Wastewater Treatment Facility, oral commun., 2004).

Channel-Geometry Data

Channel geometry in the HEC-5 and HEC-5Q models is described by cross-section flow area, top width, and water-surface elevation for a range of streamflows. The channel-geometry data for part of the study area were directly available in HEC-5/HEC-5Q format from a HEC-5Q water-quality model previously developed by the U.S. Army Corps of Engineers (2003). However, that model did not include data for the Bois de Sioux River, the Otter Tail River, the Red River from Wahpeton, N. Dak., to Fargo, N. Dak., or the Sheyenne River upstream from Peterson Coulee. Therefore, measured channel cross sections for those reaches were processed into the HEC-5/HEC-5Q format using the one-dimensional, unsteady-flow model HEC-RAS (Brunner, 2002). Channel cross sections were processed for streamflows of less than 10,000 ft^3/s because only

Table 1. Data-collection network.

Site number (figure 1)	U.S. Geological Survey site number	Site name	Active streamflow-gaging station
1	05046502	Otter Tail River at 11th Street in Breckenridge, Minnesota	No
2	05051300	Bois de Sioux River near Doran, Minnesota	Yes
3	05051500	Red River of the North at Wahpeton, North Dakota	Yes
4	05051522	Red River of the North at Hickson, North Dakota	Yes
5	05053000	Wild Rice River near Abercrombie, North Dakota	Yes
6	05053800	Red River of the North above Fargo, North Dakota	No
7	05054000	Red River of the North at Fargo, North Dakota	Yes
8	465602096472700	Red River of the North on Cass County Road 20 below Fargo, North Dakota	No
9	05054500	Sheyenne River above Harvey, North Dakota	Yes
10	05056000	Sheyenne River near Warwick, North Dakota	Yes
11	05057000	Sheyenne River near Cooperstown, North Dakota	Yes
12	05058000	Sheyenne River below Baldhill Dam, North Dakota	Yes
13	05058700	Sheyenne River at Lisbon, North Dakota	Yes
14	05059000	Sheyenne River near Kindred, North Dakota	Yes
15	05059300	Sheyenne River above Sheyenne River diversion near Horace, North Dakota	Yes
16	470000096535300	Sheyenne River at Brooktree Park, North Dakota	No
17	05062000	Buffalo River near Dilworth, Minnesota	Yes
18	05064000	Wild Rice River at Hendrum, Minnesota	Yes
19	05064500	Red River of the North at Halstad, Minnesota	Yes
20	05066500	Goose River at Hillsboro, North Dakota	Yes
21	05067500	Marsh River near Shelly, Minnesota	Yes
22	05069000	Sand Hill River at Climax, Minnesota	Yes
23	05070000	Red River of the North near Thompson, North Dakota	Yes
24	05080000	Red Lake River at Fisher, Minnesota	Yes
25	05082500	Red River of the North at Grand Forks, North Dakota	Yes
26	480239097115000	Turtle River above Manvel, North Dakota	No
27	05083500	Red River of the North at Oslo, Minnesota	No
28	482118097090500	Forest River near confluence with Red River of the North, North Dakota	No
29	482451097062500	Snake River near Big Woods, Minnesota	No
30	482736097112800	Park River near Oakwood, North Dakota	No
31	05092000	Red River of the North at Drayton, North Dakota	Yes
32	05095000	Two Rivers at Hallock, Minnesota	No
33	485636097173800	Pembina River above Pembina, North Dakota	No
34	05102500	Red River of the North at Emerson, Manitoba	Yes

Table 2. Water-quality properties and constituents for which samples were analyzed.

[Samples were analyzed by the North Dakota Department of Health Laboratory; --, no data; <, less than; NA, not applicable]

Property or constituent	Parameter code	Measurement type	Minimum reporting limit	Units
Streamflow	00060	Field	--	Cubic feet per second
Specific conductance	00095	Field	--	Microsiemens per centimeter at 25 degrees Celsius
pH	00400	Field	--	Standard units
pH	00403	Laboratory	--	Standard units
Temperature, air	00020	Field	--	Degrees Celsius
Temperature, water	00010	Field	--	Degrees Celsius
Barometric pressure	00025	Field	--	Millimeters of mercury
Turbidity	61028	Field	--	Nephelometric turbidity units
Dissolved oxygen	00300	Calculated	--	Milligrams per liter
Hardness	00905	Laboratory	--	Milligrams per liter as calcium carbonate
Acid neutralizing capacity	90410	Calculated	<1	Milligrams per liter
Total dissolved solids	70301	Calculated	--	Milligrams per liter
Calcium, dissolved	00915	Laboratory	<2	Milligrams per liter
Magnesium, dissolved	00925	Laboratory	<1	Milligrams per liter
Sodium, dissolved	00930	Laboratory	<3	Milligrams per liter
Percent sodium	00932	Calculated	--	Percent
Sodium adsorption ratio	00931	Calculated	--	NA
Potassium, dissolved	00935	Laboratory	<1	Milligrams per liter
Bicarbonate	90440	Laboratory	<1	Milligrams per liter
Carbonate	90445	Laboratory	<1	Milligrams per liter
Sulfate, dissolved	00945	Laboratory	<0.3	Milligrams per liter
Chloride, dissolved	00940	Laboratory	<0.3	Milligrams per liter
Nitrite plus nitrate, total as nitrogen	00630	Laboratory	<0.02	Milligrams per liter
Nitrite plus nitrate, dissolved as nitrogen	00631	Laboratory	<0.02	Milligrams per liter
Nitrogen, ammonia, total	00610	Laboratory	<0.010	Milligrams per liter
Nitrogen, ammonia, dissolved	00608	Laboratory	<0.010	Milligrams per liter
Nitrogen, total	00600	Laboratory	<0.015	Milligrams per liter
Nitrogen, dissolved	00602	Laboratory	<0.015	Milligrams per liter
Nitrogen, total Kjeldahl	00625	Calculated	<0.001	Milligrams per liter
Nitrogen, dissolved Kjeldahl	00623	Calculated	<0.001	Milligrams per liter

Table 2. Water-quality properties and constituents for which samples were analyzed.—Continued

[Samples were analyzed by the North Dakota Department of Health Laboratory; --, no data; <, less than; NA, not applicable]

Property or constituent	Parameter code	Measurement type	Minimum reporting limit	Units
Phosphorus, total	00665	Laboratory	<0.004	Milligrams per liter
Phosphorus, dissolved	00666	Laboratory	<0.004	Milligrams per liter
Orthophosphate, dissolved	00671	Laboratory	<0.01	Milligrams per liter
Iron, dissolved	01046	Laboratory	<10	Micrograms per liter
Manganese, dissolved	01056	Laboratory	<10	Micrograms per liter
Coliform, fecal[1]	31625	Laboratory	<10	Colonies per 100 milliliters
Chlorophyll *a*	70951	Laboratory	--	Micrograms per liter
Chlorophyll *b*	70952	Laboratory	--	Micrograms per liter

[1] Analyzed for May 2004 samples.

Table 3. Withdrawals from and return flows to the Red River of the North at Fargo, North Dakota, Grand Forks, North Dakota, and Moorhead, Minnesota, during September 2003 and May 2004.

City	Average daily withdrawals for September 2003 (cubic feet per second)	Average daily withdrawals for May 2004 (cubic feet per second)	Average daily return flows for September 15 through 16, 2003 (cubic feet per second)	Average daily return flows for May 10 through 13, 2004 (cubic feet per second)
Fargo	20.3	16.8	17.5	15.4
Grand Forks	[1]0	[2]2.2	0	32
Moorhead	[3]7.1	[4]6.3	5.8	6.7

[1] In addition, 13.0 cubic feet per second was withdrawn from the Red Lake River.

[2] In addition, 10.2 cubic feet per second was withdrawn from the Red Lake River.

[3] In addition, 1.1 cubic feet per second was withdrawn from ground-water sources.

[4] In addition, 0.4 cubic foot per second was withdrawn from ground-water sources.

6 percent of the mean daily streamflows for site 25 (Red River at Grand Forks, N. Dak.) exceeded 10,000 ft^3/s between 1904 and 2004.

Description of HEC-5 and HEC-5Q Models

The HEC-5 model (U.S. Army Corps of Engineers, 1998) is designed to simulate unsteady flows through a system of channels and reservoirs that have a branched network configuration. The model can be used to evaluate different flood-control scenarios as well as to size reservoirs and their flood-control volumes. One-dimensional channel routing is performed by using one of seven available hydrologic-routing techniques. Hydrologic routing (for example, the Muskingum method) differs from hydraulic routing in that hydrologic routing is based solely on conservation of mass. Hydraulic routing is based on both conservation of mass and conservation of momentum. The HEC-5 model has been applied to many managed rivers, including the Sacramento River (Willey, 1987), the Big Sandy River (U.S. Army Corps of Engineers, unpub. data, 1996, on file at U.S. Army Corps of Engineers Hydrologic Engineering Center, Huntington District), and the Monongahela River (U.S. Army Corps of Engineers, unpub. data, 1987, on file at U.S. Army Corps of Engineers Hydrologic Engineering Center, Pittsburgh District). A more recent version of the model, known as HEC-ResSim (Klipsch, 2003), includes a graphical user interface (GUI) to build model input files but does not include linkage to a water-quality model as was required for this study.

The HEC-5Q model (Resource Management Associates, 1996a, 1996b), a companion to the HEC-5 model, is a river and reservoir water-quality model that can be used to simulate dynamic interactions of multiple, nonlinearly coupled constituents in rivers and in longitudinally or vertically stratified reservoirs. The model can be used to simulate the transport of conservative and nonconservative properties and constituents, including temperature, dissolved oxygen, alkalinity, chloride, nitrate, ammonia, orthophosphorus, and phytoplankton. Recent applications of the HEC-5Q model include the simulation of water quality in the complex Alabama-Coosa-Tallapoosa and Apalachicola-Chattahoochee-Flint River Basins (Resource Management Associates, unpub. data, 1999, on file at U.S. Army Corps of Engineers Hydrologic Engineering Center, Sacramento District and Mobile District).

A post-processing GUI for the HEC-5/HEC-5Q models can be used to view model-generated results through time-series plots and animated longitudinal and vertical profiles of streamflows and constituent concentrations. Measurements obtained from data files can be plotted with the model-generated results for calibration exercises. The results are selected for plotting by using a map-based interface that displays a schematic of the model configuration along with various geographic information system map layers.

The HEC-5 model was used by the U.S. Army Corps of Engineers (2003) to simulate streamflow, and the HEC-5Q model was used to simulate constituent transport in the Sheyenne River from the confluence of Peterson Coulee with the Sheyenne River, through Lake Ashtabula, to the confluence of the Sheyenne River with the Red River, and down the Red River to Emerson, Manitoba. The HEC-5Q water-quality model included Lake Ashtabula but did not include the Red River from Wahpeton, N. Dak., to Fargo, N. Dak., or the Sheyenne River upstream from Peterson Coulee. The model was applied to aid in the analysis of potential environmental effects of a proposed Devils Lake outlet and underwent extensive peer review prior to publication. Documentation of the model is given in appendix A of the Devils Lake EIS (U.S. Army Corps of Engineers, 2003).

Streamflow and Water-Quality Conditions

Streamflow and water-quality conditions are discussed in this section to place the conditions that occurred during the September 2003 and May 2004 sampling periods into a historical perspective. In addition to data for total dissolved solids, sulfate, and chloride, data for selected ions (calcium, magnesium, sodium, and bicarbonate) and nutrients (nitrogen and phosphorus) are discussed to provide a perspective on overall water-quality characteristics. Nitrogen and phosphorus loads calculated from data collected during this study are compared to historical nitrogen and phosphorus loads.

Streamflows during the September 2003 sampling period were low (figure 2 at back of report). For example, streamflows for the Red Lake River at the mouth and site 34 (Red River at Emerson, Manitoba) are historically lower than streamflows measured on September 15, 2003, for site 24 (Red Lake River at Fisher, Minn.) and site 34, respectively, about 16 percent of the time (figure 2 at back of report). Streamflows for the Otter Tail River at the mouth and the Sheyenne River at the mouth are historically lower than streamflows measured on September 16, 2003, for site 1 (Otter Tail River at 11th Street in Breckenridge, Minn.) and site 16 (Sheyenne River at Brooktree Park, N. Dak.), respectively, about 30 percent of the time. Streamflows in the study area were generally decreasing before sample collection but were generally steady during the sampling period (figure 3a at back of report). Flow duration calculations were based on naturalized monthly streamflows for 1931-2001 [see Emerson (2005) for details of the calculations].

On May 11 and 12, 2004, during the middle of the May 2004 sampling period, widespread rainfall occurred throughout much of the Red River Basin. On May 11, rainfall amounts in the area east of the Red River and north of Fargo, N. Dak., were higher than those in the upper part of the Red and Sheyenne River Basins and ranged from 1.59 in. at Warren, Minn., to 2.21 in. at Perley, Minn. (North Dakota Agricultural Weather Network, 2005). Rainfall amounts in the upper part of the Red and Sheyenne River Basins on May 11 ranged from about 0.35 to 0.6 in. On May 12, rainfall amounts ranged from 0.2 to 0.5 in. (North Dakota Agricultural Weather Network, 2005).

As a result of the widespread rainfall on May 11 and 12, 2004, streamflows during the May 2004 sampling period were less steady than during the September 2003 sampling period except in the Red River upstream from Fargo, N. Dak. (figure 3b at back of report). Streamflow for site 34 (Red River at Emerson, Manitoba) increased about 50 percent during the sampling period. However, streamflows in the Sheyenne River increased only slightly because of less rainfall in that part of the basin than in other parts of the basin. In contrast to what occurred during the September 2003 sampling period when streamflows were consistently low throughout the study area, the percentage of time streamflow was equaled or exceeded during the May 2004 sampling period varied widely from site to site (figure 2 at back of report). Streamflow for the Red Lake River at the mouth is historically lower than streamflow measured on May 11, 2004, for site 24 (Red Lake River at Fisher, Minn.) about 30 percent of the time. Streamflow for the Otter Tail River at the mouth is historically lower than streamflow measured on May 11, 2004, for site 1 (Otter Tail River at 11th Street in Breckenridge, Minn.) about 55 percent of the time. In contrast, streamflow for site 34 is historically lower than streamflow measured on May 10, 2004, for that site about 70 percent of the time, and streamflow for the Sheyenne River at the mouth is historically lower than streamflow measured on May 12, 2004, for site 16 (Sheyenne River at Brooktree Park, N. Dak.) about 85 percent of the time (figure 2 at back of report). The unsteady flows and the collection of some samples during low-flow conditions and other samples during storm-runoff conditions complicated application of the model to the May 2004 sampling period.

Measured total dissolved-solids concentrations for the Red River generally were less than the U.S. Environmental Protection Agency (2005) secondary water-quality standard of 500 mg/L (figure 4a at back of report). The concentrations, which increased in a downstream direction, generally were higher during the September 2003 sampling period, when streamflows were low, than during the May 2004 sampling period, when streamflows were moderate. Sether and others (2004) measured total dissolved-solids concentrations during 1997-99 at 11 sites between the Otter Tail River above Breckenridge, Minn., and the Red River at Perley, Minn., which is between the Bois de Sioux River near Doran, Minn. (site 2, figure 1 at back of report), and the Wild Rice River at Hendrum, Minn. (site 18, figure 1 at back of report). The median concentration for each of the 11 sites, based on about 20 samples, was less than 500 mg/L except for the Bois de Sioux River and the Sheyenne River at Harwood, N. Dak. (near site 16, figure 1 at back of report). The results from this study generally are in agreement with those from Sether and others (2004) in that the concentrations for the Sheyenne River (figure 4b at back of report) and the Bois de Sioux River (figure 4c at back of report) generally were greater than 500 mg/L and the concentrations elsewhere in the Red River upstream from Fargo, N. Dak., generally were less than 500 mg/L.

The long-term median total dissolved-solids concentration for site 34 (Red River at Emerson, Manitoba) during 1970-2001 was 438 mg/L (Tornes, 2005). The measured concentration for that site during the September 2003 sampling period was 640 mg/L, and the measured concentration during the May 2004 sampling period was 464 mg/L (figure 4a at back of report). Both of those concentrations are greater than the long-term median concentration.

During the September 2003 sampling period, all measured total dissolved-solids concentrations for the Sheyenne River were greater than 500 mg/L (figure 4b at back of report). The highest concentrations were for the upstream part of the Sheyenne River Basin. The concentrations were fairly uniform for all sites from Lisbon, N. Dak., downstream during both sampling periods. Concentrations for several tributaries to the Red River were fairly large (figure 4c at back of report), but streamflows in those tributaries were less than 12 ft^3/s during the September 2003 sampling period. Thus, total dissolved-solids loads from those tributaries to the Red River were small.

Calcium and magnesium were present in approximately equal amounts for any given site (figure 5a at back of report) throughout the Red River Basin. Sodium was elevated in relation to calcium and magnesium for sites in the upper part of the Sheyenne River Basin and lower in relation to calcium and magnesium for most sites on the Red River. Most of the sodium in the Sheyenne River was likely present as sodium sulfate and sodium bicarbonate.

Bicarbonate was the predominant anion in the Red River and the Sheyenne River (figure 5b at back of report). Sulfate was much lower than bicarbonate in the upper Red River but only slightly lower downstream from the confluence of the Red and Sheyenne Rivers. Carbonate made up a small percentage of the total anions at all sites, and chloride was low in relation to the other anions except near Fargo, N. Dak., and at the downstream end of the study reach. According to Tornes and others (1997), the ionic distribution was similar for streams that drain the same physiographic area of the Red River Basin.

During the September 2003 and May 2004 sampling periods, most of the nitrogen in the Red River and the Sheyenne River was present as organic nitrogen (figures 6a and 6b at back of report). However, for site 8 (Red River below Fargo, N. Dak.) during both sampling periods and for most sites during the May 2004 sampling period, most of the nitrogen was present as nitrite plus nitrate as nitrogen, which can be derived from runoff of fertilizers or animal waste (figures 6a and 6b at back of report). Site 8 is affected by wastewater discharge from Fargo, N. Dak. Ammonia as nitrogen was present in small amounts at most sites during both sampling periods although the concentrations were slightly higher during the May 2004 sampling period than during the September 2003 sampling period. Sether and others (2004) reported median total nitrogen concentrations for 21 samples collected during 1997-99 were about 0.7 mg/L for the Red River at Hickson, N. Dak. (site 4, figure 1 at back of report), and about 0.9 mg/L for the Red River above Fargo, N. Dak. (site 6, figure 1 at back of report). Those concentrations are higher than the concentrations measured during the September 2003 and May 2004 sampling periods. The median organic nitrogen concentration was about 0.6 mg/L for both sites during 1997-99, indicating that, during 1997-99, organic nitrogen made up most of the total nitrogen for those sites.

Total nitrogen concentrations for most sites on the Red River downstream from Halstad, Minn., and on the Sheyenne River were about 40 to 100 percent higher during the May 2004 sampling period than during the September 2003 sampling period, indicating the high streamflows increased nitrogen concentrations in the rivers. The total nitrogen concentration for site 8 (Red River below Fargo, N. Dak.), however, was about one-third lower during the May 2004 sampling period than during the September 2003 sampling period. Because streamflows for site 8 during the May 2004 sampling period were about three times higher than during the September 2003 sampling period, the high streamflows for that site likely diluted the effects of the wastewater discharge from Fargo, N. Dak.

Total phosphorus concentrations followed the same pattern as total nitrogen concentrations, with typically higher concentrations during the May 2004 sampling period than during the September 2003 sampling period in the Red River downstream from Halstad, Minn., and in the Sheyenne River (figure 7 at back of report). The median total phosphorus concentration reported by Sether and others (2004) for both the Red River at Hickson, N. Dak. (site 4, figure 1 at back of report), and the Red River above Fargo, N. Dak. (site 6, figure 1 at back of report), was about 0.2 mg/L. That concentration is similar to the concentrations measured during the September 2003 and May 2004 sampling periods.

Mean daily total nitrogen and total phosphorus loads calculated from a single sample are given in table 4. The loads were calculated by multiplying concentration, in milligrams per liter, by streamflow, in cubic feet per second, and then multiplying the coefficient by a conversion factor of 5.38. The mean daily loads calculated from multiyear data-collection efforts (Tornes and others, 1997; Sether and others, 2004) are given for comparison.

Loads were much higher during the May 2004 sampling period than during the September 2003 sampling period because of the higher streamflows and generally higher concentrations during May 2004. For the Sheyenne River, the total nitrogen and total phosphorus loads increased substantially downstream from site 12 (Sheyenne River below Baldhill Dam, N. Dak.). Loads between site 12 and site 15 (Sheyenne River above Sheyenne River diversion near Horace, N. Dak.) (a distance of about 230 river miles) were generally steady during both sampling periods, but a large increase occurred between site 15 and site 16 (Sheyenne River at Brooktree Park, N. Dak.) during the May 2004 sampling period. The increase was primarily the result of an increase in streamflow from 306 to 538 ft^3/s.

Total nitrogen and total phosphorus loads increased about three to eight times between site 7 (Red River at Fargo, N. Dak.) and site 8 (Red River below Fargo, N. Dak.) during both sampling periods. The increases probably were a result of loads from wastewater-treatment discharges. Nitrogen and phosphorus likely were transformed quickly downstream from Fargo, N. Dak., during low-flow conditions. Compared to the loads at Fargo, the loads of both nutrients were lower by as much as half at all Red River sites downstream from Fargo during the September 2003 sampling period. This pattern was not evident during the May 2004 sampling period because of the complicating effects of storm runoff.

Calculated loads for the three downstream-most Red River sites generally were lower than those for the upstream sites during the May 2004 sampling period because of the sampling pattern. The downstream Red River sites were sampled early in the sampling period before the widespread rains began and before storm runoff reached those sites. For example, streamflow for site 25 (Red River at Grand Forks, N. Dak.) on the date of sample collection was 8,130 ft^3/s, but streamflow for site 34 (Red River at Emerson, Manitoba) on the date of sample collection was 3,460 ft^3/s.

Site 18 (Wild Rice River at Hendrum, Minn.), site 21 (Marsh River near Shelly, Minn.), and site 33 (Pembina River above Pembina, N. Dak.) all contributed high loads of nitrogen and phosphorus to the Red River during the May 2004 sampling period. Loads from the Marsh River represented about 40 to 50 percent of the loads measured for site 23 (Red River near Thompson, N. Dak.). That site is the nearest Red River site downstream from the confluence of the Marsh and Red Rivers.

In general, the loads measured during this study were lower than the loads calculated from multiyear data-collection efforts (table 4). Tornes and others (1997) noted that much of the annual total nitrogen load in the Red River occurs immediately after the spring thaw and during snowmelt when nitrogen is released from thawing soils. The highest phosphorus loads, in contrast, occur after runoff events during the summer when soils are not frozen.

Table 4. Mean daily total nitrogen and total phosphorus loads for September 2003 and May 2004 sampling periods and for 1992-95 and 1998-99.

[--, no data; NA, not applicable]

Site number	Site name	Total nitrogen load (pounds per day)				Total phosphorus load (pounds per day)			
		September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99	September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99
1	Otter Tail River at 11th Street in Breckenridge, Minnesota	312	764	[3]2,690	[3]2,750	24	129	[3]147	[3]597
2	Bois de Sioux River near Doran, Minnesota	0	71	6,810	1,810	0	5	984	280
3	Red River of the North at Wahpeton, North Dakota	341	1,190	--	[4]5,030	21	168	--	[4]790
4	Red River of the North at Hickson, North Dakota	396	1,320	--	5,200	133	422	--	1,250
5	Wild Rice River near Abercrombie, North Dakota	2	74	--	--	0	34	--	--
6	Red River of the North above Fargo, North Dakota	411	1,300	22,100	10,200	174	465	2,160	2,120
7	Red River of the North at Fargo, North Dakota	369	1,700	--	--	104	447	--	--
8	Red River of the North on Cass County Road 20 below Fargo, North Dakota	3,170	6,290	--	--	660	1,290	--	--
NA	Red River of the North near Harwood, North Dakota	--	--	--	11,100	--	--	--	2,310
9	Sheyenne River above Harvey, North Dakota	17	111	--	--	3	19	--	--

Table 4. Mean daily total nitrogen and total phosphorus loads for September 2003 and May 2004 sampling periods and for 1992-95 and 1998-99.—Continued

[--, no data; NA, not applicable]

Site number	Site name	Total nitrogen load (pounds per day)				Total phosphorus load (pounds per day)			
		September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99	September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99
10	Sheyenne River near Warwick, North Dakota	105	384	--	--	28	52	--	--
11	Sheyenne River near Cooperstown, North Dakota	113	884	--	--	24	154	--	--
12	Sheyenne River below Baldhill Dam, North Dakota	380	1,830	--	--	46	312	--	--
13	Sheyenne River at Lisbon, North Dakota	212	1,510	4,970	--	20	275	959	--
14	Sheyenne River near Kindred, North Dakota	209	1,520	5,690	--	35	350	903	--
15	Sheyenne River above Sheyenne River Diversion near Horace, North Dakota	187	1,550	--	--	42	410	--	--
16	Sheyenne River at Brooktree Park, North Dakota	208	3,390	--	[3]9,100	50	1,020	--	[3]2,780
17	Buffalo River near Dilworth, Minnesota	61	740	--	--	13	194	--	--
NA	Red River of the North at Perley, Minnesota	--	--	--	27,700	--	--	--	6,210
18	Wild Rice River at Hendrum, Minnesota	104	4,330	[3]2,780	--	9	1,500	[3]179	--

Table 4. Mean daily total nitrogen and total phosphorus loads for September 2003 and May 2004 sampling periods and for 1992-95 and 1998-99.—Continued

[--, no data; NA, not applicable]

Site number	Site name	Total nitrogen load (pounds per day)				Total phosphorus load (pounds per day)			
		September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99	September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99
19	Red River of the North at Halstad, Minnesota	1,960	14,800	45,500	--	430	5,670	6,280	--
20	Goose River at Hillsboro, North Dakota	48	1,100	--	--	4	73	--	--
21	Marsh River near Shelly, Minnesota	1	6,880	--	--	0	1,670	--	--
22	Sand Hill River at Climax, Minnesota	35	1,880	--	--	4	48	--	--
23	Red River of the North near Thompson, North Dakota	747	14,100	--	--	201	4,410	--	--
24	Red Lake River at Fisher, Minnesota	598	1,600	[3]10,800	--	34	90	[3]925	--
25	Red River of the North at Grand Forks, North Dakota	1,460	41,900	68,900	--	260	10,200	7,910	--
26	Turtle River above Manvel, North Dakota	7	167	[3]480	--	1	38	[3]69	--
27	Red River of the North at Oslo, Minnesota	1,990	28,600	--	--	421	13,200	--	--
28	Forest River near confluence with Red River of the North, North Dakota	64	410	--	--	3	209	--	--

Table 4. Mean daily total nitrogen and total phosphorus loads for September 2003 and May 2004 sampling periods and for 1992-95 and 1998-99.—Continued

[--, no data; NA, not applicable]

Site number	Site name	Total nitrogen load (pounds per day)				Total phosphorus load (pounds per day)			
		September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99	September 15 through 16, 2003	May 10 through 13, 2004	[1]1992-95	[2]1998-99
29	Snake River near Big Woods, Minnesota	--	130	[3]707	--	--	25	[3]78	--
30	Park River near Oakwood, North Dakota	8	409	--	--	1	68	--	--
31	Red River of the North at Drayton, North Dakota	1,671	16,200	--	--	727	2,460	--	--
32	Two Rivers at Hallock, Minnesota	27	573	--	--	2	100	--	--
33	Pembina River above Pembina, North Dakota	50	4,490	[3]8,500	--	12	2,020	[3]1,790	--
34	Red River of the North at Emerson, Manitoba	1,802	19,700	88,800	--	304	4,840	10,800	--

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[1] From Tornes and others, 1997.

[2] From Sether and others, 2004.

[3] Calculated at site upstream from current study site.

[4] Calculated at site downstream from current study site.

Simulation of Conservative-Constituent Transport

The Red River water-quality model was calibrated and tested using data collected from September 15 through 16, 2003, and from May 10 through 13, 2004. The model simulates the flow and transport of total dissolved solids, sulfate, and chloride during steady-state conditions. Those constituents are considered to be conservative constituents for this application. Sulfate also was simulated as a conservative constituent in the U.S. Army Corps of Engineers (2003) HEC-5Q water-quality model.

Model Implementation

The U.S. Army Corps of Engineers (2003) HEC-5Q water-quality model was modified for this study by (1) extending the computational grid and (2) specifying boundary conditions. Boundary conditions included natural inflows and outflows of water and constituents and withdrawals and return flows.

Computational Grid

The physical domain of the Red River water-quality model includes the Red River from the confluence of the Bois de Sioux and Otter Tail Rivers to the Red River at Emerson, Manitoba, and the Sheyenne River from above Harvey, N. Dak., to the confluence with the Red River (figure 8 at back of report). The model domain is represented by a computational grid that includes 2 main branches, 21 control points, 4 reservoirs, 15 tributaries (other than the Sheyenne River), and 331 stream elements.

The computational grid in the HEC-5 model is represented by control points and reservoirs. The downstream-most location must be a control point, and the upstream-most location on each branch must be a reservoir. Control points are locations at which incremental flow is added to or removed from a river. Incremental flow, which is the streamflow that is added to or removed from a river at a control point, accounts for changes in streamflow that occur between control points (for example, gains from tributaries, point sources, and ground-water discharge and losses from ground-water recharge and withdrawals). Reservoirs can be actual reservoirs (Lake Ashtabula) or virtual reservoirs. For this study, virtual reservoirs were created on the Otter Tail River in Breckenridge, Minn., the Bois de Sioux River near Doran, Minn., and the Sheyenne River above Harvey, N. Dak. For virtual reservoirs, outflow is equal to streamflow.

In the HEC-5Q model, stream elements and tributaries are added to the computational grid of the HEC-5 model and the reach between control points is divided into stream elements. Stream elements are reaches in which water-quality conditions are fairly uniform. Tributaries are used to add constituent mass as a proportion of incremental flow, and more than one tributary can be located between two control points [for example, three tributaries are located between the Red River at Halstad, Minn., and the Red River near Thompson, N. Dak. (figure 8 at back of report)]. Tributary streamflow is treated as part of the incremental flow between control points so that the total tributary streamflow between two control points is equal to the incremental flow, minus any withdrawals, for that reach. For the Red River water-quality model, the reaches were divided into 331 stream elements that ranged in length from 1.5 to 6 mi.

Streamflow and Water-Quality Boundary Conditions

A time series of streamflow must be specified for each control point within the HEC-5 model. For this study, only a single streamflow value was required because streamflow was assumed to be steady. Streamflow boundary conditions for the September 2003 sampling period (table 5) were computed by using a moving average of measured daily mean streamflows for 3 to 5 days (September 11 through 17, 2003), and streamflow boundary conditions for the May 2004 sampling period (table 6) were computed by using a moving average of measured daily mean streamflows for 7 days (May 9 through 23, 2004). A longer averaging period was used for the May 2004 sampling period than for the September 2003 sampling period because of the highly unsteady streamflows during May 2004.

