Nustad and Bales—**Simulation of Constituent Transport in the Red River of the North Basin, North Dakota and Minnesota, During Unsteady-Flow Conditions, 1977 and 2003-04**—Scientific Investigations Report 2006–5296

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Prepared in cooperation with the Bureau of Reclamation

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Scientific Investigations Report 2006–5296

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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Conversion Factors, Abbreviations, and Datum

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-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		
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
Transmissivity		
foot squared per second (ft^2/s)	0.0929	meter squared per second (m^2/s)

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

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

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).

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

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

Simulation of Constituent Transport in the Red River of the North Basin, North Dakota and Minnesota, During Unsteady-Flow Conditions, 1977 and 2003-04

By Rochelle A. Nustad and Jerad D. Bales

Abstract

The Bureau of Reclamation identified eight water-supply alternatives for the Red River Valley Water Supply Project. Of those alternatives, six were considered for this study. Those six alternatives include a no-action alternative, two in-basin alternatives, and three interbasin alternatives. To address concerns of stakeholders and to provide information for an environmental impact statement, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, developed and applied a water-quality model to simulate the transport of total dissolved solids, sulfate, chloride, sodium, and total phosphorus during unsteady-flow conditions and to simulate the effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River. The physical domain of the model, hereinafter referred to as the Red River model, includes the Red River from Wahpeton, North Dakota, to Emerson, Manitoba, and the Sheyenne River from below Baldhill Dam, North Dakota, to the confluence with the Red River.

Boundary conditions were specified for May 15 through October 31, 2003, and January 15 through June 30, 2004. Measured streamflow data were available for August 1 through October 31, 2003, and April 1 through June 30, 2004, but water-quality data were available only for September 15 through 16, 2003, and May 10 through 13, 2004. The water-quality boundary conditions were assumed to be time invariant for the entire calibration period and to be equal to the measured value.

The average difference between the measured and simulated streamflows was less than 4 percent for both calibration periods, and most differences were less than 2 percent. The average differences are considered to be acceptable because the differences are less than 5 percent, or the same as the error that would be expected in a typical streamflow measurement. Simulated total dissolved solids, sulfate, chloride, and sodium concentrations generally were less than measured concentrations for both calibration periods. The average absolute differences generally were less than 25 percent. Total phosphorus was simulated as a nonconservative constituent by assuming that concentrations change according to a first-order decay rate. The average difference between the measured and simulated total phosphorus concentrations was 6.2 percent for the 2003 calibration period and -24 percent for the 2004 calibration period. The Red River model demonstrates sensitivity to changes in boundary conditions so a reasonable assumption is that the model can be used to compare relative effects of the various water-supply alternatives.

The calibrated Red River model was used to simulate the effects of the six water-supply alternatives by using measured streamflows for September 1, 1976, through August 31, 1977, when streamflows throughout the Red River Basin were relatively low. Streamflows for the Red River at Fargo, North Dakota, were less than 17.9 cubic feet per second on 159 days of that 12-month period, and monthly average streamflows for the Red River at Grand Forks, North Dakota, and the Red River at Emerson, Manitoba, were less than 30 percent of the respective long-term average monthly streamflows for 11 of the 12 months during September 1976 through August 1977.

Water-quality boundary conditions were generated using a stochastic approach in which probability distributions derived from all available historical data on instream concentrations were used to produce daily concentrations at model boundaries. Return flow concentrations were estimated from source concentrations and current (2006) wastewater-treatment technology. Because no historical information on ungaged local inflow constituent concentrations is available to estimate those boundary conditions, time-invariant concentrations for the low-flow 2003 calibration period were used as the ungaged local inflow boundary conditions. The effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River were evaluated by comparing the effects of five of the alternatives relative to the No-Action Alternative.

Alternatives that involve the transfer of water from within the Red River Basin tended to have total dissolved solids, sulfate, sodium, and total phosphorus concentrations that were about the same or less than those for the No-Action Alternative. In contrast, alternatives that involve the transfer of water from the Missouri River tended to have higher sulfate and sodium concentrations than those for the No-Action Alternative.

Introduction

Population growth along with possible future droughts in the Red River of the North (Red River) Basin (fig. 1) 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). The possible effects of those alternatives on water quality in the Red River and the Sheyenne River caused concern among many stakeholders. Also, the Dakota Water Resources Act mandates that the Bureau of Reclamation prepare an environmental impact statement (EIS) that describes the specific environmental effects of each alternative. Therefore, to address the concerns of the stakeholders and to provide information for the EIS, the U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation, developed a water-quality model for part of the Red River and the Sheyenne River to simulate the transport of total dissolved solids, sulfate, and chloride during steady-flow conditions (Nustad and Bales, 2005).

Since the model to simulate the transport of total dissolved solids, sulfate, and chloride during steady-flow conditions was developed, concerns have been expressed about the transport of those constituents and additional constituents during different flow conditions. Therefore, to address those concerns and to provide further information for the EIS, the USGS, in cooperation with the Bureau of Reclamation, conducted a study to develop and apply a water-quality model for the Red River from Wahpeton, N. Dak., to Emerson, Manitoba, and the Sheyenne River from Baldhill Dam, N. Dak., to the confluence with the Red River to simulate the transport of total dissolved solids, sulfate, chloride, sodium, and total phosphorus during unsteady-flow conditions. In addition, the effects of six water-supply alternatives (table 1) on water quality in the rivers were simulated using streamflow conditions that approximated those that existed in 1976-77. Although the Bureau of Reclamation identified eight alternatives as part of the comprehensive study of water needs in the Red River Basin, two of the alternatives were removed from consideration for this study. Of the six alternatives considered, three include the interbasin transfer of water.

To determine the flow conditions and constituents to be simulated by the model for this study, representatives from the Bureau of Reclamation met with representatives from the U.S. Environmental Protection Agency, the USGS, the States of Minnesota and North Dakota, Environment Canada, and other agencies. During the meeting, which was held in January 2006, total dissolved solids, sulfate, chloride, sodium, and total phosphorus were selected as the constituents to be included in the study. Total dissolved solids, sulfate, chloride, and sodium are conservative constituents and were selected because they affect the usability of water for municipal and industrial purposes. Total phosphorus is a nonconservative constituent and was selected because of its potential effect on instream eutrophication. Representatives at the meeting agreed that transport of the selected constituents would be simulated for a 12-month period of unsteady and extremely low flows, such as those during which the water-supply alternatives would be operated. The low-flow conditions that occurred during the 1930s drought represent the low-flow conditions in which representatives of the agencies were interested, but few streamflow and water-quality data are available for that period. Therefore, after an extensive hydrologic analysis by the Bureau of Reclamation, September 1976 through August 1977 was selected as the simulation period for this study. That period was selected because it was a 365-day period during which extremely low streamflows occurred at several USGS gaging stations and for which a sufficient amount of streamflow data was available for model application.

The model developed during this study will, hereinafter, be referred to as the Red River model. The model was developed using the RIV1 modeling system (U.S. Army Corps of Engineers, 2006) and was calibrated and tested using data collected during 2003 and 2004.

Purpose and Scope

The purpose of this report is to describe the simulation of constituent transport in the Red River and the Sheyenne River during unsteady-flow conditions and to document the effects of six proposed water-supply alternatives on water quality in the rivers. Development and calibration of the Red River model also are documented.

The Red River model was used to simulate the transport of total dissolved solids, sulfate, chloride, sodium, and total phosphorus during unsteady-flow conditions. Data for August through October 2003 and April through June 2004 were used to develop, calibrate, and test the model. The physical model domain includes the Red River from Wahpeton, N. Dak., to Emerson, Manitoba, and the Sheyenne River from below Baldhill Dam, N. Dak., to the confluence with the Red River (fig. 1). The model was used to simulate flow and constituent transport for each of the six water-supply alternatives operating during conditions that approximated those that existed during September 1976 through October 1977. Inputs from Lake Ashtabula to the Sheyenne River were estimated for the water-supply alternatives by using a simple mixing model for the lake.

Study Area

The study area includes the Red River from Wahpeton, N. Dak., to Emerson, Manitoba, the Sheyenne River from below Baldhill Dam, N. Dak., to the confluence with the Red River, and selected tributaries to the Red River. The Red River

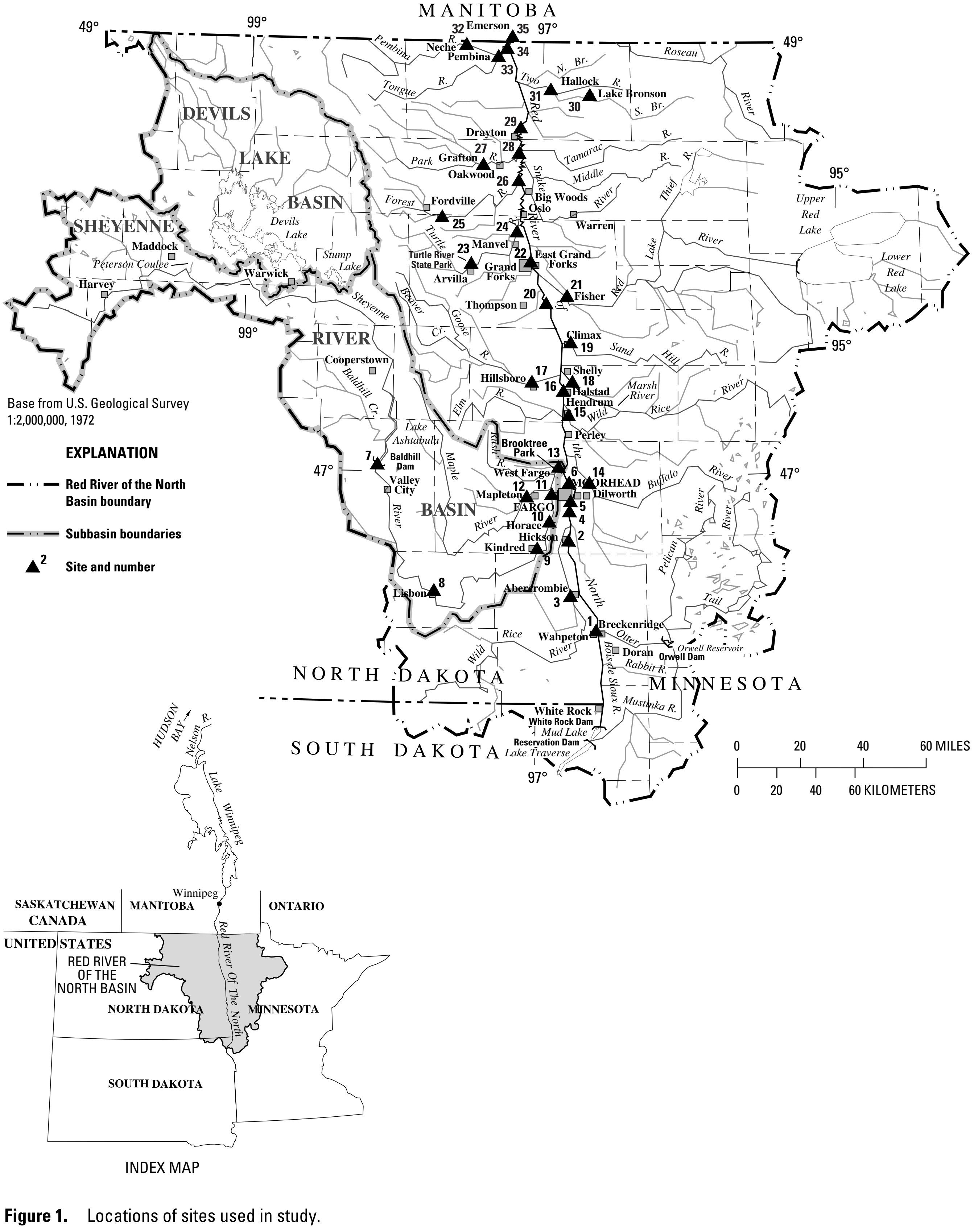


Figure 1. Locations of sites used in study.

Table 1. Description of water-supply alternatives for Red River Valley Water Supply Project.

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

Description of alternative
No-Action Alternative (NA). This 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
North Dakota In-Basin Alternative (NDIB). This alternative would supplement existing water supplies and would use the Red River of the North and other North Dakota water sources to meet future water demands. The main water-supply feature is a 48-cubic-feet-per-second pipeline that captures Red River of the North flows downstream from Grand Forks, North Dakota, and conveys flows back to Lake Ashtabula for storage and release down the Sheyenne River and the Red River of the North to meet municipal, rural, and industrial water demands. Two rural systems would be connected to cities by pipelines. The Grafton, North Dakota, water intake would be relocated farther north in the Red River of the North. The alternative also would include developing new ground-water sources in southeastern North Dakota; aquifer storage and recovery systems are proposed for Fargo, North Dakota; Moorhead, Minnesota; and West Fargo, North Dakota; and the city of Moorhead would continue to draw on Minnesota ground-water sources for some of its water demand.
Red River Basin Alternative (RRB). This alternative would supplement existing water supplies and would draw on a combination of the Red River of the North, other North Dakota water sources, and Minnesota ground-water resources to meet future water demands. Two rural systems would be connected to cities by pipelines. The main water-supply feature would be a series of well fields developed in Minnesota with an interconnecting conveyance pipeline serving the Fargo, North Dakota—Moorhead, Minnesota, metropolitan area. The alternative also would include developing new ground-water sources in southeastern North Dakota; aquifer storage and recovery systems are proposed for Fargo; Moorhead; and West Fargo, North Dakota; and the city of Moorhead would continue to draw on Minnesota ground-water sources for some of its water demand.
Interbasin alternatives
Garrison Diversion Unit Import to Sheyenne River Alternative (GDUIS). This alternative would supplement existing water supplies to meet future water needs with a combination of the Red River of the North, other North Dakota in-basin sources, and imported Missouri River water. The principal feature of this alternative would be a 122-cubic-feet-per-second pipeline from the McClusky Canal to Lake Ashtabula that would release treated Missouri River water into the Sheyenne River about 3 miles upstream from the reservoir. The biota treatment plant would be located adjacent to the McClusky Canal. The Grafton, North Dakota, water intake would be relocated farther north in the Red River of the North. The alternative would include a pipeline from Fargo, North Dakota, to the Wahpeton, North Dakota, area to serve industrial water demands in southeastern North Dakota.
Garrison Diversion Unit Import Pipeline Alternative (GDUIP). This alternative would supplement existing water supplies to meet future water needs by conveying water from the Missouri River via the McClusky Canal and a pipeline to the Red River Valley. The biota treatment plant would be located adjacent to the McClusky Canal. The principal feature of the alternative would be an 85-cubic-feet-per-second pipeline from the McClusky Canal to the Fargo, North Dakota, metropolitan area. The Grafton, North Dakota, river intake would be moved farther north in the Red River of the North. Two rural water systems would receive water from cities by pipelines. The alternative also would include developing new ground-water sources in southeastern North Dakota and expand use of the Buffalo aquifer as well as recharge of the Moorhead aquifer with an aquifer storage and recovery feature to serve the city of Moorhead, Minnesota.
Missouri River Import Pipeline to Red River Valley Alternative (MRIP). This alternative would supplement existing water supplies to meet future water needs by conveying treated water in a closed pipeline from the Missouri River south of Bismarck, North Dakota, directly to Fargo and Grand Forks, North Dakota. The principal features would be a 119-cubic-feet-per-second pipeline from the Missouri River at Bismarck to the Fargo area and a 21-cubic-feet-per-second pipeline to Grand Forks. The Missouri River water would be collected from a series of horizontal wells constructed in the sediments underlying the Missouri River. Two rural water systems would be served by pipelines from cities and the Grafton, North Dakota, river intake would be relocated farther north in the Red River of the North. The alternative would include a pipeline from Fargo to the Wahpeton, North Dakota, area to serve southeast industries.

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 (fig. 1). The drainage area of the Red River at Emerson is 40,200 mi^2, including 3,800 mi^2 of noncontributing area. 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. (fig. 1), and flows northward 394 mi to the international boundary. The slope of the river, about 0.5 ft/mi, is extremely small. 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).

The Sheyenne River, the largest tributary 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 drainage area below Baldhill Dam is about 3,240 mi^2. The Sheyenne River flows about 270 mi from Baldhill Dam to the confluence with the Red River and has an average slope of 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.

Acknowledgments

A. Schlag and D. Goetzfried from the Bureau of Reclamation assisted throughout the study. M. Deutschman from Houston Engineering supplied boundary condition data for the September 1976 through August 1977 simulation period and also provided valuable guidance throughout the study. K. Ryberg and T. Banse from the USGS constructed the notched box plots for constituent concentrations, and K. Vining from the USGS provided assistance with data preparation. A. Vecchia from the USGS supplied estimates of historical constituent loads for the Red River at Emerson, Manitoba.

Methods

The Red River model was developed primarily from the RIV1 modeling system. The RIV1 modeling system originally was released in 1991 by the U.S. Army Corps of Engineers, Waterways Experiment Station, and was known as CE-QUAL-RIV1 (U.S. Army Corps of Engineers, 2006). Version 2.0 of the modeling system was released in 1995. The RIV1 modeling system is a one-dimensional (cross-sectionally averaged), hydrodynamic, water-quality model that consists of two parts—a hydrodynamic code (RIV1H) and a water-quality code (RIV1Q). RIV1H uses the widely accepted four-point, implicit, finite-difference, numerical scheme to solve the St. Venant flow equations for flows, depths, velocities, water-surface elevations, and other hydraulic characteristics throughout a modeled reach. RIV1Q can be used to simulate temporal and longitudinal variations in each of 14 state variables—temperature, dissolved oxygen, two types of carbonaceous biochemical oxygen demand (CBOD), nitrogenous biochemical oxygen demand (NBOD), nitrate plus nitrite nitrogen, ammonia nitrogen, organic nitrogen, organic phosphorus, dissolved phosphate, dissolved iron, dissolved manganese, coliform bacteria, and algae—and in conservative constituents. Numerical accuracy for the advection of sharp concentration gradients is preserved in the code through the use of the explicit, two-point, fourth-order accurate, Holly-Preissman scheme. The RIV1 modeling system was updated to run in a Windows environment in 2002 and subsequently was called EPD-RIV1 (Martin and Wool, 2002). The EPD-RIV1 modeling system, which includes a pre- and post-processor to facilitate model application and data analysis, was used in this study.

The Red River model was calibrated and tested using streamflow and water-quality data for an extensive hydrologic network (fig. 1, table 2). Long-term records of streamflow are available for most of the network sites. Streamflow summaries for selected sites for the calibration periods, August 1 through October 31, 2003, and April 1 through June 30, 2004, and for the simulation period for model applications, September 1, 1976, through August 31, 1977, are given in table 3. The water-quality data were collected from September 15 through 16, 2003, when streamflows were low and steady and from May 10

Table 2. Data-collection network.

[Q, continuous streamflow; QW, water-quality samples]

Site number (figure 1)	U.S. Geological Survey site number	Site name	Data collected
1	05051500	Red River of the North at Wahpeton, North Dakota	Q, QW
2	05051522	Red River of the North at Hickson, North Dakota	Q, QW
3	05053000	Wild Rice River near Abercrombie, North Dakota	Q, QW
4	05053800	Red River of the North above Fargo, North Dakota	QW
5	05054000	Red River of the North at Fargo, North Dakota	Q, QW
6	465602096472700	Red River of the North on Cass County Road 20 below Fargo, North Dakota	QW
7	05058000	Sheyenne River below Baldhill Dam, North Dakota	Q, QW
8	05058700	Sheyenne River at Lisbon, North Dakota	Q, QW
9	05059000	Sheyenne River near Kindred, North Dakota	Q, QW
10	05059300	Sheyenne River above Sheyenne River diversion near Horace, North Dakota	Q, QW
11	05059500	Sheyenne River at West Fargo, North Dakota	Q
12	05060100	Maple River below Mapleton, North Dakota	Q, QW
13	470000096535300	Sheyenne River at Brooktree Park, North Dakota	QW
14	05062000	Buffalo River near Dilworth, Minnesota	Q, QW
15	05064000	Wild Rice River at Hendrum, Minnesota	Q, QW
16	05064500	Red River of the North at Halstad, Minnesota	Q, QW
17	05066500	Goose River at Hillsboro, North Dakota	Q, QW
18	05067500	Marsh River near Shelly, Minnesota	Q, QW
19	05069000	Sand Hill River at Climax, Minnesota	Q, QW
20	05070000	Red River of the North near Thompson, North Dakota	Q, QW
21	05080000	Red Lake River at Fisher, Minnesota	Q, QW
22	05082500	Red River of the North at Grand Forks, North Dakota	Q, QW
23	05082625	Turtle River at Turtle River State Park near Arvilla, North Dakota	Q
24	480239097115000	Turtle River above Manvel, North Dakota	QW
25	05084000	Forest River near Fordville, North Dakota	Q
26	482118097090500	Forest River near confluence with Red River of the North, North Dakota	QW
27	05090000	Park River at Grafton, North Dakota	Q
28	482736097112800	Park River near Oakwood, North Dakota	QW
29	05092000	Red River of the North at Drayton, North Dakota	Q, QW
30	05094000	South Branch Two Rivers at Lake Bronson, Minnesota	Q
31	05095000	Two Rivers at Hallock, Minnesota	QW
32	05100000	Pembina River at Neche, North Dakota	Q
33	485636097173800	Pembina River above Pembina, North Dakota	QW
34	05102490	Red River of the North at Pembina, North Dakota	Stage
35	05102500	Red River of the North at Emerson, Manitoba	Q, QW

Table 3. Streamflow summaries for selected sites for 2003 and 2004 calibration periods and for 1976-77 simulation period.