Incremental flow for a reach was determined by calculating the difference between streamflow at the upstream control point and streamflow at the downstream control point of the reach (tables 5 and 6). For this study, streamflows were measured for many of the reaches. If the difference between the accumulated upstream streamflows (the sum of the streamflow measured at the upstream control point and the streamflow measured for the tributaries) and the downstream streamflow was near zero, most of the inflows to the reach probably were measured (tables 5 and 6). If the difference was large in relation to the streamflow in the river, streamflows for several fairly large tributaries in the reach probably were not measured or ground-water discharge in the reach was high.

Water-quality boundary conditions were specified for the upstream-most points on each branch (the Sheyenne River above Harvey, N. Dak., the Otter Tail River at 11th Street in Breckenridge, Minn., and the Bois de Sioux River near Doran, Minn.); the mouth of each of the 15 tributaries; the incremental flows in reaches for which tributary streamflow was not measured; and the Sheyenne River below Baldhill Dam, N. Dak. (table 7). September 2003 data for Lake Ashtabula (U. S. Army

Table 5. Streamflow boundary conditions for September 2003 sampling period.

[ft^3/s, cubic feet per second; --, no data; shading indicates control point location]

Location	Streamflow measured at control point (ft^3/s)	Streamflow measured for tributary (ft^3/s)	Difference between accumulated upstream streamflows and downstream streamflow (ft^3/s)	Incremental flow	
				(ft^3/s)	Percent of streamflow measured at control point
Sheyenne River					
Sheyenne River above Harvey, North Dakota	2.5	--	--	--	--
Sheyenne River at North Dakota Highway 30 near Maddock, North Dakota[1]	[2]10.8	--	8.3	8.3	77
Sheyenne River at Peterson Coulee, North Dakota[1]	[2]11.6	--	0.8	0.8	7
Sheyenne River near Warwick, North Dakota	15	--	3.4	3.4	23
Sheyenne River near Cooperstown, North Dakota	20	--	5	5	25
Into Lake Ashtabula[1]	[2]20.7	--	0.7	0.7	3
Sheyenne River below Baldhill Dam, North Dakota	37	--	--	--	--
Sheyenne River at Valley City, North Dakota	[2]38	--	1	1	3
Sheyenne River at Lisbon, North Dakota	41	--	3	3	7
Sheyenne River near Kindred, North Dakota	69	--	28	28	41
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	71	--	2	2	3
Sheyenne River at Brooktree Park, North Dakota	80	--	9	9	11
Red River of the North and tributaries					
Otter Tail River at 11th Street in Breckenridge, Minnesota	--	114	--	--	--
Bois de Sioux River near Doran, Minnesota	--	0	--	--	--
Red River of the North at Wahpeton, North Dakota	110	--	-4	-4	4
Red River of the North at Hickson, North Dakota	119	--	9	9	8
Wild Rice River near Abercrombie, North Dakota	--	0.3	--	--	--
Fargo, North Dakota, and Moorhead, Minnesota, wastewater-treatment facilities withdrawals	--	-28	--	--	--
Red River of the North at Fargo, North Dakota	104	--	12.7	-15.0	14
Fargo, North Dakota, and Moorhead, Minnesota, wastewater-treatment facilities return flows	--	23.3	--	--	--

Table 5. Streamflow boundary conditions for September 2003 sampling period.—Continued

[ft^3/s, cubic feet per second; --, no data; shading indicates control point location]

Location	Streamflow measured at control point (ft^3/s)	Streamflow measured for tributary (ft^3/s)	Difference between accumulated upstream streamflows and downstream streamflow (ft^3/s)	Incremental flow (ft^3/s)	Incremental flow: Percent of streamflow measured at control point
Red River of the North and tributaries, Continued					
Sheyenne River at Brooktree Park, North Dakota	--	80	--	--	--
Red River of the North at confluence with Sheyenne River, North Dakota	[2]223	--	15.7	39	17
Buffalo River near Dilworth, Minnesota	--	22	--	--	--
Wild Rice River at Hendrum, Minnesota	--	46	--	--	--
Red River of the North at Halstad, Minnesota	278	--	-13.0	55	20
Goose River at Hillsboro, North Dakota	--	19	--	--	--
Marsh River near Shelly, Minnesota	--	0.1	--	--	--
Sand Hill River at Climax, Minnesota	--	22	--	--	--
Red River of the North near Thompson, North Dakota	325	--	5.9	47	14
Red Lake River at Fisher, Minnesota	--	159	--	--	--
Red River of the North at Grand Forks, North Dakota	422	--	-62	97	23
Turtle River above Manvel, North Dakota	--	2	--	--	--
Red River of the North at Oslo, Minnesota	[2]425	--	1	3	1
Forest River near confluence with Red River of the North, North Dakota	--	10	--	--	--
Snake River near Big Woods, Minnesota	--	0	--	--	--
Park River near Oakwood, North Dakota	--	2	--	--	--
Red River of the North at Drayton, North Dakota	440	--	3	15	3
Two Rivers at Hallock, Minnesota	--	5	--	--	--
Pembina River above Pembina, North Dakota	--	20	--	--	--
Red River of the North at Emerson, Manitoba	470	--	5	30	6

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[1] No data were collected at this location during this study.

[2] Estimated value.

Table 6. Streamflow boundary conditions for May 2004 sampling period.

[ft^3/s, cubic feet per second; --, no data; shading indicates control point location]

Location	Streamflow measured at control point (ft^3/s)	Streamflow measured for tributary (ft^3/s)	Difference between accumulated upstream streamflows and downstream streamflow (ft^3/s)	Incremental flow	
				(ft^3/s)	Percent of streamflow measured at control point
Sheyenne River					
Sheyenne River above Harvey, North Dakota	18	--	--	--	--
Sheyenne River at North Dakota Highway 30 near Maddock, North Dakota[1]	[2]66.2	--	48.2	48.2	73
Sheyenne River at Peterson Coulee, North Dakota[1]	[2]70.8	--	4.6	4.6	7
Sheyenne River near Warwick, North Dakota	92	--	21.2	21.2	23
Sheyenne River near Cooperstown, North Dakota	234	--	142	142	61
Into Lake Ashtabula[1]	[2]241	--	7	7	3
Sheyenne River below Baldhill Dam, North Dakota	423	--	--	--	--
Sheyenne River at Valley City, North Dakota	[2]435	--	12	12	3
Sheyenne River at Lisbon, North Dakota	468	--	33	33	7
Sheyenne River near Kindred, North Dakota	525	--	57	57	11
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	550	--	25	25	5
Sheyenne River at Brooktree Park, North Dakota	700	--	150	150	21
Red River of the North and tributaries					
Otter Tail River at 11th Street in Breckenridge, Minnesota	--	400	--	--	--
Bois de Sioux River near Doran, Minnesota	--	34	--	--	--
Red River of the North at Wahpeton, North Dakota	451	--	17	17	4
Red River of the North at Hickson, North Dakota	494	--	43	43	9
Wild Rice River near Abercrombie, North Dakota	--	20	--	--	--
Fargo, North Dakota, and Moorhead, Minnesota, wastewater-treatment facilities withdrawals	--	-23	--	--	--
Red River of the North at Fargo, North Dakota	643	--	152	149	23
Fargo, North Dakota, and Moorhead, Minnesota, wastewater-treatment facilities return flows	--	22	--	--	--

Table 6. Streamflow boundary conditions for May 2004 sampling period.—Continued

[ft^3/s, cubic feet per second; --, no data; shading indicates control point location]

Location	Streamflow measured at control point (ft^3/s)	Streamflow measured for tributary (ft^3/s)	Difference between accumulated upstream streamflows and downstream streamflow (ft^3/s)	Incremental flow (ft^3/s)	Incremental flow: Percent of streamflow measured at control point
Red River of the North and tributaries					
Sheyenne River at Brooktree Park, North Dakota	--	700	--	--	--
Red River of the North at confluence with Sheyenne River, North Dakota	[2]1,400	--	35	57	4
Buffalo River near Dilworth, Minnesota	--	266	--	--	--
Wild Rice River at Hendrum, Minnesota	--	813	--	--	--
Red River of the North at Halstad, Minnesota	2,630	--	151	1,230	47
Goose River at Hillsboro, North Dakota	--	242	--	--	--
Marsh River near Shelly, Minnesota	--	557	--	--	--
Sand Hill River at Climax, Minnesota	--	445	--	--	--
Red River of the North near Thompson, North Dakota	5,320	--	1,446	2,690	51
Red Lake River at Fisher, Minnesota	--	5,580	--	--	--
Red River of the North at Grand Forks, North Dakota	10,600	--	-300	5,280	50
Turtle River above Manvel, North Dakota	--	100	--	--	--
Red River of the North at Oslo, Minnesota	[2]11,000	--	300	400	4
Forest River near confluence with Red River of the North, North Dakota	--	130	--	--	--
Snake River near Big Woods, Minnesota	--	31	--	--	--
Park River near Oakwood, North Dakota	--	71	--	--	--
Red River of the North at Drayton, North Dakota	14,600	--	3,368	3,600	25
Two Rivers at Hallock, Minnesota	--	3,000	--	--	--
Pembina River above Pembina, North Dakota	--	1,500	--	--	--
Red River of the North at Emerson, Manitoba	17,500	--	-1,600	2,900	17

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[1] No data were collected at this location during this study.

[2] Estimated value.

Table 7. Water-quality boundary conditions for September 2003 and May 2004 sampling periods.

[mg/L, milligrams per liter]

Location	September 2003			May 2004		
	Total dissolved solids (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Total dissolved solids (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
Sheyenne River						
Sheyenne River above Harvey, North Dakota	1,060	350	20	1,320	580	26
Incremental flow from Harvey, North Dakota, to Warwick, North Dakota	770	220	25	740	230	20
Incremental flow from Cooperstown, North Dakota, to Lake Ashtabula, North Dakota	324	63	13	690	260	17
Sheyenne River below Baldhill Dam, North Dakota	713	260	19	347	130	8.7
Incremental flow from Baldhill Dam, North Dakota, to Lisbon, North Dakota	1,520	780	240	1,930	880	120
Incremental flow from Lisbon, North Dakota, to Kindred, North Dakota	460	110	14	560	53	5.0
Incremental flow from Kindred, North Dakota, to Horace, North Dakota	340	12	16	200	120	7.0
Incremental flow from Horace, North Dakota, to Brooktree Park, North Dakota	1,050	410	54	740	420	56
Incremental flow from Brooktree Park, North Dakota, to confluence with Red River of the North, North Dakota	410	380	20	440	190	0
Red River of the North and tributaries						
Otter Tail River at 11th Street in Breckenridge, Minnesota	267	31	11	243	26	11
Bois de Sioux River near Doran, Minnesota	0	0	0	1,400	860	29
Incremental flow from Wahpeton, North Dakota, to Hickson, North Dakota	1,470	270	280	420	0	140
Wild Rice River near Abercrombie, North Dakota	1,490	740	62	1,210	580	49
Incremental flow from Fargo, North Dakota, to confluence with Sheyenne River, North Dakota	1,200	200	100	940	480	84

Table 7. Water-quality boundary conditions for September 2003 and May 2004 sampling periods.—Continued

[mg/L, milligrams per liter]

Location	September 2003			May 2004		
	Total dissolved solids (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Total dissolved solids (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
Red River of the North and tributaries, Continued						
Buffalo River near Dilworth, Minnesota	407	78	8.6	440	110	33
Wild Rice River at Hendrum, Minnesota	334	52	6.7	265	52	5.3
Goose River at Hillsboro, North Dakota	1,020	470	53	981	460	37
Marsh River near Shelly, Minnesota	458	83	15	266	84	7.9
Sand Hill River at Climax, Minnesota	326	46	7.4	390	72	11
Red Lake River at Fisher, Minnesota	258	41	8.8	295	65	11
Turtle River above Manvel, North Dakota	2,550	540	980	1,210	400	250
Forest River near confluence with Red River of the North, North Dakota	3,240	680	1,300	1,120	350	270
Snake River near Big Woods, Minnesota	0	0	0	482	120	32
Park River near Oakwood, North Dakota	14,400	1,270	7,660	1,480	350	480
Two Rivers at Hallock, Minnesota	379	40	45	279	53	17
Pembina River above Pembina, North Dakota	555	190	21	382	150	12
Additional incremental flow from Drayton, North Dakota, to Emerson, Manitoba	6,000	1,500	2,000	2,100	240	0

Corps of Engineers, 2005) indicate conservative-constituent concentrations within the lake were within 3 percent of the concentrations measured for the Sheyenne River below Baldhill Dam during this study. This indicates conservative-constituent concentrations in the Sheyenne River below Baldhill Dam are representative of conservative-constituent concentrations in Lake Ashtabula.

Water-quality boundary conditions were based on water-quality data for the tributaries and on calculated incremental flows (table 7). The cases considered are as follow:

- No tributary in the reach—Constituent concentrations for the incremental flow were calculated from a mass balance of constituent load based on streamflow and constituent concentrations at the upstream and downstream control points of the reach.
- One or more tributaries in the reach—Each tributary in the reach was assigned a streamflow that was equal to a percentage of the incremental flow in the reach. Measured constituent concentrations then were assigned to each tributary in the reach. Constituent concentrations for the incremental flows not assigned to tributaries were calculated from a mass balance of constituent concentrations in the respective reach. Mass balances were computed by determining the difference between the constituent load at the upstream point and the constituent load at the downstream point and then dividing the difference by the incremental flow to determine a concentration. Streamflows assigned to the tributaries were based on field measurements, but adjustments to the measured streamflows were required to ensure that the sum of the streamflows did not exceed the incremental flow in the reach.

Small point-source discharges and withdrawals were not included in the model but were accounted for through mass balances of streamflow and constituent concentrations within a reach in a manner similar to that for unknown tributary concentrations. Withdrawals by the cities of Fargo, N. Dak., Grand Forks, N. Dak., and Moorhead, Minn., also were not included in the model but were accounted for through changes in streamflow at locations upstream and downstream from the withdrawals. Wastewater is discharged continuously from the Fargo and Moorhead wastewater-treatment facilities, but the wastewater is not routinely analyzed for total dissolved solids, sulfate, and chloride. Therefore, because concentrations for those constituents were required by the model, water-quality samples were collected from the Red River immediately upstream and immediately downstream from both facilities during the September 2003 sampling period. Concentrations attributed to the discharges then were determined by mass balance (incremental flow from Fargo, N. Dak., to the Red River on Cass County Road 20 below Fargo, N. Dak., table 7). Discharge from the Grand Forks wastewater-treatment facility is pumped to a lagoon system and subsequently released to the Red River during the spring and fall. Because no releases were made from the lagoon during the September 2003 sampling period, discharge from the Grand Forks facility was assumed to be zero.

Model Calibration

Simulated streamflows and total dissolved-solids, sulfate, and chloride concentrations at 11 model calibration points (table 8) were compared to measured streamflows and concentrations. The calibration points are located throughout the model domain and several are located near withdrawal and return-flow locations.

Streamflow

The model was calibrated for steady-state conditions throughout the reach (streamflow varied from site to site but did not vary with time at a site). During September 2003, the streamflows ranged from 2.5 ft^3/s for the Sheyenne River above Harvey, N. Dak., to 470 ft^3/s for the Red River at Emerson, Manitoba (figures 9a and 9b at back of report). Because of the assumption of steady-state conditions, the simulated streamflows were the same as the measured streamflows for all sites in the model domain.

Water Quality

During the September 2003 sampling period, measured total dissolved-solids concentrations ranged from 262 mg/L for the Red River at Wahpeton, N. Dak., to 1,060 mg/L for the Sheyenne River above Harvey, N. Dak. (figures 10a and 10b at back of report). The concentrations for the Sheyenne River were higher than the concentrations for the Red River (figure 4 at back of report), and the concentrations for the remaining tributaries were higher than the concentrations for the Sheyenne River [for example, the concentration for site 30 (Park River near Oakwood, N. Dak.) was 14,400 mg/L (figure 4c at back of report)]. The simulated concentrations were within 5 percent of the measured concentrations for all model calibration points (figures 10a and 10 b at back of report).

Measured sulfate concentrations ranged from 31.6 mg/L for the Red River at Wahpeton, N. Dak., to 348 mg/L for the Sheyenne River above Harvey, N. Dak., during the September 2003 sampling period (figures 11a and 11b at back of report). The concentrations for the Sheyenne River were higher than the concentrations for the Red River (figure 5b at back of report), and the concentrations for the remaining tributaries were higher in some instances than the concentrations for the Sheyenne River [for example, the concentration for site 30 (Park River near Oakwood, N. Dak.) was 1,270 mg/L or 26.44 meq/L]. The

Table 8. Model calibration points used for simulation of conservative-constituent transport in the Red River of the North Basin.

Model calibration point	U.S. Geological Survey site number
Sheyenne River above Harvey, North Dakota	05054500
Sheyenne River near Cooperstown, North Dakota	05057000
Sheyenne River below Baldhill Dam, North Dakota	05058000
Sheyenne River at Lisbon, North Dakota	05058700
Sheyenne River near Kindred, North Dakota	05059000
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	05059300
Red River of the North at Wahpeton, North Dakota	05051500
Red River of the North at Fargo, North Dakota	05054000
Red River of the North near Thompson, North Dakota	05070000
Red River of the North at Grand Forks, North Dakota	05082500
Red River of the North at Emerson, Manitoba	05102500

simulated concentrations were within 5 percent of the measured concentrations for all model calibration points except the Red River at Fargo, N. Dak., and the Red River at Grand Forks, N. Dak. (figures 11a and 11b at back of report). The difference between the measured and simulated concentrations for the Red River at Fargo was larger than 5 percent because loss of streamflow between Hickson, N. Dak., and Fargo (table 5) resulted in no changes in concentration in that reach (concentrations for the Wild Rice River near Abercrombie, N. Dak., were added in the reach and withdrawals from Fargo and from Moorhead, Minn., were made in the reach). The simulated concentrations for the Red River at Fargo could be improved if another control point was added to the model at the Red River above Fargo. The difference between the measured and simulated concentrations for the Red River at Grand Forks was larger than 5 percent because the combined streamflow for the Red River near Thompson, N. Dak., and the Red Lake River at Fisher, Minn., was 62 ft^3/s more than the streamflow measured for the Red River at Grand Forks (table 5).

Measured chloride concentrations ranged from 10.8 mg/L for the Red River at Wahpeton, N. Dak., to 96.7 mg/L for the Red River at Emerson, Manitoba, during the September 2003 sampling period (figures 12a and 12b at back of report). The concentrations for the Sheyenne River were similar in range to those for the Red River except for the Red River at Emerson (figure 5b at back of report). The concentration for the Red River at Emerson is high because some of the tributaries downstream from the Red River at Grand Forks, N. Dak., are affected by ground water that has high chloride concentrations [for example, the concentration for site 30 (Park River near Oakwood, N. Dak.) was 1,300 mg/L or 36.67 meq/L]. The simulated concentrations were within 5 percent of the measured concentrations for all model calibration points except the Red River at Fargo, N. Dak., and the Red River at Grand Forks (figures 12a and 12b at back of report). The difference between the measured and simulated concentrations for the Red River at Fargo was larger than 5 percent because loss of streamflow between Hickson, N. Dak., and Fargo (table 5) resulted in no changes in concentration in that reach (concentrations for the Wild Rice River near Abercrombie, N. Dak., were added in the reach and withdrawals from Fargo and from Moorhead were made in the reach). The difference between the measured and simulated concentrations for the Red River at Grand Forks was larger than 5 percent because the combined streamflow for the Red River near Thompson, N. Dak., and the Red Lake River at Fisher, Minn., was 62 ft^3/s more than the streamflow measured for the Red River at Grand Forks (table 5).

Because of the steady-flow conditions for the model simulation and because total dissolved solids, sulfate, and chloride are considered to be conservative constituents, the model had no kinetic or transport parameters to adjust. Therefore, model calibration was accomplished by making small adjustments to estimated loads from unmeasured sources. Generally, the differences between the measured and simulated total dissolved-solids, sulfate, and chloride concentrations were less than 5 percent of the measured concentrations.

To determine the mean calibration error for the model domain, the absolute difference between the measured and simulated concentrations was calculated for the 11 model calibration points. The absolute difference was averaged and the average difference was considered to be the mean calibration error. The mean calibration error, which is shown in table 9 along with the maximum and minimum absolute differences, ranged from 1.3 mg/L for chloride to 13 mg/L for total dissolved solids. If the mean calibration error is expressed as a percentage, the error for each of the three constituents is similar. For total dissolved solids and sulfate, the error is 2 percent, and for chloride, the error is 4 percent.

Table 9. Mean calibration errors and maximum and minimum absolute differences between measured (September 2003) and simulated total dissolved-solids, sulfate, and chloride concentrations.

[The mean calibration error was determined by averaging the absolute difference between the measured and simulated concentrations for the 11 model calibration points; the location for which the maximum or minimum difference occurred is indicated in parentheses]

Constituent	Mean calibration error (milligrams per liter)	Maximum absolute difference (milligrams per liter)	Minimum absolute difference (milligrams per liter)
Total dissolved solids	13	27 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)	8 (Red River of the North at Emerson, Manitoba)
Sulfate	4.4	20 (Red River of the North at Grand Forks, North Dakota)	0 (Sheyenne River at Lisbon, North Dakota)
Chloride	1.3	5.9 (Red River of the North at Fargo, North Dakota)	0.4 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)

Model Performance Testing

The Red River water-quality model was tested using data collected from May 10 through 13, 2004. The unsteadiness in the measured streamflows was smoothed using a 7-day average streamflow (May 9 through 23, 2004) (figures 13a and 13b at back of report).

Measured and simulated total dissolved-solids, sulfate, and chloride concentrations for the Sheyenne River were in agreement (figures 14a, 15a, and 16a at back of report), primarily because streamflows in the Sheyenne River during the May 2004 sampling period were fairly steady and instream water-quality conditions were not affected by storm runoff. Measured and simulated concentrations for the Red River were not in agreement (figures 14b, 15b, and 16b at back of report) because streamflows in the Red River were unsteady and samples were collected during differing flow conditions. The measured and simulated concentrations for the Red River at Fargo, N. Dak., and the Red River at Emerson, Manitoba, differed by as much as 194 percent. The large difference probably resulted from unmeasured and unknown loads from storm runoff during the sampling period. Concentrations in the runoff could have been estimated by mass balance, but the model then would apply only to conditions such as those that occurred during the rainfall event that preceded the runoff.

Model Applications

The Red River water-quality model was used to simulate conservative-constituent transport in the Red River and the Sheyenne River for the eight water-supply alternatives identified by the Bureau of Reclamation (table 10). For the first set of eight simulations, September 2003 streamflows were used with projected 2050 return flows and withdrawals. Because the calibrated model does not directly include return flows and withdrawals, the model was modified to accept projected return flows and withdrawals for the alternatives (table 11). Also, because the calibrated model does not directly include return flows and withdrawals, the projected return flows were represented as the difference between the average August 2050 return flows modeled by the Bureau of Reclamation for 1931-40 streamflows and the average August 2005 return flows modeled by the Bureau of Reclamation for 1990-99 streamflows (G. Hiemenz, Bureau of Reclamation, written commun., 2005). The projected withdrawals were represented as the difference between the average August 2050 withdrawals modeled by the Bureau of Reclamation for 1931-40 streamflows and the average August 2005 withdrawals modeled by the Bureau of Reclamation for 1990-99 streamflows for Fargo, N. Dak., West Fargo, N. Dak., Grand Forks, N. Dak., and Moorhead, Minn. (G. Hiemenz, Bureau of Reclamation, written commun., 2005). Those cities account for 85 percent of the withdrawals in the Red River Basin. For the second set of eight simulations, the September 2003 streamflows were reduced by 25 percent. Projected return flows, imported flows, and withdrawals were not adjusted from previous simulations. The effects of the alternatives on constituent concentrations probably would be greatest during low-flow conditions.

Projected return flows were added to the model through virtual reservoirs so that the flows and the constituents in the flows were added as point sources at a given return location. One set of projected return flows was used for alternative 1 (the no-action alternative) and another set of projected return flows was used for alternatives 2 through 8 (the action alternatives) (G. Hiemenz, Bureau of Reclamation, written commun., 2005). Because of the structure of the STATEMOD flow model, the projected return flow for Halstad, Minn., represented the return flows from Fargo, N. Dak., and Moorhead, Minn. Projected return flows ranged from 1 ft^3/s for the Red River at Grand Forks, N. Dak., to 49 ft^3/s for the Red River at Halstad, Minn. (table 11). Imported flows were added to the model for alternatives 2, 5, and 7. During project operation, imported flows would be conveyed into Lake Ashtabula. However, because the water-quality processes in Lake Ashtabula were not included in the model and conservative-constituent concentrations in the Sheyenne River below Baldhill Dam, N. Dak., are representative of those in Lake Ashtabula, the imported flows were modeled to be conveyed to the Sheyenne River below Baldhill Dam. Imported flows ranged from 30 ft^3/s for alternative 2 to 114 ft^3/s for alternative 5. For alternative 5, additional flow was added to the Sheyenne River at Valley City, N. Dak., to account for water conveyance in the Sheyenne River during nonpeak water-use demand. The additional flow for alternative 5 was modeled as a return flow but, during project operation, actually would be an additional release for Baldhill Dam.

Projected withdrawals were applied at three locations. The projected withdrawal for the Red River at Fargo, N. Dak., represents withdrawals from Fargo and from Moorhead, Minn.; the projected withdrawal for the Sheyenne River above the Sheyenne River diversion near Horace, N. Dak., represents withdrawals from West Fargo, N. Dak.; and the projected withdrawal for the Red River near Thompson, N. Dak., represents withdrawals from Grand Forks, N. Dak. For alternative 2, an exported flow of 30 ft^3/s at Grand Forks also was applied as a withdrawal.

Estimated constituent concentrations for the projected return flows were obtained from the Bureau of Reclamation (G. Hiemenz, Bureau of Reclamation, written commun., 2005). The concentrations were estimated on the basis of source concentrations and current (2005) wastewater-treatment technology. Constituent concentrations for the imported flows for alternatives 2 and 7 were assumed to be equal to the median concentrations of all available USGS water-quality data for the Red River at Grand Forks, N. Dak., and the Missouri River at Bismarck, N. Dak., respectively (U.S. Geological Survey, accessed December 5, 2005). The concentration for the imported flow for alternative 5 was assumed to be equal to the median concentration for Lake Audubon at the McClusky Canal Headworks (G. Hiemenz, Bureau of Reclamation, written commun., 2005).

Simulations with September 2003 Streamflows

The effects of the water-supply alternatives identified by the Bureau of Reclamation (table 10) on conservative-constituent transport in the Red River Basin were simulated with the low streamflows that occurred during September 2003. The simulated streamflows for each alternative (figures 17a and 17b at back of report) reflect the changes in streamflow that resulted from the projected return flows and withdrawals.

Total Dissolved Solids

Simulated total dissolved-solids concentrations for alternatives 2 through 8 (the action alternatives) for the Sheyenne River generally were equal to or less than those for alternative 1 (the no-action alternative) (figures 18a and 18b at back of report). Simulated concentrations for alternatives 2 through 8 for the Red River generally were higher than those for alternative 1 except for alternatives 6 and 8 (figures 18c and 18d at back of report). Alternative 7 had the largest effect on total dis-

Table 10. Description of water-supply alternatives for Red River Valley Water Supply Project.

[Modified from U.S. Department of the Interior, Bureau of Reclamation, 2005]

Alternative number	Description of alternative
1	No-action alternative. Would use the current water supply in the Red River of the North Basin without the Red River Valley Water Supply Project.
	In-basin alternatives
2	North Dakota in-basin alternative. Would use the Red River of the North and other North Dakota water sources to supplement the current water supply to meet predicted water shortages.
3	Red River Basin alternative. Would use the Red River of the North, other North Dakota water sources, and Minnesota ground water to supplement the current water supply to meet predicted water shortages.
4	Lake of the Woods alternative. Would use the Red River of the North, other North Dakota water sources, and water from Lake of the Woods, Minnesota, to supplement the current water supply to meet predicted water shortages.
	Import alternatives
5	Garrison Diversion Unit import to Sheyenne River alternative. Would use the Red River of the North, other North Dakota in-basin sources, and Missouri River water to supplement the current water supply to meet predicted water shortages. The Garrison Diversion Unit Principal Supply Works would be linked to the Sheyenne River through a pipeline. The Principal Supply Works include the Snake Creek Pumping Plant on Lake Sakakawea, Audubon Lake, and McClusky Canal.
6	Garrison Diversion Unit import pipeline alternative. Would use the Red River of the North, other North Dakota in-basin sources, and imported Missouri River water to supplement the current water supply to meet predicted water shortages. The Garrison Diversion Unit Principal Supply Works and a pipeline system would convey water to the Red River Valley.
7	Missouri River import to Red River Valley alternative. Would use the Red River of the North, other North Dakota in-basin sources, and imported Missouri River water to supplement the current water supply to meet predicted water shortages. A pipeline from the Missouri River would convey water to the Red River Valley.
8	Garrison Diversion Unit water supply replacement pipeline alternative. Would use water imported from the Missouri River to replace other water supplies in the service area and to meet predicted water shortages. The Garrison Diversion Unit Principal Supply Works and a pipeline system would convey water to the Red River Valley.

Table 11. Projected return flows, imported flows, and withdrawals and estimated total dissolved-solids, sulfate, and chloride concentrations for water-supply alternatives.

[From G. Hiemenz, Bureau of Reclamation, written commun., 2005; ft^3/s, cubic feet per second; mg/L, milligrams per liter; --, no data; negative withdrawals indicate less water is being withdrawn in 2050 than what was withdrawn in the 1990s; GDU, Garrison Diversion Unit]

Location	Projected return flows and imported flows (ft^3/s)	Projected withdrawals (ft^3/s)	Estimated concentration: Total dissolved solids (mg/L)	Estimated concentration: Sulfate (mg/L)	Estimated concentration: Chloride (mg/L)
Alternative 1					
Red River of the North at Halstad, Minnesota	23	--	1,009	110	60
Red River of the North at Fargo, North Dakota	--	7	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	12	--	--	--
Red River of the North near Thompson, North Dakota	--	30	--	--	--
Alternative 2					
Sheyenne River below Baldhill Dam, North Dakota (imported flow from Grand Forks, North Dakota)	[1]30	--	339	70	9
Red River of the North at Halstad, Minnesota	49	--	1,053	112	72
Red River of the North at Grand Forks, North Dakota	1	--	1,053	112	72
Red River of the North at Drayton, North Dakota	4	--	1,053	112	72
Red River of the North at Fargo, North Dakota	--	13	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	60	--	--	--
Red River of the North near Thompson, North Dakota	--	30	--	--	--
Alternative 3					
Red River of the North at Halstad, Minnesota	49	--	1,113	109	84
Red River of the North at Grand Forks, North Dakota	1	--	1,113	109	84
Red River of the North at Drayton, North Dakota	4	--	1,113	109	84
Red River of the North at Fargo, North Dakota	--	13	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	-6	--	--	--
Red River of the North near Thompson, North Dakota	--	30	--	--	--

Table 11. Projected return flows, imported flows, and withdrawals and estimated total dissolved-solids, sulfate, and chloride concentrations for water-supply alternatives.—Continued

[From G. Hiemenz, Bureau of Reclamation, written commun., 2005; ft^3/s, cubic feet per second; mg/L, milligrams per liter; --, no data; negative withdrawals indicate less water is being withdrawn in 2050 than what was withdrawn in the 1990s; GDU, Garrison Diversion Unit]

Location	Projected return flows and imported flows (ft^3/s)	Projected withdrawals (ft^3/s)	Estimated concentration: Total dissolved solids (mg/L)	Estimated concentration: Sulfate (mg/L)	Estimated concentration: Chloride (mg/L)
Alternative 4					
Red River of the North at Halstad, Minnesota	49	--	1,001	95	90
Red River of the North at Grand Forks, North Dakota	1	--	1,001	95	90
Red River of the North at Drayton, North Dakota	4	--	1,001	95	90
Red River of the North at Fargo, North Dakota	--	17	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	-3	--	--	--
Red River of the North near Thompson, North Dakota	--	11	--	--	--
Alternative 5					
Sheyenne River below Baldhill Dam, North Dakota (imported flow from GDU)	[1]114	--	583	256	15
Sheyenne River at Valley City, North Dakota (return flow to account for nonpeak demand)	[2]71	--	736	270	25
Red River of the North at Halstad, Minnesota	49	--	1,056	143	82
Red River of the North at Grand Forks, North Dakota	1	--	1,056	143	82
Red River of the North at Drayton, North Dakota	4	--	1,056	143	82
Red River of the North at Fargo, North Dakota	--	13	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	68	--	--	--
Red River of the North near Thompson, North Dakota	--	30	--	--	--
Alternative 6					
Red River of the North at Halstad, Minnesota	49	--	1,037	191	75
Red River of the North at Grand Forks, North Dakota	1	--	1,037	191	75
Red River of the North at Drayton, North Dakota	4	--	1,037	191	75
Red River of the North at Fargo, North Dakota	--	-8	--	--	--

Table 11. Projected return flows, imported flows, and withdrawals and estimated total dissolved-solids, sulfate, and chloride concentrations for water-supply alternatives.—Continued

[From G. Hiemenz, Bureau of Reclamation, written commun., 2005; ft^3/s, cubic feet per second; mg/L, milligrams per liter; --, no data; negative withdrawals indicate less water is being withdrawn in 2050 than what was withdrawn in the 1990s; GDU, Garrison Diversion Unit]

Location	Projected return flows and imported flows (ft^3/s)	Projected withdrawals (ft^3/s)	Estimated concentration		
			Total dissolved solids (mg/L)	Sulfate (mg/L)	Chloride (mg/L)
Alternative 6, Continued					
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	-32	--	--	--
Red River of the North near Thompson, North Dakota	--	-23	--	--	--
Alternative 7					
Sheyenne River below Baldhill Dam, North Dakota (imported flow from Missouri River)	[1]60	--	436	172	9.5
Red River of the North at Halstad, Minnesota	49	--	1,024	94	91
Red River of the North at Grand Forks, North Dakota	1	--	1,024	94	91
Red River of the North at Drayton, North Dakota	4	--	1,024	94	91
Red River of the North at Fargo, North Dakota	--	13	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	20	--	--	--
Red River of the North near Thompson, North Dakota	--	10	--	--	--
Alternative 8					
Red River of the North at Halstad, Minnesota	49	--	980	270	58
Red River of the North at Grand Forks, North Dakota	1	--	980	270	58
Red River of the North at Drayton, North Dakota	4	--	980	270	58
Red River of the North at Fargo, North Dakota	--	-8	--	--	--
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	--	-32	--	--	--
Red River of the North near Thompson, North Dakota	--	-23	--	--	--

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[1] Imported flow.

[2] Return flow.

solved solids in the Sheyenne River at Lisbon, N. Dak. (figure 18a at back of report). The concentrations for alternative 7 for that site decreased from 792 mg/L to 581 mg/L as a result of an imported flow of 60 ft^3/s from the Missouri River to the Sheyenne River below Baldhill Dam, N. Dak. (table 11). The water from the Missouri River had a fairly low total dissolved-solids concentration. Alternative 2 had the largest effect on total dissolved solids in the Red River at Emerson, Manitoba. The concentrations for alternative 2 increased in relation to those for alternative 1. The concentrations increased from 709 to 798 mg/L as a result of low streamflow in the reach between Grand Forks, N. Dak., and Emerson and high total dissolved-solids concentrations in tributary flows to that reach (figure 18c at back of report).

Sulfate

Simulated sulfate concentrations for alternatives 2 through 8 (the action alternatives) for the Sheyenne River were equal to or less than those for alternative 1 (the no-action alternative) except for alternative 5 (figures 19a and 19b at back of report). Simulated concentrations for alternatives 2 through 8 for the Red River varied in relation to those for alternative 1 (figures 19c and 19d at back of report). Alternative 2 had the largest effect on sulfate in the Sheyenne River at Lisbon, N. Dak. (figure 19a at back of report). The concentrations for alternative 2 for that site decreased from 306 to 207 mg/L as a result of an imported flow of 30 ft^3/s from the Red River at Grand Forks, N. Dak., to the Sheyenne River below Baldhill Dam, N. Dak. (figure 19a at back of report). The water from the Red River at Grand Forks had a fairly low sulfate concentration. The concentrations for alternative 5 for the Sheyenne River downstream from Lisbon and for the Red River downstream from Fargo, N. Dak., were consistently higher than those for alternative 1 (figures 19b and 19d at back of report) as a result of an imported flow of 114 ft^3/s from the Garrison Diversion Unit to the Sheyenne River below Baldhill Dam, N. Dak., and an additional release of 71 ft^3/s to the Sheyenne River at Valley City, N. Dak. (table 11). The water from the Garrison Diversion Unit and the additional release from Baldhill Dam had fairly high sulfate concentrations.

Chloride

Simulated chloride concentrations for alternatives 2 through 8 (the action alternatives) for the Sheyenne River generally were equal to or less than those for alternative 1 (the no-action alternative) (figures 20a and 20b at back of report). Simulated concentrations for alternatives 2 through 8 for the Red River varied in relation to those for alternative 1 (figures 20c and 20d at back of report). Alternative 7 had the largest effect on chloride in the Sheyenne River at Lisbon, N. Dak. (figure 20b at back of report). The concentrations for alternative 7 for that site decreased from 40.4 to 22.0 mg/L as a result of an imported flow of 60 ft^3/s from the Missouri River (table 11). The water from the Missouri River had a fairly low chloride concentration. The concentrations for alternative 2 for the Red River at Emerson, Manitoba, increased in relation to those for alternative 1 (figure 20c at back of report). The concentrations increased from 103 to 112 mg/L as a result of low streamflow in the reach between Grand Forks, N. Dak., and Emerson and high chloride concentrations in tributary flows to that reach.

Uncertainty of Simulation Results

Simulation results obtained with the September 2003 streamflows contain some uncertainty as reflected in the mean calibration errors give in table 9. This uncertainty is a result of uncertainty in the data, limiting assumptions in the model framework, and uncertainty about constituent loads from all sources. If the difference between the simulated concentration for alternative 1 (the no-action alternative) and the simulated concentration for an action alternative exceeds the mean calibration error for a particular constituent, the proposed alternative may have some effect on water quality. If, however, the difference is less than the mean calibration error, the effect of the proposed alternative on water quality is uncertain.

To determine the effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River, mean simulated total dissolved-solids, sulfate, and chloride concentrations for each of the alternatives were calculated from concentrations at the 11 model calibration points (table 8). The mean simulated concentration for each action alternative then was subtracted from the mean simulated concentration for alternative 1 (the no-action alternative) (table 12). Results indicate total dissolved-solids concentrations may decrease for alternatives 2 and 7, sulfate concentrations may decrease for alternatives 2 and 7 and increase for alternative 5, and chloride concentrations may decrease for alternatives 5, 7, and 8. The differences between the mean simulated concentrations for alternatives 3, 4, 6, and 8 were less than calibration errors, indicating the effects of those alternatives on water quality in the rivers is uncertain.

Simulations with Reduced Streamflows

The effects of the water-supply alternatives identified by the Bureau of Reclamation (table 10) on conservative-constituent transport in the Red River Basin also were simulated with reduced streamflows. For this set of simulations, the streamflows that occurred during September 2003 were reduced by 25 percent (table 13). The mean differences between the total dissolved-solids, sulfate, and chloride concentrations simulated with the September 2003 streamflows and those simulated with the reduced streamflows then were computed for each of the 11 model calibration points. The absolute mean differences are given in tables 14 through 16 along with the maximum and minimum absolute differences for each calibration point.

Table 12. Mean simulated concentrations for water-supply alternatives and difference between concentration for alternative and concentration for alternative 1 (the no-action alternative).

[--, no data]

Alternative number	Mean simulated concentration (milligrams per liter)	Difference between concentration for alternative and concentration for alternative 1 (milligrams per liter)	Mean calibration error (milligrams per liter)
Total dissolved solids			
1	635	--	--
2	615	-20	13
3	644	9	13
4	642	7	13
5	636	1	13
6	634	-1	13
7	600	-35	13
8	632	-3	13
Sulfate			
1	189	--	4.4
2	172	-17	4.4
3	189	0	4.4
4	189	0	4.4
5	200	11	4.4
6	190	1	4.4
7	178	-11	4.4
8	192	3	4.4
Chloride			
1	33.1	--	1.3
2	32.2	-0.9	1.3
3	33.7	0.6	1.3
4	33.9	0.8	1.3
5	28.7	-4.4	1.3

Table 12. Mean simulated concentrations for water-supply alternatives and difference between concentration for alternative and concentration for alternative 1 (the no-action alternative).—Continued

[--, no data]

Alternative number	Mean simulated concentration (milligrams per liter)	Difference between concentration for alternative and concentration for alternative 1 (milligrams per liter)	Mean calibration error (milligrams per liter)
Chloride, Continued			
6	32.0	-1.1	1.3
7	29.4	-3.7	1.3
8	31.6	-1.5	1.3

The effects of reduced streamflow on simulated total dissolved-solids concentrations were greatest for alternative 2 (table 14). Alternatives 2, 3, 5, and 7 each had an absolute mean difference that was larger than the mean calibration error of 13 mg/L for total dissolved solids (table 9). Because the absolute mean differences for alternatives 2, 3, 5, and 7 are greater than the calibration error of 13 mg/L, reduced streamflow probably has an effect on total dissolved-solids concentrations for those alternatives. The effects of reduced streamflows on simulated sulfate concentrations also were greatest for alternative 2 (table 15). Except for alternatives 2 and 5, each alternative had an absolute mean difference that was less than the mean calibration error of 4.4 mg/L for sulfate. Therefore, reduced streamflow probably has an effect on sulfate concentrations for alternatives 2 and 5. Except for alternative 2, reduced streamflow had little effect on simulated chloride concentrations (table 16).

Model Limitations

Although the Red River water-quality model includes several assumptions and limitations, the model provides initial insight into the effects of the water-supply alternatives identified by the Bureau of Reclamation on water quality in the Red River Basin. Because streamflows in the model were assumed to be steady, the model cannot be applied to storm-runoff conditions such as those that occurred during the May 2004 sampling period. However, the model can be applied to low, steady-flow conditions such as those that occurred during the September 2003 sampling period. Steady flows often occur during low-flow conditions when the effects of the alternatives probably would be greatest.

Although water-quality processes in Lake Ashtabula were not included in the model, the September 2003 data indicate this was not a limiting factor for the simulation of conservative-constituent transport during low-flow conditions. However, the effects of those processes on nutrients may need to be considered in future water-quality studies. Also, although the model currently simulates only conservative-constituent transport, the measured conditions were represented accurately. Therefore, testing of the model with a second set of data collected during steady-flow conditions would be beneficial.

Summary

Population growth along with possible future droughts in the Red River of the North (Red River) Basin in North Dakota, Minnesota, and South Dakota will create an increasing need for reliable water supplies. Therefore, as a result of the Dakota Water Resources Act of 2000, the Bureau of Reclamation identified eight water-supply alternatives (including a no-action alternative) to meet future water needs in the basin. Of those alternatives, four include the interbasin transfer of water.

Because of concerns about the possible effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River and in Lake Winnipeg, Manitoba, the Bureau of Reclamation needs to prepare an environmental impact statement that describes the specific environmental effects of each alternative. To provide information for the environmental impact statement, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, conducted a study to develop and apply a water-quality model, hereinafter referred

Table 13. Reduced streamflows used in Red River water-quality model.

Location	Reduced streamflow (cubic feet per second)
Sheyenne River above Harvey, North Dakota	1.9
Sheyenne River near Warwick, North Dakota	11.3
Sheyenne River near Cooperstown, North Dakota	15.8
Sheyenne River below Baldhill Dam, North Dakota	27.8
Sheyenne River at Valley City, North Dakota	28.5
Sheyenne River at Lisbon, North Dakota	30.8
Sheyenne River near Kindred, North Dakota	51.8
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	53.2
Sheyenne River at Brooktree Park, North Dakota	60
Bois de Sioux River near Doran, Minnesota	0
Otter Tail River at 11th Street in Breckenridge, Minnesota	85.5
Red River of the North at Wahpeton, North Dakota	82.5
Red River of the North at Hickson, North Dakota	83.3
Red River of the North at Fargo, North Dakota	78
Red River of the North at confluence with Sheyenne River, North Dakota	167
Red River of the North at Halstad, Minnesota	209
Red River of the North near Thompson, North Dakota	244
Red River of the North at Grand Forks, North Dakota	317
Red River of the North at Oslo, Minnesota	319
Red River of the North at Drayton, North Dakota	330
Red River of the North at Emerson, Manitoba	353

to as the Red River water-quality model, to part of the Red River and the Sheyenne River to simulate conservative-constituent transport in the Red River Basin. The Red River water-quality model is a one-dimensional, steady-state flow and transport model for selected conservative constituents in the Red River and the Sheyenne River.

The data-collection network consisted of 34 sites (11 Red River sites, 8 Sheyenne River sites, and 15 other tributary sites). Of the 34 sites, 23 were co-located with active U.S. Geological Survey streamflow-gaging stations. Of the remaining sites, three were located on the main stem of the Red River, and one was located on the main stem of the Sheyenne River. Ungaged tributaries to the Red River (other than the Sheyenne River) were sampled at either the downstream-most gaging station or at ungaged sites near the mouth of the tributary.

Table 14. Absolute mean differences and maximum and minimum absolute differences between total dissolved-solids concentrations simulated with September 2003 streamflows and those simulated with reduced streamflows.

[Location for which the maximum or minimum difference occurred is indicated in parentheses]

Alternative number	Absolute mean difference (milligrams per liter)	Maximum absolute difference (milligrams per liter)	Minimum absolute difference (milligrams per liter)
1	12	38 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
2	38	88 (Red River of the North at Emerson, Manitoba)	6 (Red River of the North at Fargo, North Dakota)
3	14	33 (Red River of the North at Emerson, Manitoba)	1 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
4	13	31 (Red River of the North near Thompson, North Dakota)	1 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
5	15	39 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
6	6	16 (Red River of the North near Thompson, North Dakota)	0 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
7	18	24 (Red River of the North at Grand Forks, North Dakota)	6 (Red River of the North at Fargo, North Dakota)
8	5	14 (Red River of the North near Thompson, North Dakota)	0 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)

Table 15. Absolute mean differences and maximum and minimum absolute differences between sulfate concentrations simulated with September 2003 streamflows and those simulated with reduced streamflows.

[Location for which the maximum or minimum difference occurred is indicated in parentheses]

Alternative number	Absolute mean difference (milligrams per liter)	Maximum absolute difference (milligrams per liter)	Minimum absolute difference (milligrams per liter)
1	1.6	7.2 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
2	9.1	16.5 (Sheyenne River at Lisbon, North Dakota)	0.8 (Red River of the North at Fargo, North Dakota)
3	0.7	2.4 (Red River of the North at Emerson, Manitoba)	0 (Red River of the North at Grand Forks, North Dakota)
4	0.5	1.1 (Red River of the North at Fargo, North Dakota)	0.3 (Red River of the North at Emerson, Manitoba)
5	5.4	15.0 (Red River of the North at Emerson, Manitoba)	0.8 (Red River of the North at Fargo, North Dakota)
6	1.2	4.5 (Red River of the North at Emerson, Manitoba)	0.2 (Red River of the North at Fargo, North Dakota)
7	3.2	8.8 (Sheyenne River at Lisbon, North Dakota)	0.4 (Red River of the North near Thompson, North Dakota)
8	1.6	4.0 (Red River of the North near Thompson, North Dakota)	0.2 (Red River of the North at Fargo, North Dakota)

Table 16. Absolute mean differences and maximum and minimum absolute differences between chloride concentrations simulated with September 2003 streamflows and those simulated with reduced streamflows.

[Location for which the maximum or minimum difference occurred is indicated in parentheses]

Alternative number	Absolute mean difference (milligrams per liter)	Maximum absolute difference (milligrams per liter)	Minimum absolute difference (milligrams per liter)
1	0.9	3.5 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
2	2.9	8.0 (Red River of the North at Emerson, Manitoba)	0.6 (Red River of the North at Fargo, North Dakota)
3	1.0	2.6 (Red River of the North near Thompson, North Dakota)	0 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
4	1.1	3.2 (Red River of the North near Thompson, North Dakota)	0 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
5	0.9	1.7 (Red River of the North at Emerson, Manitoba)	0.5 (Red River of the North at Fargo, North Dakota)
6	0.8	3.1 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)
7	1.4	2.1 (Sheyenne River at Lisbon, North Dakota)	0.5 (Red River of the North at Fargo, North Dakota)
8	0.7	3.5 (Red River of the North at Emerson, Manitoba)	0 (Sheyenne River near Kindred, North Dakota, and Sheyenne River above Sheyenne River diversion near Horace, North Dakota)

Water-quality samples were collected during low, steady-flow conditions from September 15 through 16, 2003, and during medium, unsteady-flow conditions from May 10 through 13, 2004. During the September 2003 sampling period, water-quality samples were collected from the Red River immediately upstream and immediately downstream from the Fargo, N. Dak., and Moorhead, Minn., wastewater-treatment facilities. Loads and concentrations then were determined by mass balance, and the differences between the upstream and downstream concentrations were attributed to the wastewater discharges. Only withdrawals and return flows that were large in relation to flow in the river were included in the water-quality model.

Streamflows during the September 2003 sampling period were low. For example, streamflows for the Red Lake River at the mouth and the Red River at Emerson, Manitoba, are historically lower than streamflows measured on September 15, 2003, for the Red Lake River at Fisher, Minn., and the Red River at Emerson, Manitoba, respectively, about 16 percent of the time. Streamflows for the Otter Tail River at the mouth and the Sheyenne River at the mouth are historically lower than streamflows measured on September 16, 2003, for the Otter Tail River at 11th Street in Breckenridge, Minn., and the Sheyenne River at Brooktree Park, N. Dak., respectively, about 30 percent of the time. Streamflows were generally steady during the sampling period.

On May 11 and 12, 2004, during the middle of the May 2004 sampling period, widespread rainfall occurred throughout much of the Red River Basin. On May 11, rainfall amounts in the area east of the Red River and north of Fargo, N. Dak., were higher than those in the upper part of the Red and Sheyenne River Basins. As a result of the widespread rainfall, streamflows during the May 2004 sampling period were less steady than during the September 2003 sampling period except in the Red River upstream from Fargo, N. Dak. Streamflow for the Red River at Emerson, Manitoba, increased about 50 percent during the sampling period. However, streamflows in the Sheyenne River increased only slightly because of less rainfall in that part of the basin than in other parts of the basin. In contrast to what occurred during the September 2003 sampling period when streamflows were consistently low throughout the study area, the percentage of time streamflow was equaled or exceeded during the May 2004 sampling period varied widely from site to site. Streamflow for the Red Lake River at the mouth is historically lower than streamflow measured on May 11, 2004, for the Red Lake River at Fisher, Minn., about 30 percent of the time. Streamflow for the Otter Tail River at the mouth is historically lower than streamflow measured on May 11, 2004, for the Otter Tail River at 11th Street in Breckenridge, Minn., about 55 percent of the time. In contrast, streamflow for the Red River at Emerson, Manitoba, is historically lower than streamflow measured on May 10, 2004, for that site about 70 percent of the time, and streamflow for the Sheyenne River at the mouth is historically lower than streamflow measured on May 12, 2004, for the Sheyenne River at Brooktree Park, N. Dak., about 85 percent of the time. The unsteady flows and the collection of some samples during low-flow conditions and other samples during storm-runoff conditions complicated application of the model to the May 2004 sampling period.

Measured total dissolved-solids concentrations for the Red River generally were less than the U.S. Environmental Protection Agency secondary water-quality standard of 500 milligrams per liter. During the September 2003 sampling period, concentrations for the Sheyenne River were greater than 500 milligrams per liter. The highest concentrations were for the upstream part of the Sheyenne River Basin. Concentrations for several tributaries to the Red River were fairly large, but streamflows in those tributaries were less than 12 cubic feet per second during the September 2003 sampling period. Thus, total dissolved-solids loads from those tributaries to the Red River were small.

The Red River water-quality model was calibrated and tested using data collected from September 15 through 16, 2003, and from May 10 through 13, 2004. The model simulates flow and transport of total dissolved solids, sulfate, and chloride during steady-state conditions. The U.S. Army Corps of Engineers HEC-5Q water-quality model was modified for this study by (1) extending the computational grid and (2) specifying boundary conditions. Boundary conditions included natural inflows and outflows of water and constituents and withdrawals and return flows. The physical domain of the Red River water-quality model included the Red River from the confluence of the Bois de Sioux and Otter Tail Rivers to the Red River at Emerson, Manitoba, and the Sheyenne River from above Harvey, N. Dak., to the confluence with the Red River.

Small point-source discharges and withdrawals were not included in the model but were accounted for through mass balances of streamflow and constituent concentrations within a reach. Withdrawals by the cities of Fargo, N. Dak., Grand Forks, N. Dak., and Moorhead, Minn., also were not included in the model but were accounted for through changes in streamflow at locations upstream and downstream from the withdrawals.

Simulated streamflows and total dissolved-solids, sulfate, and chloride concentrations at 11 model calibration points were compared to measured streamflows and concentrations. The calibration points are located throughout the model domain and several are located near withdrawal and return-flow locations. The simulated total dissolved-solids concentrations were within 5 percent of the measured concentrations for all model calibration points. The simulated sulfate and chloride concentrations were within 5 percent of the measured concentrations for all model calibration points except the Red River at Fargo, N. Dak., and the Red River at Grand Forks, N. Dak. The differences for those locations were larger than 5 percent because of loss of streamflow or a combined tributary streamflow that was more than the streamflow measured for the next downstream location.

The Red River water-quality model was used to simulate conservative-constituent transport in the Red River and the Sheyenne River for the eight water-supply alternatives identified by the Bureau of Reclamation. For the first set of eight simulations, September 2003 streamflows were used with projected 2050 return flows and withdrawals. For the second set of eight simulations, the September 2003 streamflows were reduced by 25 percent. Projected return flows, imported flows, and withdrawals were not adjusted from previous simulations. The effects of the alternatives on constituent concentrations probably would be greatest during low-flow conditions.

Simulation results indicate total dissolved-solids concentrations may decrease for alternatives 2 and 7, sulfate concentrations may decrease for alternatives 2 and 7 and increase for alternative 5, and chloride concentrations may decrease for alternatives 5, 7, and 8. Other than for sulfate for alternative 5, the concentrations for alternatives 2, 5, and 7 generally were lower than for alternative 1 (the no-action alternative). For alternatives 3, 4, 6 and 8, the differences between the mean simulated concentrations were less than calibration errors, indicating the effects of those alternatives on water quality in the rivers is uncertain.

The effects of reduced streamflow on simulated total dissolved-solids, sulfate, and chloride concentrations were greatest for alternative 2. Reduced streamflow probably has an effect on simulated total dissolved-solids concentrations for alternatives 2, 3, 5, and 7 and on simulated sulfate concentrations for alternatives 2 and 5. Except for alternative 2, reduced streamflow had little effect on simulated chloride concentrations.

Although the Red River water-quality model includes several assumptions and limitations, the model provides initial insight into the effects of the water-supply alternatives on water quality in the Red River Basin. Because streamflows in the model were assumed to be steady, the model cannot be applied to storm-runoff conditions such as those that occurred during the May 2004 sampling period. However, the model can be applied to low, steady-flow conditions such as those that occurred during the September 2003 sampling period. Steady flows often occur during low-flow conditions when the effects of the alternatives probably would be greatest.

Although water-quality processes in Lake Ashtabula were not included in the model, the September 2003 data indicate this was not a limiting factor for the simulation of conservative-constituent transport during low-flow conditions. However, the effects of those processes on nutrients may need to be considered in future water-quality studies. Also, although the model currently simulates only conservative-constituent transport, the measured conditions were represented accurately. Therefore, testing of the model with a second set of data collected during steady-flow conditions would be beneficial.

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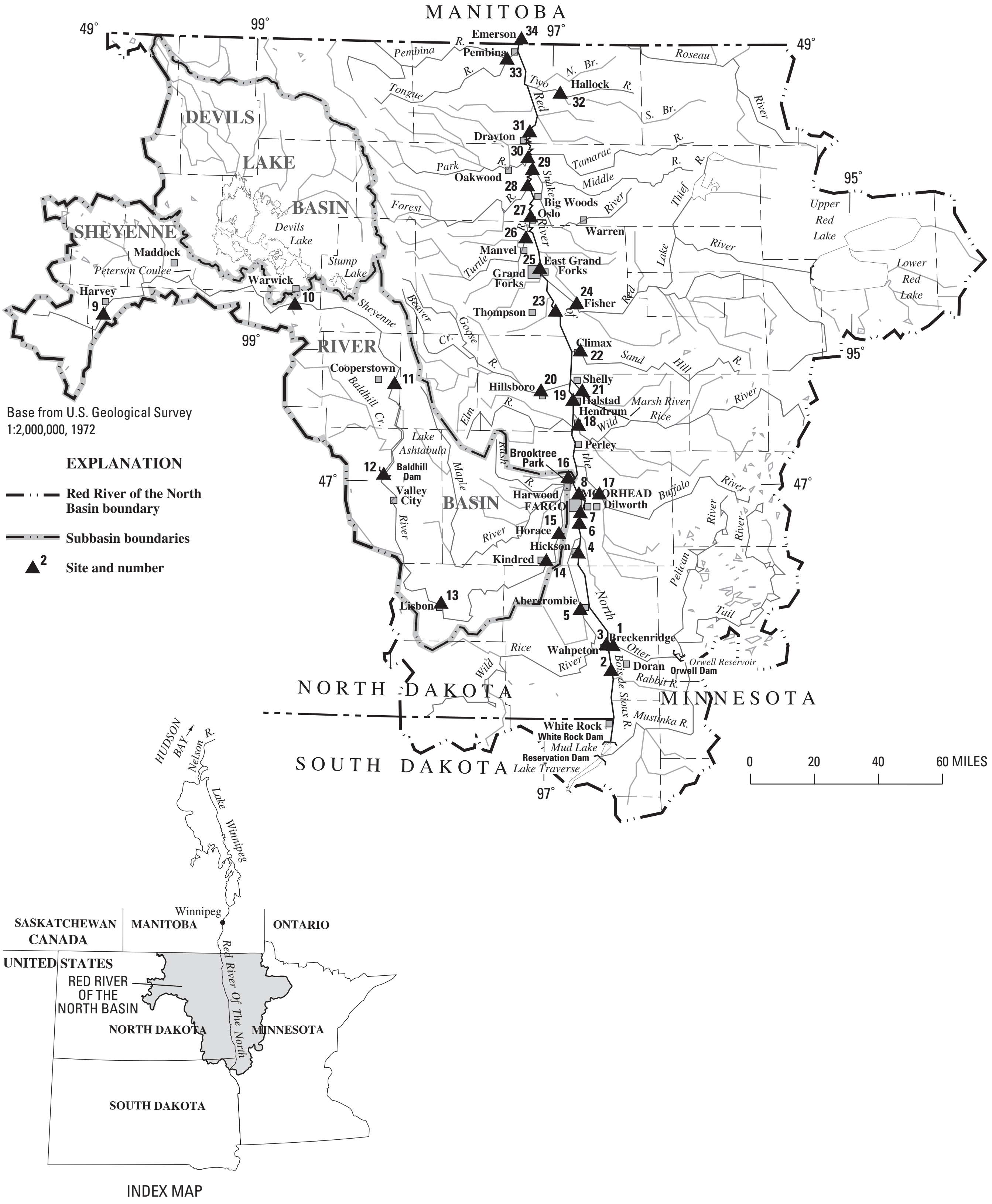

Figure 1. Locations of sites used in study.

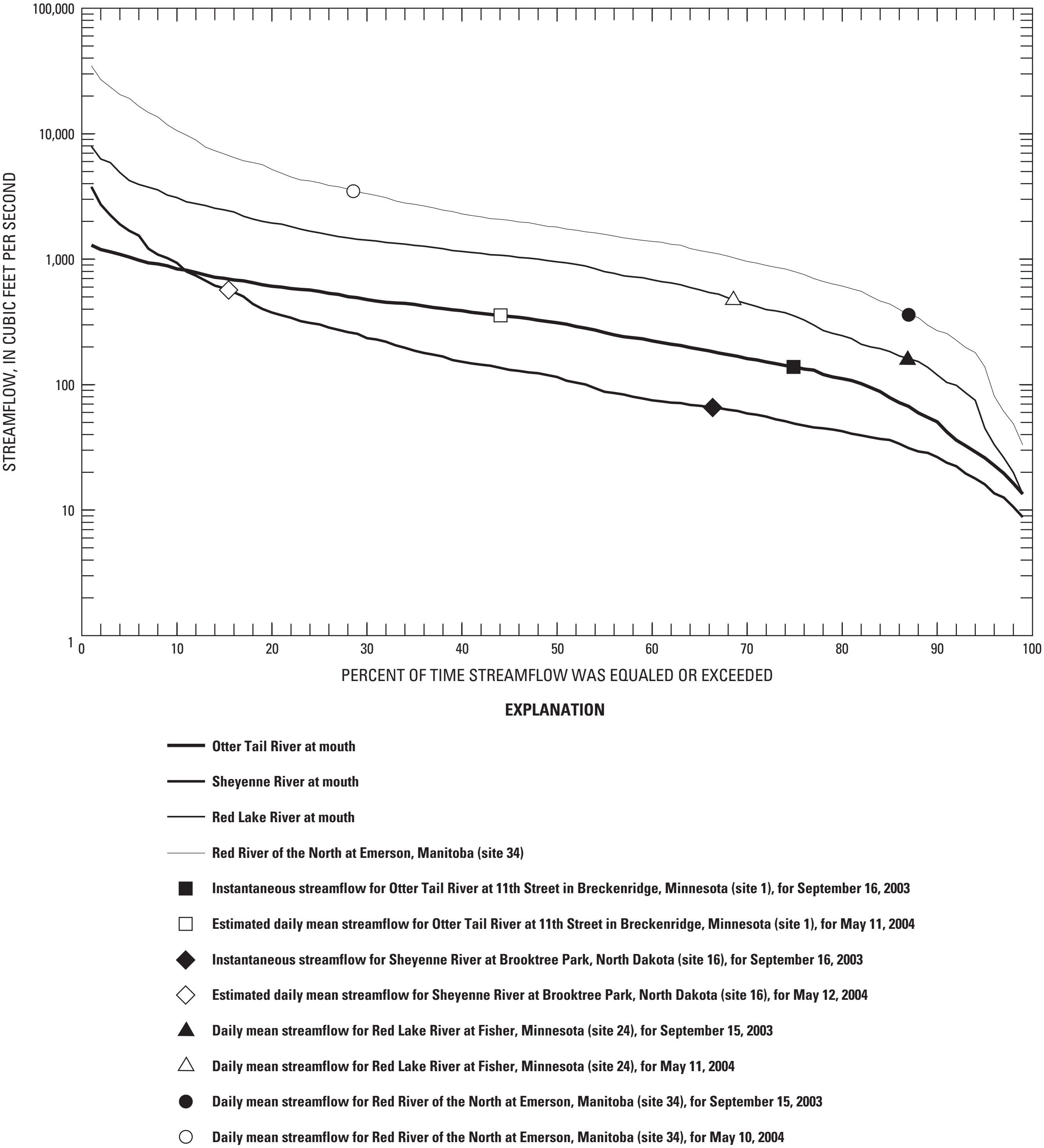

Figure 2. Streamflows and flow duration curves for selected sites (sites at the mouth are those given in Emerson, 2005).