[ft^3/s, cubic feet per second; --, no available data]

Location	Calibration periods						Simulation period		
	August 1 through October 31, 2003			April 1 through June 30, 2004			September 1, 1976, through August 31, 1977		
	Maximum (ft^3/s)	Minimum (ft^3/s)	Average (ft^3/s)	Maximum (ft^3/s)	Minimum (ft^3/s)	Average (ft^3/s)	Maximum (ft^3/s)	Minimum (ft^3/s)	Average (ft^3/s)
Red River of the North and tributaries									
Red River of the North at Wahpeton, North Dakota	789	82	220	2,260	393	710	513	1.7	42
Red River of the North at Hickson, North Dakota	894	85	254	2,720	396	807	388	0	41
Red River of the North at Fargo, North Dakota	934	46	239	5,380	406	1,173	638	0	51
Red River of the North at Halstad, Minnesota	1,900	225	523	11,000	1,270	4,251	1,980	10	199
Red River of the North at Grand Forks, North Dakota	2,730	318	821	32,800	1,890	9,340	2,150	104	506
Red River of the North at Drayton, North Dakota	2,880	351	942	37,000	2,820	13,061	3,250	120	552
Red River of the North at Emerson, Manitoba	2,890	452	1,014	42,500	3,320	18,740	4,440	144	619
Sheyenne River									
Sheyenne River below Baldhill Dam, North Dakota	94	33	57	3,610	163	257	38	5.0	15
Sheyenne River at Lisbon, North Dakota	138	33	62	3,210	155	1,285	838	5.0	30
Sheyenne River near Kindred, North Dakota	386	59	99	3,060	310	1,299	479	18	56
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	454	59	105	3,140	295	1,327	--	--	--
Sheyenne River at West Fargo, North Dakota	454	59	105	3,140	295	1,327	437	1.0	42

through 13, 2004, when streamflows were medium and unsteady (Nustad and Bales, 2005). The water-quality properties and constituents for which water-quality samples were analyzed included total dissolved solids, sulfate, chloride, and sodium, all of which are conservative, and total phosphorus. For this study, the transport of total phosphorus was simulated by assuming a first-order decay rate as a function of traveltime. Streamflow and water-quality boundary conditions are discussed in a later section of the report.

Simulation of Constituent Transport

Implementation, calibration and testing, and application of the one-dimensional, unsteady-flow, Red River model are described in this section. Data for implementation include the computational grid and boundary conditions.

Model Implementation

The Red River model was configured for implementation to the study reaches by developing a computational grid that represents the physical domain of the study area. Boundary conditions were specified for inflows and outflows of water and constituents to the river. The inflows and outflows included measured tributary flows, ungaged local inflows, return flows, and municipal withdrawals.

Computational Grid

The physical model domain includes the Red River from Wahpeton, N. Dak., to Emerson, Manitoba, and the Sheyenne River from below Baldhill Dam, N. Dak., to the confluence with the Red River (fig. 2). The model domain is represented by a computational grid that includes two main branches. The 394-mi reach of the Red River from Wahpeton to Emerson is branch 1 in the Red River model and is represented by 99 segments in the computational grid. Model segments in branch 1 range from 1.9 to 5.3 mi in length and average 4.0 mi in length. The 271-mi reach of the Sheyenne River from Baldhill Dam to the confluence with the Red River is branch 2 in the model and is represented by 59 segments. Model segments in branch 2 range from 1.6 to 5.8 mi in length and average 4.5 mi in length.

Inputs to the model included gaged inflows from the Sheyenne River and 12 tributaries to the Red River, inflows and outflows for 10 ungaged areas that were bounded by main-stem USGS gaging stations, return flows from 6 point-source wastewater-treatment facilities, and withdrawals from 3 water-treatment facilities (fig. 2, table 4). The tributaries for which gaged inflows were included are the Wild Rice River in North Dakota, Buffalo River, Wild Rice River in Minnesota, Goose River, Marsh River, Sand Hill River, Red Lake River, Turtle River, Forest River, Park River, Two Rivers, Pembina River, and Maple River.

The inflows and outflows for the 10 ungaged areas were represented as point inflows and outflows and, hereinafter, will be referred to collectively as ungaged local inflows (fig. 2, table 4). Positive ungaged local inflows, which represent inflows to the river from unmeasured surface-water and ground-water sources, were treated as tributaries. Negative ungaged local inflows, which represent outflows from the river from unmeasured surface-water and ground-water sinks, unmonitored withdrawals, and evapotranspiration, were treated as withdrawals. Ungaged local inflows typically were added (or subtracted) in the middle of the reach bounded by respective USGS gaging stations.

Return flows were included for Wahpeton, Fargo, Grand Forks, and West Fargo, N. Dak., and for Moorhead and East Grand Forks, Minn., and withdrawals were included for Fargo, Grand Forks, and Moorhead. The return flows for Fargo and Moorhead were combined because those flows are in the same model segment, and the return flows for Grand Forks and East Grand Forks were combined for the same reason. The withdrawals for Fargo and Moorhead also were combined and represented as a single withdrawal.

Channel-geometry data for the Red River and the Sheyenne River were provided by the U.S. Army Corps of Engineers (Stuart Dobberpuhl and Aaron Buesing, written commun., 2005). The data were used by the Corps in the one-dimensional, unsteady-flow, HEC-RAS model (Brunner, 2002), which was used in a flood-insurance study. Channel cross-section profiles, thalweg elevations, and segment lengths were extracted from the HEC-RAS model and reformatted for the Red River model. The record for cross-section and invert elevation data for the Red River from Hickson, N. Dak., to Red River at Fargo, N. Dak., reach and the Sheyenne River from Kindred, N.Dak., to the confluence with the Red River reach was less complete than the record for other locations. Therefore, channel-geometry data for those reaches were interpolated from available information, such as cross sections at stream gage sites.

Boundary Conditions

Boundary conditions were specified for May 15 through October 31, 2003, and January 15 through June 30, 2004. The first 2.5 months were used as an initialization period. The initialization period was considered to be the period at the beginning of a model simulation and was used to allow the effects of the estimated initial conditions to be transported out of the model domain. Thus, simulated results after the initialization period should be unaffected by the initial conditions.

Streamflow

A continuous time series of measured data was used to define streamflow boundary conditions for May 15 through October 31, 2003, and January 15 through June 30, 2004. The boundary conditions were specified for the upstream ends of branches 1 and 2, and a stage boundary condition was specified

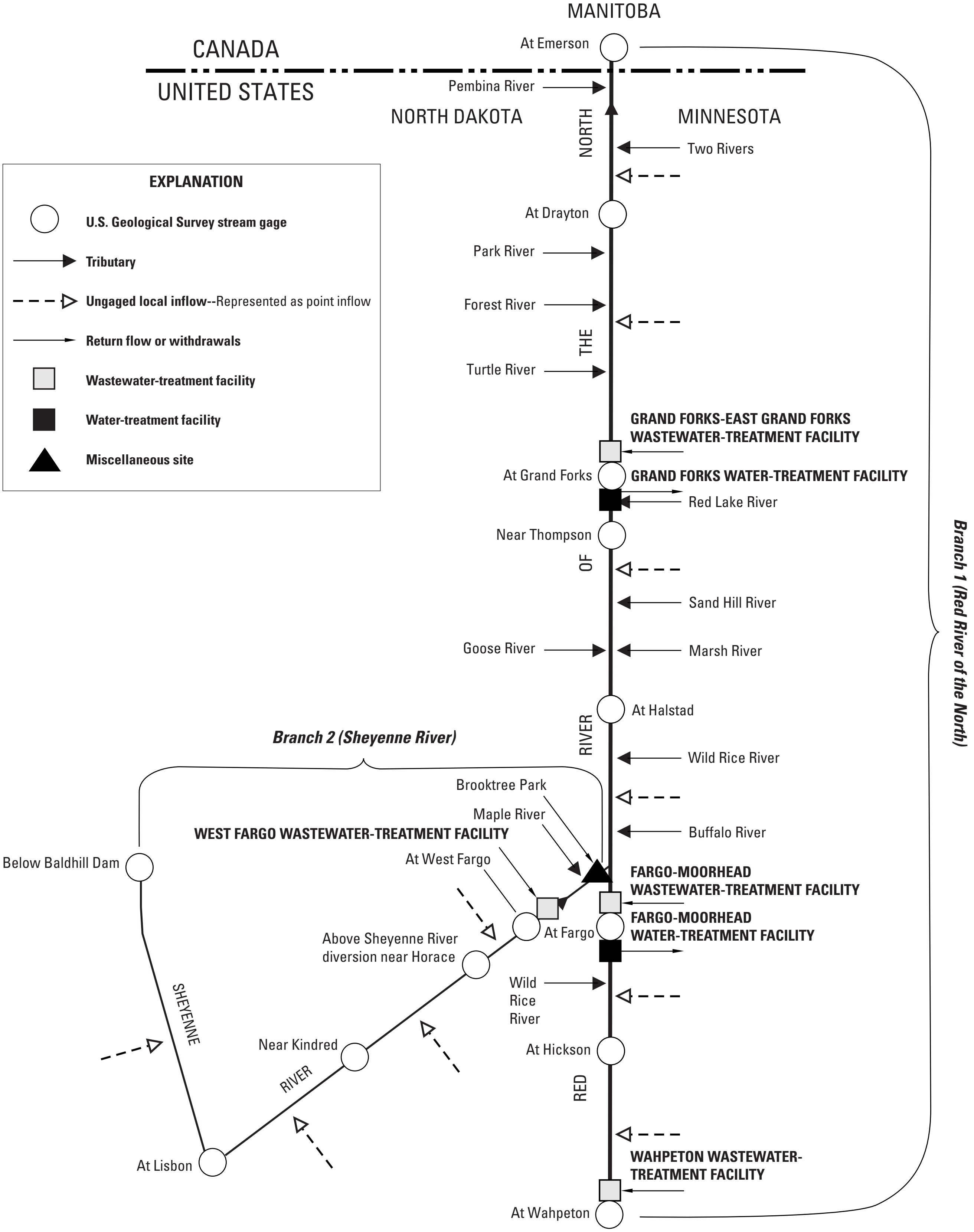


Figure 2. Schematic of Red River model.

Table 4. Boundary condition and flow/water-quality calibration points for Red River model.

Location	Type of information	Source of data
	Red River of the North	
Red River of the North at Wahpeton, North Dakota	Upstream flow boundary	Site 1, U.S. Geological Survey site number 05051500
Wahpeton, North Dakota, wastewater-treatment facility	Return flow	Leo Murr (Wahpeton Wastewater Treatment Facility, oral commun., 2006)
Red River of the North at Wahpeton, North Dakota, to Red River of the North at Hickson, North Dakota	Ungaged local inflow	Estimated
Red River of the North at Hickson, North Dakota	Flow/water-quality calibration point	Site 2, U.S. Geological Survey site number 05051522
Red River of the North at Hickson, North Dakota, to Red River of the North at Fargo, North Dakota	Ungaged local inflow	Estimated
Wild Rice River near Abercrombie, North Dakota	Gaged tributary inflow	Site 3, U.S. Geological Survey site number 05053000
Fargo, North Dakota, water-treatment facility and Moorhead, Minnesota, water-treatment facility	Withdrawal	Ron Hendrickson (Fargo Water Treatment Facility, written commun., 2006) and Troy Hall (Moorhead Water Treatment Facility, written commun., 2006)
Red River of the North at Fargo, North Dakota	Flow/water-quality calibration point	Site 5, U.S. Geological Survey site number 05054000
Fargo, North Dakota, wastewater-treatment facility and Moorhead, Minnesota, wastewater-treatment facility	Return flow	Peter Bilstad (Fargo Wastewater Treatment Facility, written commun., 2006) and Andy Bradshaw (Moorhead Wastewater Treatment Facility, written commun., 2006)
Buffalo River near Dilworth, Minnesota	Gaged tributary inflow	Site 14, U.S. Geological Survey site number 05062000
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota	Ungaged local inflow	Estimated
Wild Rice River at Hendrum, Minnesota	Gaged tributary inflow	Site 15, U.S. Geological Survey site number 05064000
Red River of the North at Halstad, Minnesota	Flow/water-quality calibration point	Site 16, U.S. Geological Survey site number 05064500
Goose River at Hillsboro, North Dakota	Gaged tributary inflow	Site 17, U.S. Geological Survey site number 05066500
Marsh River near Shelly, Minnesota	Gaged tributary inflow	Site 18, U.S. Geological Survey site number 05067500
Sand Hill River at Climax, Minnesota	Gaged tributary inflow	Site 19, U.S. Geological Survey site number 05069000
Red River of the North at Halstad, Minnesota, to Red River of the North at Grand Forks, North Dakota	Ungaged local inflow	Estimated

Table 4. Boundary condition and flow/water-quality calibration points for Red River model.—Continued

Location	Type of information	Source of data
Red River of the North—Continued		
Red River of the North near Thompson, North Dakota	Water-quality calibration point	Site 20, U.S. Geological Survey site number 05070000
Red Lake River at Fisher, Minnesota	Gaged tributary inflow	Site 21, U.S. Geological Survey site number 05080000
Grand Forks, North Dakota, water-treatment facility	Withdrawal	Hazel Sletten (Grand Forks Water Treatment Facility, written commun., 2006)
Red River of the North at Grand Forks, North Dakota	Flow/water-quality calibration point	Site 22, U.S. Geological Survey site number 05082500
Grand Forks, North Dakota, wastewater-treatment facility and East Grand Forks, Minnesota, wastewater-treatment facility	Return flow	Don Tucker (Grand Forks Wastewater Treatment Facility, written commun., 2006) and Mark Kotrba (East Grand Forks Wastewater Treatment Facility, written commun., 2006)
Turtle River at Turtle River State Park near Arvilla, North Dakota, and Turtle River above Manvel, North Dakota	Gaged tributary inflow	Sites 23 and 24, U.S. Geological Survey site numbers 05082625 and 480239097115000
Red River of the North at Grand Forks, North Dakota, to Red River of the North at Drayton, North Dakota	Ungaged local inflow	Estimated
Forest River near Fordville, North Dakota, and Forest River near confluence with Red River of the North, North Dakota	Gaged tributary inflow	Sites 25 and 26, U.S. Geological Survey site numbers 05084000 and 482118097090500
Park River at Grafton, North Dakota, and Park River near Oakwood, North Dakota	Gaged tributary inflow	Sites 27 and 28, U.S. Geological Survey site numbers 05090000 and 482736097112800
Red River of the North at Drayton, North Dakota	Flow/water-quality calibration point	Site 29, U.S. Geological Survey site number 05092000
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba	Ungaged local inflow	Estimated
South Branch Two Rivers at Lake Bronson, Minnesota, and Two Rivers at Hallock, Minnesota	Gaged tributary inflow	Sites 30 and 31, U.S. Geological Survey site numbers 05094000 and 05095000
Pembina River at Neche, North Dakota, and Pembina River above Pembina, North Dakota	Gaged tributary inflow	Sites 32 and 33, U.S. Geological Survey site numbers 05100000 and 485636097173800
Red River of the North at Emerson, Manitoba	Flow/water-quality calibration point	Site 35, U.S. Geological Survey site number 05102500
Sheyenne River		
Sheyenne River below Baldhill Dam, North Dakota	Upstream flow boundary	Site 7, U.S. Geological Survey site number 05058000
Sheyenne River below Baldhill Dam, North Dakota, to Sheyenne River at Lisbon, North Dakota	Ungaged local inflow	Estimated
Sheyenne River at Lisbon, North Dakota	Flow/water-quality calibration point	Site 8, U.S. Geological Survey site number 05058700

Table 4. Boundary condition and flow/water-quality calibration points for Red River model.—Continued

Location	Type of information	Source of data
	Sheyenne River—Continued	
Sheyenne River at Lisbon, North Dakota, to Sheyenne River near Kindred, North Dakota	Ungaged local inflow	Estimated
Sheyenne River near Kindred, North Dakota	Flow/water-quality calibration point	Site 9, U.S. Geological Survey site number 05059000
Sheyenne River near Kindred, North Dakota, to Sheyenne River above Sheyenne River diversion near Horace, North Dakota	Ungaged local inflow	Estimated
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	Flow/water-quality calibration point	Site 10, U.S. Geological Survey site number 05059300
Sheyenne River above Sheyenne River diversion near Horace, North Dakota, to Sheyenne River at West Fargo, North Dakota	Ungaged local inflow	Estimated
Sheyenne River at West Fargo, North Dakota	Flow/water-quality calibration point	Site 11, U.S. Geological Survey site number 05059500
West Fargo, North Dakota, wastewater-treatment facility	Return flow	Terry Rust (West Fargo Wastewater Treatment Facility, written commun., 2006)
Maple River below Mapleton, North Dakota	Gaged tributary inflow	Site 12, U.S. Geological Survey site number 05060100
Sheyenne River at Brooktree Park, North Dakota	Water-quality calibration point	Site 13, U.S. Geological Survey site number 470000096535300

for the downstream end of branch 1. The boundary condition for the downstream end of branch 2 was computed internally by the model.

Hourly streamflow data for the Red River at Wahpeton, N. Dak., were used for the boundary condition for the upstream end of branch 1, and hourly streamflow data for the Sheyenne River below Baldhill Dam, N. Dak., were used for the boundary condition for the upstream end of branch 2. Because RIV1H requires a water-depth time series for the boundary condition for the downstream end of branch 1, 15-minute measured stage data for the Red River at Pembina, N. Dak., were converted to 15-minute depth data and used as that boundary condition. High-frequency fluctuations in the data were smoothed using a 2-hour moving average centered in the 2-hour time window. Gaged tributary inflows were specified using a daily time series of streamflows (Robinson and others, 2004, 2005) for the downstream-most gaging location on each of the 12 tributaries to the Red River (table 4).

Ungaged local inflows were calculated using streamflows for the upstream and downstream gaging locations of a reach and inflows and outflows within the reach into which the ungaged local inflow was added (table 4). The actual method of calculation differed slightly by reach and was determined during calibration. Because ungaged local inflows can represent both inflows and losses within a reach, both positive and negative values were calculated. Positive flows were treated as tributaries, and negative flows were treated as withdrawals.

Daily return flows for six major cities in the Red River Basin were obtained from the respective wastewater-treatment facilities (table 4). Return flows were combined for Fargo, N. Dak., and Moorhead, Minn., and for Grand Forks, N. Dak., and East Grand Forks, Minn., and then added, along with return flows for West Fargo, N. Dak., and Wahpeton, N. Dak., as point inflows in the model segment that best represented the actual location of the return flow. Daily withdrawals for three major cities that use the Red River for source water were obtained from the respective water-treatment facilities (table 4). The withdrawals were combined for Fargo and Moorhead and then were subtracted, along with the combined withdrawals for Grand Forks and East Grand Forks, from the model segment that best represented the actual location of the withdrawal.

Water Quality

Measured data for September 15 through 16, 2003, and May 10 through 13, 2004, were used to define water-quality boundary conditions. The data sets for those periods each contain a single measurement for each location used in this study. Because no other water-quality data are available, the water-quality boundary conditions were assumed to be time invariant for the entire calibration period and to be equal to the measured value.

Time-invariant water-quality boundary conditions were specified for the upstream ends of branches 1 and 2 and for the tributaries (table 5). Constituent concentrations for ungaged local inflows were calculated in a manner similar to that used to calculate streamflow for the ungaged local inflows. The concentrations were based on constituent mass at the upstream and downstream gaging locations and on inflows and outflows of mass within the reach into which the ungaged local inflows were added. As with streamflow, the actual method of calculation was determined during calibration and differed by reach. Constituent concentrations for daily return flows (unpublished data on file in North Dakota Water Science Center, Grand Forks, N. Dak., field office) were measured concurrently with instream sampling. The same constituent concentration was used for the return flows for both calibration periods.

Model Calibration and Testing

The Red River model was calibrated by adjusting selected boundary conditions, model parameters, and channel-geometry data to obtain reasonable agreement between measured and simulated streamflows and concentrations for 10 flow/water-quality calibration points (table 4). This section describes the calibration process, results, and limited model testing.

Streamflow

The time step that can be used in the Red River model is limited by the Courant number. The Courant number, as described by Chaudhry (1993), is as follows:

$$C_n = \frac{a\Delta t}{\Delta x} \tag{1}$$

where

C_n is the Courant number

a is the wave velocity,

Δt is the time-step size,

and

Δx is the spatial step size.

The computational time step for the Red River model was set at 300 seconds for all simulations. At this time step, Courant numbers always were less than 0.05, or much less than the maximum allowable Courant number of 1.0.

RIV1H includes three parameters that affect aspects of the computational scheme in the model. The first parameter, THETA, controls weighting of the four-point, implicit, numerical method used to solve the governing differential equations in the model (Martin and Wool, 2002). The recommended range for THETA is 0.55 to 0.75, and the optimal value for numerical accuracy is 0.55 although a higher value can be used to enhance numerical stability. After initial testing, THETA was set at 0.75 for the Red River model. The second parameter, BETA, is a momentum correction coefficient that generally is used when structures affect flow in the river. The recommended value for BETA is 1.0, which was the value used for the Red River model, indicating no momentum correction. The third parameter, TOLER, is the tolerance factor. The differential equations in RIV1H are solved iteratively, and the solution is assumed to have converged when the difference between the current water-level calculation and the previous water-level calculation differs by less than TOLER. TOLER was set at 0.05 ft for the Red River model. That value is a compromise between the best value for accuracy and the best value for computational time (Martin and Wool, 2002).

As previously noted, channel-geometry data were extracted from a HEC-RAS model developed by the U.S. Army Corps of Engineers. These data were adjusted slightly during calibration of the Red River model to improve model performance. For example, when the Red River model is initialized, large instabilities in water level are generated throughout the model domain for the first few time steps. Therefore, channel cross sections were arbitrarily extended upward and outward to contain the instabilities. Streamflows are within the original cross sections after the instabilities dissipate, typically within 7 days of the beginning of the simulation period. (As previously stated, a 2.5-month initialization period was used in the model to allow the effects of estimated initial conditions to be transported out of the model.) Bottom-geometry and bottom-slope data also were adjusted for selected locations. For example, during low-flow conditions at cross sections that have a wide, relatively flat bottom, small changes in water level can result in large changes in wetted width and, thus, cause numerical oscillations. Therefore, the bottom-geometry data were adjusted to avoid the numerical oscillations. The HEC-RAS channel slope for the entire Red River was increased 1 percent from 0.529 ft/mi to 0.537 ft/mi, and the bottom slope for the Sheyenne River between Baldhill Dam and Lisbon, N. Dak., was increased 1 percent from 1.36 ft/mi to 1.37 ft/mi. Also, negative slopes used in the HEC-RAS model for some model segments between Fargo and Grand Forks, N. Dak., were removed to avoid computational problems during the water-quality simulations.