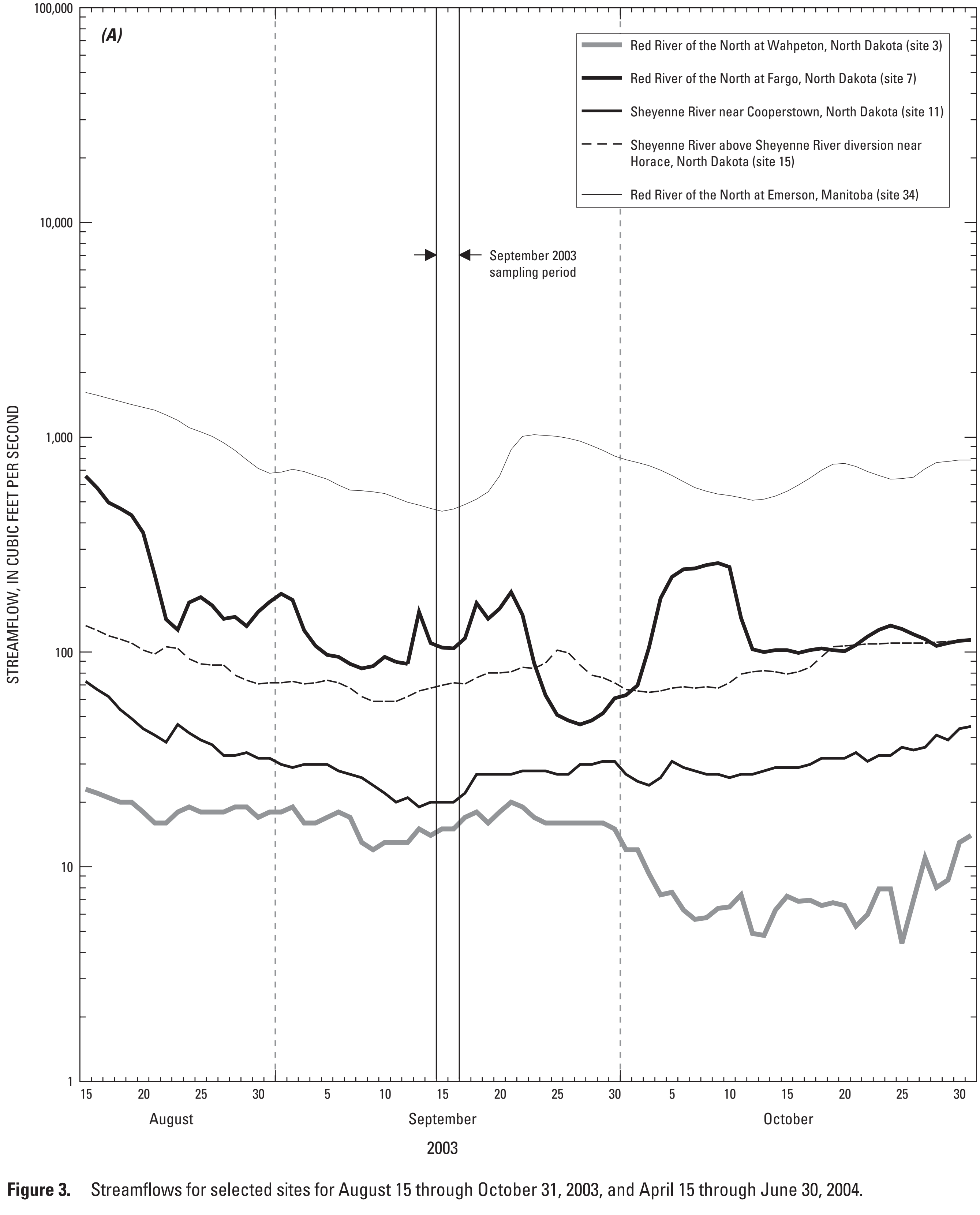

Figure 3. Streamflows for selected sites for August 15 through October 31, 2003, and April 15 through June 30, 2004.

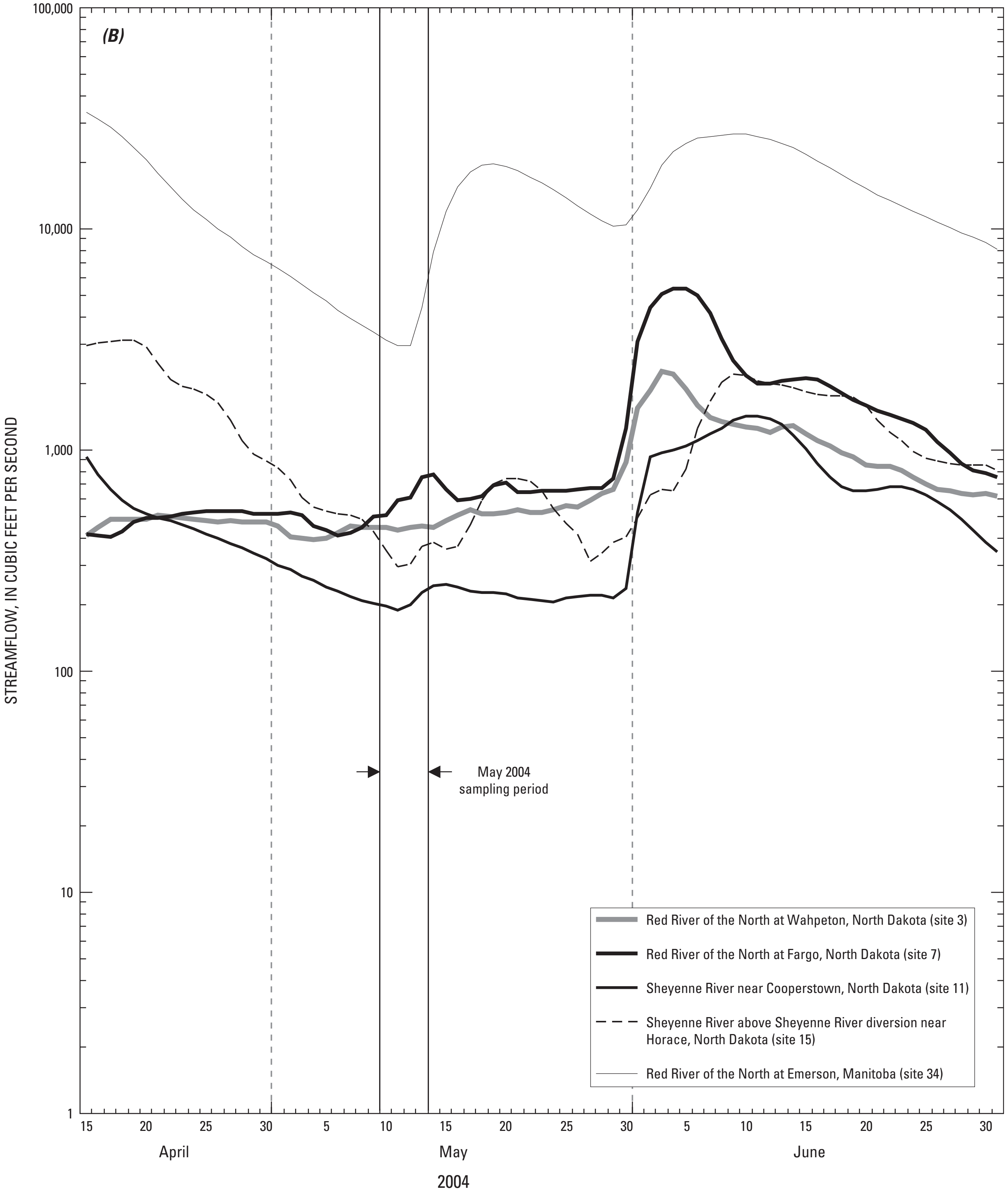

Figure 3. Streamflows for selected sites for August 15 through October 31, 2003, and April 15 through June 30, 2004--Continued.

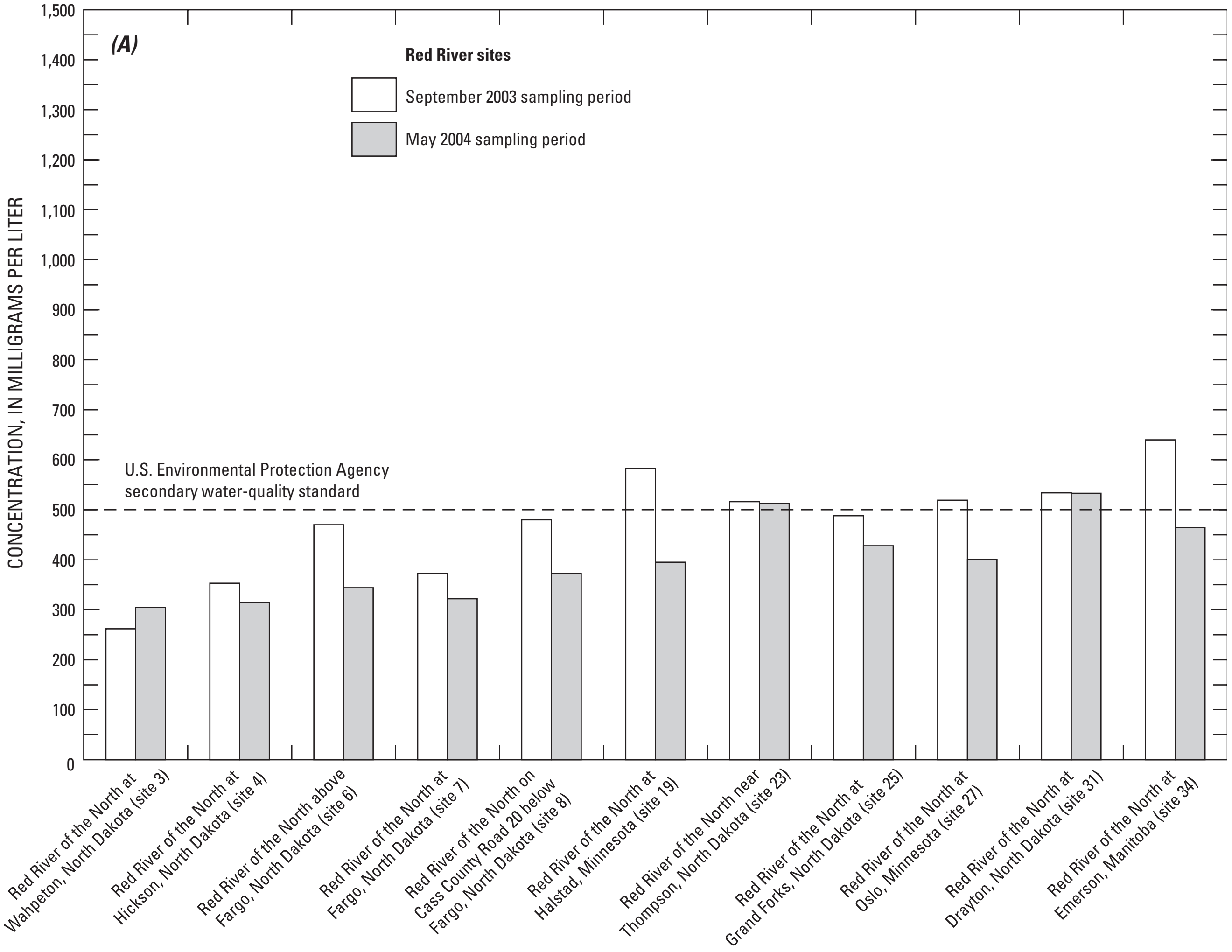

Figure 4. Measured total dissolved-solids concentrations for September 2003 and May 2004 sampling periods.

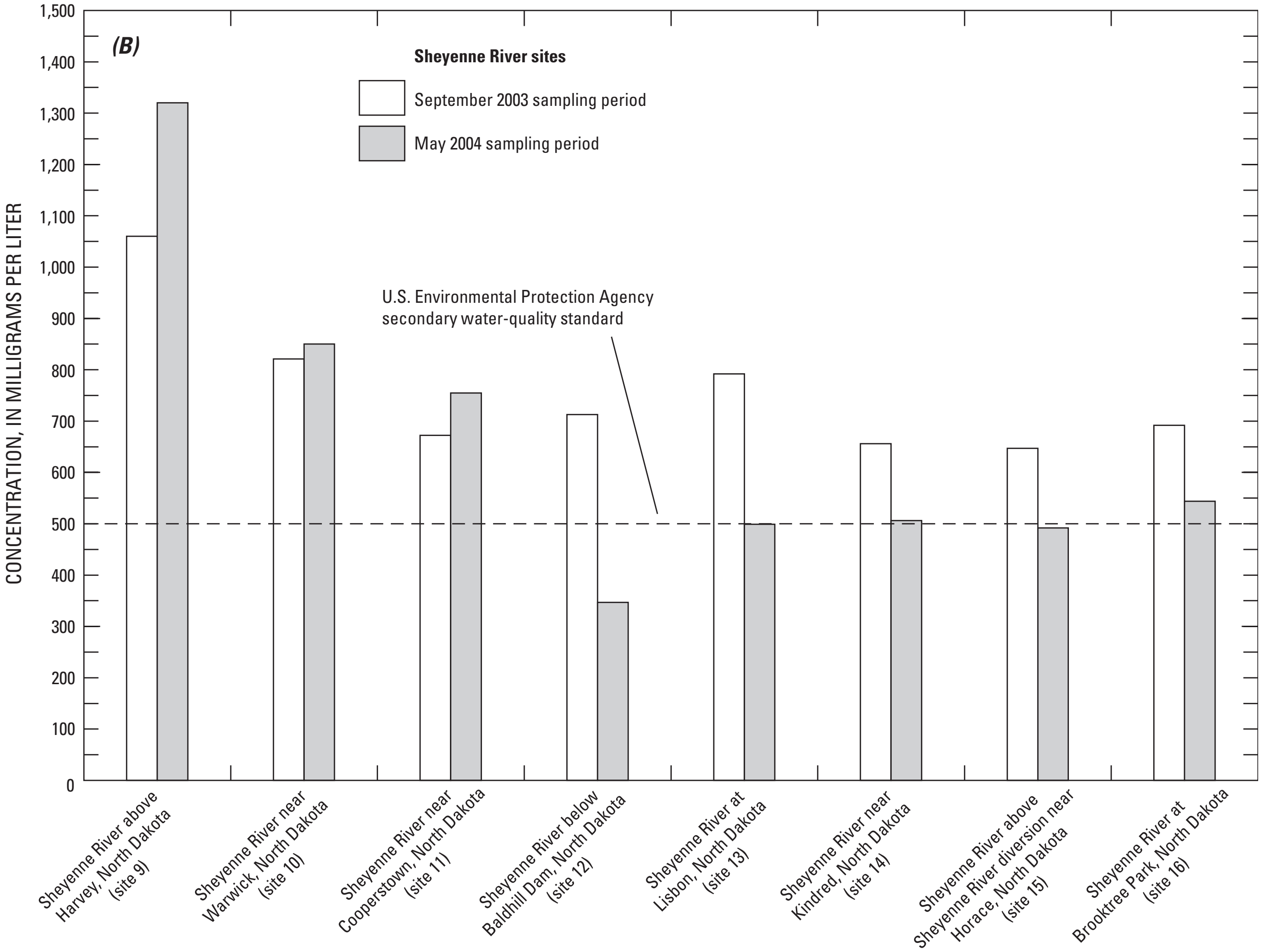

Figure 4. Measured total dissolved-solids concentrations for September 2003 and May 2004 sampling periods--Continued.

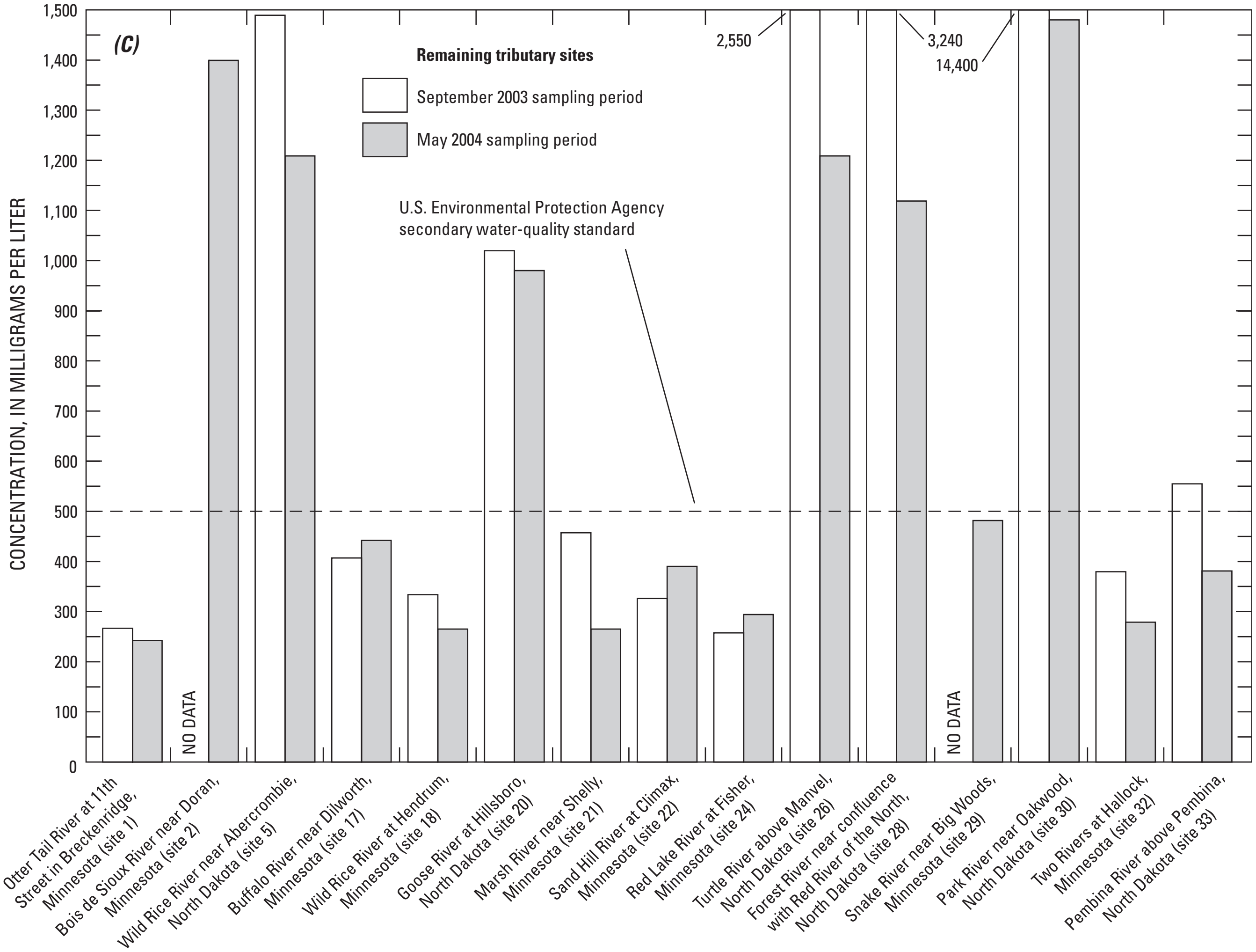

Figure 4. Measured total dissolved-solids concentrations for September 2003 and May 2004 sampling periods--Continued.

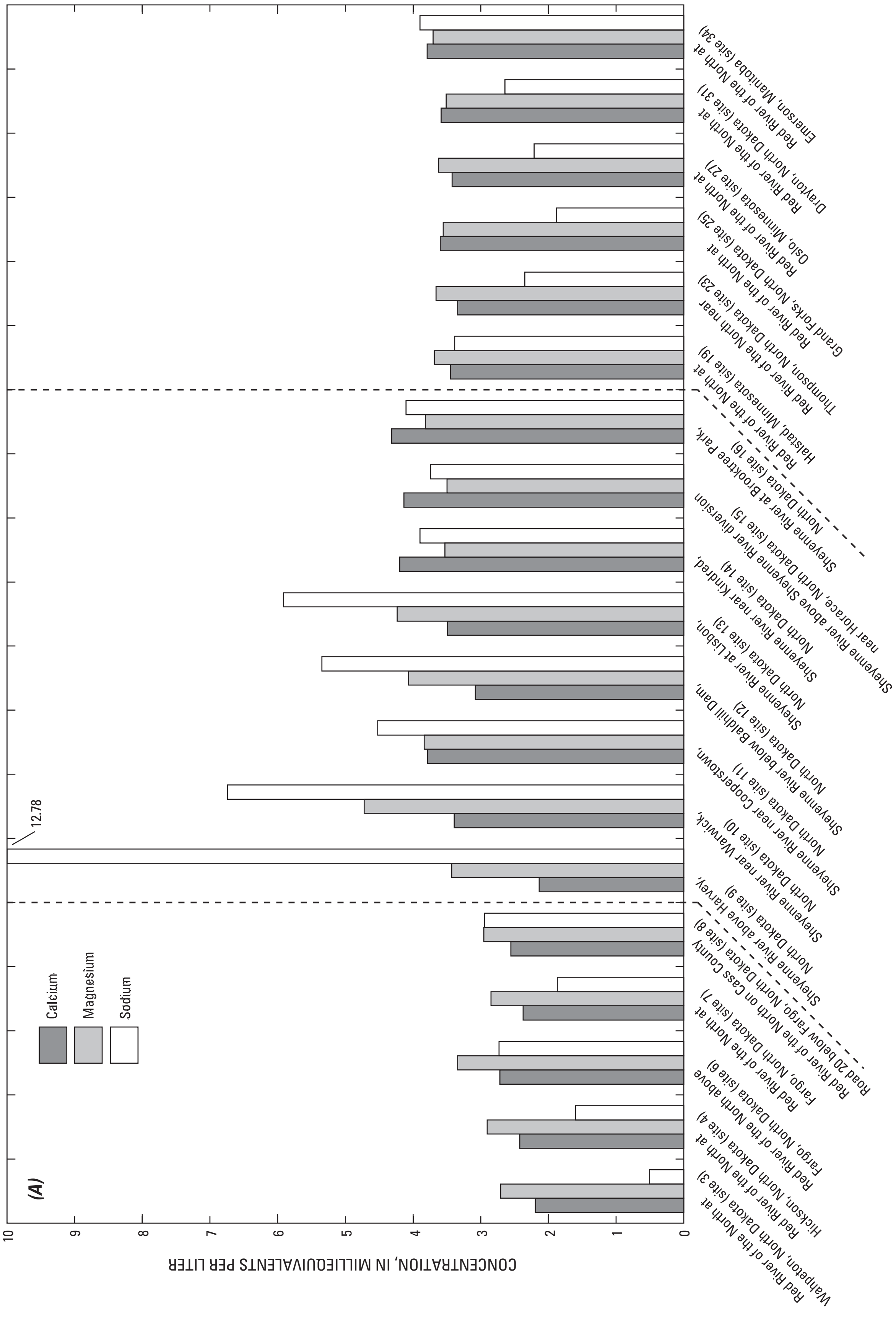

Figure 5. Measured calcium, magnesium, sodium, bicarbonate, carbonate, sulfate, and chloride concentrations for selected sites for September 2003 and May 2004 sampling periods.

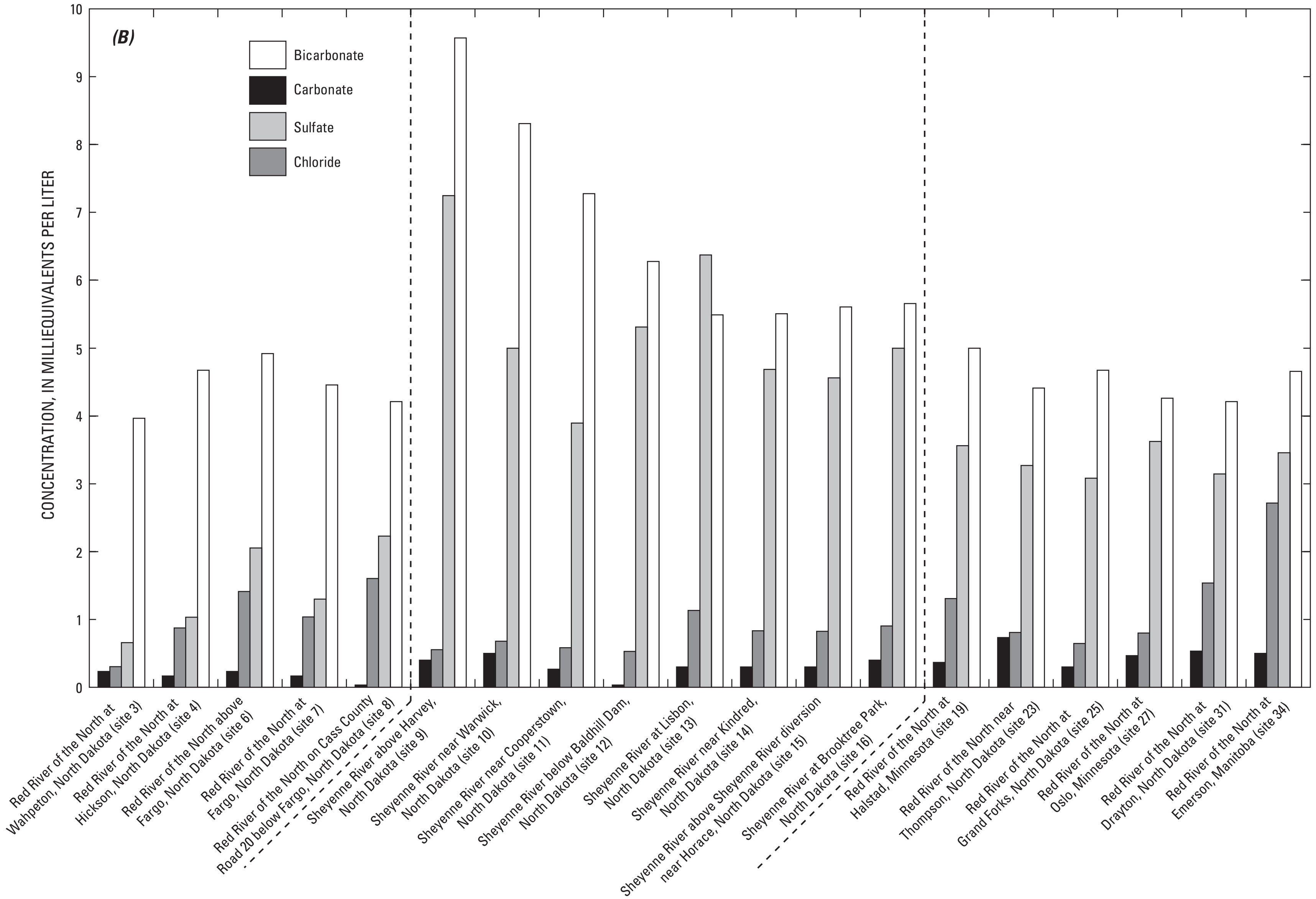

Figure 5. Measured calcium, magnesium, sodium, bicarbonate, carbonate, sulfate, and chloride concentrations for selected sites for September 2003 and May 2004 sampling periods--Continued.

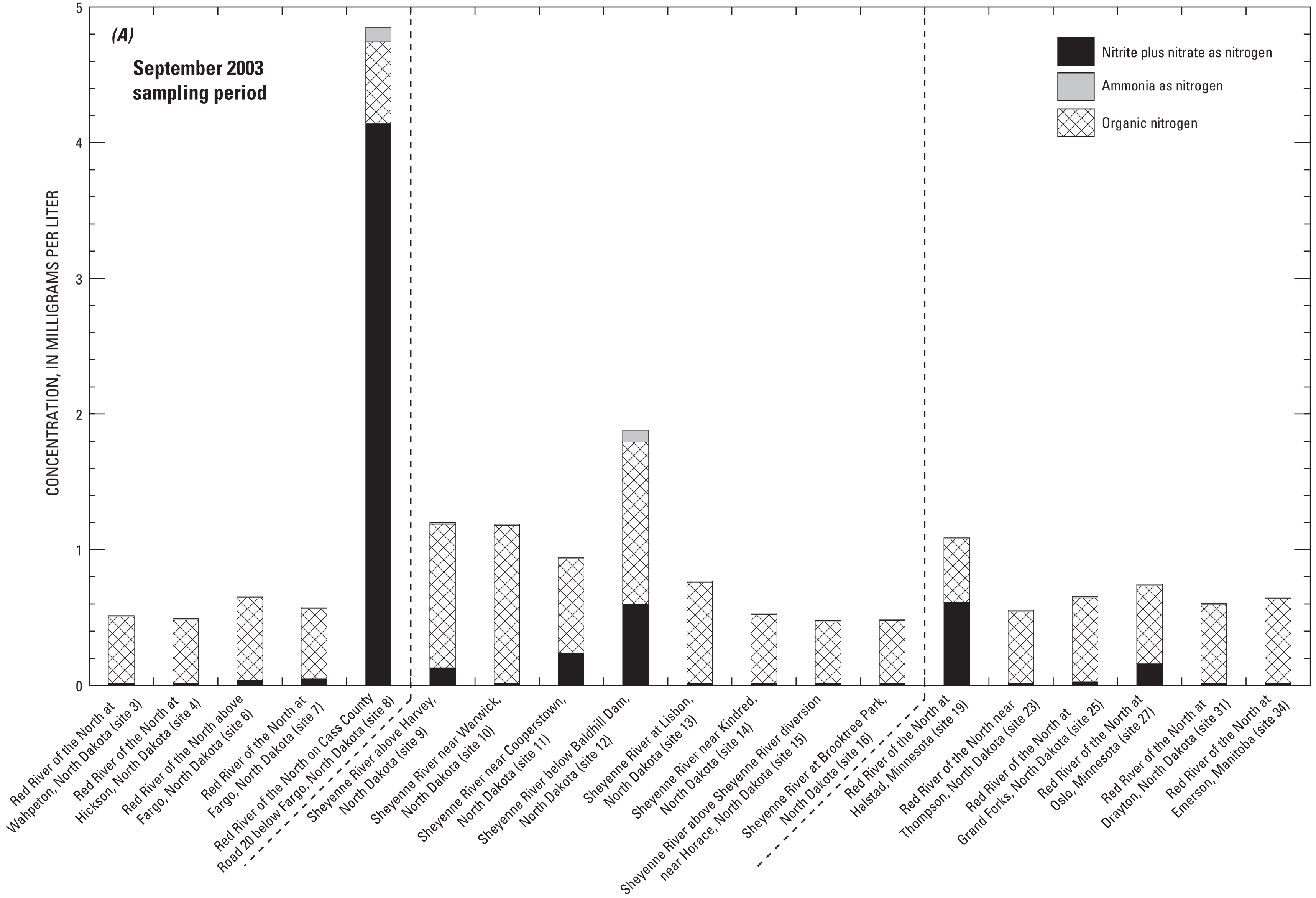

Figure 6. Measured nitrite plus nitrate as nitrogen, ammonia as nitrogen, and organic nitrogen concentrations for selected sites for September 2003 and May 2004 sampling periods.