Initial simulations using measured hourly streamflow data for the Sheyenne River below Baldhill Dam, N. Dak., resulted in oscillations in the simulations for the downstream locations. Therefore, because abrupt changes in upstream boundary conditions, such as those that occur immediately downstream from a dam, can cause instabilities in the simulations from some models, including RIV1H (Martin and Wool, 2002), the

Table 5. Water-quality boundary conditions for 2003 and 2004 calibration periods.

Location	Total dissolved solids (milligrams per liter)		Dissolved sulfate (milligrams per liter)		Dissolved chloride (milligrams per liter)		Dissolved sodium (milligrams per liter)		Total phosphorus (milligrams per liter)	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Red River of the North and tributaries										
Red River of the North at Wahpeton, North Dakota	262	305	32	67	11	12	12	11	0.03	0.07
Wahpeton, North Dakota, wastewater-treatment facility return flow	1,940	1,940	950	950	150	150	230	230	4.5	4.5
Wild Rice River near Abercrombie, North Dakota	1,490	1,210	740	580	62	49	170	120	.19	.24
Fargo, North Dakota, wastewater-treatment facility and Moorhead, Minnesota, wastewater-treatment facility return flow	981	981	380	380	110	110	190	190	3.7	3.7
Buffalo River near Dilworth, Minnesota	407	442	78	110	9.0	33	18	28	.10	.29
Wild Rice River at Hendrum, Minnesota	334	265	52	52	7.0	5.0	16	8.0	.04	.46
Goose River at Hillsboro, North Dakota	1,020	981	470	460	53	37	100	91	.07	.07
Marsh River near Shelly, Minnesota	458	266	83	84	15	8.0	28	11	.43	.58
Sand Hill River at Climax, Minnesota	326	390	46	72	7.0	11	10	13	.03	.01
Red Lake River at Fisher, Minnesota	258	295	41	65	9.0	11	11	8.0	.04	.04
Grand Forks, North Dakota, wastewater-treatment facility and East Grand Forks, Minnesota, wastewater-treatment facility return flow	1,300	1,300	460	460	150	150	180	180	4.7	4.7
Turtle River above Manvel, North Dakota	2,550	1,210	540	400	980	250	640	190	.15	.13
Forest River near confluence with Red River of the North, North Dakota	3,240	1,120	680	350	1,300	270	880	210	.06	.45

Table 5. Water-quality boundary conditions for 2003 and 2004 calibration periods.—Continued

Location	Total dissolved solids (milligrams per liter)		Dissolved sulfate (milligrams per liter)		Dissolved chloride (milligrams per liter)		Dissolved sodium (milligrams per liter)		Total phosphorus (milligrams per liter)	
	2003	**2004**	**2003**	**2004**	**2003**	**2004**	**2003**	**2004**	**2003**	**2004**
Red River of the North and tributaries—Continued										
Park River near Oakwood, North Dakota	14,400	1,480	1,270	350	7,660	480	4,880	350	0.14	0.18
Two Rivers at Hallock, Minnesota	379	279	40	53	45	17	23	8.0	.06	.14
Pembina River above Pembina, North Dakota	555	382	190	150	21	12	51	33	.11	.44
Sheyenne River										
Sheyenne River below Baldhill Dam, North Dakota	713	347	260	130	19	9.0	120	39	0.23	0.27
West Fargo, North Dakota, wastewater-treatment facility return flow	2,280	2,280	640	640	570	570	580	580	4.6	4.6
Maple River below Mapleton, North Dakota	1,110	737	510	310	66	31	31	91	.26	.25

upstream boundary conditions for the Sheyenne River were smoothed slightly by using a 12-hour moving average flow centered in the 12-hour time window.

Ungaged local inflows were estimated for the 10 reaches bounded by main-stem long-term gaging stations (fig. 2). Several approaches were considered to estimate the ungaged local inflows but, in general, the approach was to calculate the difference between the daily average streamflow for the upstream location and the daily average streamflow for the downstream location, accounting for gaged tributary inflows, return flows, and withdrawals within the reach. The difference was designated as the ungaged local inflow for the reach. The estimates (both timing and magnitude) of the ungaged local inflows to the Red River and the Sheyenne River had a large effect on simulated streamflows.

The approach used to estimate the ungaged local inflows was complicated by the differences in reach length, by unsteady flows, and by the location of the ungaged local inflows and the gaged tributary inflows (or outflows) in relation to the downstream end of the reach. To account for traveltime through the reach, the difference between the upstream and downstream streamflows was based on a lagged value of streamflow. For example, if the traveltime through the reach was about L days, the ungaged local inflow for day X was calculated using the following mass-balance equation:

$$Q_{X+A} = DS_{X+L} - (US_X + I_{X+T} - W_X) \qquad (2)$$

where

Q is the ungaged local inflow, in cubic feet per second, for the reach;

X is the date on which the ungaged local inflow was applied;

A is an adjustment to the date on which the ungaged local inflow was applied;

DS is the average daily streamflow, in cubic feet per second, for the downstream end of the reach;

L is the lag, in days, applied to the downstream end of the reach;

US is the average daily streamflow, in cubic feet per second, for the upstream end of the reach;

I is the mean daily gaged tributary inflow and the return flow, in cubic feet per second;

T is the lag between the occurrence of the gaged tributary inflow and day X;

and

W is the mean daily withdrawal, in cubic feet per second.

Because of the differences in reach length and reach traveltime, the lag time varied among the reaches (table 6). Also, because of the differences in streamflow within a reach, the lag time varied with streamflow (table 6). Therefore, to account for the differences at the point where the ungaged local inflow entered the reach, adjustments were made to the date (A in eq. 2) on which the ungaged local inflow was applied to the model. In most cases, T in equation 2 was equal to L (table 6). T was not used for reaches that had no tributary inflow.

The variables A, L, and T in equation 2 were adjusted during model calibration. The variables differed from reach to reach and varied with streamflow (table 6). The values for A, L, and T were determined using the 2003 data set and then tested using the 2004 data set. The calibrated values of A, L, and T resulted in good agreement between the measured and simulated streamflows for both 2003 streamflows and 2004 streamflows that were about the same magnitude as the 2003 streamflows (table 3). The values for A, L, and T then were determined using the 2004 data set (table 6).

The mean estimated ungaged local inflow for the 2003 calibration period was determined for each reach and then compared to the average streamflow for the same period for the downstream end of the reach. For the Sheyenne River at Lisbon, N. Dak., to Sheyenne River near Kindred, N. Dak., reach, ungaged local inflow was estimated to be about one-third of the total streamflow in the reach. The estimated ungaged local inflow for the Sheyenne River at Lisbon to Sheyenne River near Kindred reach is not unusual given the effects of the Sheyenne River Delta aquifer in the reach (G. Wiche, U.S. Geological Survey, oral commun., 2006). Ungaged local inflows for all other reaches accounted for -4 to 6 percent of the total streamflow in the respective reach. Ungaged local inflows for the 2003 calibration period were negative for two reaches [the Red River at Hickson, N. Dak., to Red River at Fargo, N. Dak., reach (-4 percent) and the Red River at Drayton, N. Dak., to Red River at Emerson, Manitoba, reach (-1 percent)], indicating a slight loss of flow in the reaches as a result of evaporation, unmonitored withdrawals, ground-water recharge, or errors in streamflow measurements. For the 2004 calibration period, ungaged local inflows accounted for a slightly higher percentage (-3 to 15 percent) of the total streamflow in each reach than for the 2003 calibration period except for the Sheyenne River at Lisbon to Sheyenne River near Kindred reach. That reach had a loss of flow during the 2004 calibration period. Estimated ungaged local inflows accounted for more than 10 percent of the total streamflow in only three reaches (the Red River at Wahpeton, N. Dak., to Red River at Hickson reach at 11 percent; the Red River at Grand Forks, N. Dak., to Red River at Drayton reach at 15 percent, and the Red River at Drayton to Red River at Emerson reach at 14 percent).

The roughness coefficient, Manning's n, was adjusted for each model segment to complete the streamflow calibration. RIV1H includes an option that allows n to vary with depth such that

$$n = N1 - [N2\ (\text{depth})] \qquad (3)$$

where

$N1$ and $N2$ are variables that are adjusted during model calibration.

Table 6. Variables used to estimate ungaged local inflows and Manning's *n*.

[$N1$, variable that is adjusted during model calibration; $N2$, variable that is adjusted during model calibration; <, less than; --, no gaged tributary in reach; ≥, greater than or equal to; >, greater than]

Location	Main-stem streamflow range to which A, L, and T apply (cubic feet per second)	Calibration variables				
		Adjustment to date on which ungaged local inflow was applied (days) (A in equation 2)	Lag applied to downstream end of reach (days) (L in equation 2)	Lag between occurrence of gaged tributary inflow and date on which ungaged local inflow was applied (days) (T in equation 2)[1]	$N1$	$N2$
		Red River of the North				
Red River of the North at Wahpeton, North Dakota, to Red River of the North at Hickson, North Dakota	<300	1	3	--	0.030	0.0001
	≥300	1	2	--		
Red River of the North at Hickson, North Dakota, to Red River of the North at Fargo, North Dakota	<400	1	2	2	.033	.0001
	≥400	0	1	1		
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota	<500	2	4	[2]4	.035	.0001
	≥500	1	2	[2]2		
Red River of the North at Halstad, Minnesota, to Red River of the North at Grand Forks, North Dakota	<1,000	1	3	[3]3	.035	0
	≥1,000	0	2	[3]2		
Red River of the North at Grand Forks, North Dakota, to Red River of the North at Drayton, North Dakota	<1,000	2	4	[4]4	.030	0
	≥1,000	1	3	[4]3		
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba	<1,200	0	3	3	.030	0
	≥1,200	1	2	[5]2		

Table 6. Variables used to estimate ungaged local inflows and Manning's *n*.—Continued

[$N1$, variable that is adjusted during model calibration; $N2$, variable that is adjusted during model calibration; <, less than; --, no gaged tributary in reach; ≥, greater than or equal to; >, greater than]

Location	Main-stem streamflow range to which *A*, *L*, and *T* apply (cubic feet per second)	Calibration variables				
		Adjustment to date on which ungaged local inflow was applied (days) (*A* in equation 2)	Lag applied to downstream end of reach (days) (*L* in equation 2)	Lag between occurrence of gaged tributary inflow and date on which ungaged local inflow was applied (days) (*T* in equation 2)[1]	$N1$	$N2$
Sheyenne River						
Sheyenne River below Baldhill Dam, North Dakota, to Sheyenne River at Lisbon, North Dakota	<100	2	4	--	0.034	0
	≥100	2	3	--		
Sheyenne River at Lisbon, North Dakota, to Sheyenne River near Kindred, North Dakota	<150	1	3	--	.031	0
	150 to 500	1	2	--		
	>500	0	1	--		
Sheyenne River near Kindred, North Dakota, to Sheyenne River above Sheyenne River diversion near Horace, North Dakota	<500	0	2	--	.037	.0001
	≥500	0	1	--		
Sheyenne River above Sheyenne River diversion near Horace, North Dakota, to Sheyenne River at West Fargo, North Dakota	<300	0	1	--	.035	0
	≥300	0	0	--		

[1] Unless otherwise specified, all tributaries within the reach had the same *T* value.

[2] Wild Rice River at Hendrum, Minnesota–1.

[3] Grand Forks, North Dakota, water-treatment facility–0; Red Lake River at Fisher, Minnesota–1.

[4] Forest River near Fordville, North Dakota–2; Park River at Grafton, North Dakota–0.

[5] South Branch Two Rivers at Lake Bronson, Minnesota–0; Pembina River at Neche, North Dakota–0.

$N2$ was used to adjust n so that the highest n values were at the shallowest depths. For the Red River model, $N1$ ranged from 0.030 to 0.037, and $N2$ ranged from zero to 0.0001 (table 6). Using these values in RIV1H, Manning's n was computed to be between 0.028 and 0.037. Those values were the same as those used by Wesolowski (1994) for the Red River.

Simulated streamflows for selected Red River model calibration points were in reasonable agreement with measured streamflows for the 2003 (low-flow) and 2004 (medium-flow) calibration periods (fig. 3). The average difference between the measured and simulated streamflows for all calibration points was less than 4 percent for both periods, and most average differences were less than 2 percent (table 7). In general, streamflows for the 2003 calibration period were somewhat underpredicted, and streamflows for the 2004 calibration period were slightly overpredicted. However, the average differences between the measured and simulated streamflows are considered to be acceptable because the differences are less than 5 percent, or the same as the error that would be expected in a typical streamflow measurement.

The root mean square difference and the average absolute difference between the measured and simulated streamflows were higher for the 2004 calibration period than for the 2003 calibration period (table 7) because of the higher streamflows during 2004. To account for the differences between the streamflows for the two calibration periods, the root mean square difference and the average absolute difference can be expressed as a percentage of the average streamflow for each calibration period. For example, the root mean square difference for the Red River at Emerson, Manitoba, for the 2004 calibration period represents 15 percent of the average streamflow for that location, and the average absolute difference represents 9.1 percent of the average streamflow. Average absolute differences, expressed as a percentage of the average streamflow for the respective calibration period, ranged from 2.0 percent for the Red River at Hickson, N. Dak., to 6.3 percent for the Sheyenne River near Kindred, N. Dak., for the 2003 calibration period and from 2.0 percent for the Red River at Hickson to 9.3 percent for the Red River at Drayton, N. Dak., for the 2004 calibration period. The mean of the average absolute differences for all 10 calibration points was 3.9 percent of the average streamflow for the 2003 calibration period and 5.4 percent of the average streamflow for the 2004 calibration period.

Calibration results indicate differences between measured and simulated streamflows tended to be smaller for the upstream locations than for the downstream locations. The smaller differences for the upstream locations probably resulted from the smaller accumulated error in ungaged local inflow estimates for the upstream locations relative to the accumulated error for the downstream locations. Calibration results also indicate differences were larger for the 2004 calibration period than for the 2003 calibration period, again a probable result of errors in the ungaged local inflow estimates. Streamflows were moderate during the 2004 calibration period, and the percentage of flow being contributed to the main-stem rivers from the tributaries was larger than during the 2003 calibration period. Thus, ungaged local inflows were difficult to estimate and errors in the estimates were higher for the 2004 calibration period than for the 2003 calibration period. Further refinement of local inflow estimates probably would improve predictions, but these refinements are not justified by the relatively small streamflow prediction errors or by the future intended application of the model.

Water Quality

The locations used for the water-quality calibration were the same as those used for the streamflow calibration except that the Red River near Thompson, N. Dak., was added and the Sheyenne River at Brooktree Park, N. Dak., was used instead of the Sheyenne River at West Fargo, N. Dak. Constituent concentrations for the ungaged local inflows were estimated and two model variables were adjusted as part of the calibration process. The variables that were adjusted were the dispersion coefficient and the first-order decay coefficient for total phosphorus. Measured and simulated constituent concentrations were compared for the single sample date for each calibration period.

Constituent concentrations for the ungaged local inflows were estimated using a modified version of equation 2 such that

$$C_{X+A} = \frac{(DS_{X+L}\,\mathrm{C}_{DS}) - [(US_X C_{US}) + (I_{X+T} C_I) - (W_X C_W)]}{Q_{X+A}} \qquad (4)$$

where

C is the estimated concentration, in milligrams per liter, for the reach;

C_{DS} is the measured concentration, in milligrams per liter, for the downstream end of the reach;

C_{US} is the measured concentration, in milligrams per liter, for the upstream end of the reach;

C_I is the measured concentration, in milligrams per liter, for the gaged tributary inflows and return flows;

and

C_W is the measured concentration, in milligrams per liter, for the location nearest to the location of the withdrawal.

Concentrations and corresponding streamflows for the single sample dates in both 2003 and 2004 were used to estimate a single concentration for each constituent for ungaged local inflow within a reach. Constituent concentrations were estimated for both calibration periods (table 8). The values used for A, L, and T (table 6) were the same as those used for the streamflow calibration. Equation 4 was not applied if the calculated ungaged local inflow was negative. As previously noted, negative ungaged local inflows were treated as withdrawals so the calculation was unnecessary. If negative concentrations

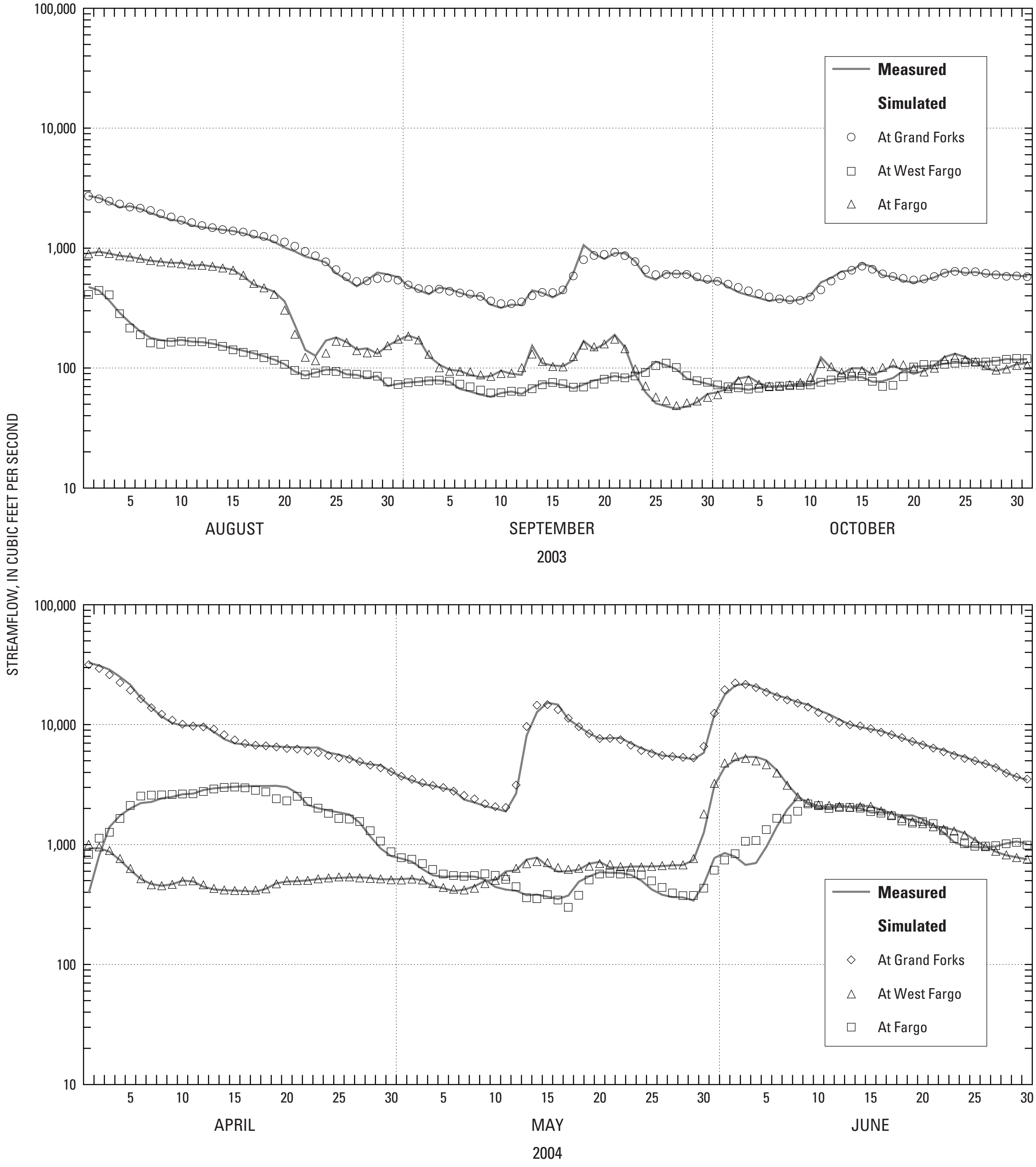


Figure 3. Measured and simulated streamflows for selected Red River model calibration points, 2003 and 2004 calibration periods.

Table 7. Differences between measured and simulated streamflows for Red River model calibration points for 2003 and 2004 calibration periods.

Location	Average difference between measured and simulated streamflows (percent)		Root mean square difference between measured and simulated streamflows (cubic feet per second)		Average absolute difference between measured and simulated streamflows (cubic feet per second)	
	2003	2004	2003	2004	2003	2004
		Red River of the North				
Red River of the North at Hickson, North Dakota	0	0.1	8.9	37	5.2	16
Red River of the North at Fargo, North Dakota	-.5	.7	11	105	6.7	47
Red River of the North at Halstad, Minnesota	-.2	.7	23	206	16	140
Red River of the North at Grand Forks, North Dakota	1.4	0	51	686	35	393
Red River of the North at Drayton, North Dakota	1.4	-.4	47	2,050	35	1,220
Red River of the North at Emerson, Manitoba	.3	-.1	43	2,820	33	1,710
		Sheyenne River				
Sheyenne River at Lisbon, North Dakota	0.8	0	7.0	149	2.7	79
Sheyenne River near Kindred, North Dakota	1.6	1.7	14	182	6.2	110
Sheyenne River above Sheyenne River diversion near Horace, North Dakota	-.2	2.5	7.0	194	3.3	111
Sheyenne River at West Fargo, North Dakota	-.5	3.1	9.3	183	4.0	114

were determined from equation 4, the concentration was assumed to be zero.