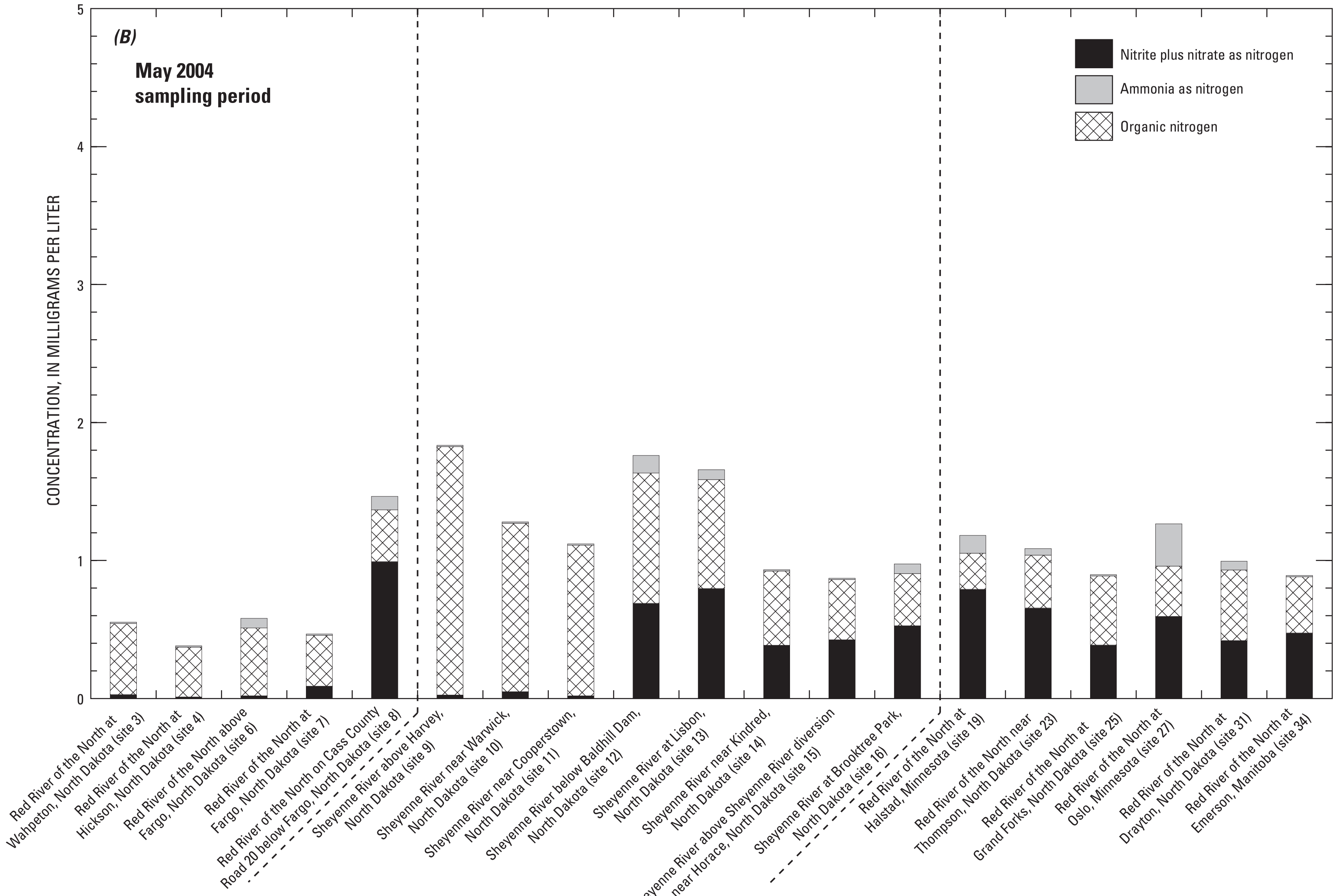

Figure 6. Measured nitrite plus nitrate as nitrogen, ammonia as nitrogen, and organic nitrogen concentrations for selected sites for September 2003 and May 2004 sampling periods--Continued.

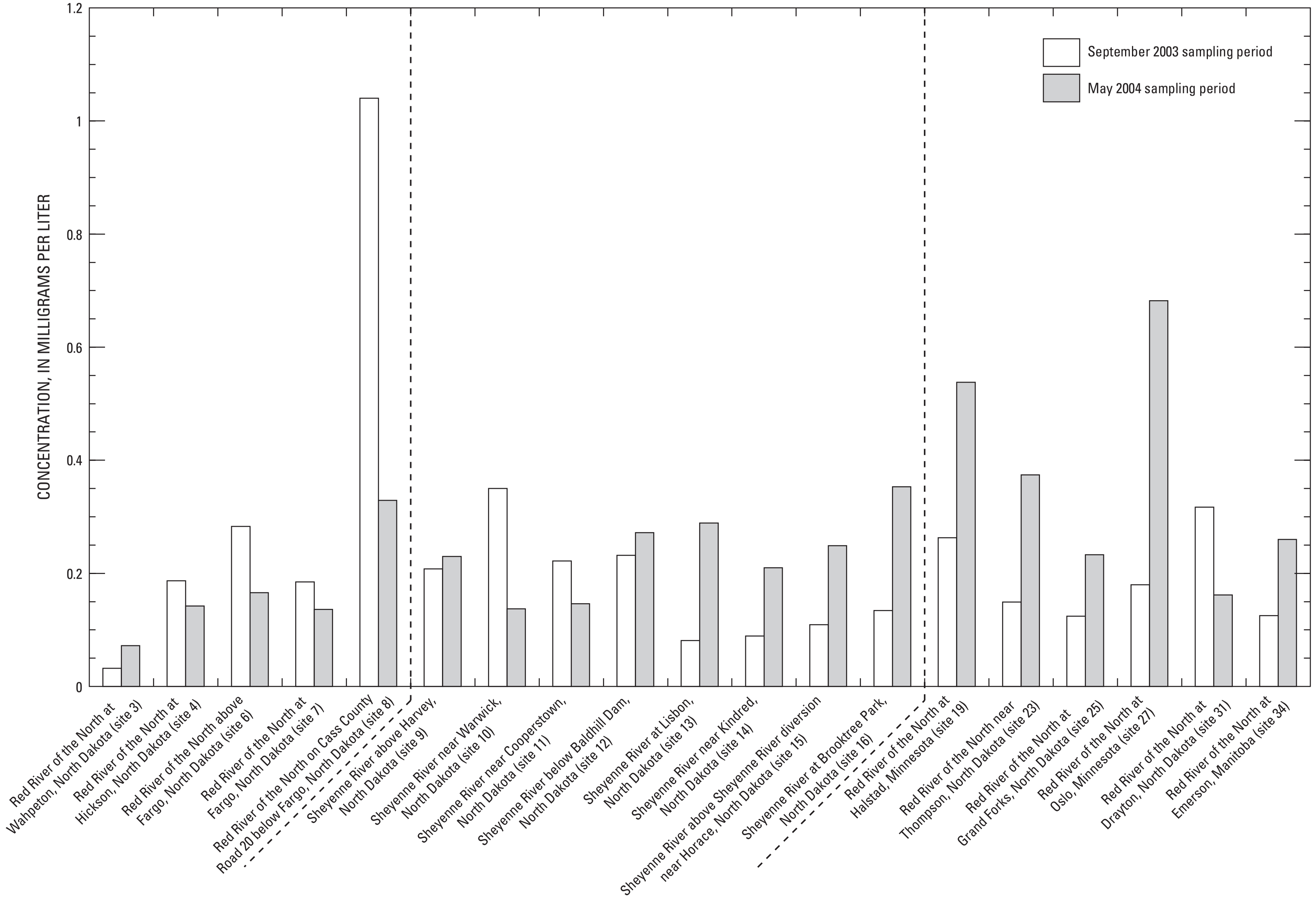

Figure 7. Measured total phosphorus concentrations for selected sites for September 2003 and May 2004 sampling periods.

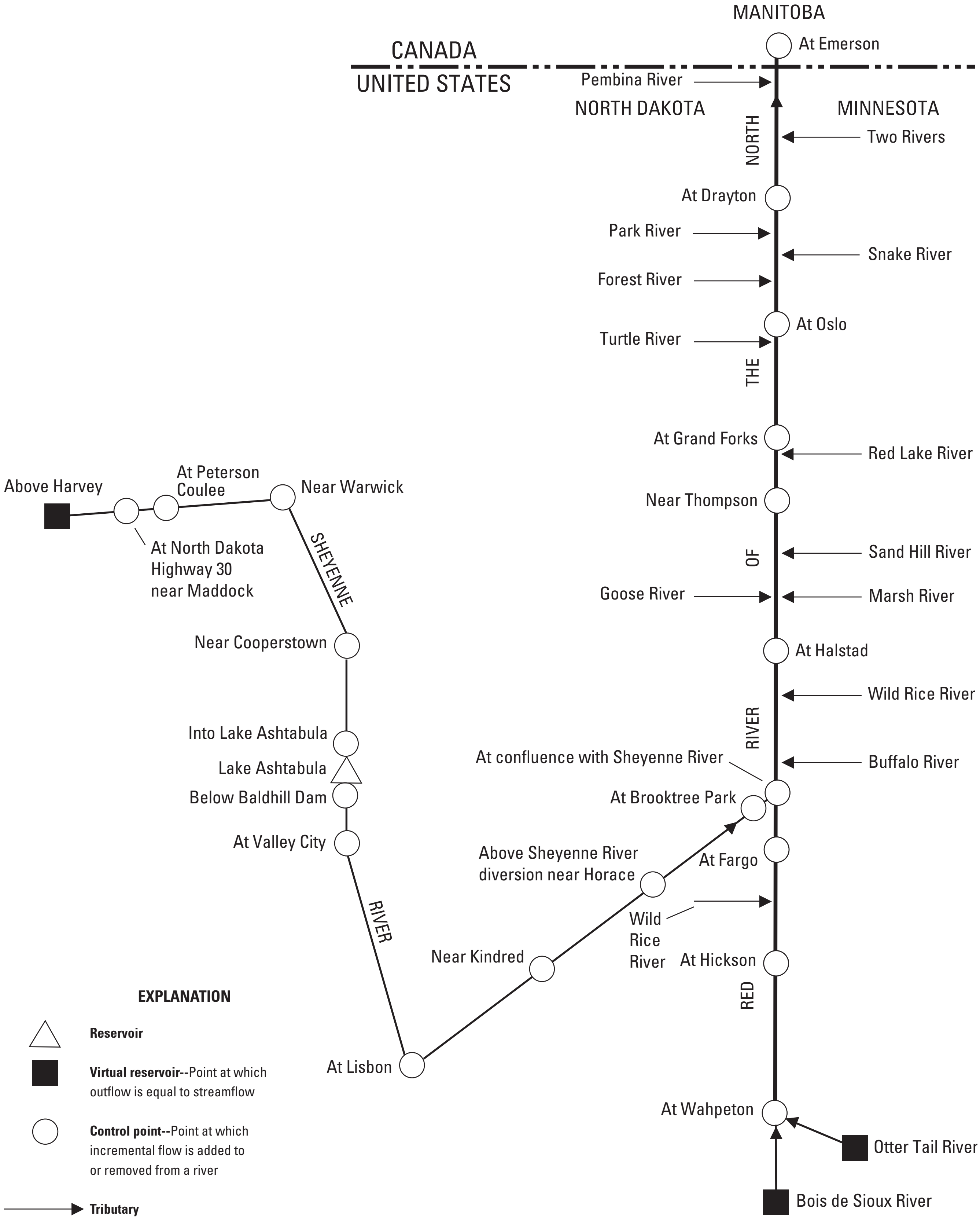

Figure 8. Schematic of Red River water-quality model.

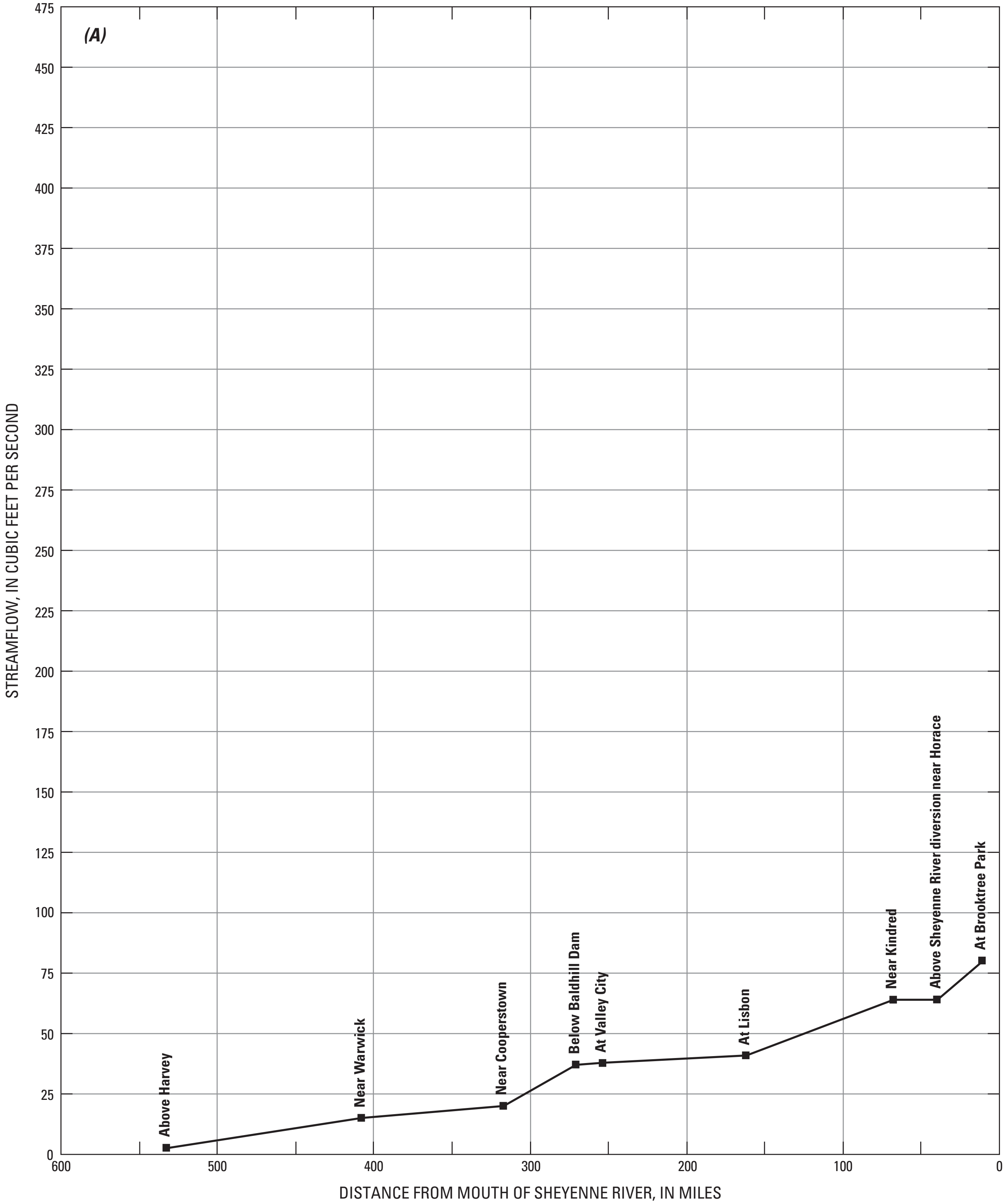

Figure 9. Measured and simulated streamflows for selected Red River water-quality model control points for September 15, 2003 (the simulated streamflows are the same as the measured streamflows for all sites in the model domain).

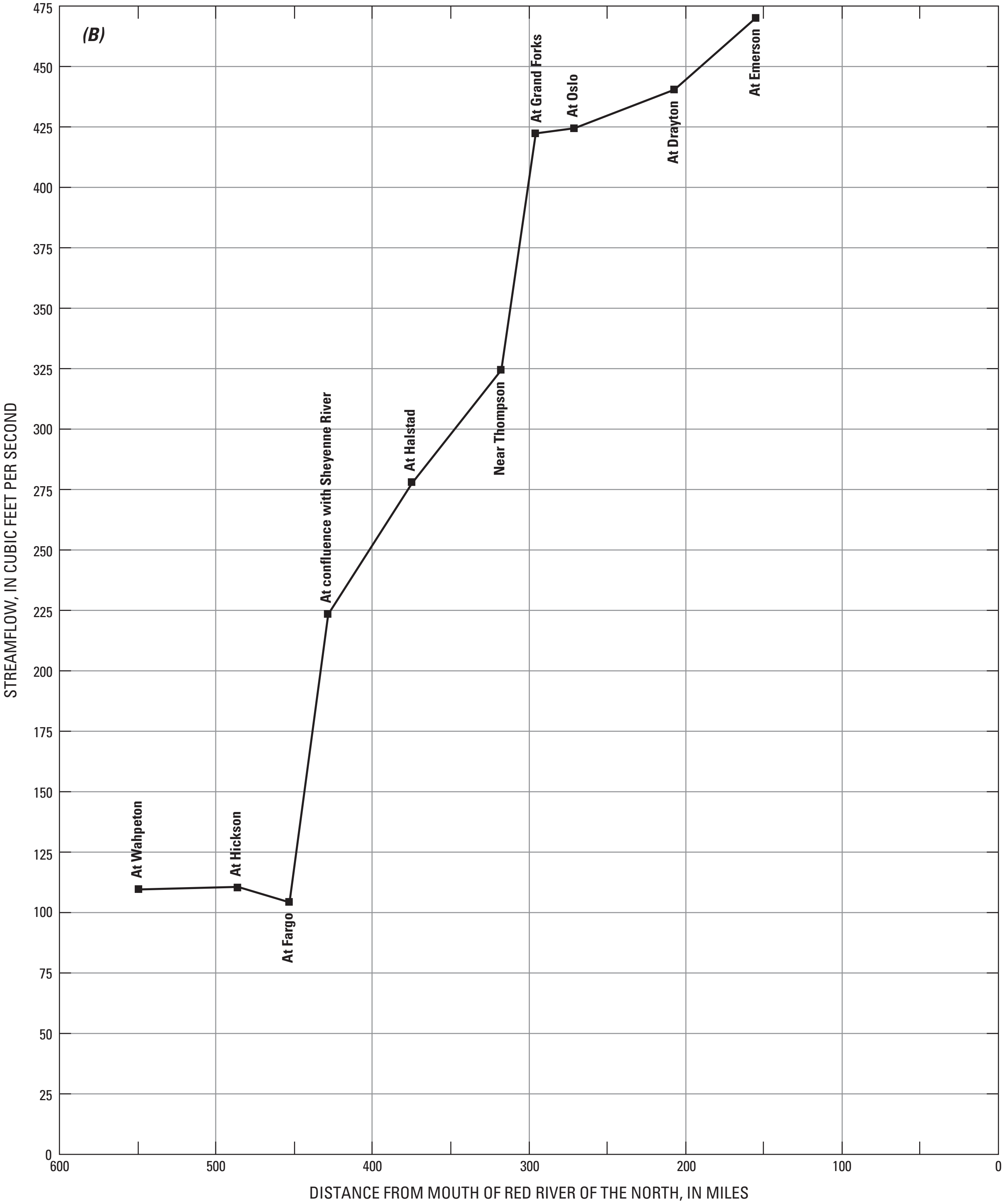

Figure 9. Measured and simulated streamflows for selected Red River water-quality model control points for September 15, 2003 (the simulated streamflows are the same as the measured streamflows for all sites in the model domain)--Continued.

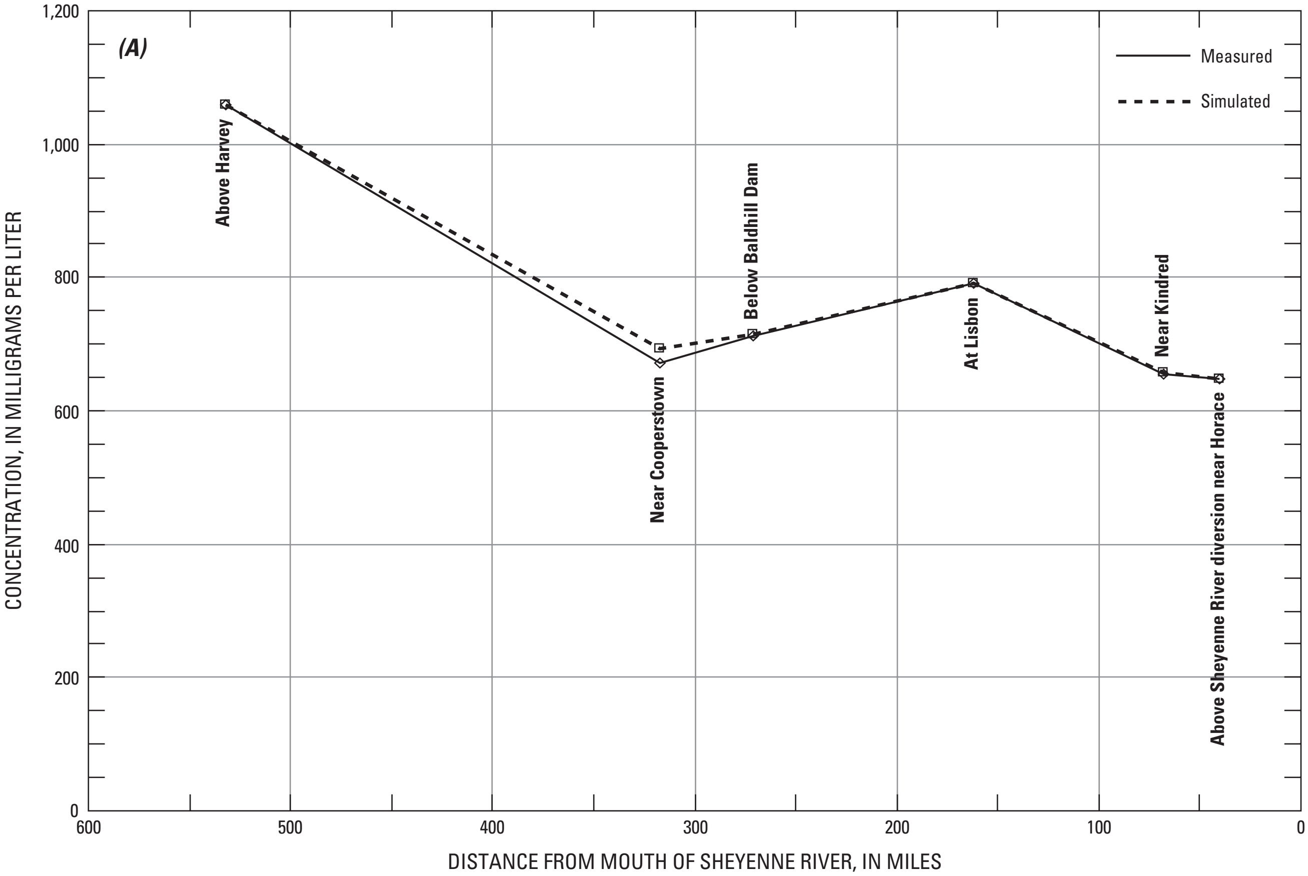

Figure 10. Measured and simulated total dissolved-solids concentrations for Red River water-quality model calibration points for September 15, 2003.

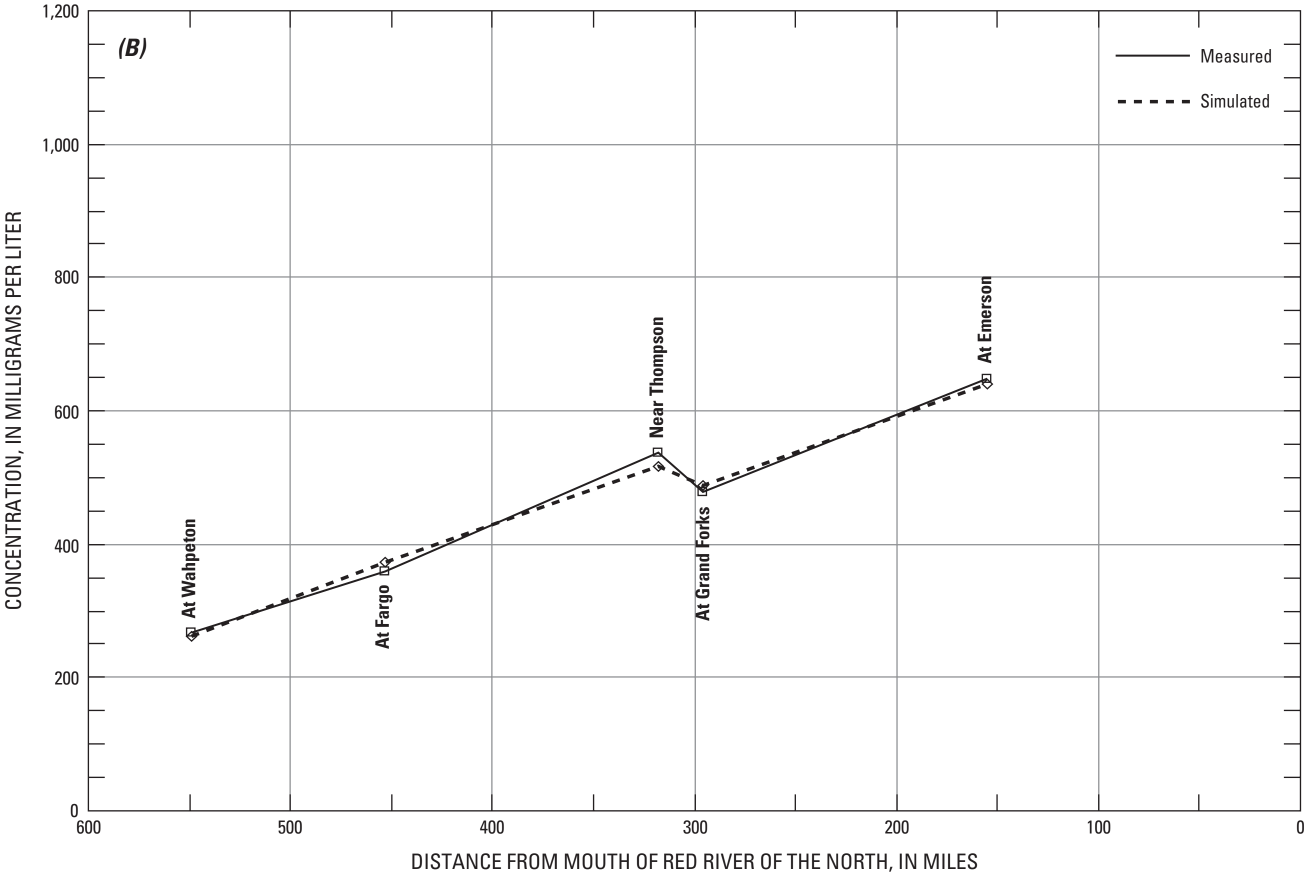

Figure 10. Measured and simulated total dissolved-solids concentrations for Red River water-quality model calibration points for September 15, 2003--Continued.

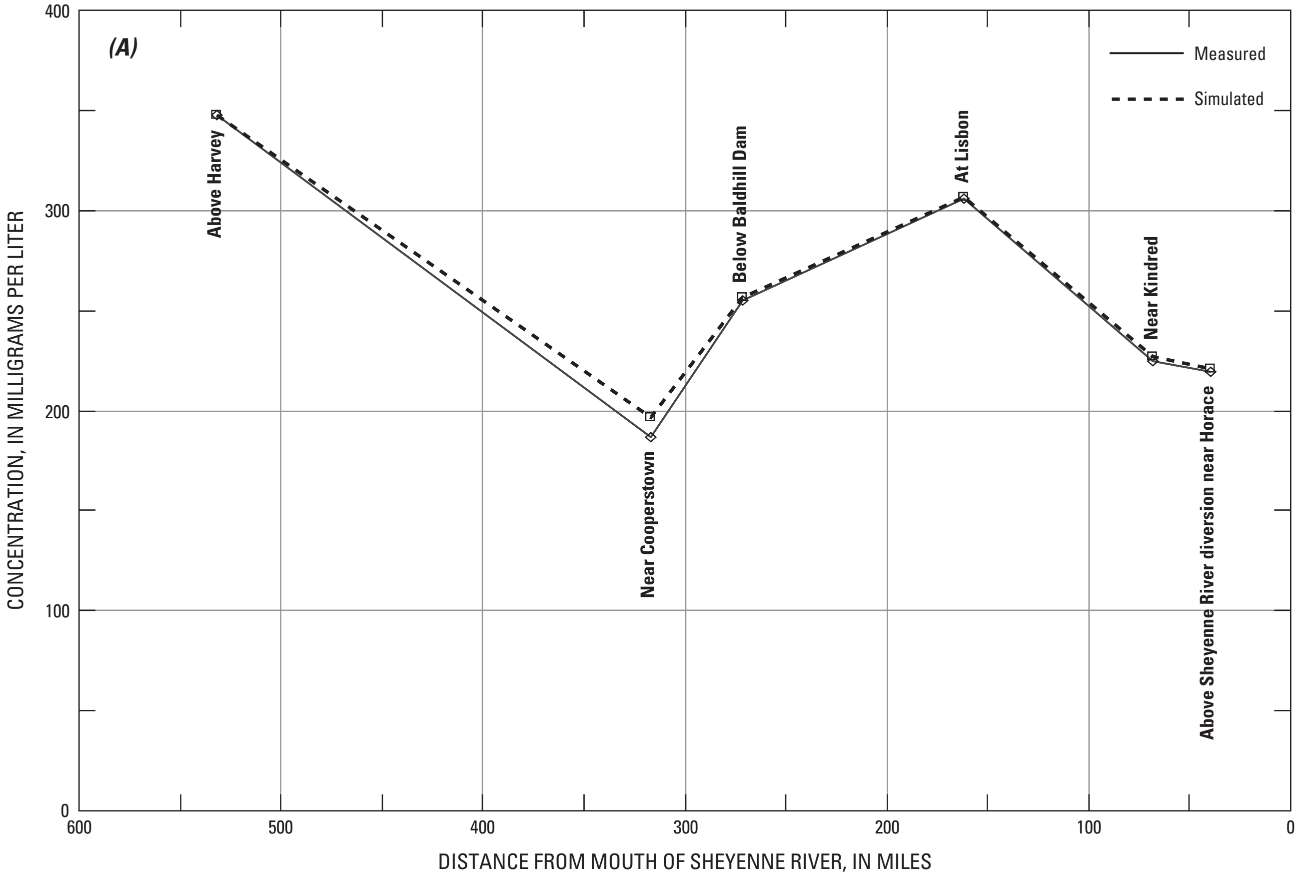

Figure 11. Measured and simulated sulfate concentrations for Red River water-quality model calibration points for September 15, 2003.