Ranges of historical measured constituent concentrations for tributaries within selected Red River model reaches were compiled from Rowland and Dressler (2002) (table 9) to place the estimated constituent concentrations for ungaged local inflows (table 8) into the context of historical measured constituent concentrations for the Red River Basin. For the 2003 calibration period, the estimated concentrations generally were within the range of historical concentrations except for the Red River at Fargo, N. Dak., to Red River at Halstad, Minn., and Red River at Drayton, N. Dak., to Red River at Emerson, Manitoba, reaches. For the 2004 calibration period, the estimated concentrations also generally were within the range of historical concentrations. For the Red River at Fargo to Red River at Halstad and Red River at Drayton to Red River at Emerson reaches, the estimated concentrations for the 2003 calibration period may be high because of sample collection bias. High concentrations for the Red River at Halstad and the Red River at Emerson caused the estimated concentrations for those reaches to be substantially higher than the historical concentrations for tributaries within the reaches. Therefore, the median historical measured concentration for all tributaries within each of the two reaches was used as the estimated concentration for the ungaged local inflow (table 10). Sample sizes used to compute the medians given in table 10 differ slightly from those used by Rowland and Dressler (2002) because of additional years of data and because changes have been made to the USGS water-quality database to accommodate new methodologies and procedures. Not all reaches (for example, the Red River at Hickson, N. Dak., to Red River at Fargo reach) had tributaries for which historical measured concentrations were available for comparison to concentrations for the ungaged local inflows. Therefore, for those reaches, the concentrations for the ungaged local inflows were compared to the historical range of concentrations in adjacent reaches; agreement between the values generally was acceptable.

Few total phosphorus concentrations are available for the USGS sites used by Rowland and Dressler (2002). However, ranges of historical measured total phosphorus concentrations for many locations in the Red River Basin in addition to those for USGS gaging stations are given by Tornes and Brigham

Table 8. Estimated constituent concentrations for ungaged local inflows for 2003 and 2004 calibration periods.

Location	Total dissolved solids (milligrams per liter)		Dissolved sulfate (milligrams per liter)		Dissolved chloride (milligrams per liter)		Dissolved sodium (milligrams per liter)		Total phosphorus (milligrams per liter)	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Red River of the North										
Red River of the North at Wahpeton, North Dakota, to Red River of the North at Hickson, North Dakota	1,165	365	210	0	210	78	260	78	1.57	0.49
Red River of the North at Hickson, North Dakota, to Red River of the North at Fargo, North Dakota	475	235	130	60	74	20	80	17	.17	.10
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota[1]	1,702	400	749	130	185	17	175	31	0	.73
Red River of the North at Halstad, Minnesota, to Red River of the North at Grand Forks, North Dakota	0	452	0	140	0	17	0	32	0	.22
Red River of the North at Grand Forks, North Dakota, to Red River of the North at Drayton, North Dakota	0	526	0	180	0	43	0	53	0	.12
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba[1]	1,326	0	262	0	371	0	277	0	0	0
Sheyenne River										
Sheyenne River below Baldhill Dam, North Dakota, to Sheyenne River at Lisbon, North Dakota	1,047	1,210	470	570	110	76	180	150	0	0.38
Sheyenne River at Lisbon, North Dakota, to Sheyenne River near Kindred, North Dakota	465	513	110	170	15	16	24	53	.10	.13

Table 8. Estimated constituent concentrations for ungaged local inflows for 2003 and 2004 calibration periods.—Continued

Location	Total dissolved solids (milligrams per liter)		Dissolved sulfate (milligrams per liter)		Dissolved chloride (milligrams per liter)		Dissolved sodium (milligrams per liter)		Total phosphorus (milligrams per liter)	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Sheyenne River—Continued										
Sheyenne River near Kindred, North Dakota, to Sheyenne River above Sheyenne River diversion near Horace, North Dakota	0	0	0	0	0	0	0	0	0	0
Sheyenne River above Sheyenne River diversion near Horace, North Dakota, to Sheyenne River at West Fargo, North Dakota	568	500	180	320	63	47	160	31	.60	.81

[1] Historical median concentrations for tributaries within this reach were used to represent ungaged local inflow median concentrations.

Table 9. Ranges of historical measured constituent concentrations for tributaries within selected Red River model reaches.

[From Rowland and Dressler, 2002; --, no available data]

Location	Number of tributaries within reach for which historical data are available	Period of record	Total dissolved solids		Dissolved sulfate		Dissolved chloride		Dissolved sodium		Total phosphorus	
			Number of samples	Range (mg/L)	Number of samples	Range (mg/L)	Number of samples	Range (mg/L)	Number of samples	Range (mg/L)	Number of samples	Range (mg/L)
Red River of the North at Hickson, North Dakota, to Red River of the North at Fargo, North Dakota	1	1996-2001	448	0-2,660	233	11-1,200	217	2.3-180	271	5.3-420	2	0.18-0.21
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota	[1]3	1962-99	38	0-666	14	35-210	48	4.5-41	14	5.9-59	35	0.01-0.41
Red River of the North at Halstad, Minnesota, to Red River of the North at Grand Forks, North Dakota	4	1966-2001	350	0-2,060	97	49-800	97	5.4-310	97	8.5-330	2	0.09-0.39
Red River of the North at Grand Forks, North Dakota, to Red River of the North at Drayton, North Dakota	4	1968-2001	626	0-8,120	211	36-1,600	211	1.3-3,660	211	6.0-2,100	--	--
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba	1	1971-2001	320	0-761	51	56-250	54	3.4-34	54	19-59	--	--

[1] Does not include the Sheyenne River.

Table 10. Median historical measured concentrations for tributaries within selected Red River model reaches.

[From Rowland and Dressler, 2002]

Location	Tributaries within reach for which historical data are available	Period of record	Total dissolved solids		Dissolved sulfate		Dissolved chloride		Dissolved sodium	
			Number of samples	Median (mg/L)	Number of samples	Median (mg/L)	Number of samples	Median (mg/L)	Number of samples	Median (mg/L)
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota	Buffalo River near Dilworth, Minnesota; Elm River near Kelso, North Dakota; and Wild Rice River at Hendrum, Minnesota	1964-2004	22	318	34	72	144	4.6	28	18
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba	Pembina River at Neche, North Dakota	1972-2006	77	505	77	170	77	14	76	43

(1994). Except for the Red River at Wahpeton, N. Dak., to Red River at Hickson, N. Dak., and Red River at Grand Forks, N. Dak., to Red River at Drayton, N. Dak., reaches, the estimated total phosphorous concentrations for the ungaged local inflows (table 8) generally were within the range of the historical measured total phosphorus concentrations given by Tornes and Brigham (1994). The high estimated total phosphorus concentration for the Red River at Wahpeton to Red River at Hickson reach seems reasonable because two major industrial plants release wastewater into the reach. The high concentration for the Red River at Grand Forks to Red River at Drayton reach also is reasonable because that reach is greatly affected by ground water that may have relatively high phosphorus concentrations.

Model results were insensitive to changes in the dispersion coefficient when the coefficient ranged from zero to 10,000 ft^2/s. Further testing using time-varying boundary conditions with strong concentration gradients is needed to determine if simulations are insensitive to the dispersion coefficient for all conditions.

Total dissolved solids concentrations generally were underpredicted for both calibration periods (fig. 4). The average difference between the measured and simulated concentrations was -9.9 percent for the 2003 calibration period and -5.5 percent for the 2004 calibration period. The average absolute differences, 10.1 and 7.2 percent for the 2003 and 2004 calibration periods, respectively, were higher than the average differences. Except for the Red River at Halstad, Minn., for the 2003 calibration period and the Sheyenne River at Lisbon, N. Dak., for the 2004 calibration period, all differences were within 23 percent of the measured concentrations. The magnitude of the average absolute differences was less for the 2004 calibration period than for the 2003 calibration period. The differences averaged about 58 mg/L for the 2003 calibration period and 34 mg/L for the 2004 calibration period.

Sulfate concentrations also generally were underpredicted for both calibration periods (fig. 5). The patterns for the sulfate concentrations (for example, poor agreement between the measured and simulated concentrations for the Red River at Halstad, Minn., for the 2003 calibration period and the Sheyenne River at Lisbon, N. Dak., for the 2004 calibration period) were similar to those for total dissolved solids because sulfate is a major component of dissolved solids in the Red River. The average absolute differences, 19 and 21 percent for the 2003 and 2004 calibration periods, respectively, were about double the average absolute differences for total dissolved solids. The magnitude of the average absolute differences for both calibration periods, however, was less than the magnitude for total dissolved solids. The differences for sulfate averaged about 32 mg/L for the 2003 calibration period and 31 mg/L for the 2004 calibration period.

Chloride and sodium concentrations generally were underpredicted for both calibration periods (figs. 6 and 7). The patterns for both constituents were similar, but the average differences generally were smaller for the 2004 calibration period than for the 2003 calibration period. The average differences for the 2003 calibration period were largest for the Red River at Halstad, Minn., and the Red River at Emerson, Manitoba. The measured and simulated sodium concentrations for the Red River at Emerson for the 2003 calibration period were in closer agreement than the measured and simulated chloride concentrations for that period. For the 2003 calibration period, the average absolute difference for chloride, 11 mg/L, was about 27 percent of the average measured concentration, and the average absolute difference for sodium, 12 mg/L, was about 16 percent of the average measured concentration. For the 2004 calibration period, the average absolute difference for chloride, 4 mg/L, was about 16 percent of the average measured concentration, and the average absolute difference for sodium, 6 mg/L, was about 14 percent of the average measured concentration.

Total dissolved solids, sulfate, chloride, and sodium were simulated as conservative constituents so the only parameters (eq. 4) estimated in the calibration process were those associated with ungaged local inflows. Total phosphorus is a nonconservative constituent and undergoes complex interactions in the water column, in bed sediments, and in living organisms. Therefore, to account for the loss of phosphorus from the system as a result of algae and plant uptake and particulate phosphorus settling to the riverbed, and in the absence of any internal inputs, total phosphorus was simulated by assuming that phosphorus concentrations change according to a first-order decay rate. In RIV1Q, decay coefficients can be specified to vary seasonally and spatially by model branch and model segment. The decay coefficient for the Red River probably varies seasonally, but too few data were available to estimate a seasonally varying decay coefficient for phosphorus. Therefore, an iterative process was used to estimate a first-order decay coefficient for each of the branches in the model. The decay coefficient was used for each model segment in a branch because a more spatially detailed approach was not justified with the small amount of available data. Decay coefficients of $0.01\ d^{-1}$ and $0.05\ d^{-1}$ were determined for branches 1 and 2, respectively.

The effects of the decay coefficients on the loss of total phosphorus from branches 1 and 2 were determined by expressing the percent loss of total phosphorus as a function of the first-order decay coefficient (k) and traveltime (T):

$$\text{Loss} = (1 - e^{-(k)(T)})100 \tag{5}$$

where

k is the first-order decay coefficient,

and

T is traveltime.

Assuming a decay coefficient of $0.01\ d^{-1}$ and a traveltime of 7 to 14 days for branch 1, the loss of total phosphorus from the system is between 7 and 13 percent. This implies that the loss of total phosphorus probably is from physical processes within the Red River, an implication that is consistent with current (2006) understanding of biological and physical processes in the river. Particle sizes in the Red River generally are very fine and sediment losses to bed sediment probably are small because the par-

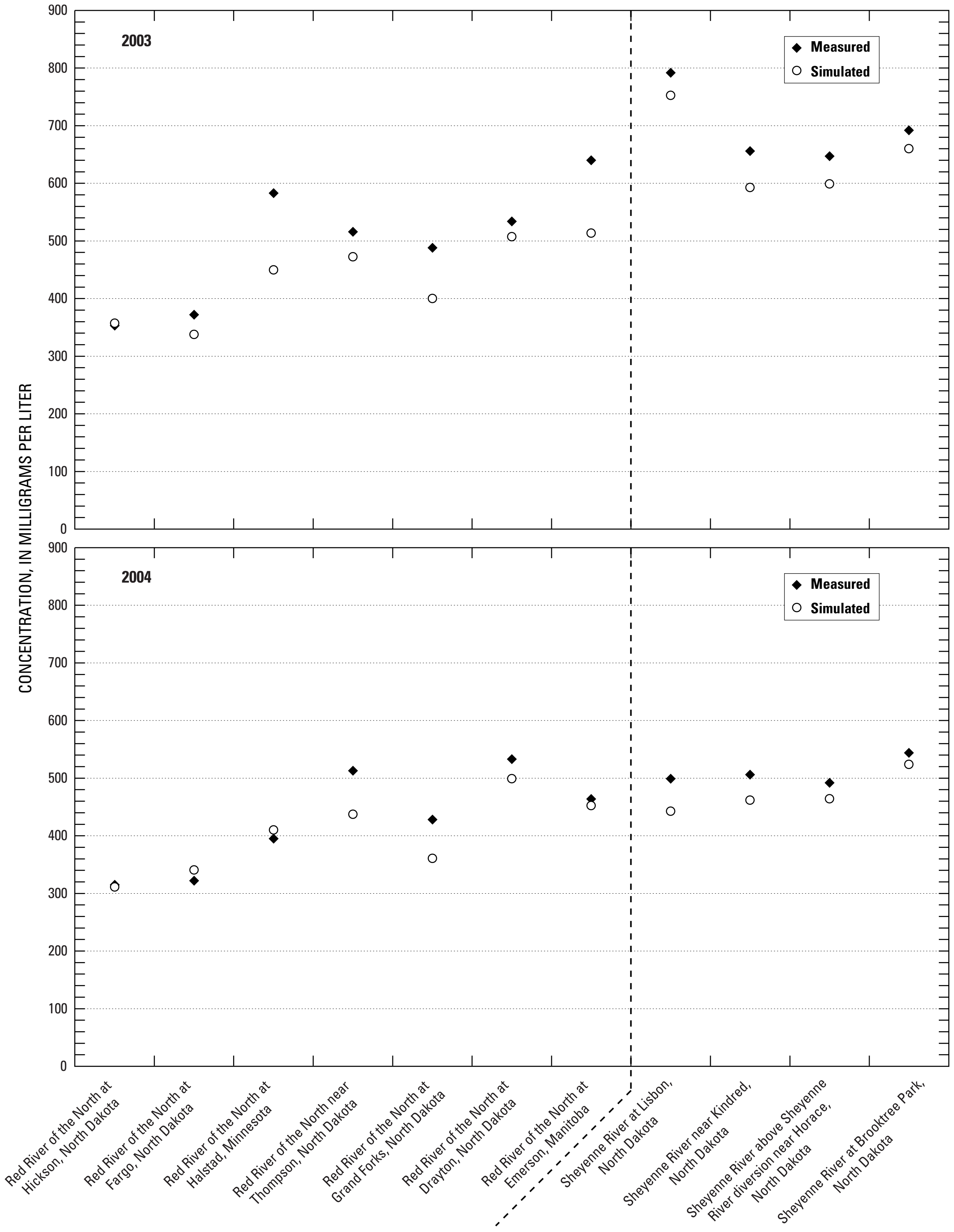


Figure 4. Measured and simulated total dissolved solids concentrations for selected Red River model calibration points for 2003 and 2004 calibration periods.

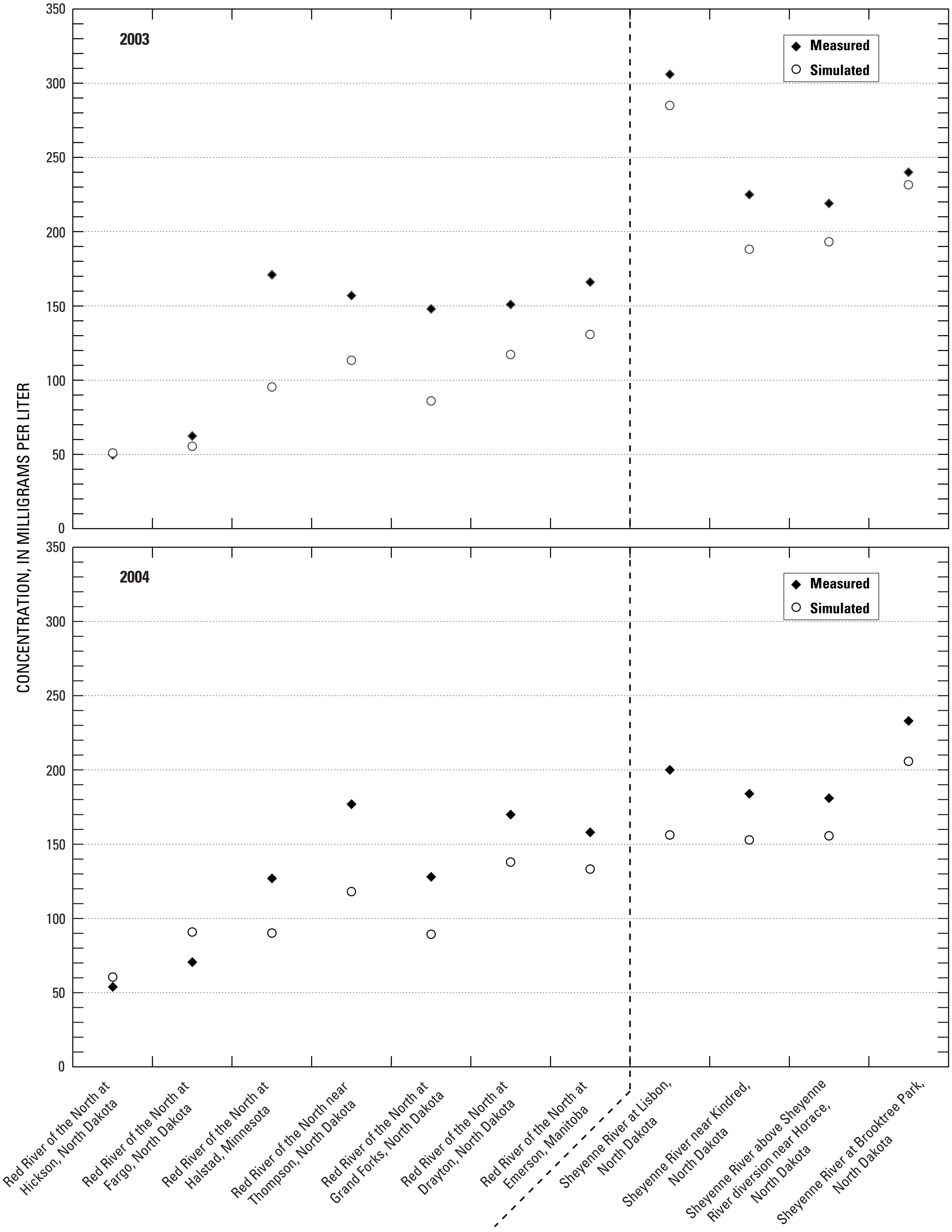


Figure 5. Measured and simulated dissolved sulfate concentrations for selected Red River model calibration points for 2003 and 2004 calibration periods.

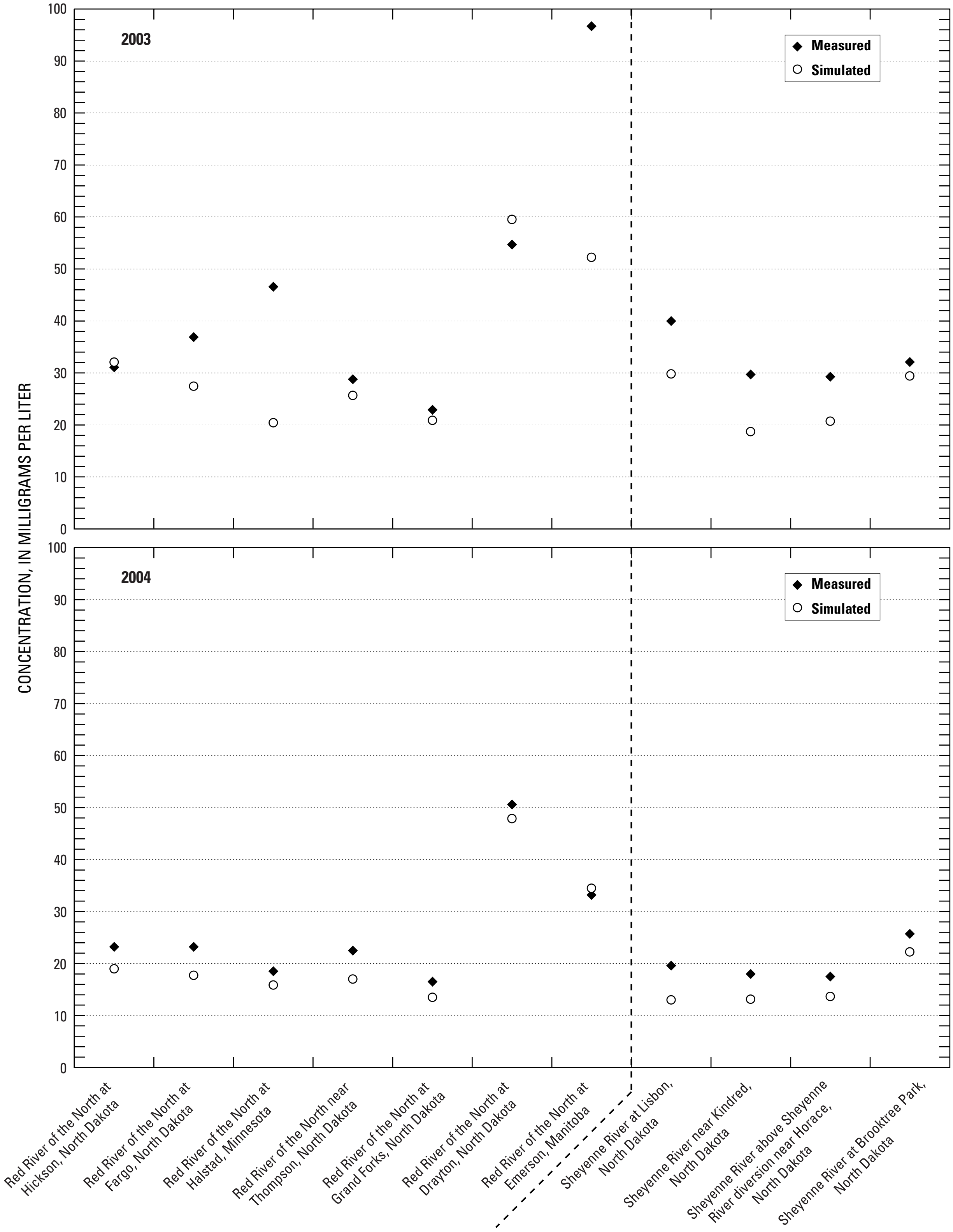


Figure 6. Measured and simulated dissolved chloride concentrations for selected Red River model calibration points for 2003 and 2004 calibration periods.

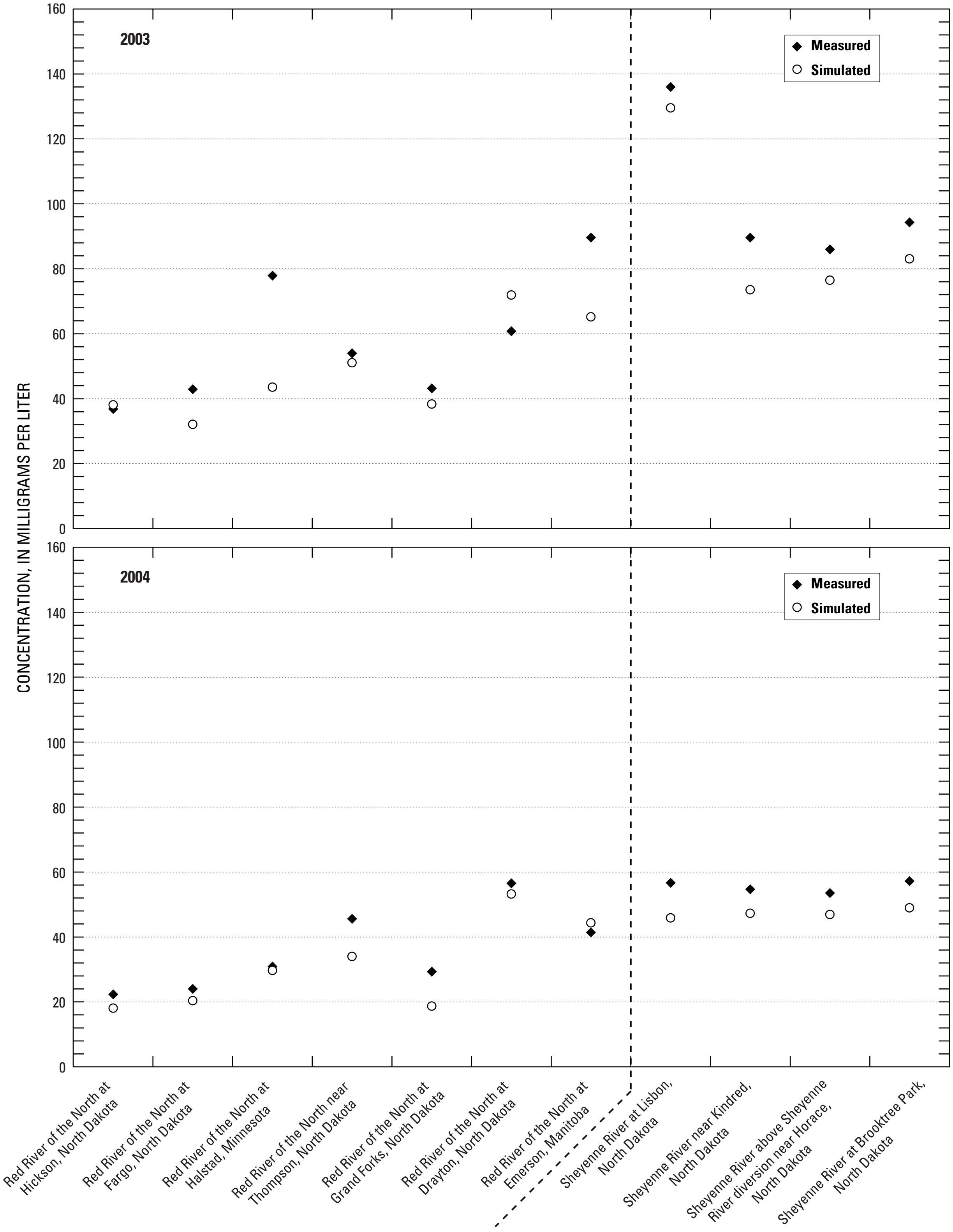


Figure 7. Measured and simulated dissolved sodium concentrations for selected Red River model calibration points for 2003 and 2004 calibration periods.

ticles become resuspended. In more than half of the suspended sediment samples for the Red River at Emerson, Manitoba, 98 percent of the sediment was finer than sand (Tornes and Brigham, 1994). Also, the Red River is turbid and phytoplankton growth is light-limited (Heiskary and Markus, 2003) so phosphorus loss to algae and aquatic plants probably is small. For the Sheyenne River, a decay coefficient of 0.05 d^{-1} and a traveltime of 4 to 7 days resulted in a loss of total phosphorus from the system of between 18 and 30 percent. The Sheyenne River is shallower and, therefore, not as light-limited as the Red River. As a result, the amount of phosphorus lost to plant and algae uptake probably is greater than that for the Red River. However, the loss still is considered to be small and, as for the Red River, probably is related to resuspension of fine particles on which phosphorus is adsorbed. For the Sheyenne River at Lisbon, N. Dak., in 18 of 25 suspended sediment samples collected from 1977 to 1995, 98 percent of the sediment was finer than sand.

Total phosphorus concentrations generally were underpredicted for both calibration periods (fig. 8). The average difference between the measured and simulated concentrations was 6.2 percent for the 2003 calibration period and -24 percent for the 2004 calibration period. The average absolute differences, 23 and 29 percent for the 2003 and 2004 calibration periods, respectively, were higher than the average differences. The magnitude of the average absolute difference was less for the 2003 calibration period than for the 2004 calibration period. The differences averaged about 0.034 mg/L for the 2003 calibration period and 0.082 mg/L for the 2004 calibration period.

Model Testing

Model testing was conducted to determine the effects of the small amount of water-quality data on model calibration. Because few water-quality data are available for the gaging locations used for the calibration, water-quality boundary conditions were not known. Therefore, to calibrate the model, time-invariant boundary conditions of measured and estimated constituent concentrations (tables 5, 8, and 10) were used for the unsteady-flow simulations. The effects of the assumed boundary conditions on simulated concentrations was demonstrated by comparing results from the calibrated model to results simulated using (1) unsteady total dissolved solids upstream boundary conditions for the Red River at Wahpeton, N. Dak., and steady total dissolved solids boundary conditions for tributaries and ungaged local inflows and (2) unsteady total dissolved solids boundary conditions for the Red River at Wahpeton and unsteady total dissolved solids boundary conditions for tributaries and ungaged local inflows.

The upstream boundary condition for the Red River at Wahpeton, N. Dak., was estimated from measured daily mean specific-conductance values for the Red River at Fargo, N. Dak. The values were converted to total dissolved solids concentrations by using a conversion factor of 0.65, which is an average conversion factor for the Red River Basin (M. Deutschman, Houston Engineering, written commun., 2006). This estimated time series of total dissolved solids concentrations then was used as an unsteady upstream boundary condition for one simulation. In a second simulation, this same time series of total dissolved solids was used for the Red River at Wahpeton and for all inflows between the Red River at Wahpeton and the Red River at Fargo (the Red River at Wahpeton, the Wahpeton wastewater-treatment facility, the Wild Rice River in North Dakota, the Fargo-Moorhead water-treatment facility, and the two ungaged local inflows between Wahpeton and Fargo). Simulation results indicate total dissolved solids concentrations are sensitive to assumed boundary conditions (fig. 9). The change from time-invariant boundary conditions used for model calibration to unsteady upstream boundary conditions had a large effect on the magnitude of the simulated concentrations for the Red River at Fargo although the temporal distribution of total dissolved solids was similar for both sets of boundary conditions (fig. 9). Unsteady boundary conditions for the gaged tributary inflows and the ungaged local inflows not only affected the magnitude of the simulated concentrations for the Red River at Fargo but also the relative temporal distribution. For example, the simulation using time-invariant boundary conditions and the simulation using unsteady upstream boundary conditions showed relatively large increases in concentration beginning about September 18, 2003, but the simulation using all unsteady boundary conditions showed only a small increase in concentration at that time.

Constituent concentrations for the ungaged local inflows also were not known because of the small amount of water-quality data. Therefore, the concentrations were calculated using a simplified mass-balance approach (eq. 4). Simulations of chemical constituent concentrations during unsteady-flow conditions are highly dependent on accurate estimates of the magnitude and timing of chemical loads contributed by ungaged local inflows. The method used to estimate the concentrations for the ungaged local inflows resulted in good agreement between measured and simulated streamflows, but, unlike for the water-quality boundary conditions, continuous records of streamflow were available to develop the estimates.

The percentages of the total simulated constituent loads contributed by estimated ungaged local inflows are given in table 11 for the 2003 and 2004 calibration periods. Generally, the reaches for which the percentages were the highest were the upstream reaches—the Red River at Wahpeton, N. Dak., to Red River at Hickson, N. Dak., reach and the Red River at Hickson to Red River at Fargo, N. Dak., reach. The drainage area between Wahpeton and Hickson increases less than 5 percent (a relatively small increase), but no gaged tributaries are located within the reach. The drainage area between Hickson and Fargo increases 37 percent, but the Wild Rice River, a major gaged tributary, is located within that reach. Other than for the Red River at Wahpeton to Red River at Hickson and Red River at Hickson to Red River at Fargo reaches, which were highly affected by the assumed boundary conditions for the Red River at Wahpeton, estimated ungaged local inflows generally contributed less than about 35 percent of the total conservative-

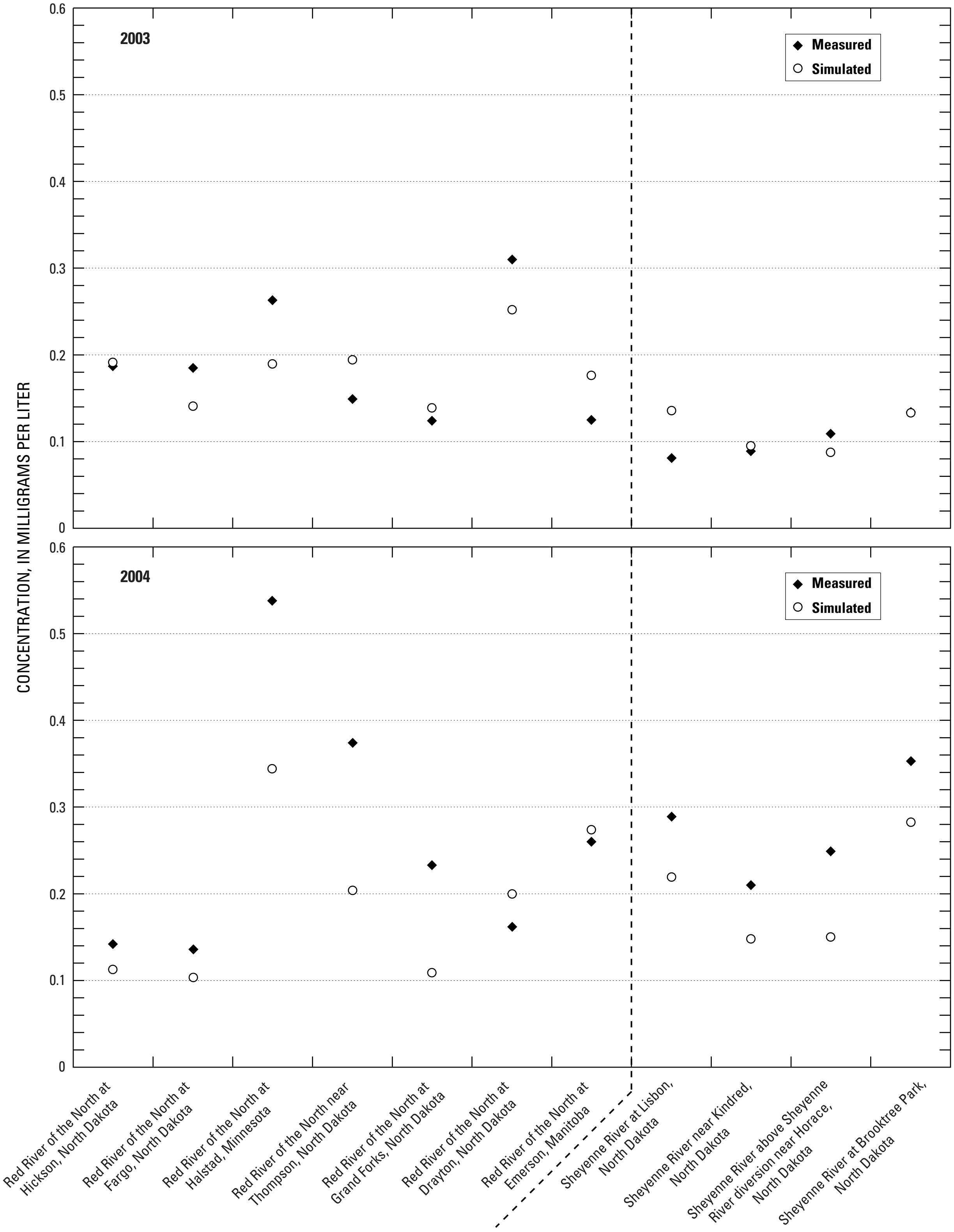


Figure 8. Measured and simulated total phosphorus concentrations for selected Red River model calibration points for 2003 and 2004 calibration periods.

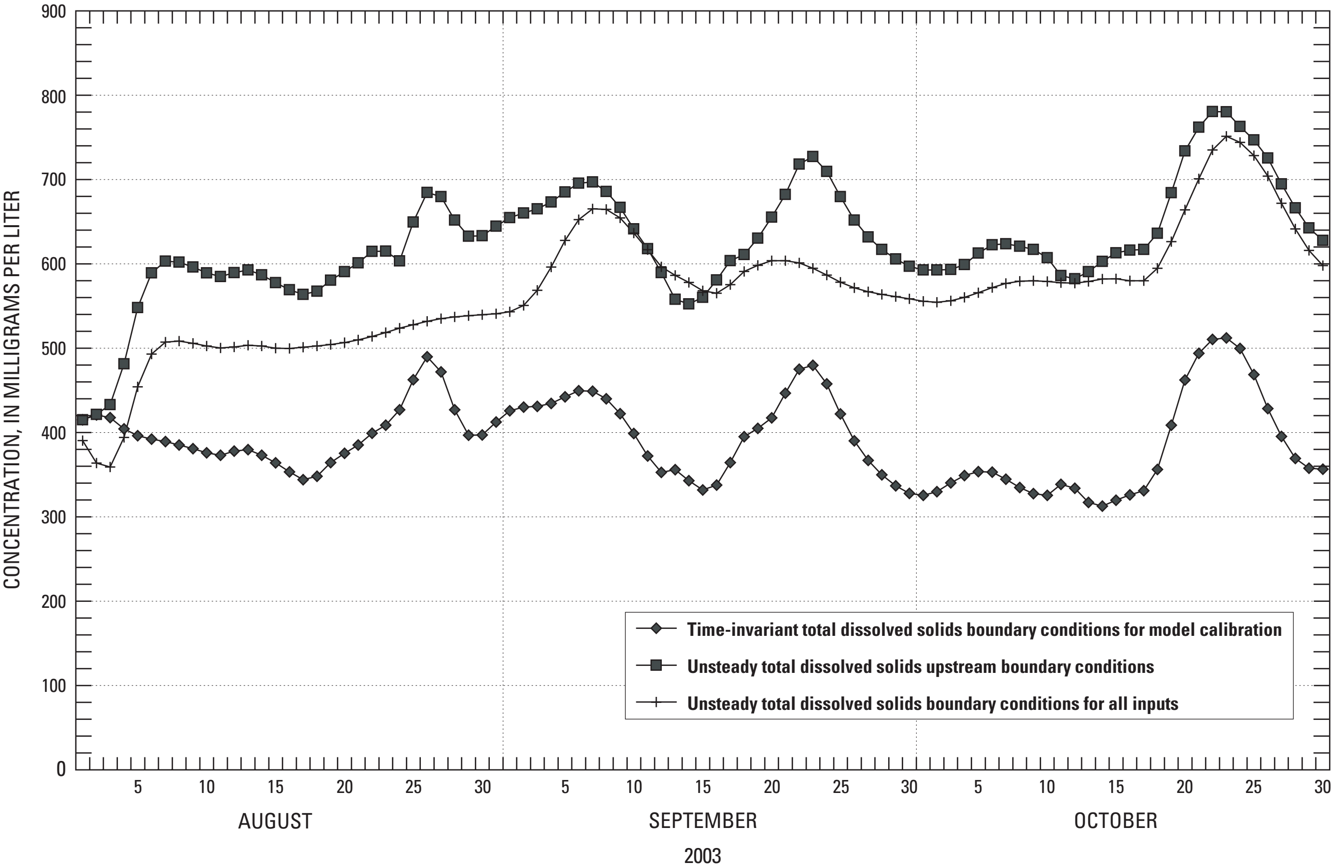


Figure 9. Simulated total dissolved solids concentrations for the Red River of the North at Fargo, North Dakota, for three sets of boundary conditions.

constituent load in a reach. Ungaged local inflows also contributed a smaller part of the total constituent load during the 2004 calibration period, when streamflows in the river were high, than during the 2003 calibration period.

Model testing indicated that improved point-by-point agreement between measured and simulated concentrations can be obtained by adjusting boundary conditions for rivers, tributaries, and ungaged flows. Such a model, however, would be considered "overtuned" and would be applicable only to the very specific conditions for which the model was calibrated (Bales and others, 2001). The Red River model provided good simulations of streamflow throughout the model domain. Therefore, a reasonable assumption is that simulations made using more realistic and complete boundary condition information than used for this study would provide better results than those obtained during the study. Also, the Red River model demonstrates a sensitivity to changes in boundary conditions so a reasonable assumption is that the model can be used to compare relative effects of various water-supply alternatives.

Model Application

The calibrated Red River model was used to simulate the relative effects of six water-supply alternatives identified by the Bureau of Reclamation (table 1) on water quality in the Red River and the Sheyenne River. Boundary conditions were specified for April 1, 1976, through August 31, 1977. However, because April 1 through August 31, 1976, was used as an initialization period, simulation results for the alternatives were compared for September 1, 1976, through August 31, 1977. Streamflows throughout the Red River Basin during September 1976 through August 1977 were relatively low (table 3). Based on the period of record, 1942-94, for the Red River at Fargo, N. Dak., the minimum mean streamflow for a 7-consecutive-day period can be expected to be equal to or less than 17.9 ft^3/s an average of once every 10 years. This statistic often is referred to as the 7Q10 streamflow. Streamflows for the Red River at Fargo were less than the 7Q10 streamflow on 159 days during September 1976 through August 1977. Monthly average streamflows for the Red River at Grand Forks, N. Dak., and the Red River at Emerson, Manitoba, were less than 30 percent of the respective long-term average monthly streamflows for those

Table 11. Percentage of total simulated constituent load contributed by estimated ungaged local inflows for 2003 and 2004 calibration periods.

Location	Total dissolved solids (percent)		Dissolved sulfate (percent)		Dissolved chloride (percent)		Dissolved sodium (percent)		Total phosphorus (percent)	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Red River of the North										
Red River of the North at Wahpeton, North Dakota, to Red River of the North at Hickson, North Dakota	27	10	36	0	70	33	74	34	100	33
Red River of the North at Hickson, North Dakota, to Red River of the North at Fargo, North Dakota	36	4	50	4	73	6	62	4	25	6
Red River of the North at Fargo, North Dakota, to Red River of the North at Halstad, Minnesota	5	7	6	9	2	7	3	7	0	15
Red River of the North at Halstad, Minnesota, to Red River of the North at Grand Forks, North Dakota	0	7	0	7	0	6	0	7	0	9
Red River of the North at Grand Forks, North Dakota, to Red River of the North at Drayton, North Dakota	0	15	0	18	0	14	0	16	0	11
Red River of the North at Drayton, North Dakota, to Red River of the North at Emerson, Manitoba	5	0	8	0	1	0	3.2	0	0	0
Sheyenne River										
Sheyenne River below Baldhill Dam, North Dakota, to Sheyenne River at Lisbon, North Dakota	12	2	15	3	35	28	12	18	0	11
Sheyenne River at Lisbon, North Dakota, to Sheyenne River near Kindred, North Dakota	25	18	18	17	24	20	9	18	35	11

Table 11. Percentage of total simulated constituent load contributed by estimated ungaged local inflows for 2003 and 2004 calibration periods.—Continued

Location	Total dissolved solids (percent)		Dissolved sulfate (percent)		Dissolved chloride (percent)		Dissolved sodium (percent)		Total phosphorus (percent)	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Sheyenne River—Continued										
Sheyenne River near Kindred, North Dakota, to Sheyenne River above Sheyenne River diversion near Horace, North Dakota	0	0	0	0	0	0	0	0	0	0
Sheyenne River above Sheyenne River diversion near Horace, North Dakota, to Sheyenne River at West Fargo, North Dakota	4	7	3	12	9.9	18	7	5	20	19

locations for 11 of the 12 months between September 1976 and August 1977.