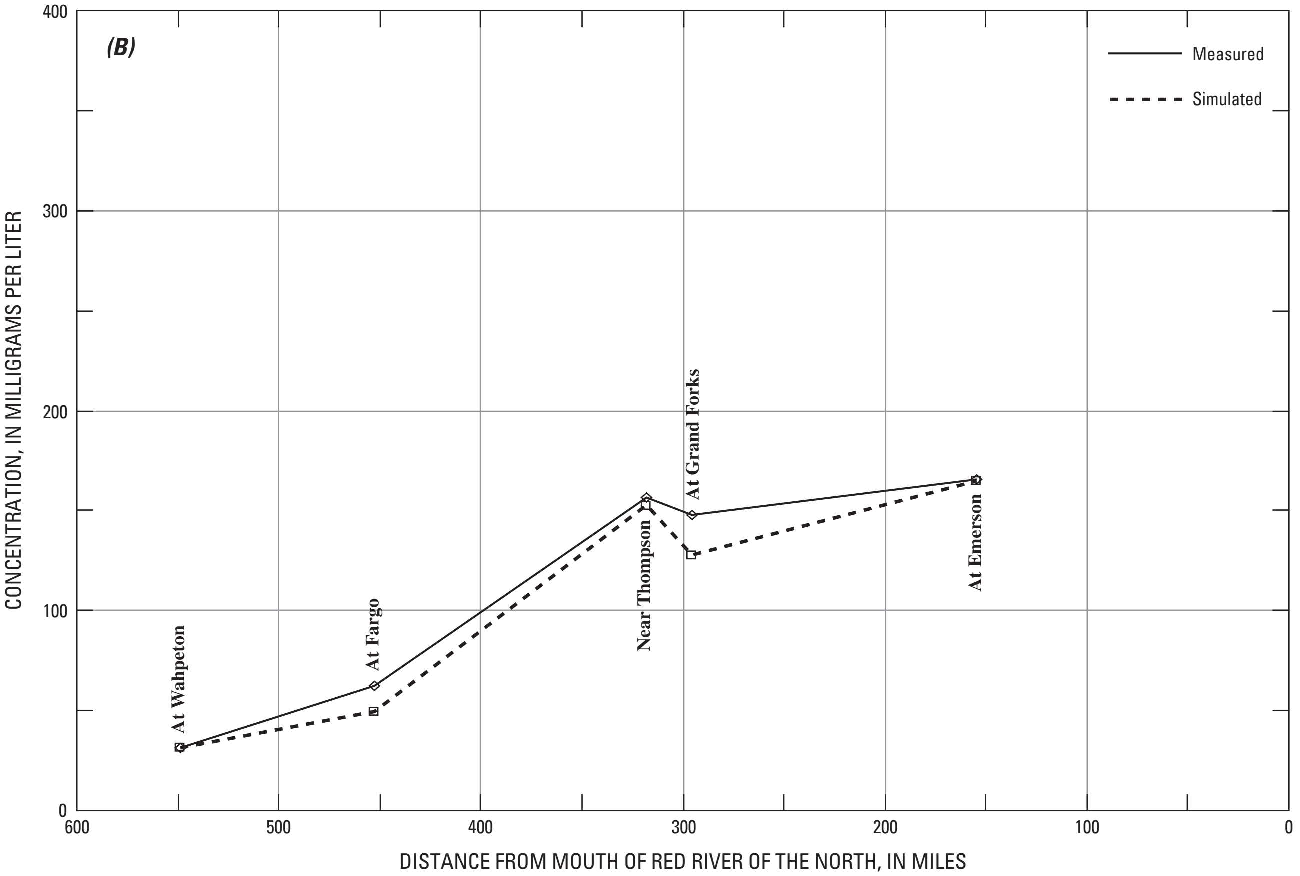

Figure 11. Measured and simulated sulfate concentrations for Red River water-quality model calibration points for September 15, 2003--Continued.

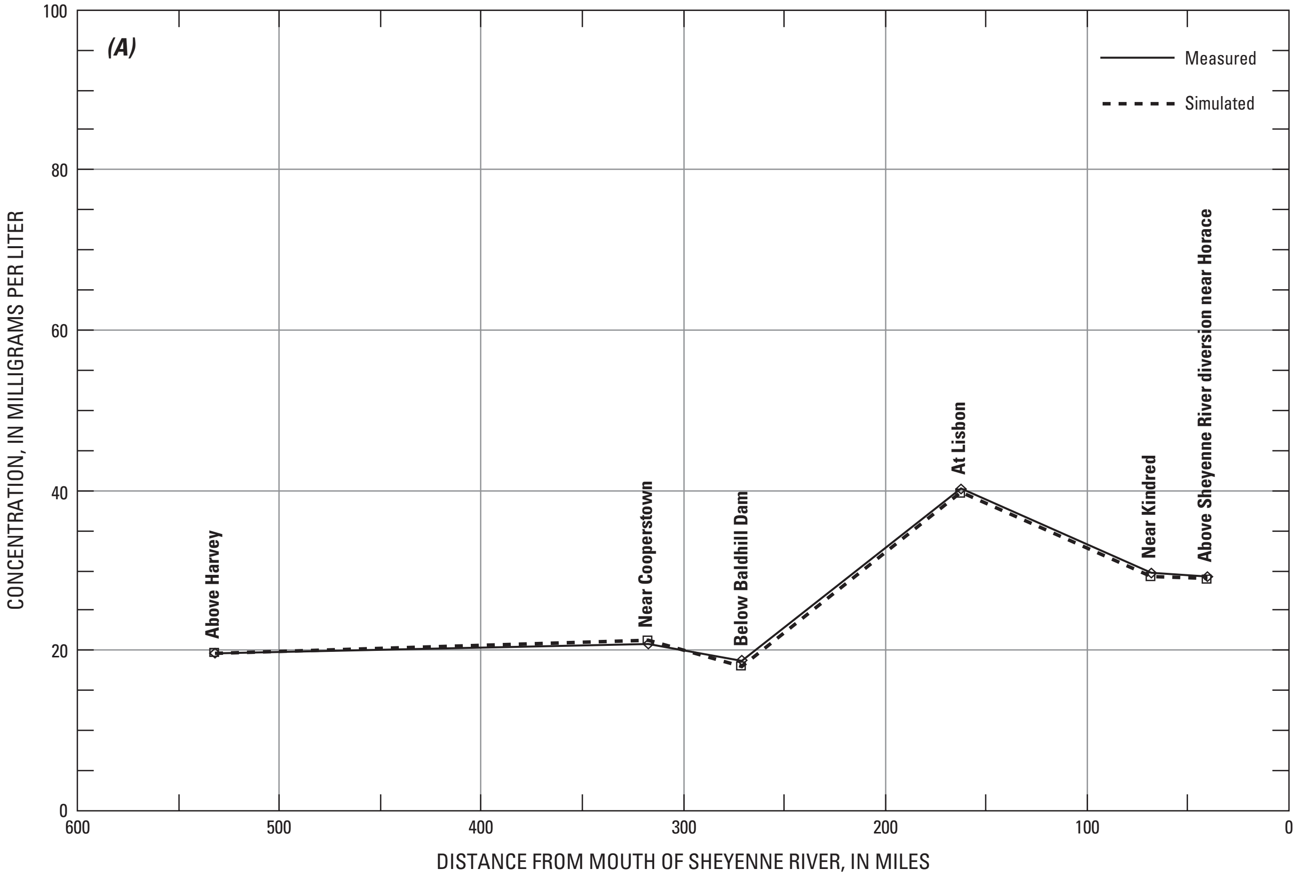

Figure 12. Measured and simulated chloride concentrations for Red River water-quality model calibration points for September 15, 2003.

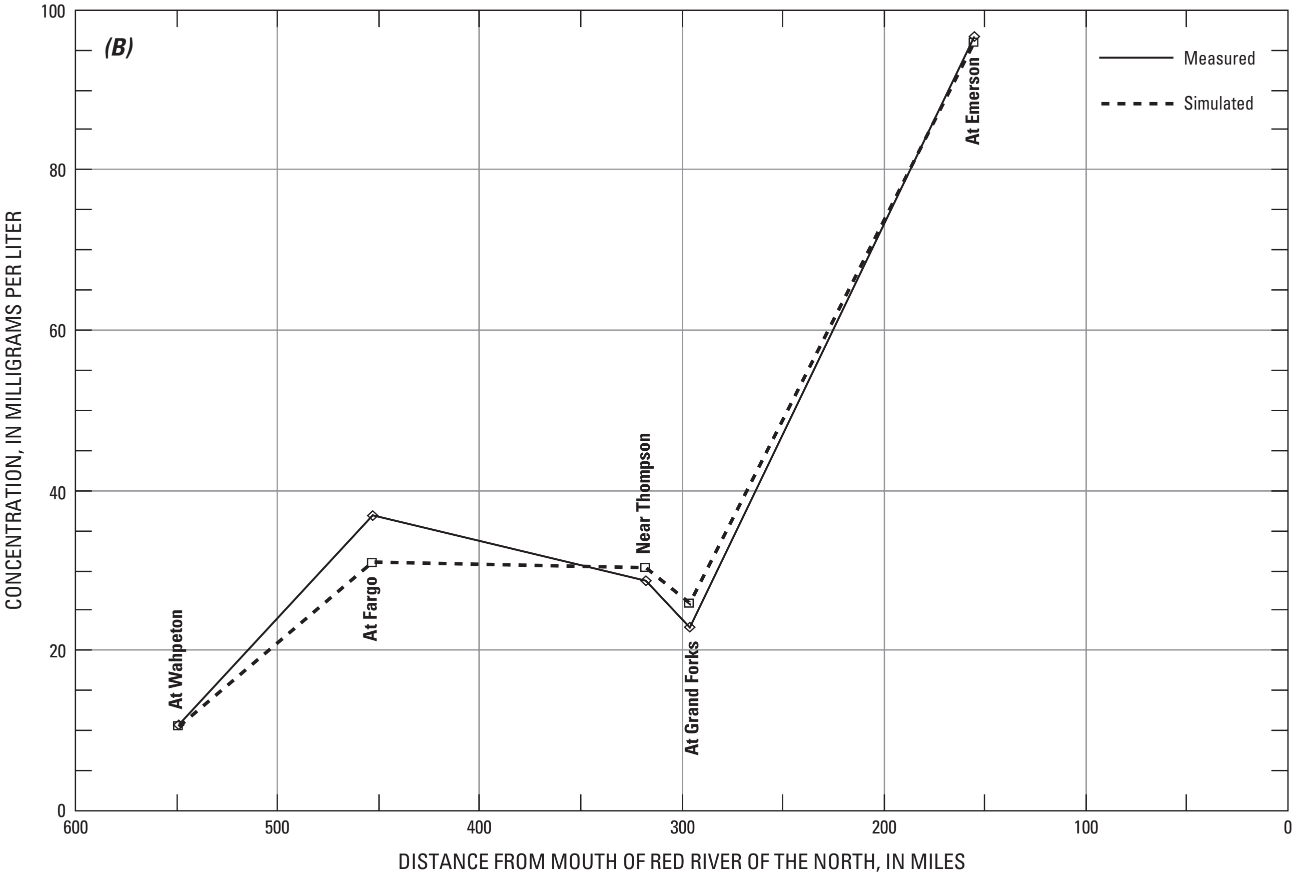

Figure 12. Measured and simulated chloride concentrations for Red River water-quality model calibration points for September 15, 2003--Continued.

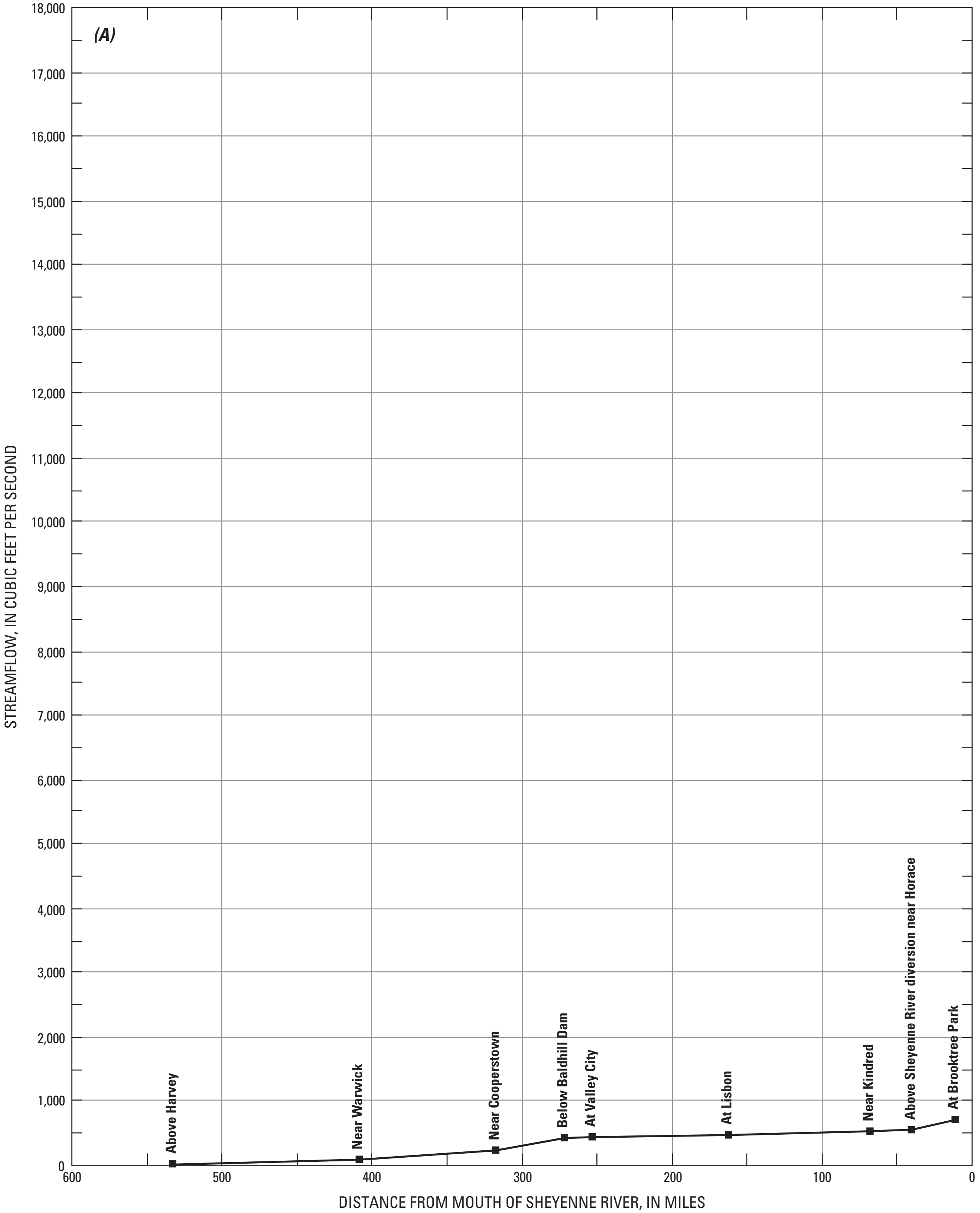

Figure 13. Measured and simulated streamflows for selected Red River water-quality model control points for May 10, 2004 (the simulated streamflows are the same as the measured streamflows for all sites in the model domain).

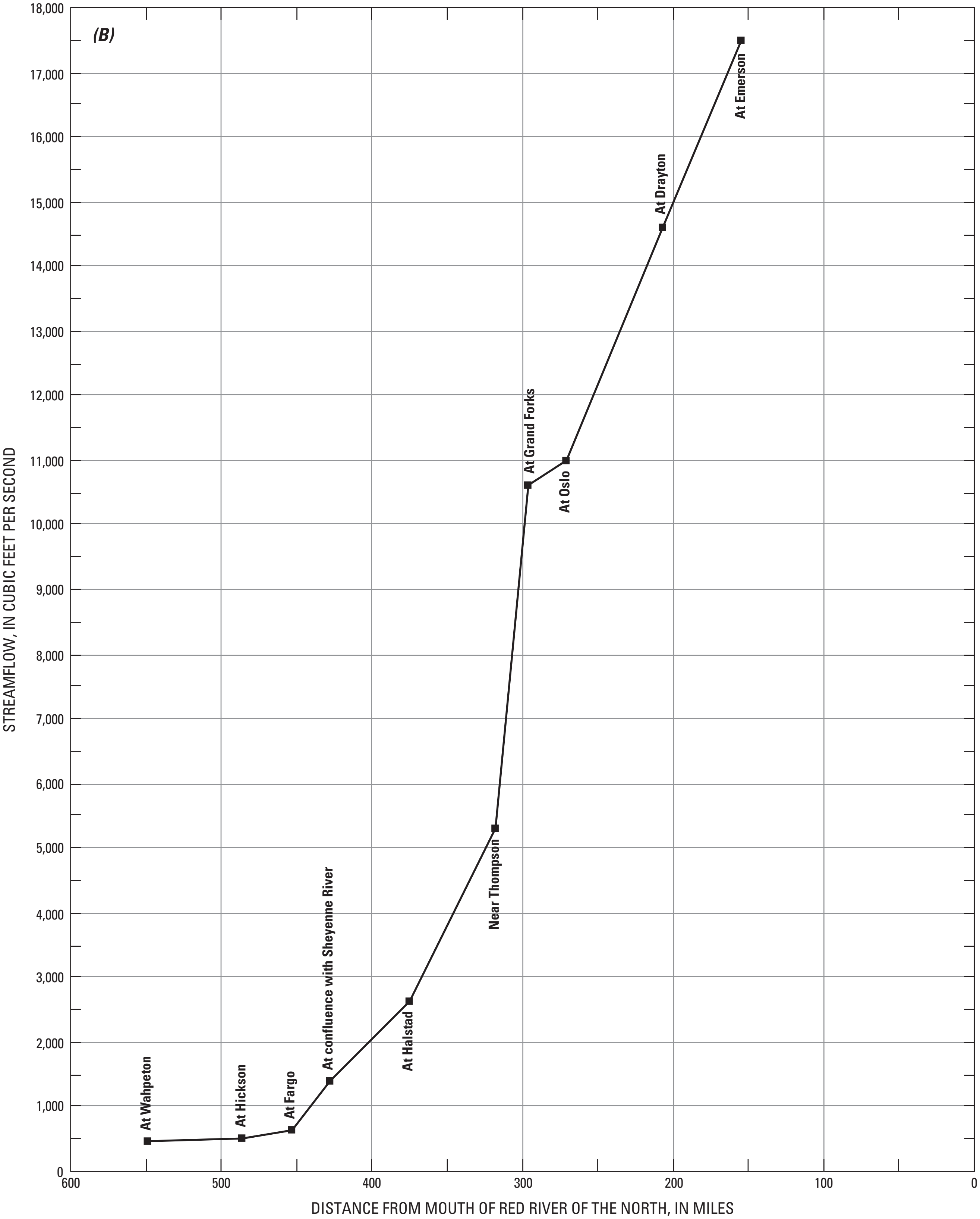

Figure 13. Measured and simulated streamflows for selected Red River water-quality model control points for May 10, 2004 (the simulated streamflows are the same as the measured streamflows for all sites in the model domain)--Continued.

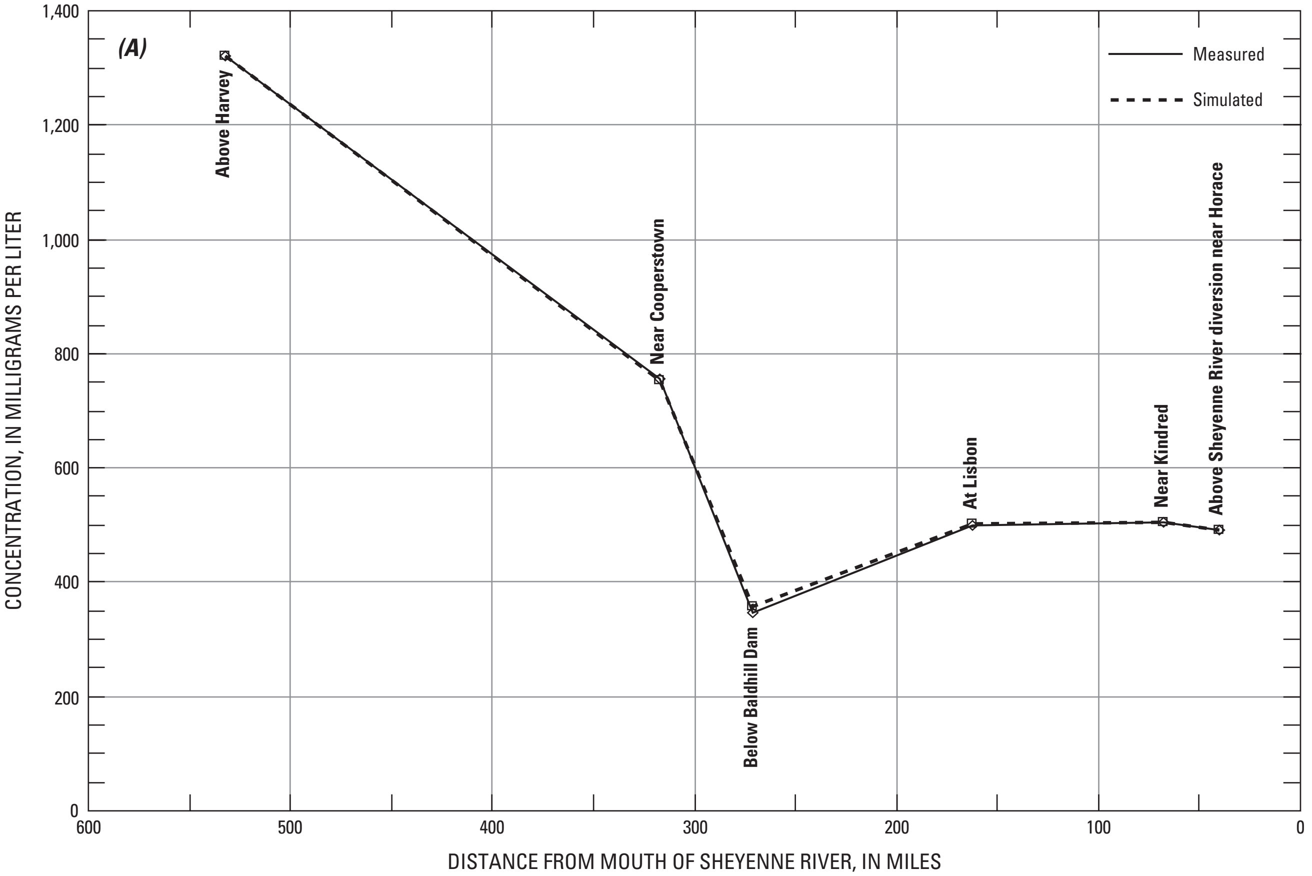

Figure 14. Measured and simulated total dissolved-solids concentrations for Red River water-quality model calibration points for May 10, 2004.

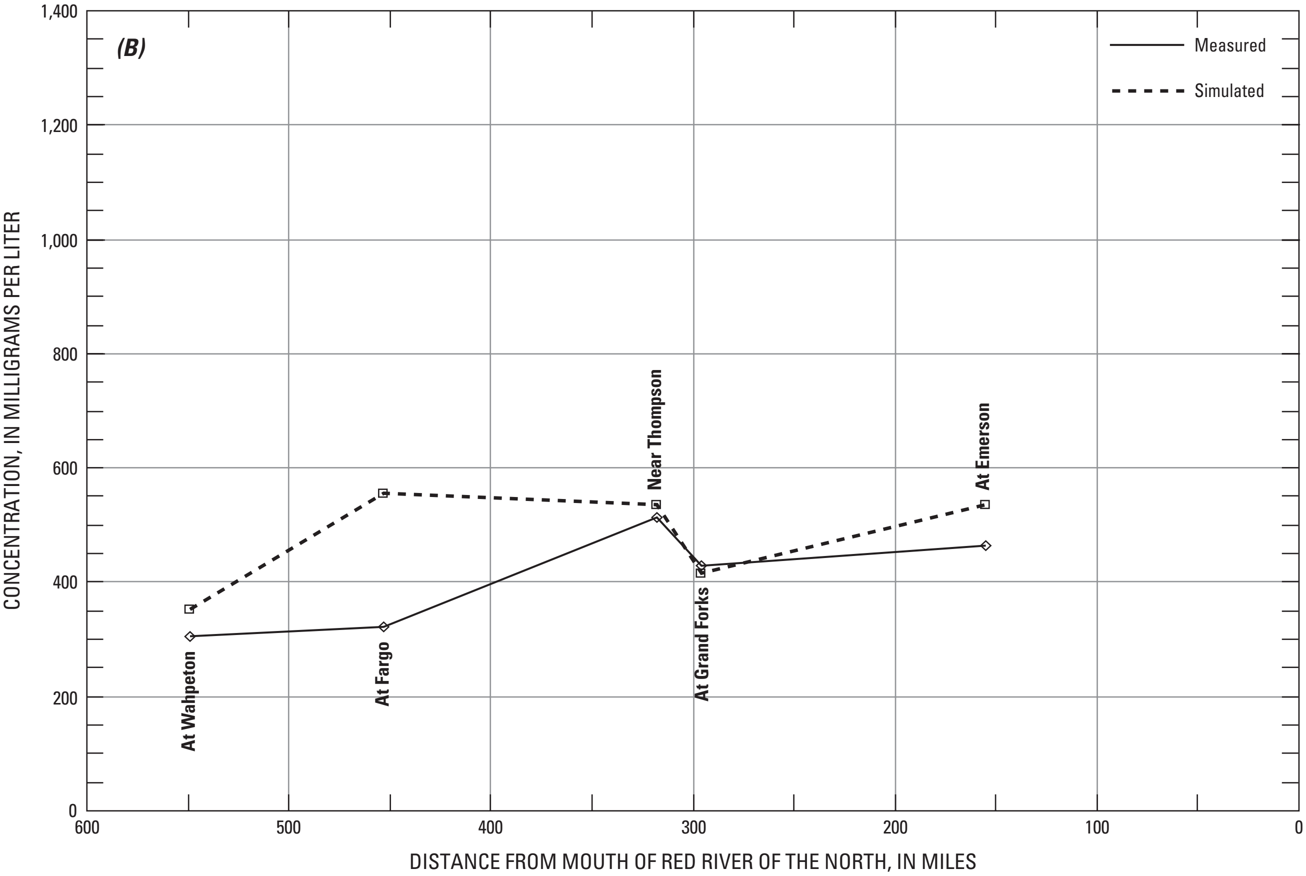

Figure 14. Measured and simulated total dissolved-solids concentrations for Red River water-quality model calibration points for May 10, 2004--Continued.

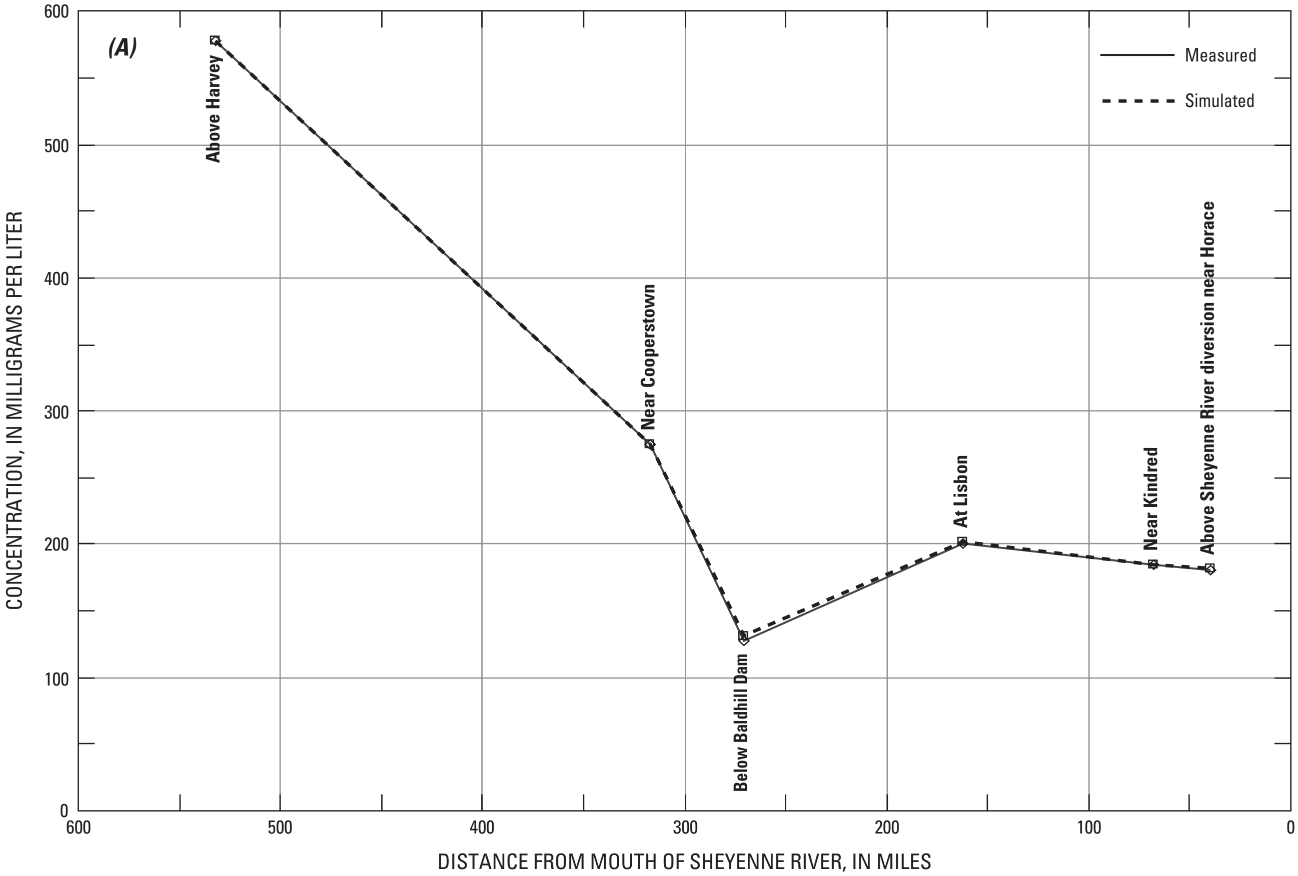

Figure 15. Measured and simulated sulfate concentrations for Red River water-quality model calibration points for May 10, 2004.