Several minor modifications were made to the model grid to accommodate the water-supply alternatives. Return flows and withdrawals for Fargo, West Fargo, and Grand Forks, N. Dak., and Moorhead, Minn., were represented in the model as well as return flows and withdrawals for Wahpeton Industrial use. Wahpeton Industrial is used herein as a generic term that represents existing industries and potential future industries in the Wahpeton, N. Dak., area. Also, point-source withdrawals were added immediately upstream from the return flows for Wahpeton and West Fargo to account for withdrawals from the Red River at river mile 545 for Wahpeton Industrial use and from the Sheyenne River at river mile 28.1 for West Fargo. Withdrawals for Wahpeton and West Fargo were not included in the model because ground water is the current (2006) water-supply source for those cities. Another withdrawal was added immediately upstream from the Grand Forks return flow at river mile 290.8 to account for the North Dakota In-Basin Alternative (table 1). Finally, Fargo and Moorhead return flows were separated for the alternative simulations.

Streamflow boundary conditions for the water-supply alternative simulations were provided by the Bureau of Reclamation (A. Schlag, Bureau of Reclamation, written commun., 2006). The streamflows were generated by the Bureau of Reclamation using the surface-water model StateMod. StateMod is a monthly and daily water allocation and accounting model that is used for comparative analysis of various historical and future water policies for a river basin (State of Colorado, 2004). StateMod was used to superimpose projected 2050 water demands on naturalized flows in the Red River Basin. The resulting flows and water-source volumes for each community then were used to develop upstream streamflow boundary conditions and return flow boundary conditions for the included communities. Those results were used in the Red River model with September 1976 through August 1977 streamflows to simulate the effects of the alternatives on water quality in the Red River and the Sheyenne River,

StateMod-generated monthly streamflows were disaggregated into daily streamflows for the Red River model. Daily patterns for 2006 withdrawals for Moorhead, Minn., were used to disaggregate 2050 monthly withdrawals for Fargo and West Fargo, N. Dak., and Moorhead, and daily patterns for 2006 withdrawals for Grand Forks, N. Dak., were used to disaggregate 2050 monthly withdrawals for Grand Forks. Thus, for example, if 3 percent of the October 2006 monthly total withdrawal for Moorhead occurred on October 1, the assumption was made that 3 percent of the 2050 monthly total withdrawal for the water-quality alternative simulations occurred on October 1. Upstream streamflow boundary conditions for the Red River at Wahpeton, N. Dak., and the Sheyenne River below Baldhill Dam, N. Dak., were synchronized with downstream withdrawals by disaggregating the StateMod-generated monthly streamflows for those locations into daily streamflows based on 2006 daily withdrawals for Moorhead and West Fargo, respectively. StateMod-generated monthly tributary streamflows were disaggregated into daily streamflows by using 1976-77 historical daily tributary streamflows. StateMod also produces a monthly streamflow gain and loss value for each reach. That value, rather than the value estimated from equation 4, was used to represent ungaged local inflows because all other streamflow boundary conditions for the model were generated by StateMod. StateMod-generated monthly ungaged local inflows were disaggregated into daily inflows by using 1976-77 historical daily inflows for the tributary nearest to the ungaged local inflow input location.

To offset operational limitations, StateMod simulations included the assumption that the monthly water-supply demand for a municipality was equal to the peak daily demand that occurred each day of the month. This assumption resulted in frequent periods of zero daily flow during the model application period for the Red River at Fargo, N. Dak., and periods of relatively low flow (less than 5 ft^3/s) for the Sheyenne River at West Fargo, N. Dak., for some of the water-supply alternatives. These occurrences are mathematically acceptable within an accounting software like StateMod, but the algorithms within the RIV1 modeling system would not allow for multiple instances of zero flow. Therefore, to maintain numerical stability in the Red River model, a minimal amount of streamflow was added upstream from the withdrawals on the Red River and the Sheyenne River. Through a trial-and-error process, between 1 and 20 ft^3/s of streamflow was added to the Red River and between 5 and 15 ft^3/s of streamflow was added to the Sheyenne River. These additional streamflow amounts were considered by project partners to be reasonable to offset the operational assumptions made for StateMod. The same volume of water was added for each of the alternative simulations. Limited sensitivity analysis was conducted using the Red River Basin Alternative to determine the effects of the additional streamflows on simulated constituent concentrations because no additional flows were required for that alternative to maintain model stability for branch 2. Therefore, two simulations—one without additional streamflow and one with additional streamflow—could be compared. Median concentrations for the Red River at Emerson, Manitoba, were reduced by 0.2 percent or less for all constituents because of the additional streamflow (table 12). For the Sheyenne River at West Fargo, which is immediately downstream from where additional streamflows were input, median concentrations were reduced in relation to those for the base condition by about 1 to 5 percent for all constituents.

Historical water-quality data for the 1976-77 simulation period were not available. Therefore, stochastically generated constituent concentrations for the upstream boundary conditions, the tributaries, and the return flows for all water-supply alternatives were provided by Houston Engineering (M. Deutschman, Houston Engineering, written commun., 2006) under contract to the Bureau of Reclamation. Probability distributions were fit to the measured concentrations for locations for which a sufficient amount of data was available. Data were grouped for locations that had a small amount of available data; grouping was based on geographic location. The probability distributions

Table 12. Change in median constituent concentrations as a result of additional streamflow required to maintain model stability.

Location	Total dissolved solids (percent)	Dissolved sulfate (percent)	Dissolved chloride (percent)	Dissolved sodium (percent)	Total phosphorus (percent)
Red River at Emerson, Manitoba	-0.2	-0.1	0	0	0
Sheyenne River at West Fargo, North Dakota	-1.3	-4.4	-5.3	-3.1	-1.0

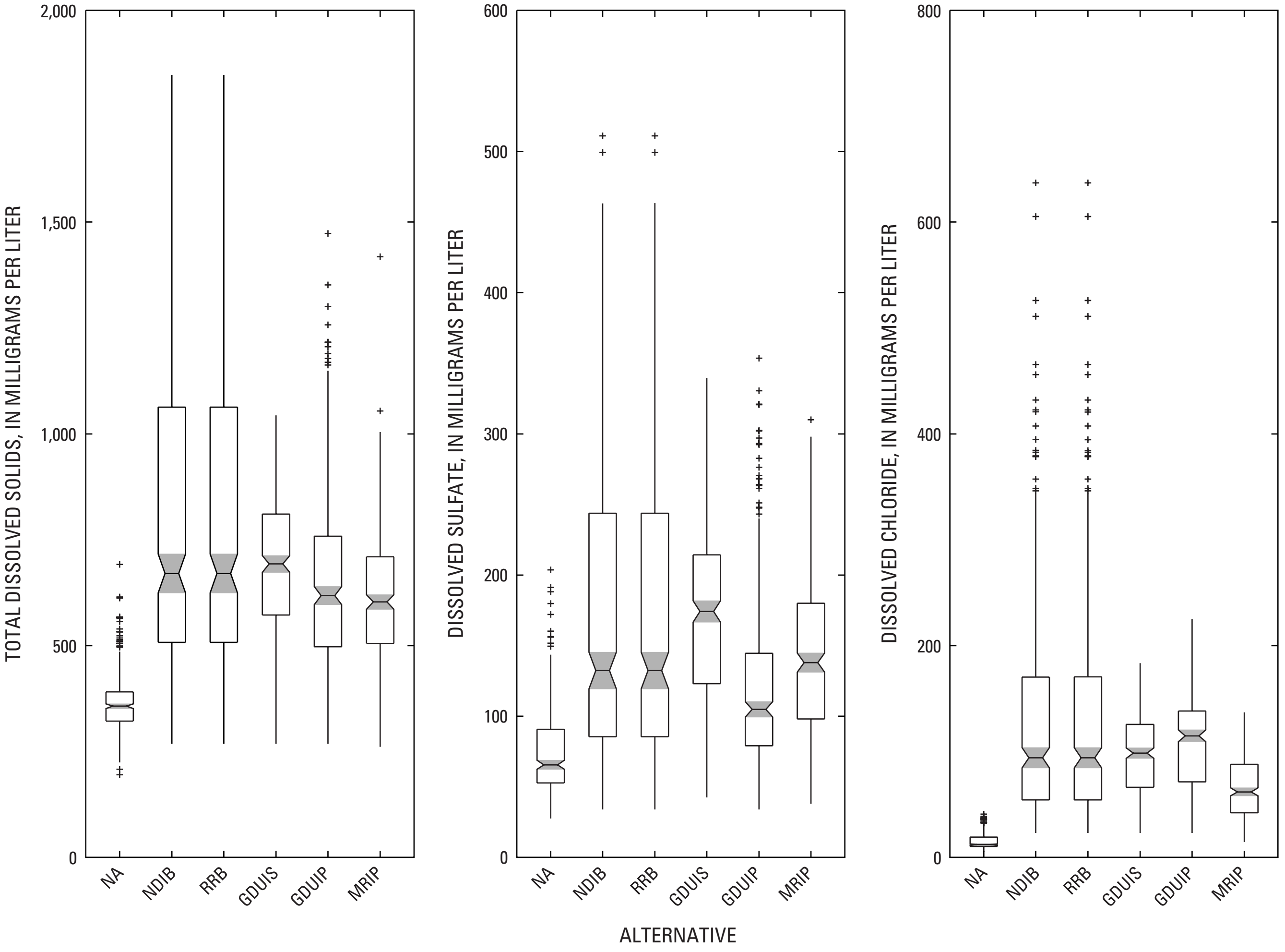
were stochastically sampled using a Monte Carlo approach, and the probability distribution of 3 years of stochastically generated daily concentrations was compared to the measured probability distribution. In all but one case, the statistics of the measured and stochastically generated distributions were similar, indicating the stochastic approach provided a reasonable approximation to the measured concentrations. The stochastic approach was used to generate water-quality boundary conditions for the Red River at Wahpeton, N. Dak., and for all tributary inflows. The approach also was used for the boundary conditions for the Sheyenne River below Baldhill Dam, N. Dak. (branch 2), for four of the water-supply alternatives. Because water is imported into Lake Ashtabula for the North Dakota In-Basin Alternative and for the Garrison Diversion Unit Import to Sheyenne River Alternative, stochastically generated historical water-quality conditions for the Sheyenne River below Baldhill Dam would not necessarily represent the conditions that result from those two alternatives. Boundary conditions for the Sheyenne River below Baldhill Dam for the two interbasin alternatives were estimated by using a simple mixing model for Lake Ashtabula in which imported constituent loads were conservatively mixed with Lake Ashtabula water to estimate concentrations for below the dam (M. Deutschman, Houston Engineering, written commun., 2006).

Return flow concentrations were estimated from source concentrations and current (2006) wastewater-treatment technology (M. Deutschman, Houston Engineering, written commun., 2006). A factor that accounted for the combined effects of water and wastewater treatment on the source water was applied to the different source-water qualities for each alternative to compute a time series of volume-weighted average concentrations for each return flow location (M. Deutschman, Houston Engineering, written commun., 2006). Because no historical information on ungaged local inflow concentrations is available to estimate those boundary conditions, time-invariant concentrations estimated for the low-flow 2003 calibration period (table 8) were used as the ungaged local inflow boundary conditions. Streamflows added to maintain model stability, as previously described, were assumed to have constituent concentrations of zero.

Effects of Water-Supply Alternatives on Total Dissolved Solids, Sulfate, Chloride, Sodium, and Total Phosphorus

The effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River during low-flow conditions that approximated those that existed in 1976-77 were evaluated by comparing the effects of five of the alternatives relative to the No-Action Alternative. Results of the water-supply alternative simulations for selected locations are presented using notched box plots that summarize statistical information for the simulated annual concentration distribution for each of five constituents.

Each notched box plot (see, for example, fig. 10) shows several statistics for the simulated annual concentration distribution for a particular water-supply alternative and a particular location. The box plots include the median, 25th and 75th percentiles, maximum and minimum values, and outliers for the simulated daily mean concentration for the 1976-77 simulation period. The notches in each box plot represent the 95-percent confidence interval for the simulated annual median concentration. If the notches for a selected alternative overlap the notches for the No-Action Alternative at the same location for a given constituent, then the selected alternative probably will have no effect relative to the No-Action Alternative on the annual median concentration for that constituent for that location. Conversely, if the notches for a selected alternative do not overlap the notches for the No-Action Alternative, then the selected alternative probably will result in a change in the annual median concentration relative to the annual median concentration for the No-Action Alternative. Simulation results are given for the Red River at river mile 536.3, which is immediately downstream from the Wahpeton Industrial return flow (fig. 10), and for the Red River at Fargo, N. Dak. (fig. 11), the Red River at Grand Forks, N. Dak. (fig. 12), the Red River at Emerson, Manitoba (fig. 13), the Sheyenne River below Baldhill Dam, N. Dak. (fig. 14), and the Red River at West Fargo, N. Dak. (fig. 15). It is important to remember that (1) results are presented for extremely low flow conditions, (2) changes in annual median concentrations likely will be less for higher flow conditions, and (3) results are reported relative to the No-Action Alternative rather than as actual expected annual median concentrations.



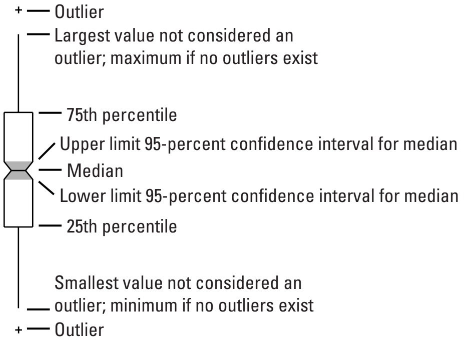
EXPLANATION

Outlier--Values greater than 75th percentile plus 1.5 times interquartile range or less than 25th percentile minus 1.5 times interquartile range

Percentile--Percentage of analyses equal to or less than individual values

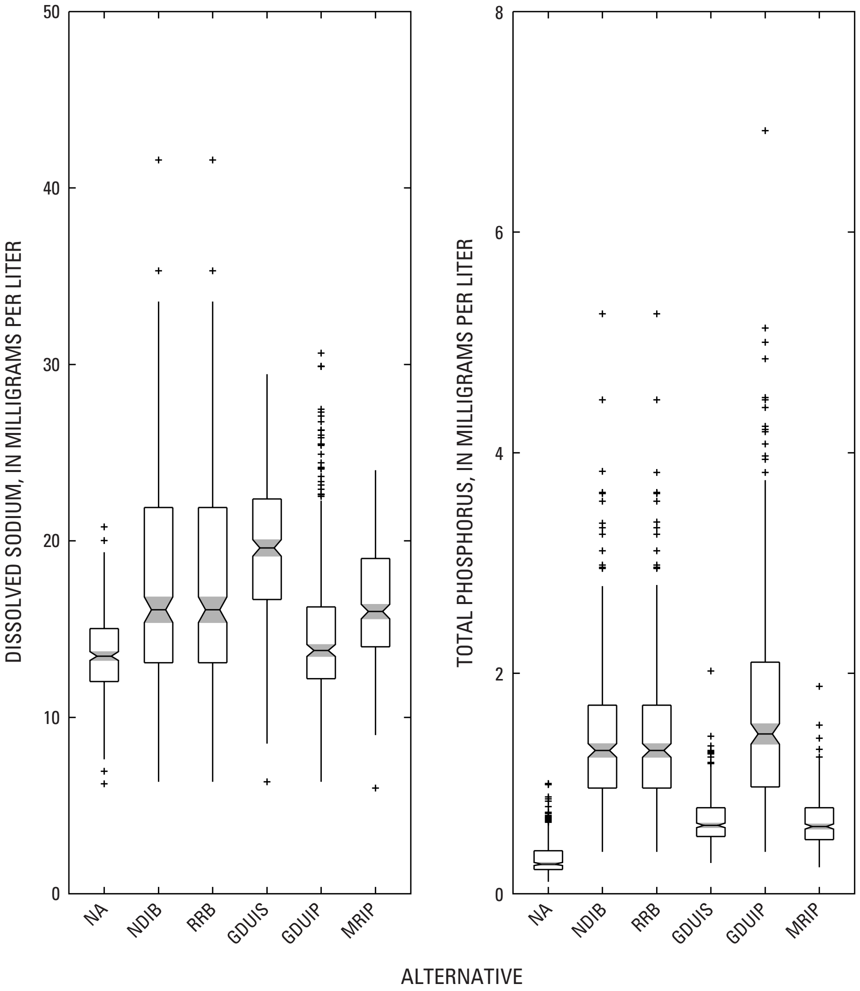
Interquartile range--Upper quartile, or 75th percentile, minus lower quartile, or 25th percentile

95-percent confidence interval for median--An estimated range of values, calculated from sample data, that probably includes the unknown population median. The width of the confidence interval indicates the degree of uncertainty in the estimated population median. The confidence coefficient, 0.95, indicates that, if sampling is repeated, 95 percent of the confidence intervals will contain the actual population median



No-Action Alternative (NA)
North Dakota In-Basin Alternative (NDIB)
Red River Basin Alternative (RRB)
Garrison Diversion Unit Import to Sheyenne River Alternative (GDUIS)
Garrison Diversion Unit Import Pipeline Alternative (GDUIP)
Missouri River Import to Red River Valley Alternative (MRIP)

Figure 10. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at river mile 536.3 immediately downstream from the Wahpeton Industrial return flow, 1976-77 simulation period.



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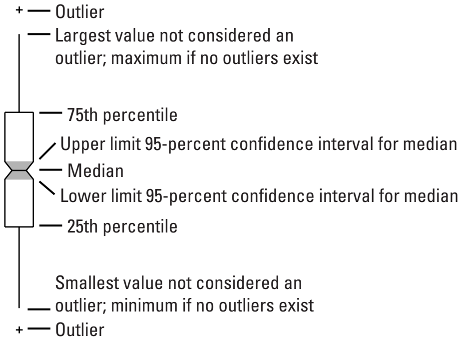

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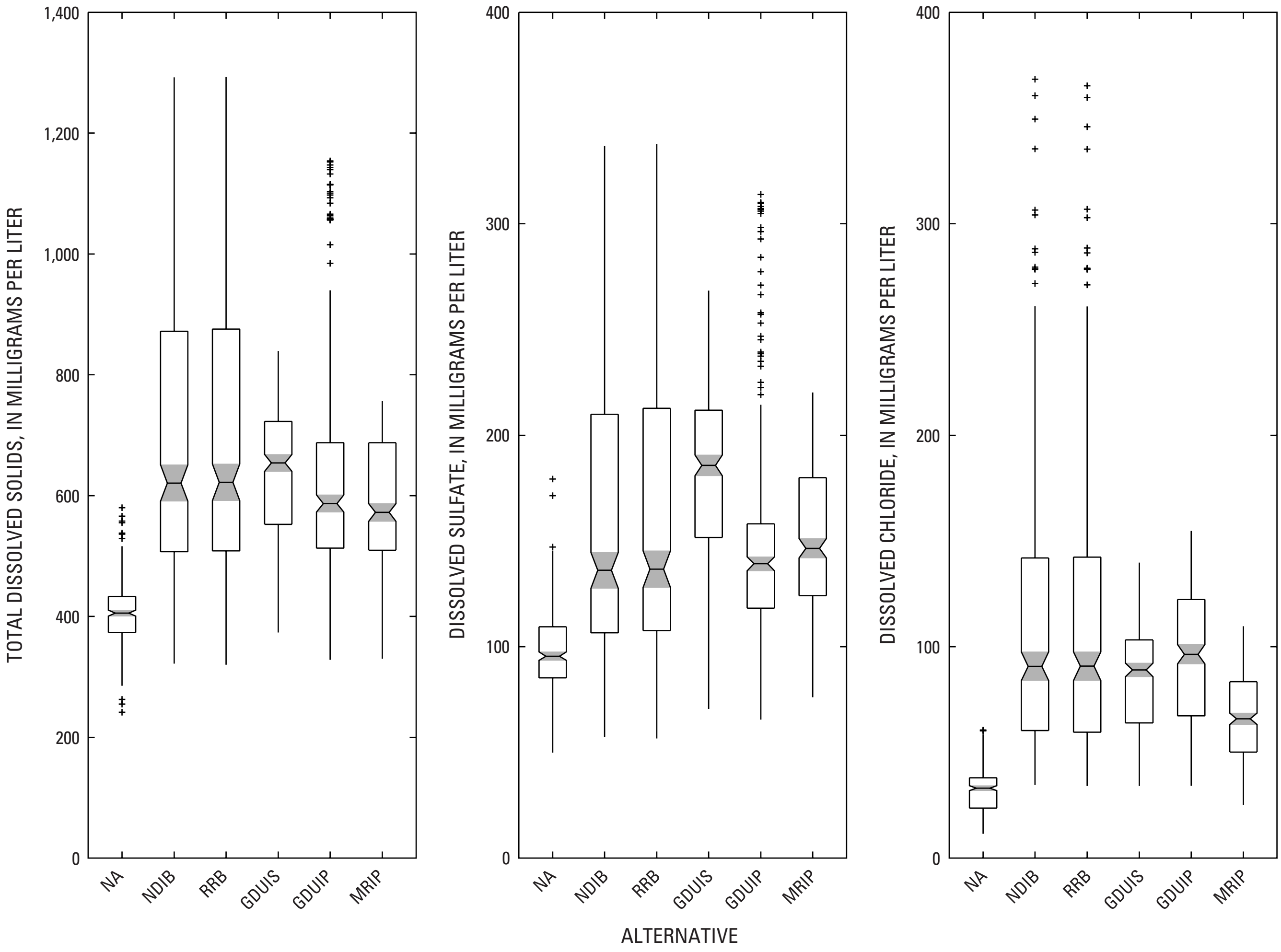
Figure 10. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at river mile 536.3 immediately downstream from the Wahpeton Industrial return flow, 1976-77 simulation period--Continued.