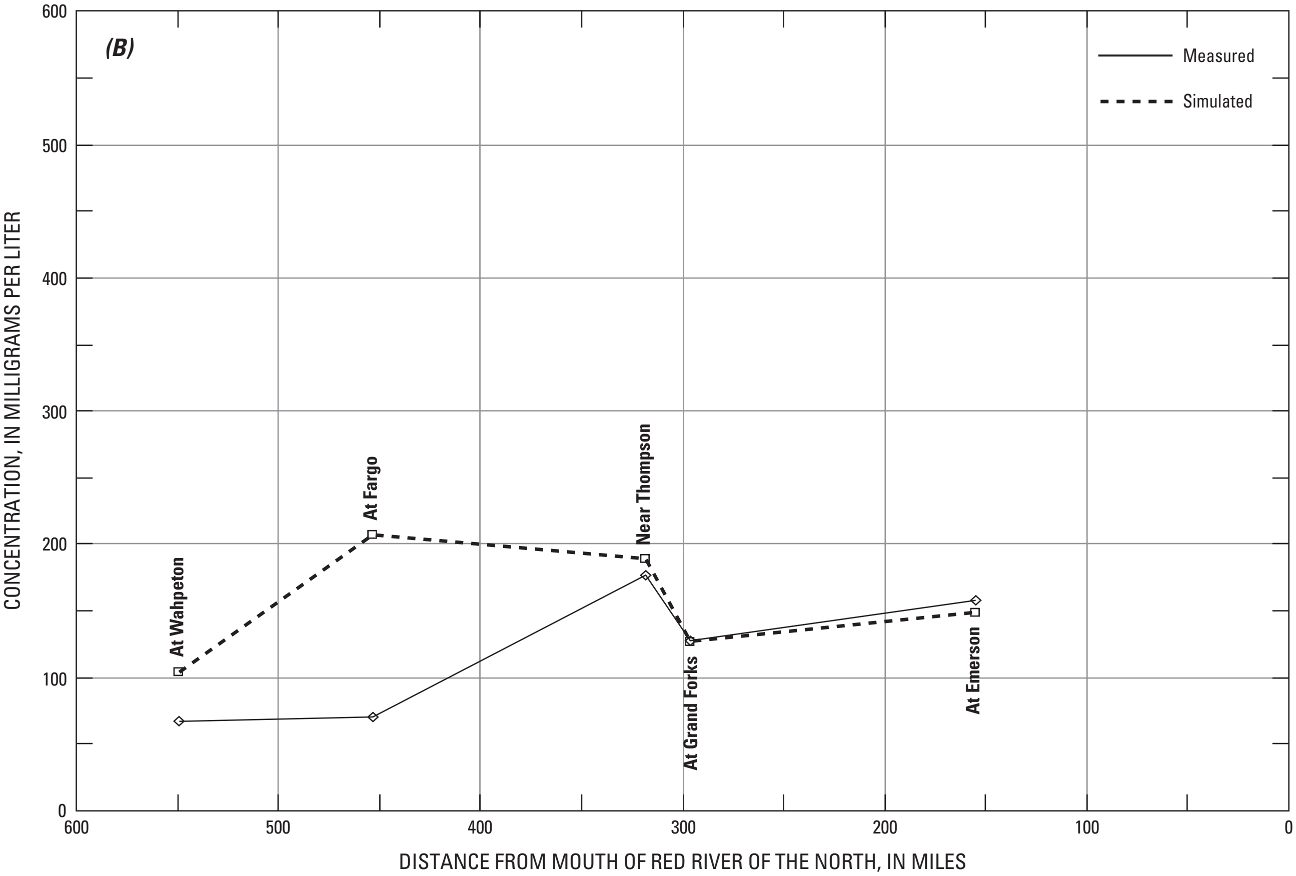

Figure 15. Measured and simulated sulfate concentrations for Red River water-quality model calibration points for May 10, 2004--Continued.

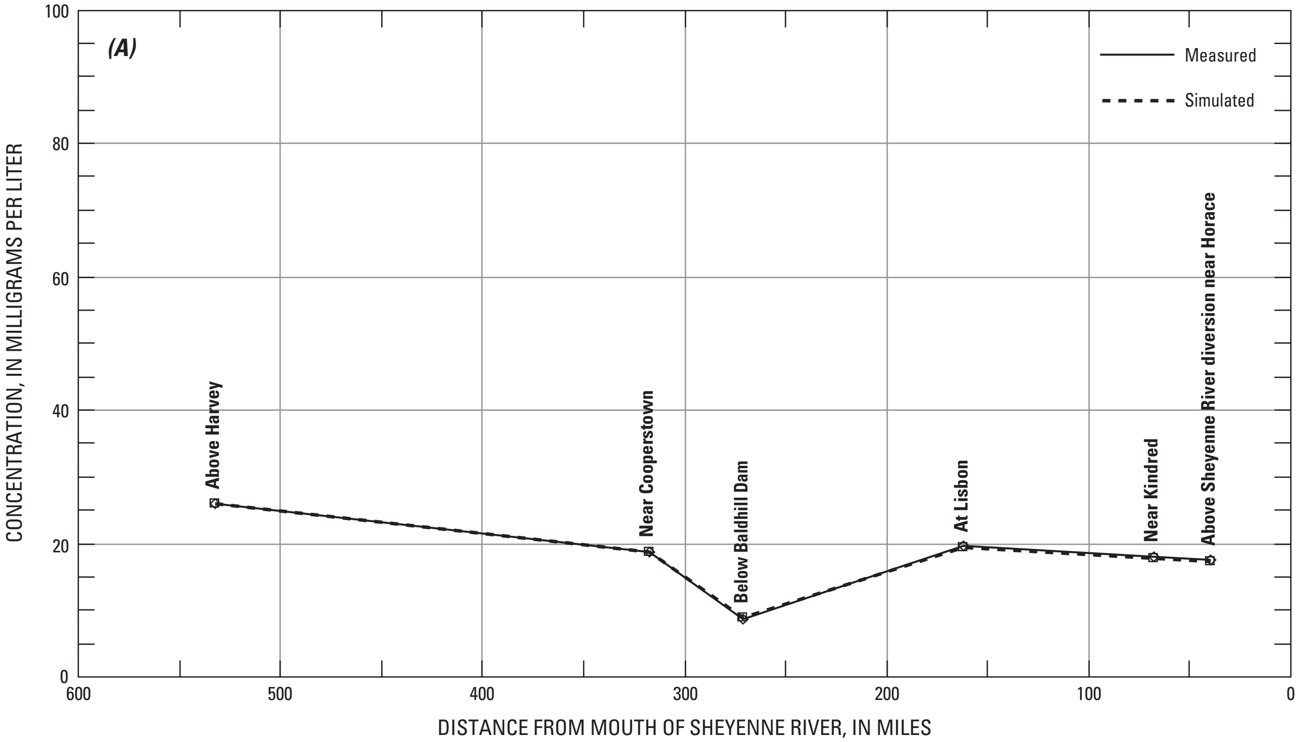

Figure 16. Measured and simulated chloride concentrations for Red River water-quality model calibration points for May 10, 2004.

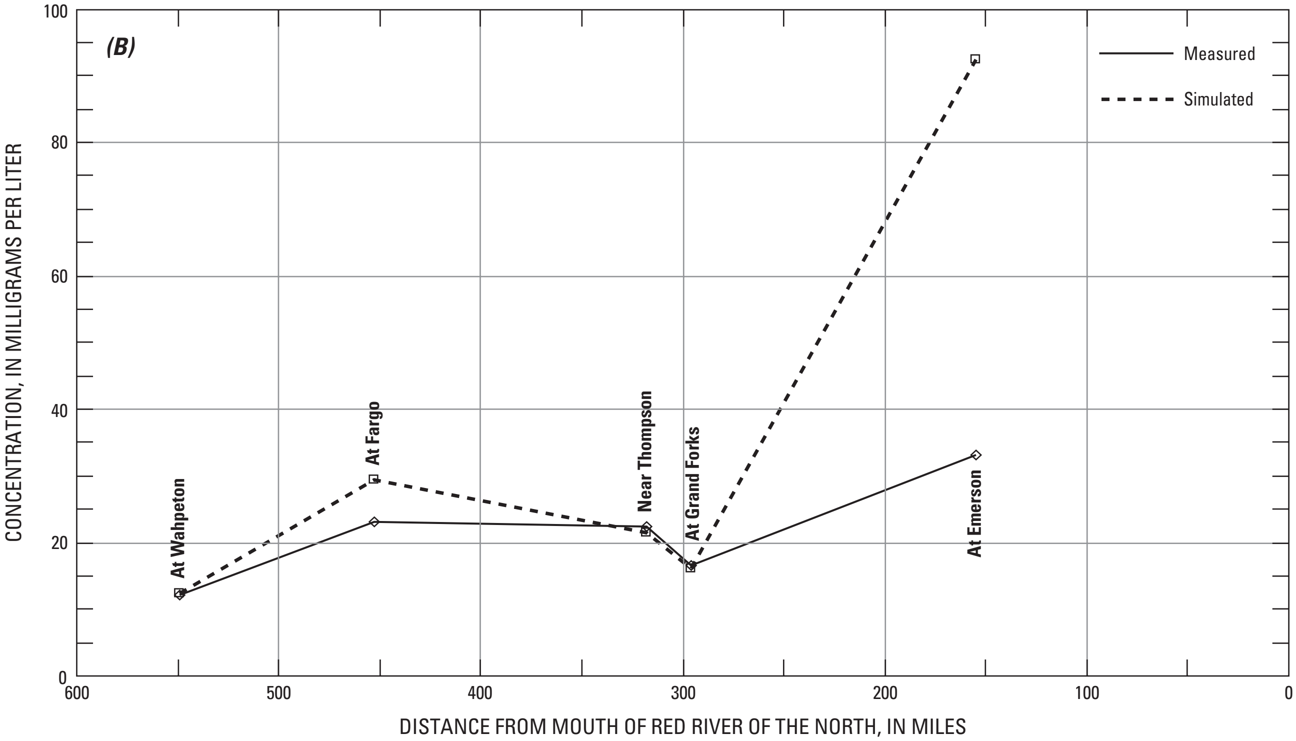

Figure 16. Measured and simulated chloride concentrations for Red River water-quality model calibration points for May 10, 2004--Continued.

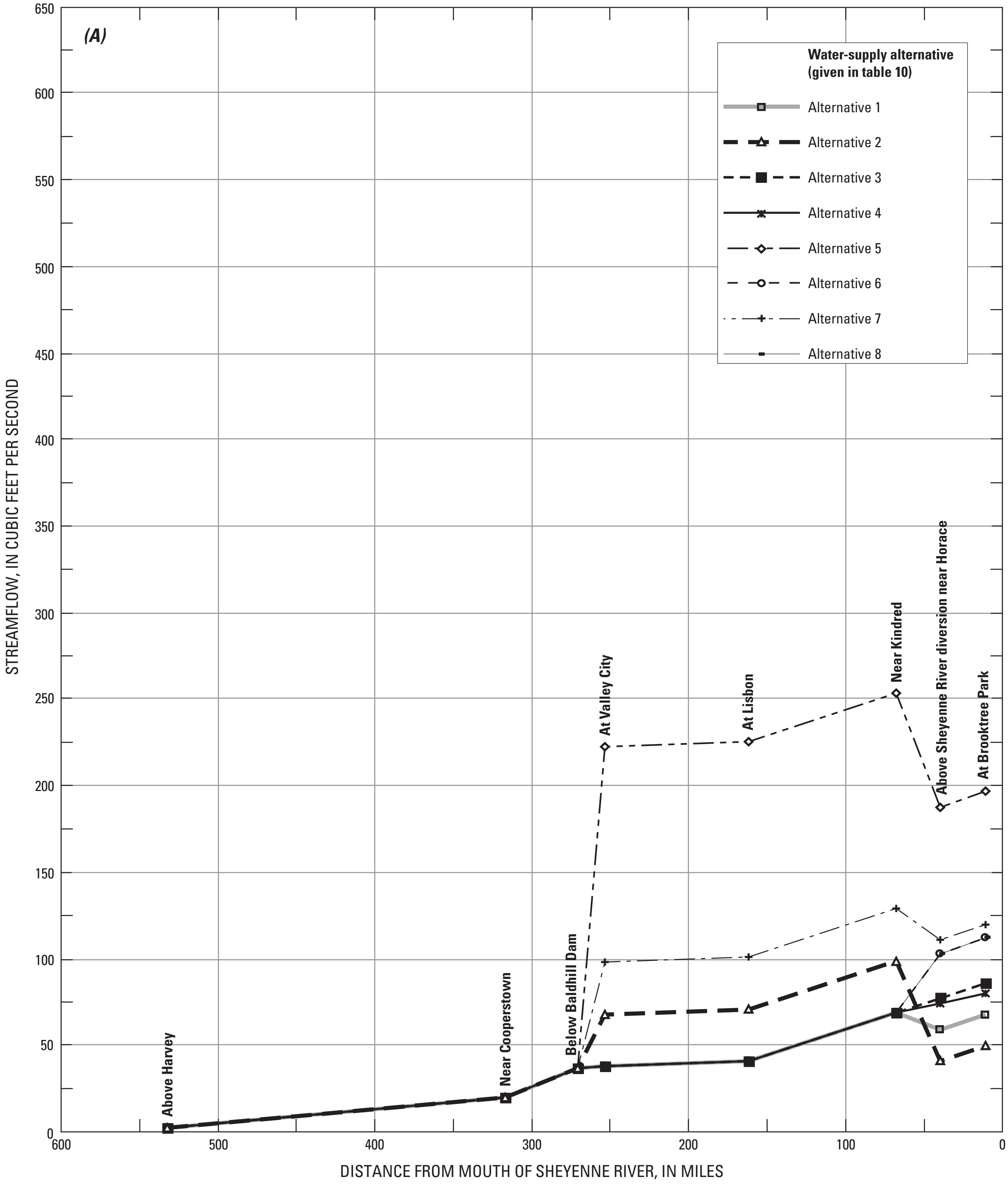

Figure 17. Simulated streamflows for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003.

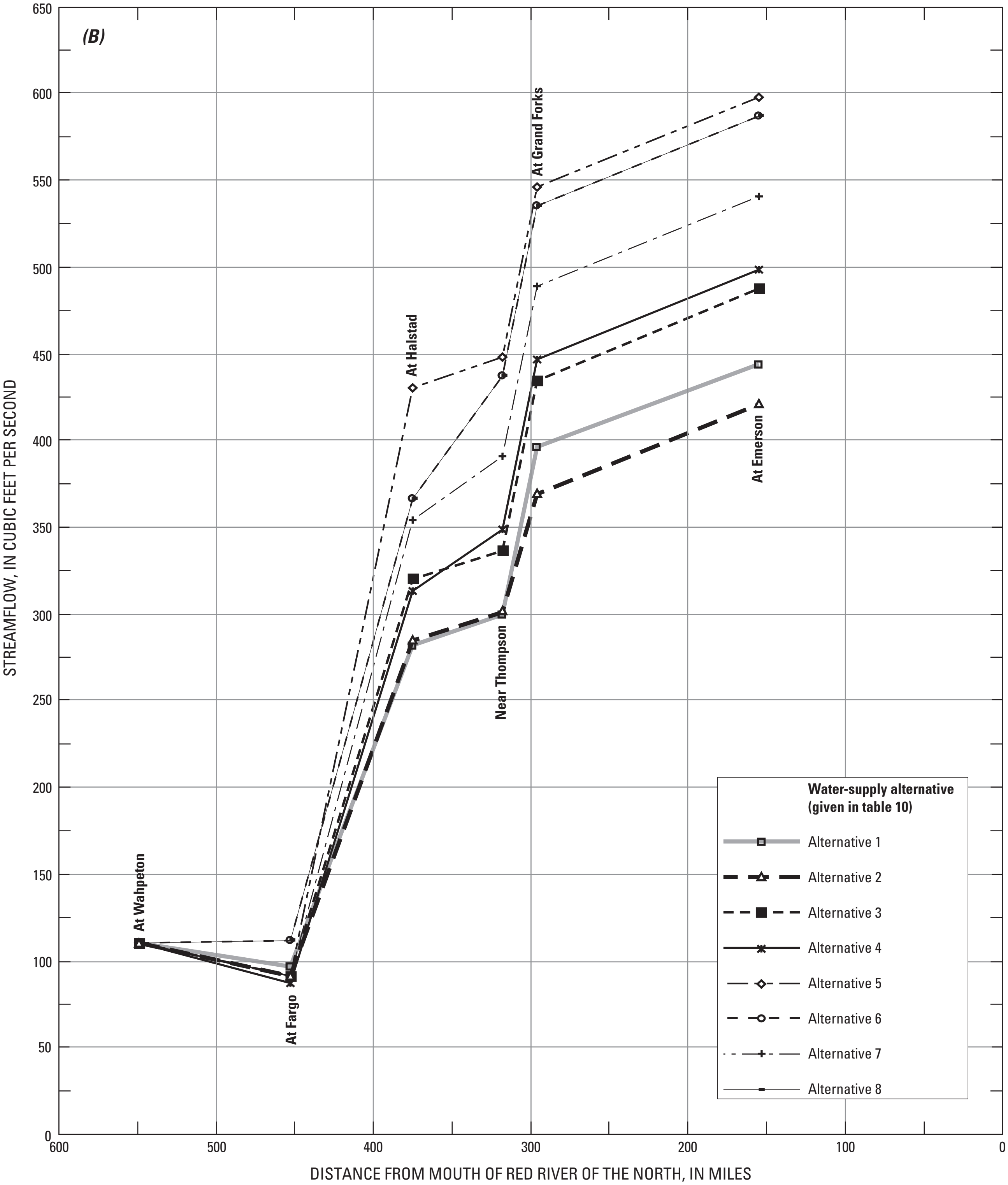

Figure 17. Simulated streamflows for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

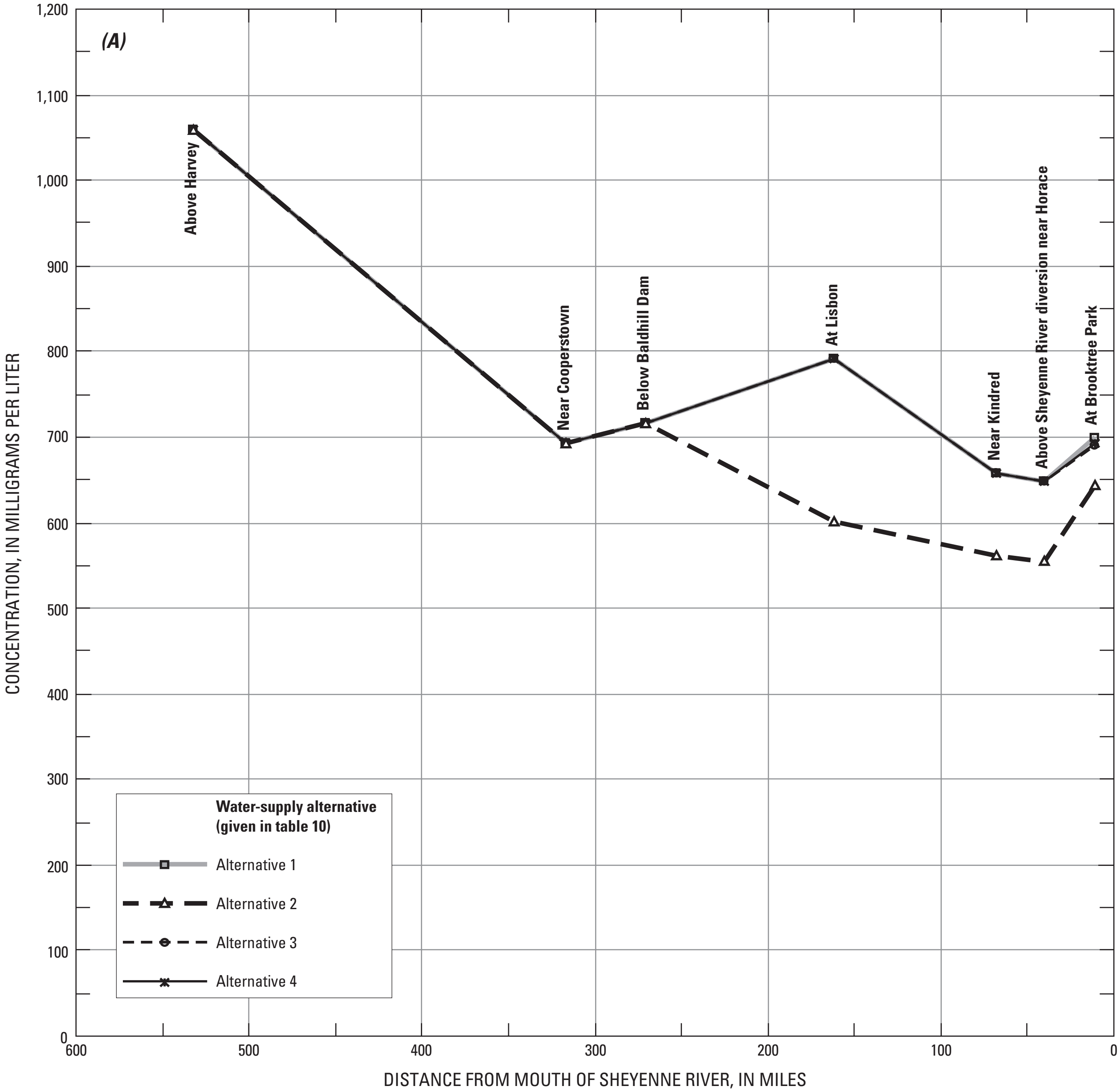

Figure 18. Simulated total dissolved-solids concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003.

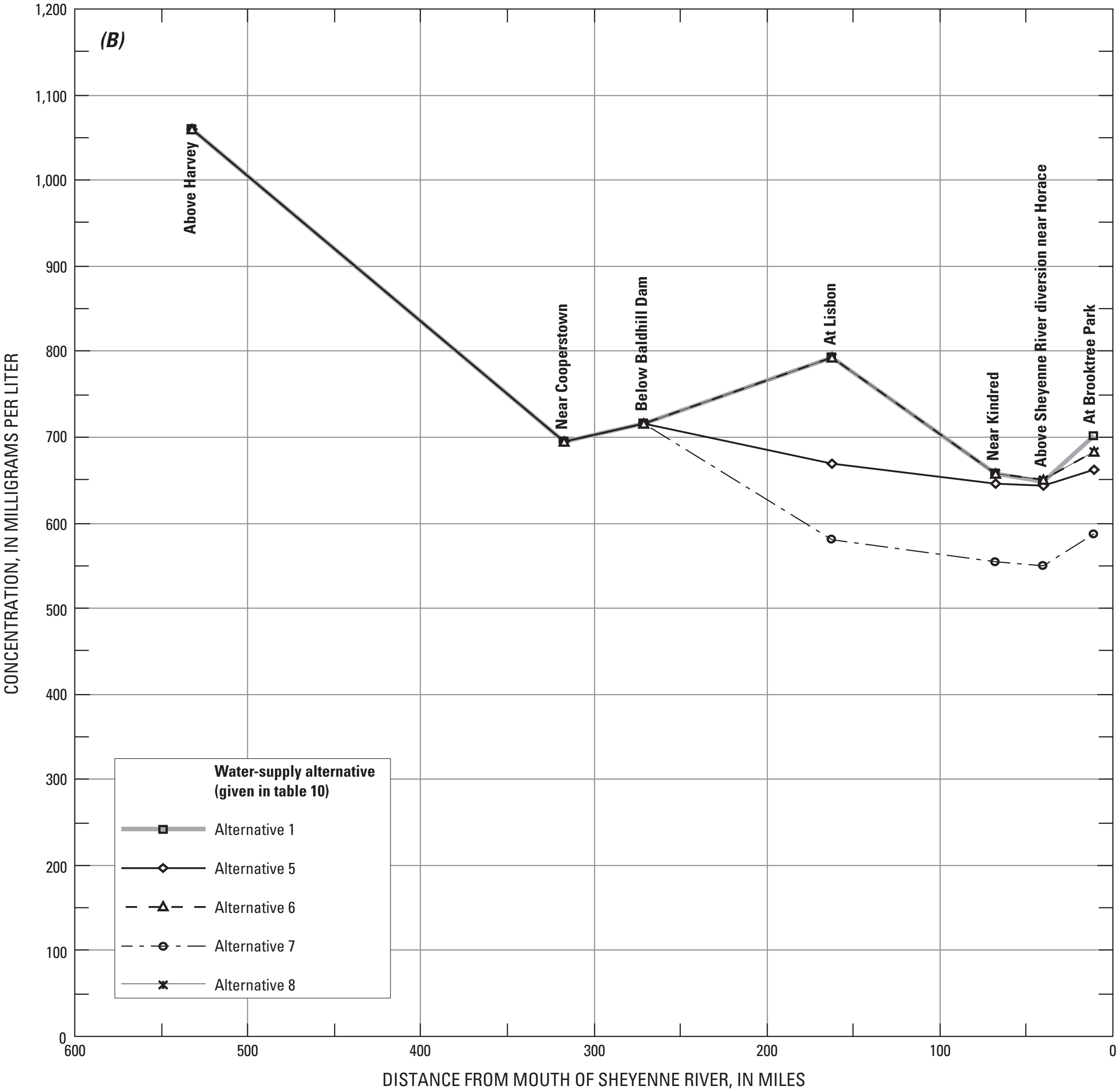

Figure 18. Simulated total dissolved-solids concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

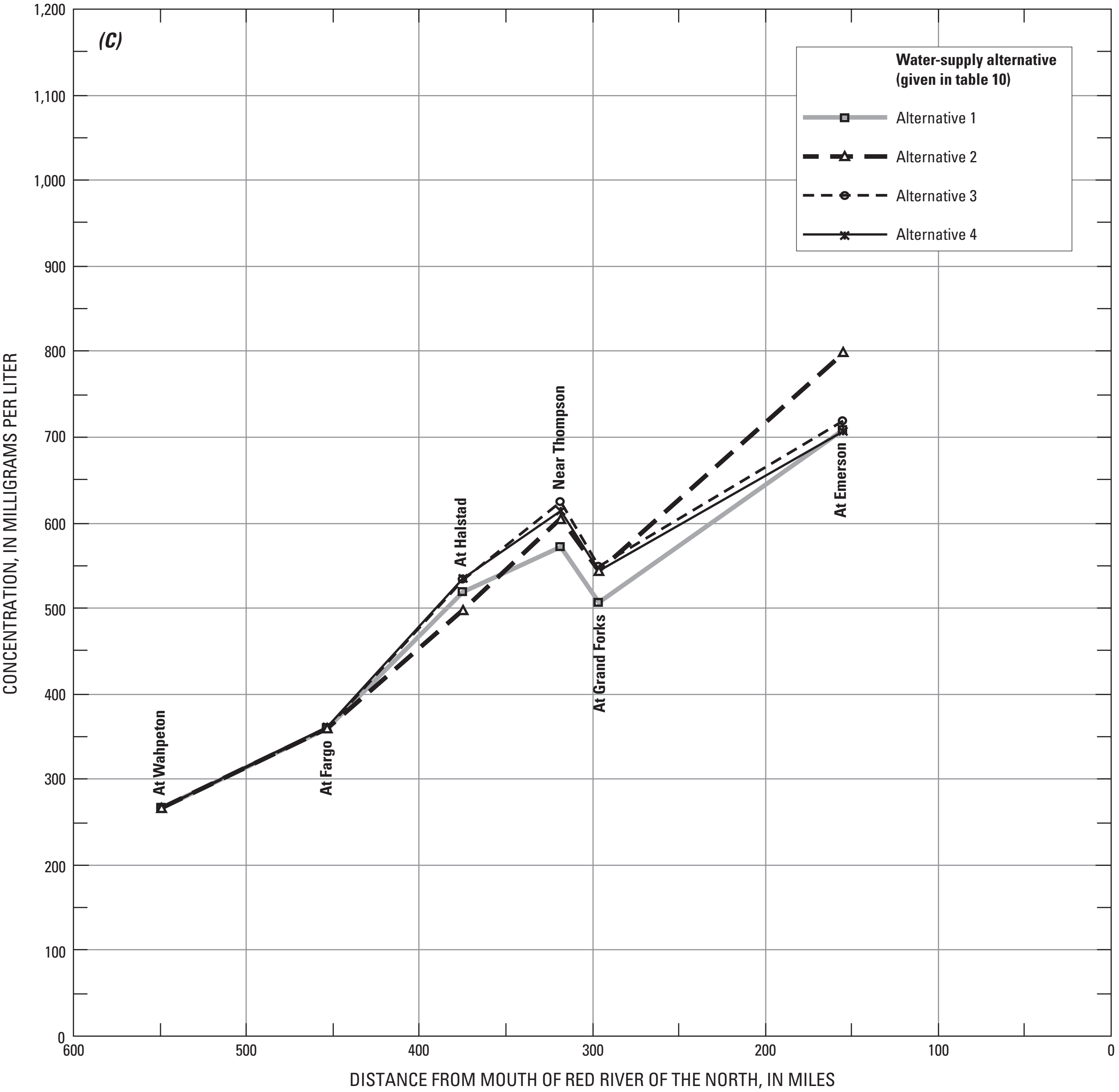

Figure 18. Simulated total dissolved-solids concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

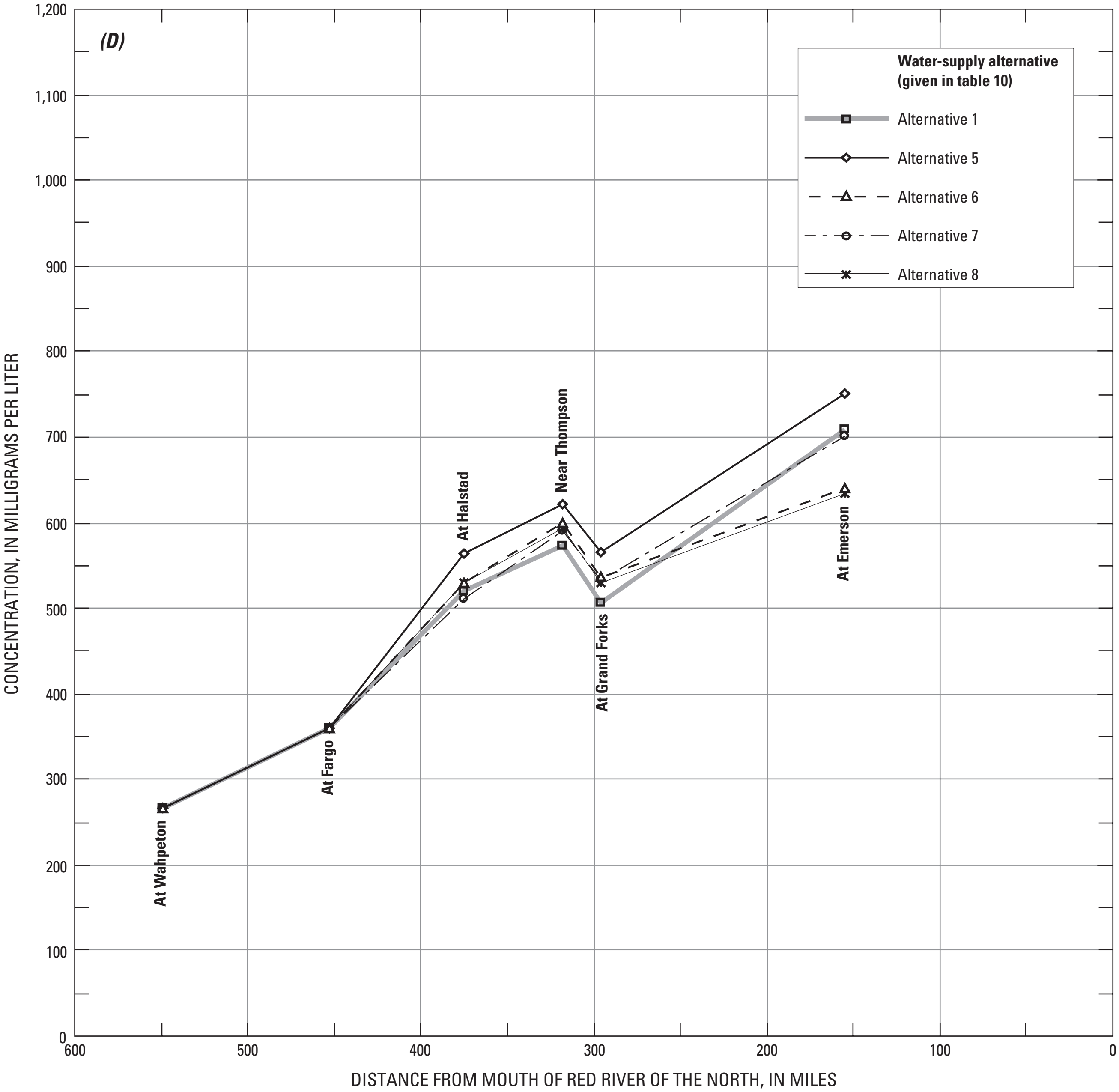

Figure 18. Simulated total dissolved-solids concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

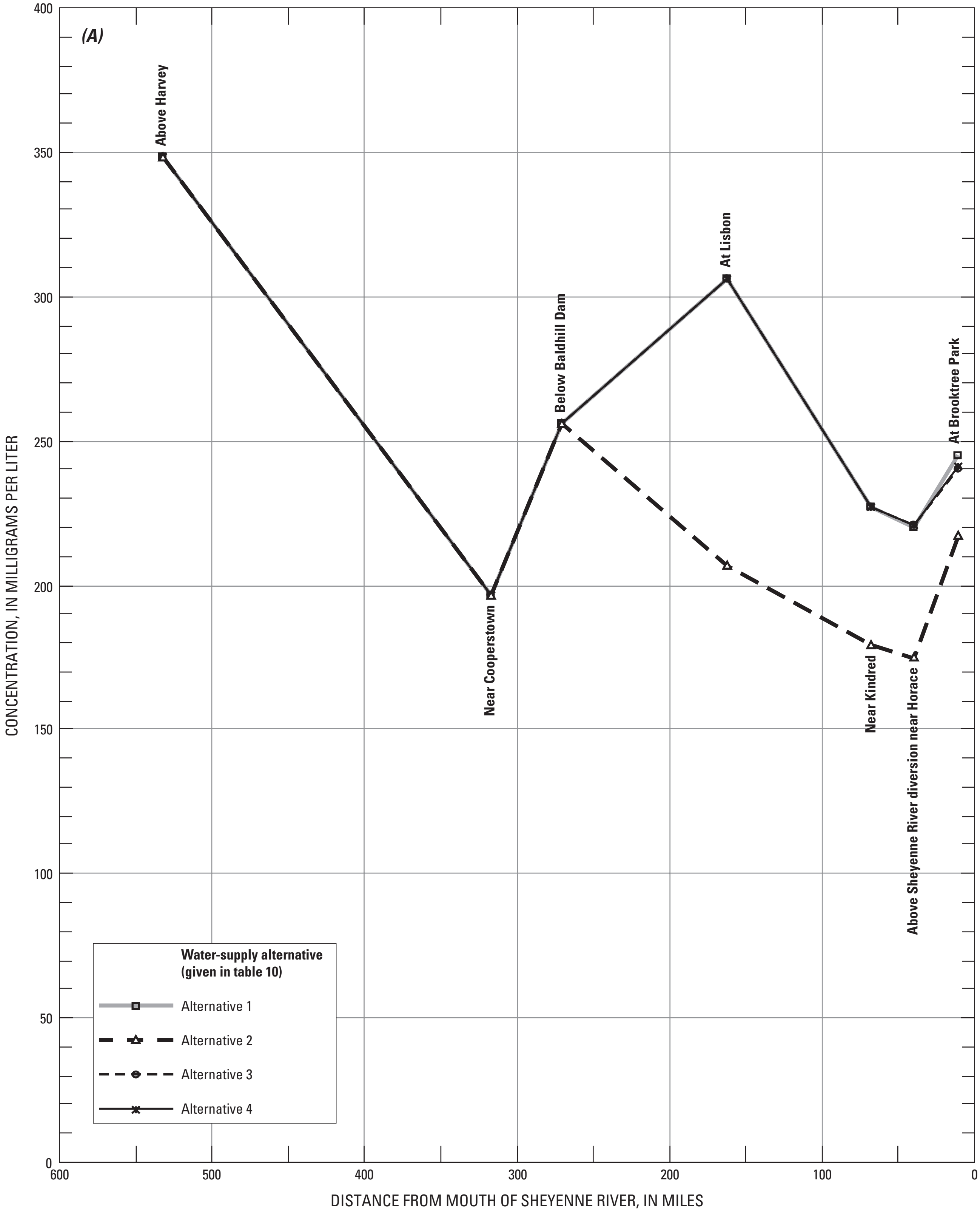

Figure 19. Simulated sulfate concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003.