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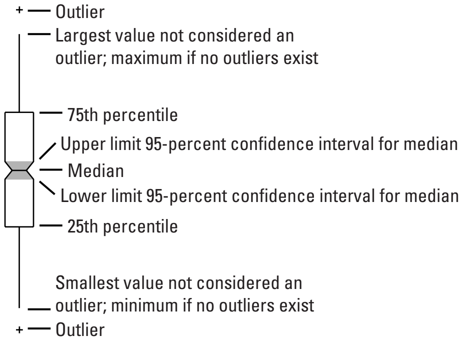

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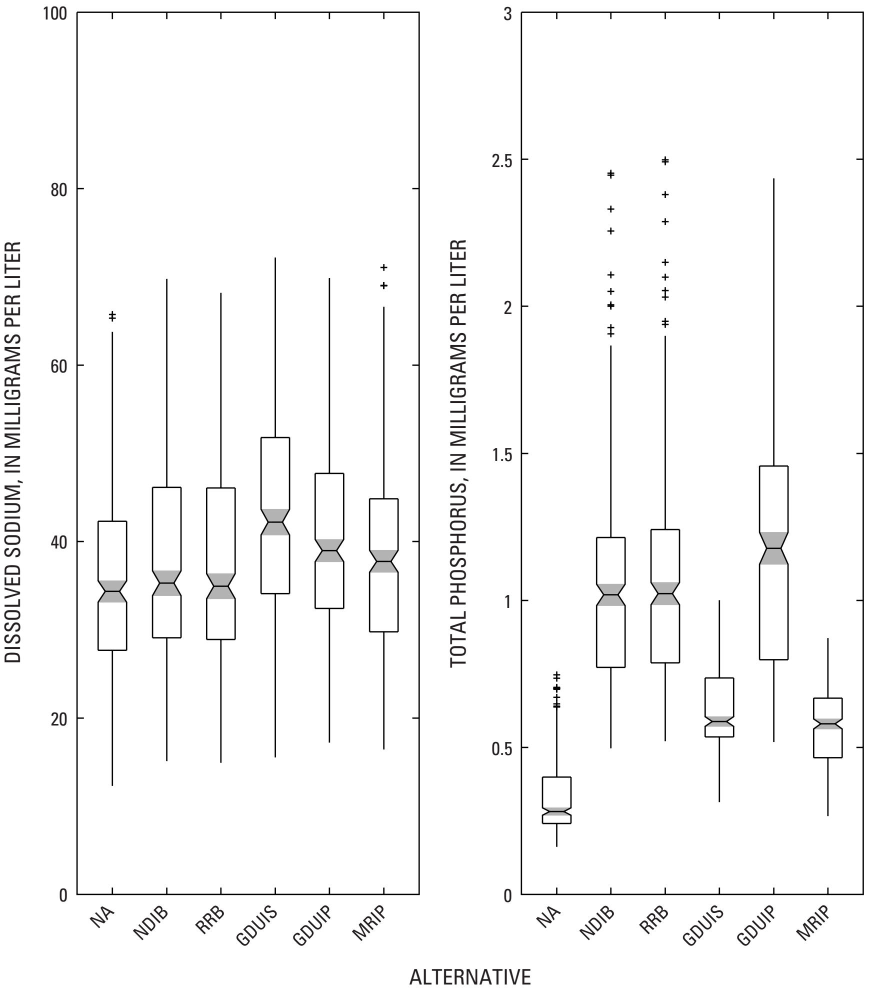
Figure 11. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Fargo, North Dakota, 1976-77 simulation period.



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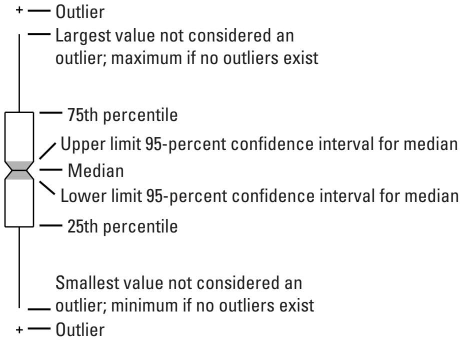

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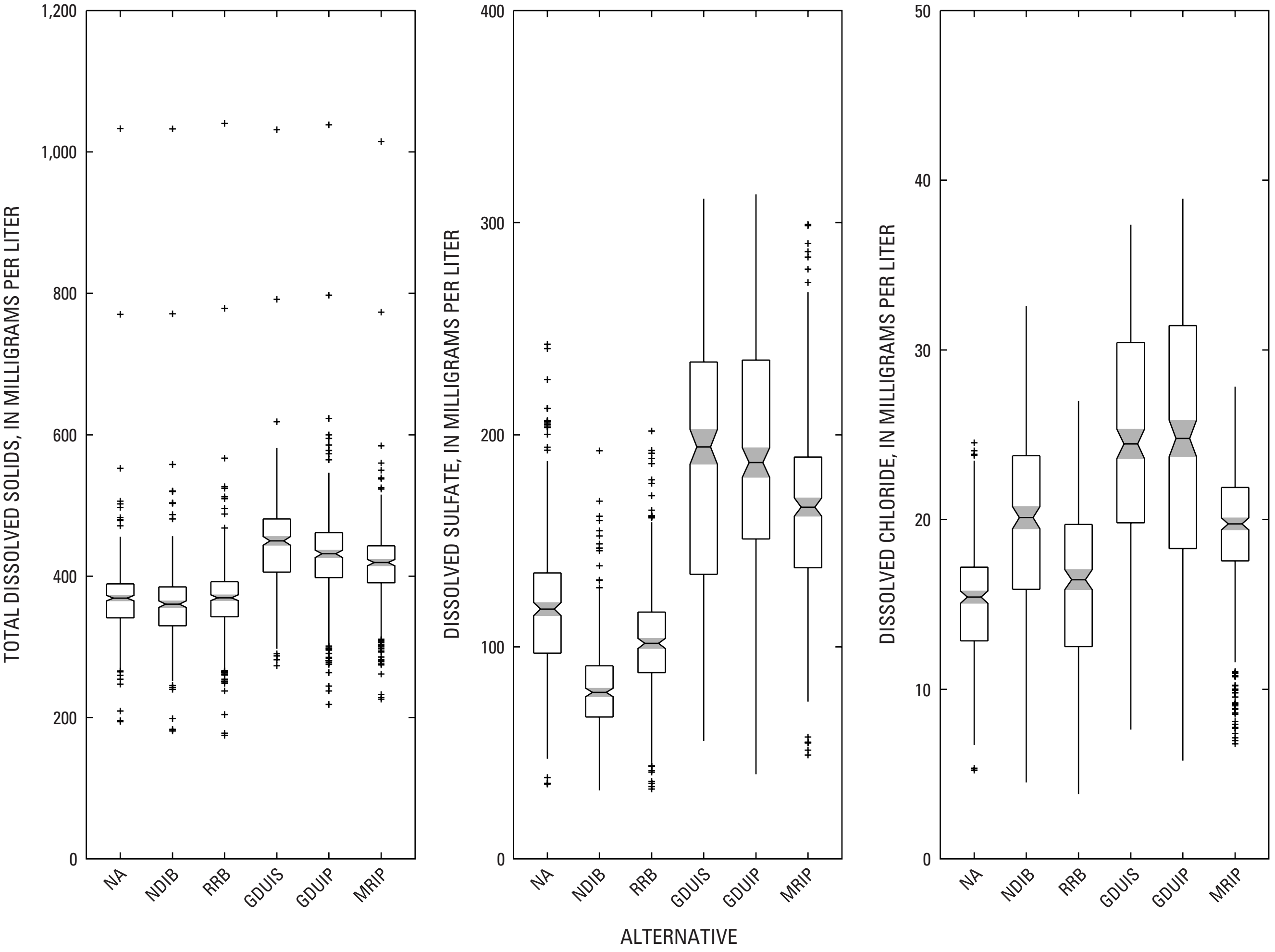
Missouri River Import to Red River Valley Alternative (MRIP)

Figure 11. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Fargo, North Dakota, 1976-77 simulation period--Continued.



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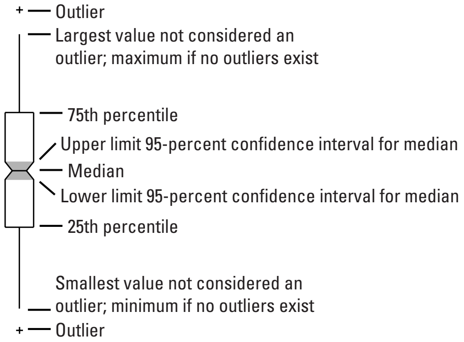

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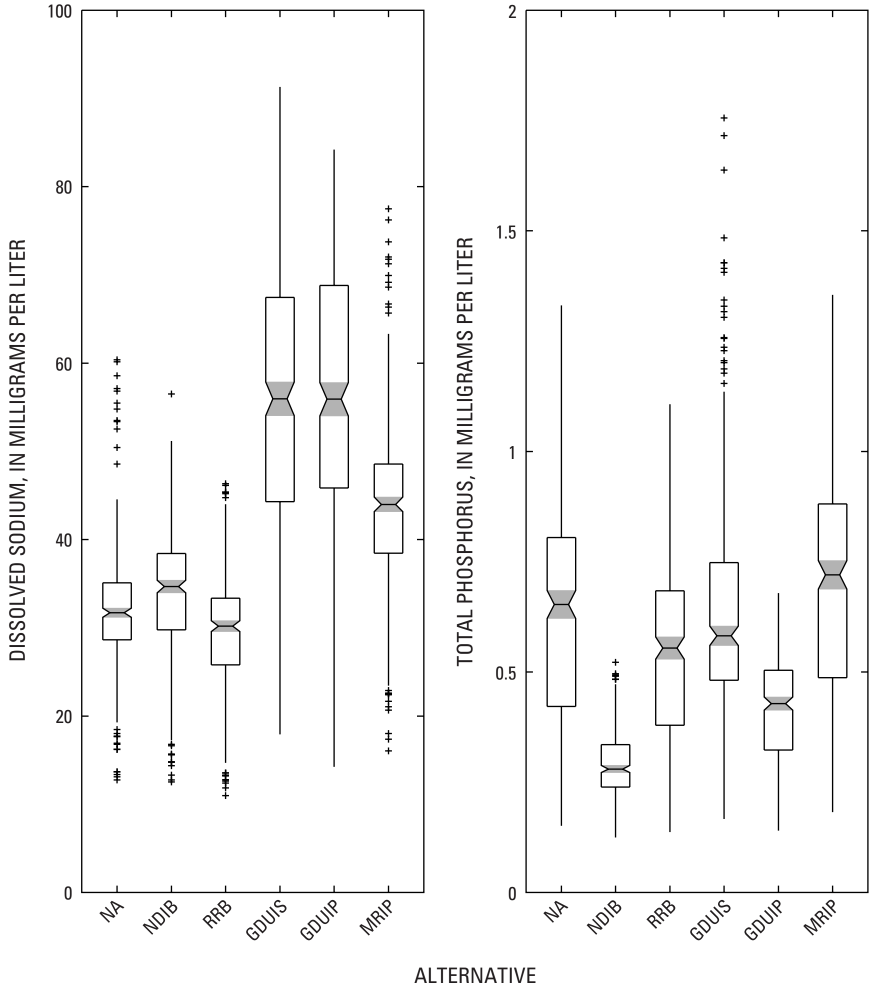
Figure 12. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Grand Forks, North Dakota, 1976-77 simulation period.



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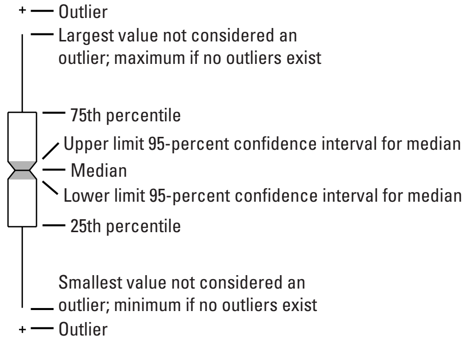

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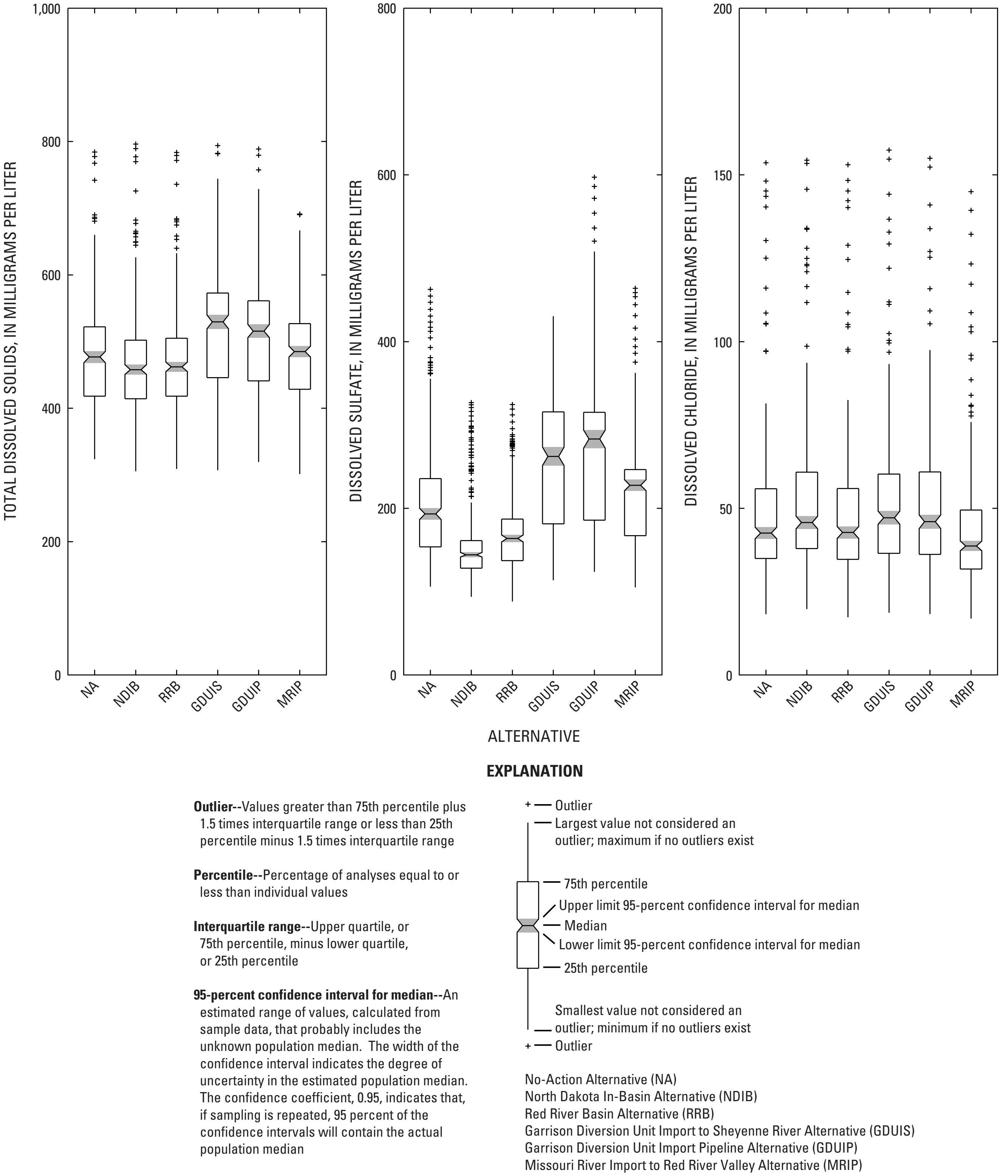
Figure 12. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Grand Forks, North Dakota, 1976-77 simulation period--Continued.



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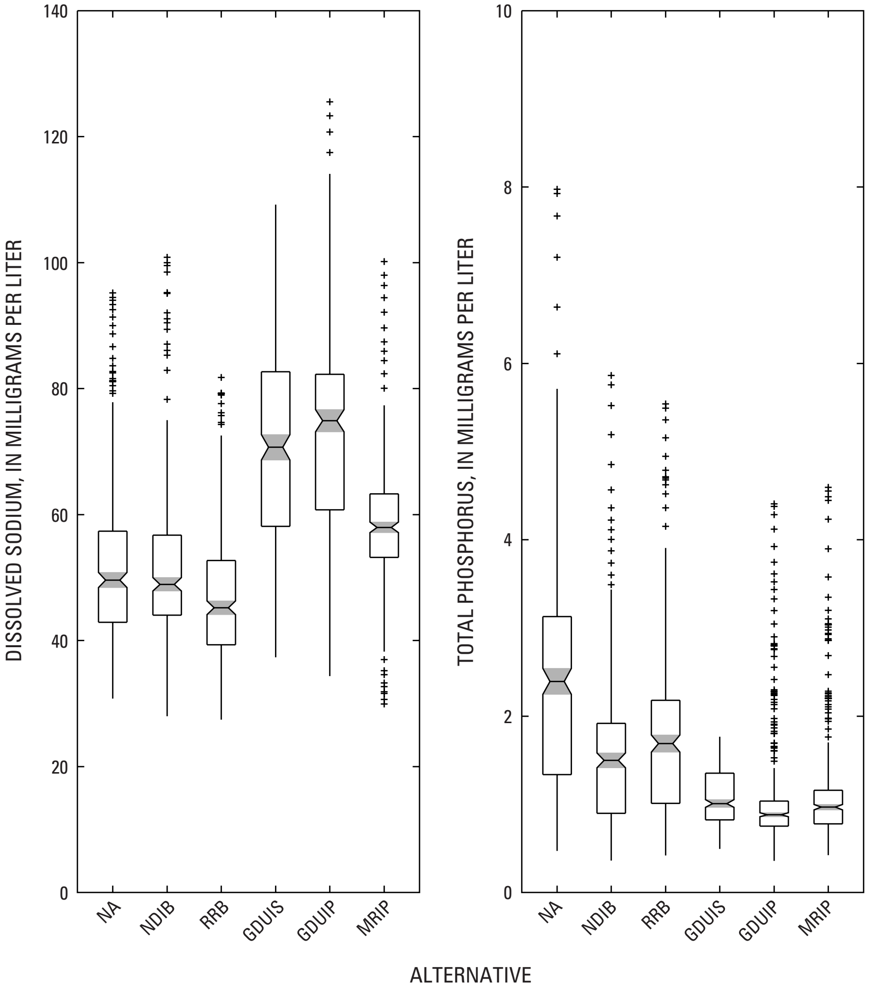
Missouri River Import to Red River Valley Alternative (MRIP)

Figure 13. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Emerson, Manitoba, 1976-77 simulation period.



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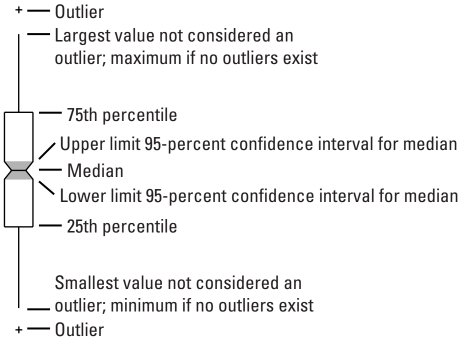

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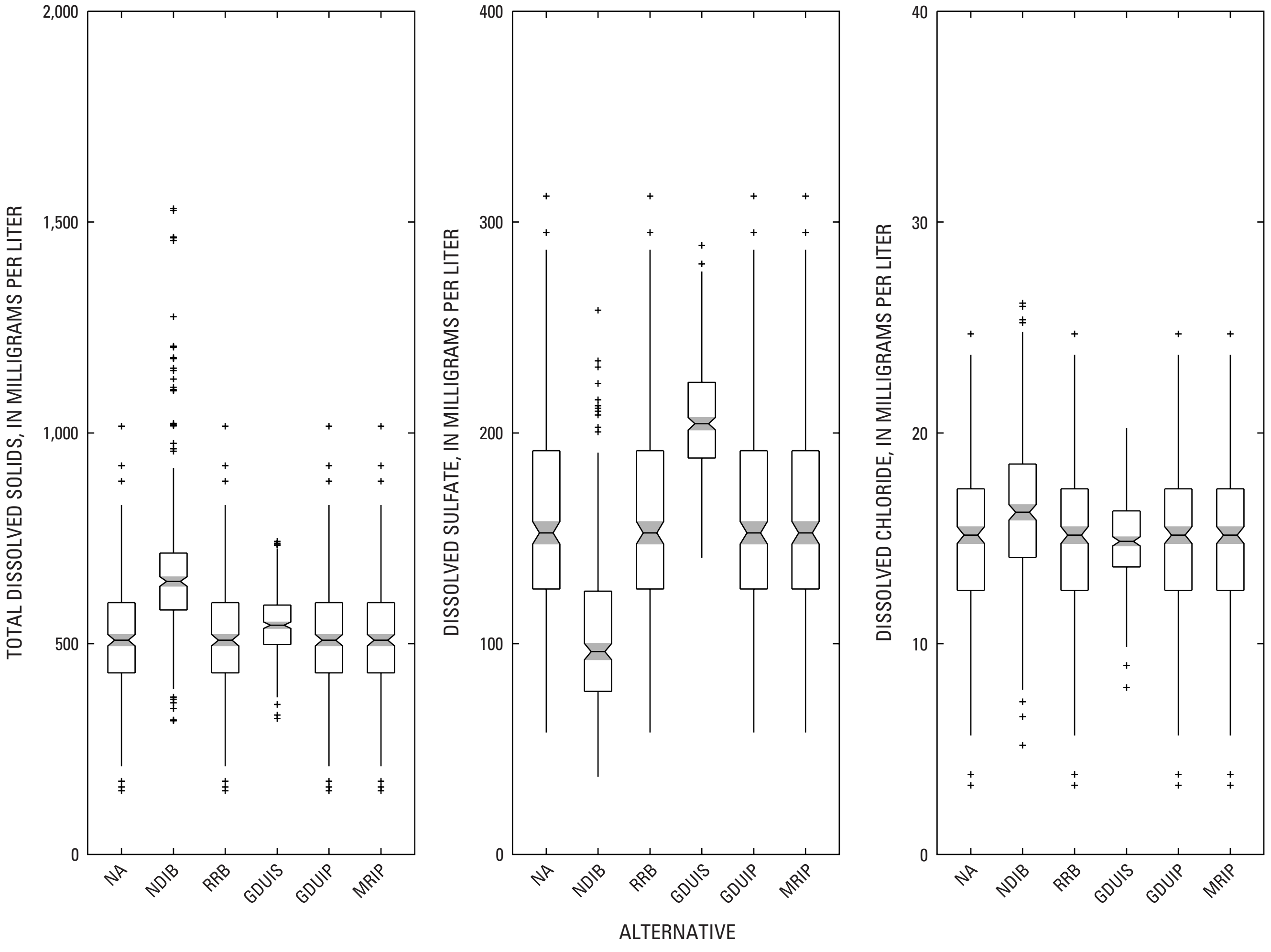
Figure 13. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at Emerson, Manitoba, 1976-77 simulation period--Continued.