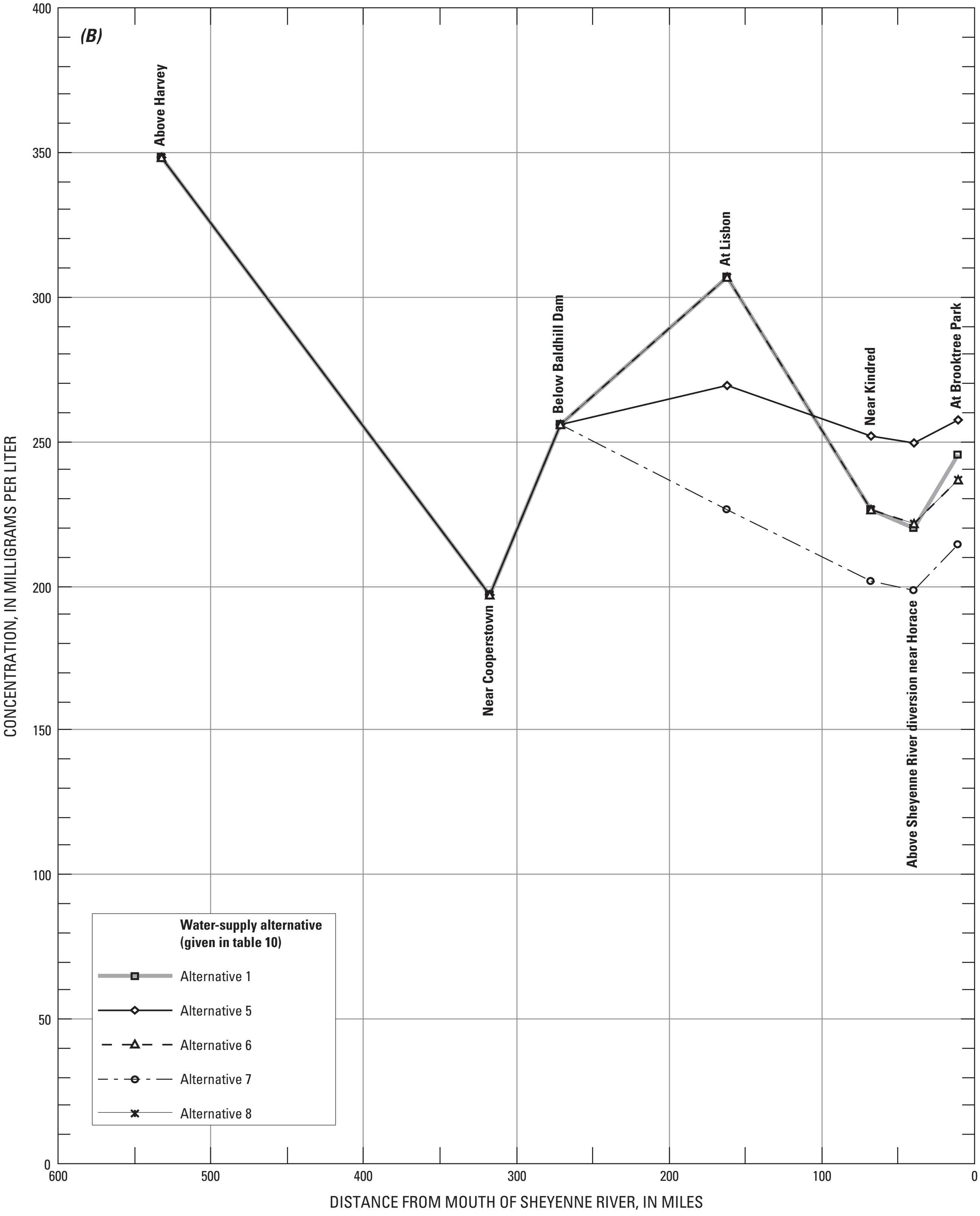

Figure 19. Simulated sulfate concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

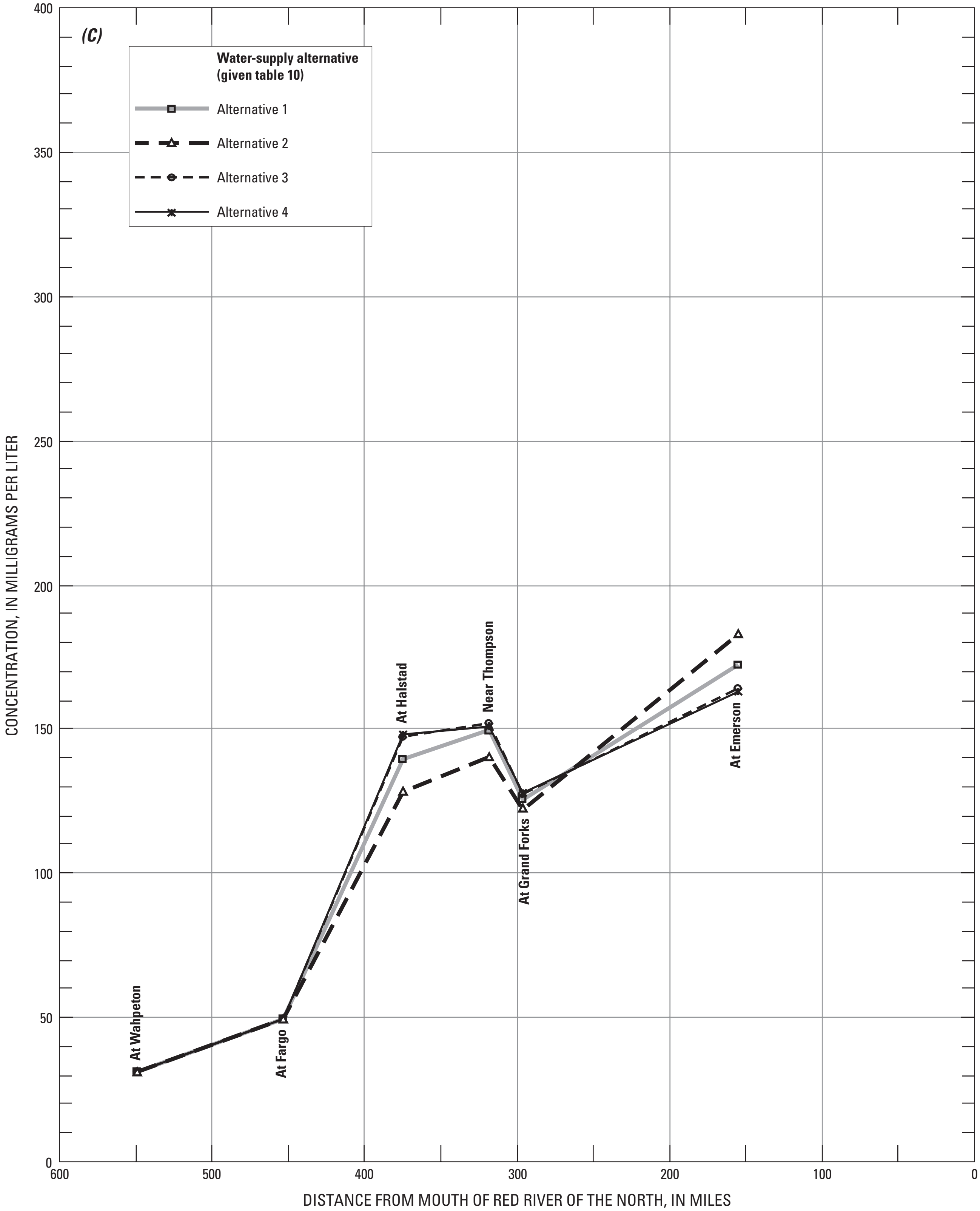

Figure 19. Simulated sulfate concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

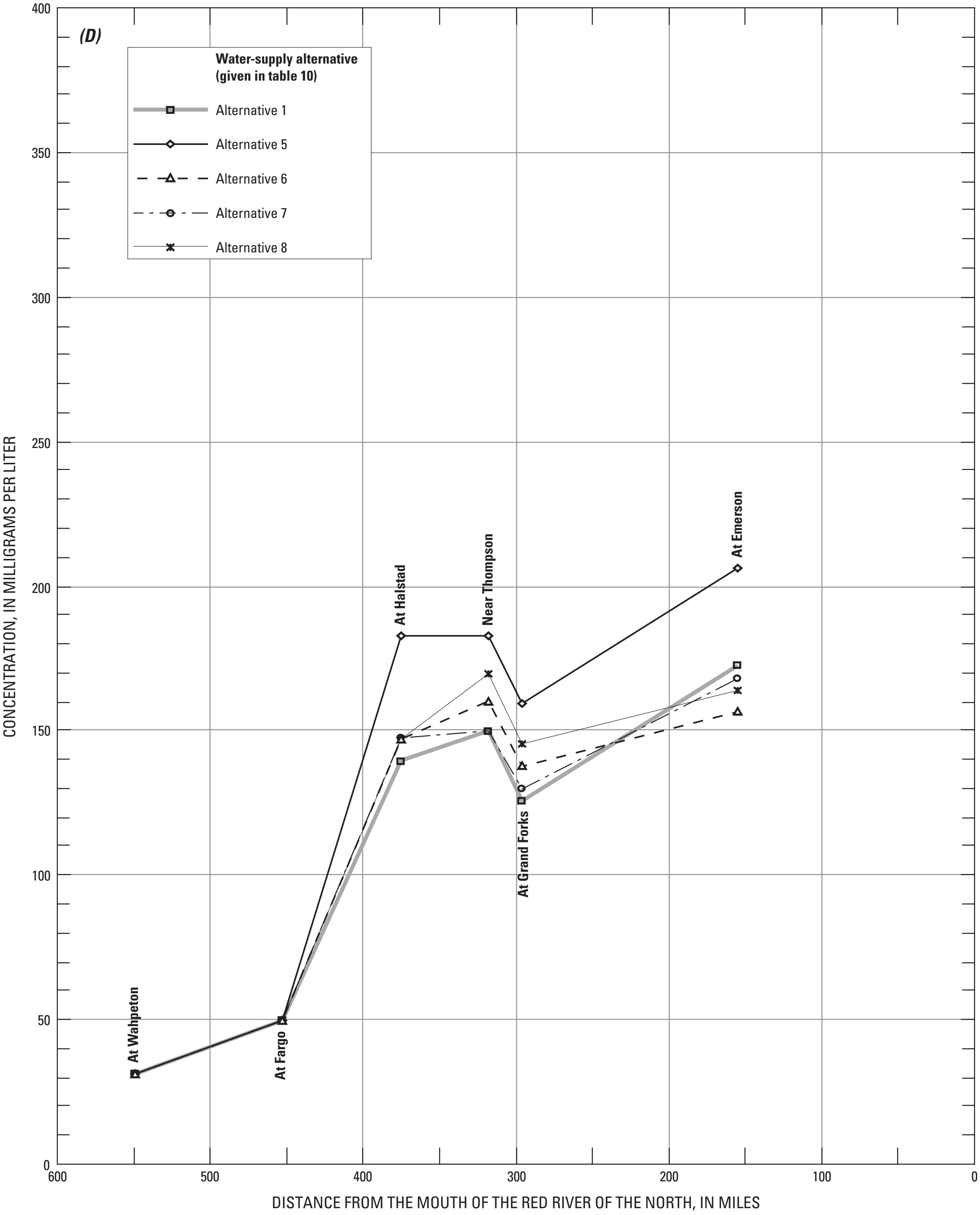

Figure 19. Simulated sulfate concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

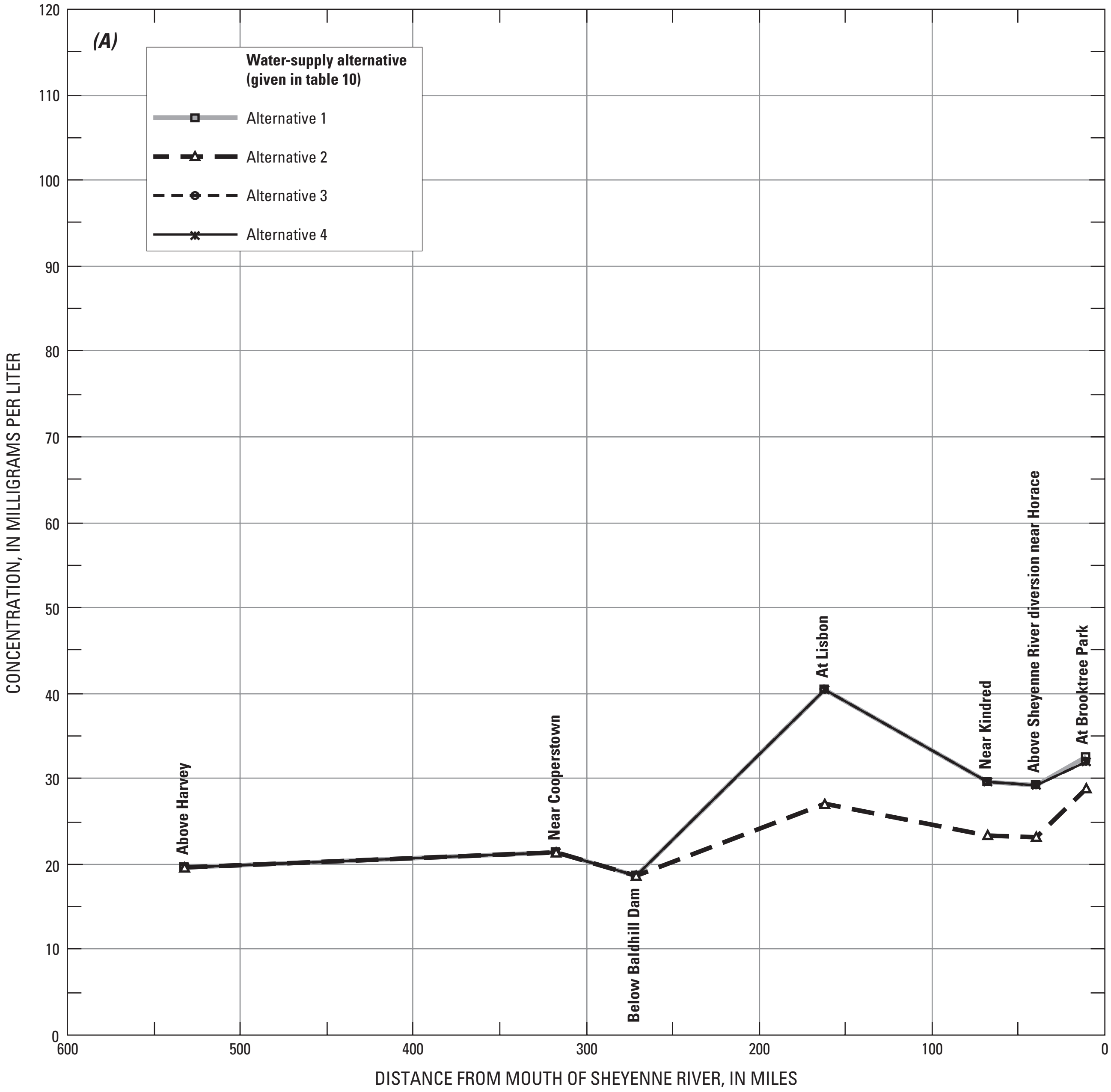

Figure 20. Simulated chloride concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003.

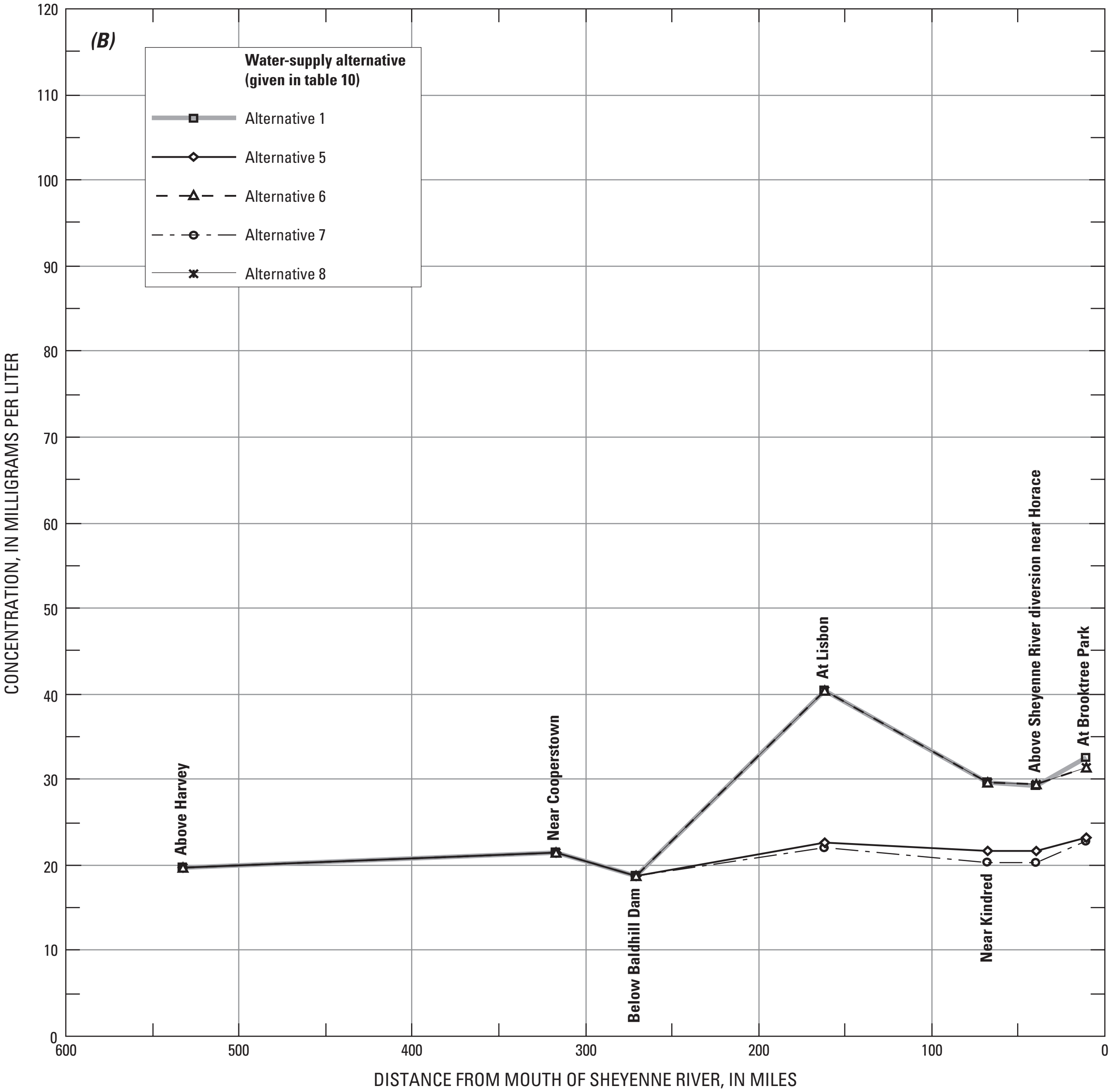

Figure 20. Simulated chloride concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

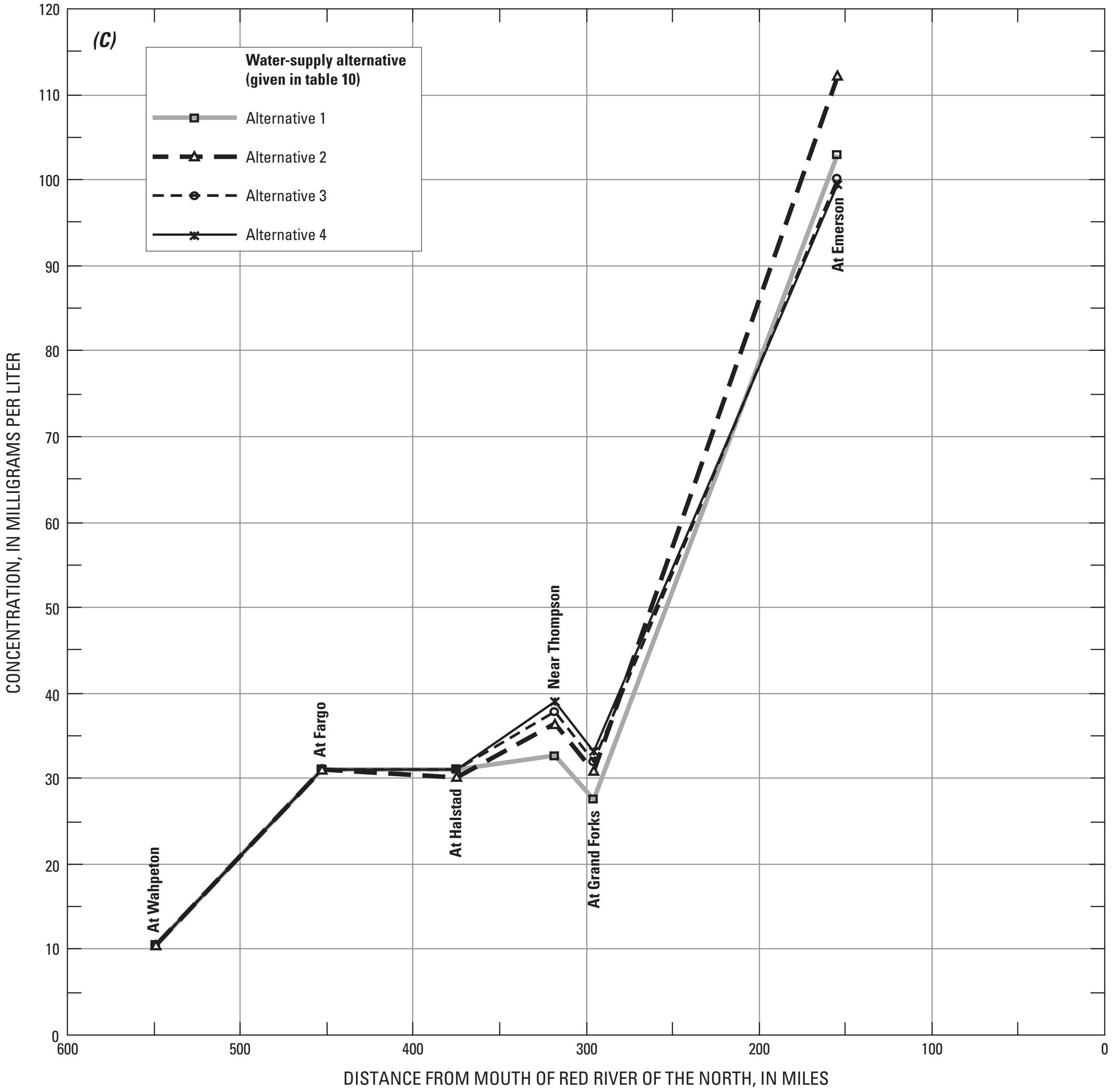

Figure 20. Simulated chloride concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

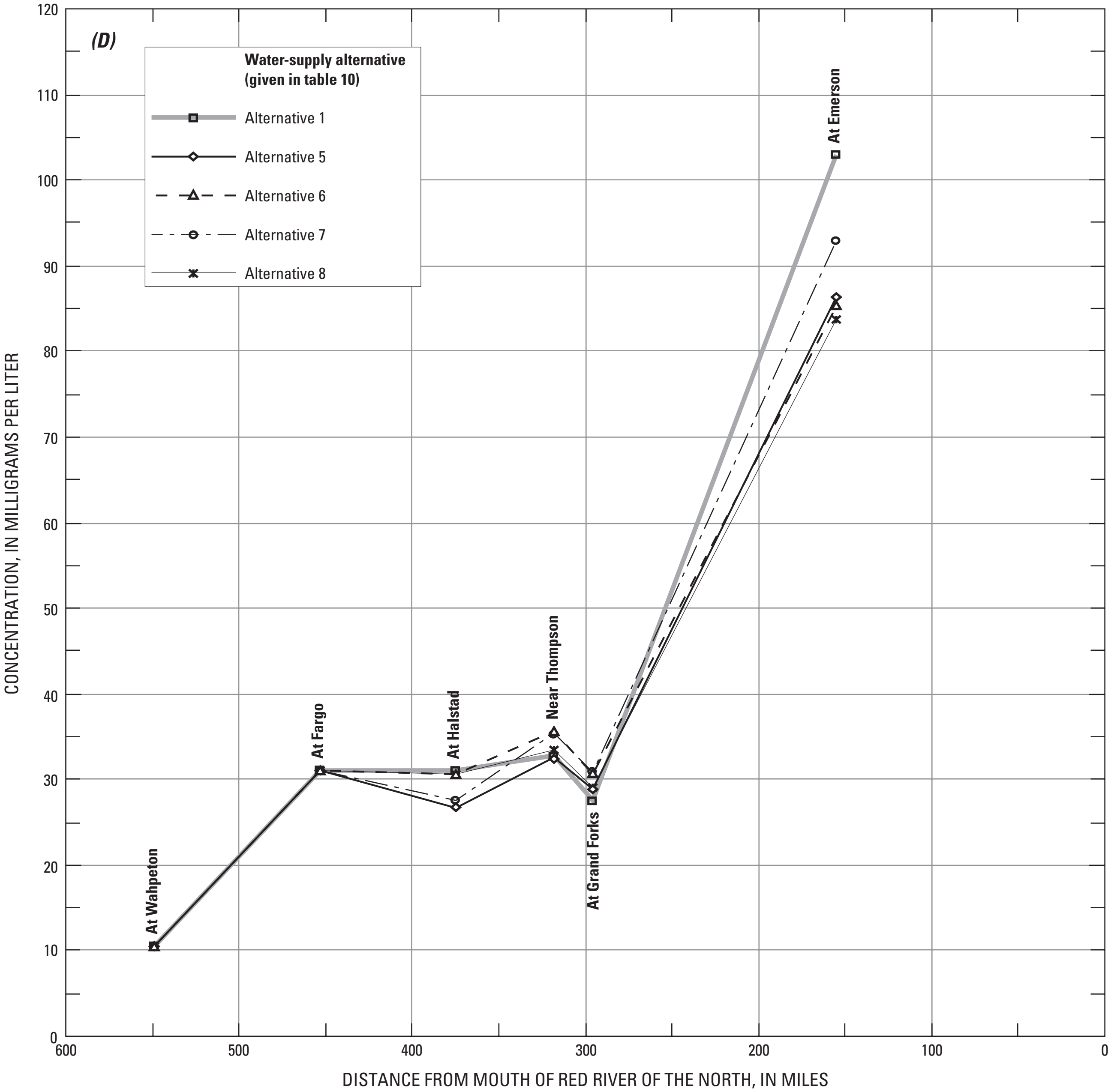

Figure 20. Simulated chloride concentrations for water-supply alternatives for the Red River of the North and the Sheyenne River for September 15, 2003--Continued.

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