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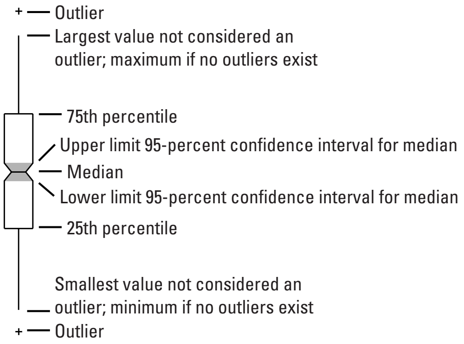

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Figure 14. Simulated annual concentration distribution of daily mean concentrations for the Sheyenne River below Baldhill Dam, North Dakota, 1976-77 simulation period.

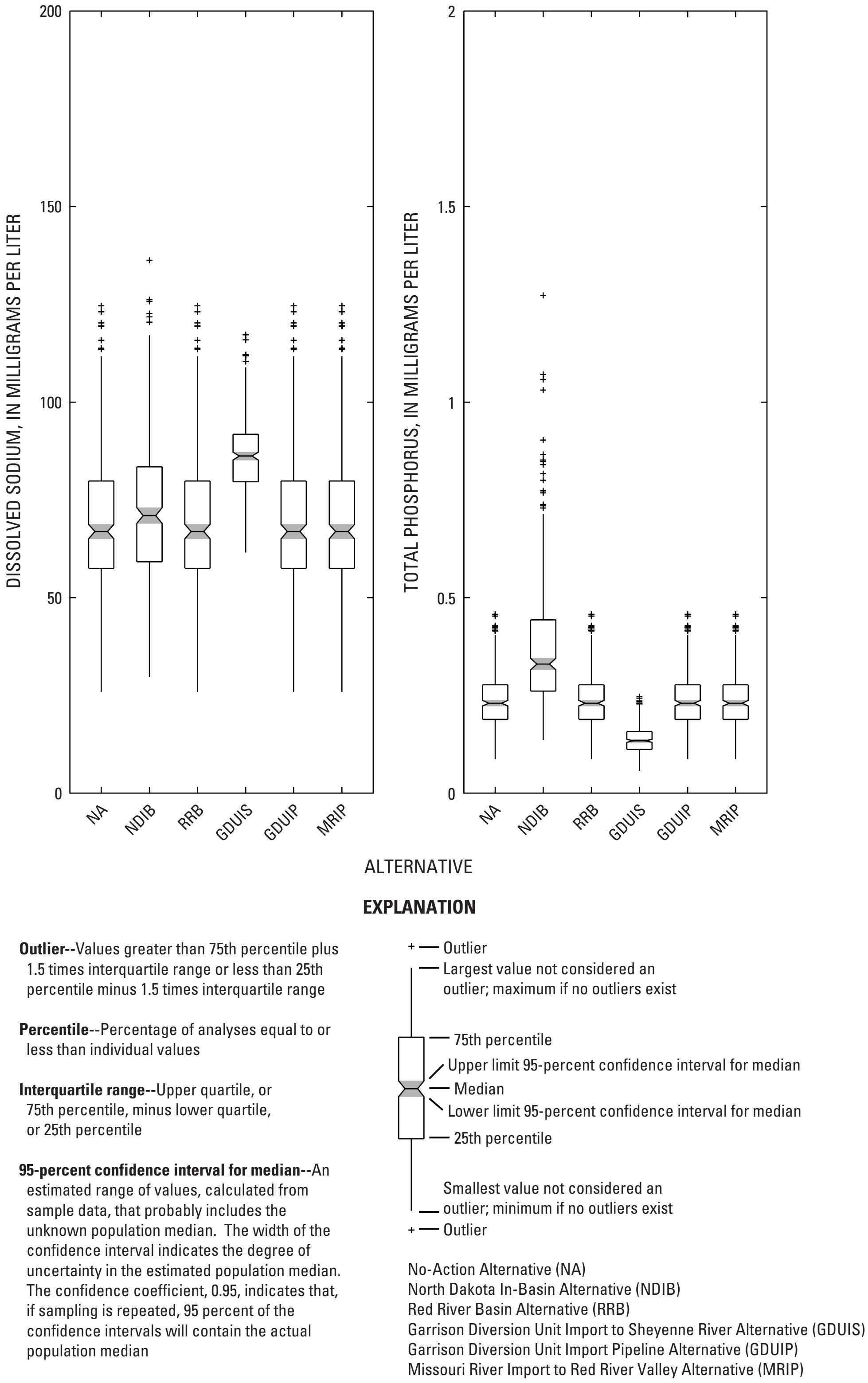

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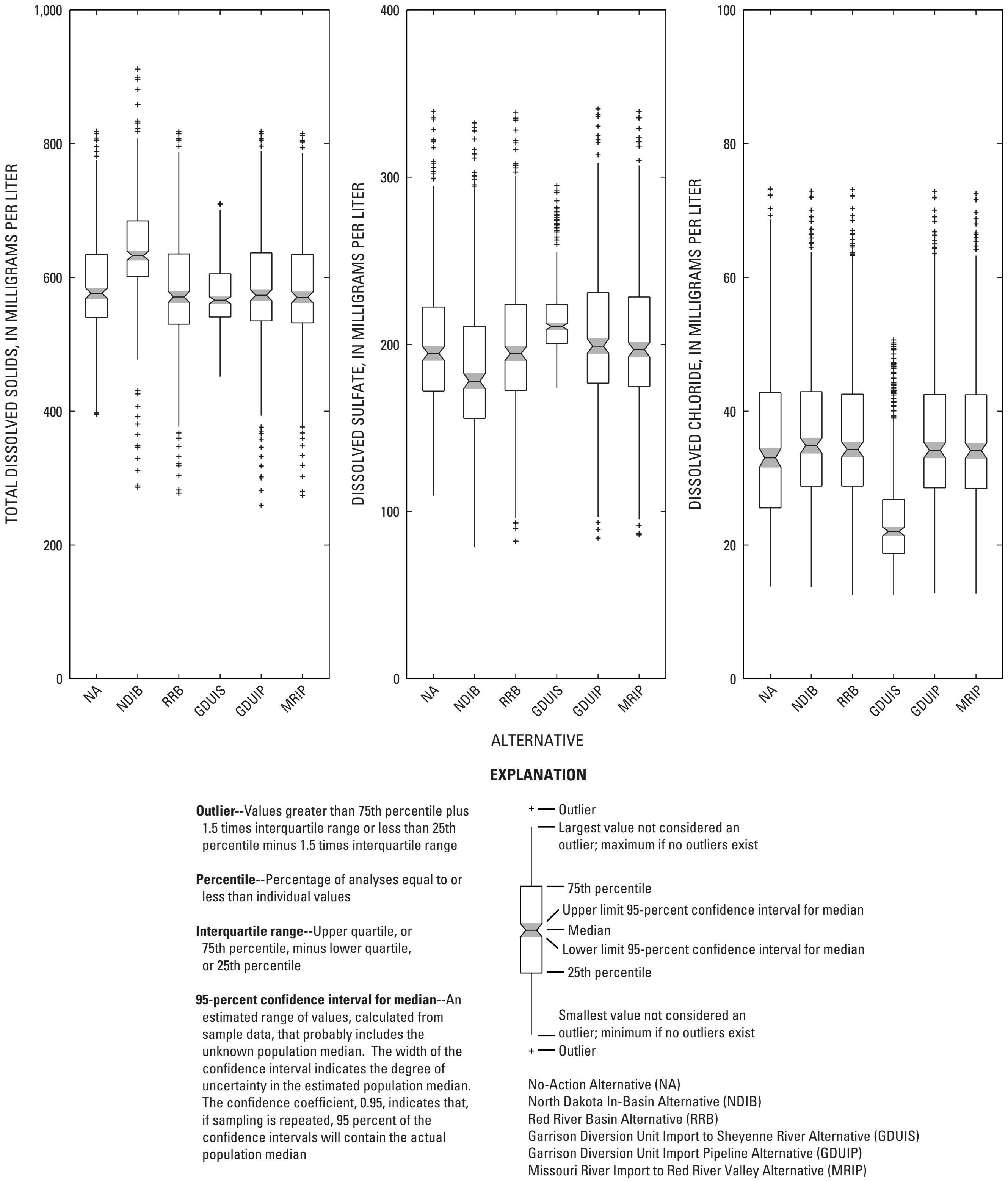
Figure 14. Simulated annual concentration distribution of daily mean concentrations for the Sheyenne River below Baldhill Dam, North Dakota, 1976-77 simulation period--Continued.



Outlier--Values greater than 75th percentile plus 1.5 times interquartile range or less than 25th percentile minus 1.5 times interquartile range

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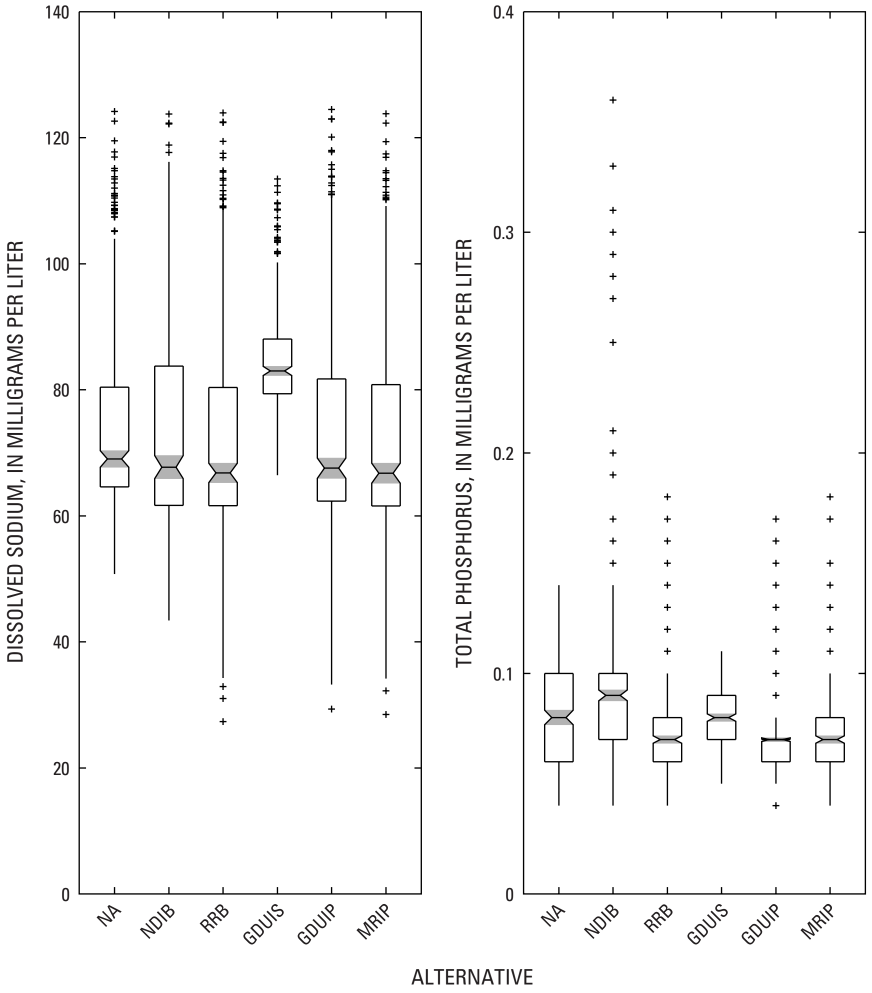
Figure 15. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at West Fargo, North Dakota, 1976-77 simulation period.



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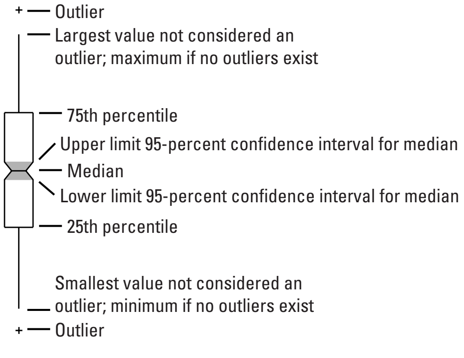

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Missouri River Import to Red River Valley Alternative (MRIP)

Figure 15. Simulated annual concentration distribution of daily mean concentrations for the Red River of the North at West Fargo, North Dakota, 1976-77 simulation period--Continued.

Simulated annual median concentrations for the Red River at river mile 536.3 are noticeably greater for the action alternatives than for the No-Action Alternative for all simulated constituents (fig. 10). This is because of the combination of smaller return flows and lower return flow concentrations for Wahpeton Industrial with the No-Action Alternative than with the action alternatives. In StateMod, the No-Action Alternative was the only alternative allowed to have water shortages, and, for the No-Action Alternative, an approximate 75-percent shortage occurred in the water supply for Wahpeton Industrial (D. Goetzfried, Bureau of Reclamation, oral commun., 2006). This water shortage corresponds to the smaller return flows for Wahpeton Industrial with the No-Action Alternative and the Red River model. The action alternatives had a larger native-water-to-return-flow ratio than the No-Action Alternative. In addition, average return flow concentrations for Wahpeton Industrial for the No-Action Alternative were lower than those for the action alternatives because source waters used to compute return flow concentrations did not contain any ground water that had elevated constituent concentrations.

Simulated annual median concentrations for the Red River at Fargo, N. Dak., are statistically greater for the action alternatives than for the No-Action Alternative for all constituents except sodium (fig. 11). The higher annual median concentrations for the action alternatives are a result of the return flow assumptions previously discussed for the No-Action Alternative. Simulated annual median sodium concentrations for the North Dakota In-Basin Alternative and the Red River Basin Alternative are not statistically different from that for the No-Action Alternative. The relatively high sodium concentrations contributed from ungaged local inflows to the Red River at Fargo resulted in median concentrations that are similar for all alternatives.

Return flows for Fargo, N. Dak., and Moorhead, Minn., and for several tributaries, including the Sheyenne River and Red Lake River, enter the Red River between Fargo and Grand Forks, N. Dak. In general, the interquartile ranges for the Red River at Grand Forks are small and maximum concentrations are low relative to those for other sites (fig. 12) largely because of the inflow of relatively good quality water from the Red Lake River. Relative differences between simulated concentrations for the No-Action Alternative and the action alternatives for the Red River at Grand Forks are affected by return flows for Fargo and Moorhead. Simulated annual median total dissolved solids, sulfate, chloride, and sodium concentrations for the Garrison Diversion Unit Import to Sheyenne River Alternative, Garrison Diversion Unit Import Pipeline Alternative, and Missouri River Import to Red River Valley Alternative are statistically greater than the corresponding annual median concentrations for the No-Action Alternative. These differences are the result of the upstream return flows for Wahpeton Industrial for the No-Action Alternative and the large constituent loads from return flows for Fargo and Moorhead. For example, the combined sodium load from return flows for Fargo and Moorhead for the Garrison Diversion Unit Import Pipeline Alternative is nearly triple that for the No-Action Alternative. Simulated annual median total dissolved solids, sulfate, sodium, and total phosphorus concentrations for the Red River Basin Alternative are either not statistically different from or are less than those for the No-Action Alternative. Constituent loads from Fargo and Moorhead return flows are, again, the reason for this result. For example, the combined sulfate load from Fargo and Moorhead for the Red River Basin Alternative is 28 percent less than that for the No-Action Alternative. Simulated annual median total dissolved solids, sulfate, and total phosphorus concentrations for the North Dakota In-Basin Alternative are less than those for the No-Action Alternative. This is, again, the result of considerably smaller loads from return flows for Fargo and Moorhead for the North Dakota In-Basin Alternative than for the No-Action Alternative.

Generally, the three interbasin alternatives resulted in an increase in simulated annual median total dissolved solids, sulfate, and sodium concentrations for the Red River at Emerson, Manitoba, relative to those for the No-Action Alternative (fig. 13). In contrast, the North Dakota In-Basin Alternative and the Red River Basin Alternative either had no effect on the simulated annual median total dissolved solids, sulfate, and sodium concentrations or caused a reduction in the concentrations relative to those for the No-Action Alternative. Of the action alternatives, two had a slight effect on annual median chloride concentrations relative to the No-Action Alternative. The interquartile ranges for chloride and the annual median chloride concentrations for all alternatives are similar. This similarity probably is a result of water contributed from the Forest and Park Rivers to the Red River between Grand Forks, N. Dak., and Emerson. Water in the Forest and Park Rivers is poor in quality, primarily as a result of ground-water discharge, and those tributaries contribute large chloride loads to the Red River within the Red River at Grand Forks to Red River at Emerson reach. For example, about half of the chloride load in the reach between Grand Forks and Emerson is attributed to the Forest and Park Rivers. Simulated annual median total phosphorus concentrations for all action alternatives are significantly less than that for the No-Action Alternative. Simulated total phosphorus concentrations are controlled largely by return flow concentrations from Grand Forks. The simulated total phosphorus load for the return flow for Grand Forks for the No-Action Alternative was between 140 and 240 percent greater than the loads for the action alternatives. The source water at Grand Forks for the No-Action Alternative was assumed to be dominated by return flows for Fargo, N. Dak., and Moorhead, Minn., thus causing a compounding effect on concentrations for the return flow for Grand Forks. The action alternatives had additional source water that diluted the return flows for Fargo and Moorhead.

Simulated concentrations for the Sheyenne River below Baldhill Dam, N. Dak., represent the effects of mixing of upstream boundary conditions for branch 2 with the concentrations for one model segment downstream from the dam. As previously noted, the same time series of stochastically generated boundary conditions for the Sheyenne River below Baldhill Dam was used for the No-Action Alternative, the Red River

Basin Alternative, the Garrison Diversion Unit Import Pipeline Alternative, and the Missouri River Import to Red River Valley Alternative, but a different set of boundary conditions, which takes into account inputs from Lake Ashtabula, was used for the North Dakota In-Basin Alternative and the Garrison Diversion Unit Import to Sheyenne River Alternative. Therefore, all simulated annual median constituent concentrations for the Red River Basin Alternative, the Garrison Diversion Unit Import Pipeline Alternative, and the Missouri River Import to Red River Valley Alternative are the same as those for the No-Action Alternative (fig. 14). The North Dakota In-Basin Alternative had no statistically significant effect on simulated annual median sodium concentrations but resulted in a statistically significant increase in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative. Simulated annual median sulfate concentrations are lower for the North Dakota In-Basin Alternative than for the No-Action Alternative. The Garrison Diversion Unit Import to Sheyenne River Alternative either had no effect on or caused a decrease in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative. Simulated annual median sulfate and sodium concentrations are greater for the Garrison Diversion Unit Import to Sheyenne River Alternative than for the No-Action Alternative.

Boundary conditions within the Sheyenne River below Baldhill Dam, N. Dak., to Sheyenne River at West Fargo, N. Dak., reach were the same for all alternatives. As a result, the Red River Basin Alternative, the Garrison Diversion Unit Import Pipeline Alternative, and the Missouri River Import to Red River Valley Alternative had no statistically significant effect on simulated annual median total dissolved solids, sulfate, chloride, and sodium concentrations relative to those for the No-Action Alternative for the Sheyenne River at West Fargo (fig. 15). In contrast, those alternatives caused a decrease in simulated annual median total phosphorus concentrations relative to those for the No-Action Alternative. This decrease is a result of less streamflow in the Sheyenne River for those alternatives than for the No-Action Alternative. The smaller amounts of streamflow resulted in a longer traveltime and, thus, more time for phosphorus decay. The North Dakota In-Basin Alternative either had no statistically significant effect on or caused a decrease in simulated annual median sulfate, chloride, and sodium concentrations relative to those for the No-Action Alternative. Simulated annual median total dissolved solids and total phosphorus concentrations are statistically higher for the North Dakota In-Basin Alternative than for the No-Action Alternative. The Garrison Diversion Unit Import to Sheyenne River Alternative either had no effect on or caused a decrease in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative. Simulated annual median sulfate and sodium concentrations for that alternative increased relative to those for the No-Action Alternative.

Annual constituent loads for the Red River at Emerson, Manitoba, were estimated from simulated concentrations and streamflows for each alternative (table 13). Except for total phosphorus, simulated loads for the Garrison Diversion Unit Import to Sheyenne River Alternative were about 20 to 40 percent greater than those for the No-Action Alternative. This difference resulted, in part, from the minimum instream flow for aquatic life that was incorporated into the Garrison Diversion Unit Import to Sheyenne River Alternative. The minimum instream flow resulted in streamflows that were about 14 percent higher for the Garrison Diversion Unit Import to Sheyenne River Alternative than those for the No-Action Alternative. In general, the simulated annual loads for total dissolved solids, sulfate, and sodium were higher for alternatives that include interbasin transfer of water than for the No-Action Alternative. For the North Dakota In-Basin Alternative, loads for all constituents were either less than or about the same as those for the No-Action Alternative. This corresponds, in part, to the lower streamflows for that alternative in relation to those for the No-Action Alternative.

Annual constituent loads for the Red River at Emerson, Manitoba, were estimated using LOADEST and available historical data (Runkel and others, 2004) for comparison with the September 1976 through August 1997 simulated loads. Water-quality data for the Red River at Emerson were unavailable before 1978, so the annual loads (by water year) were estimated for 1978-2001. Those loads were used for comparison with simulated September 1976 through August 1977 loads for the six water-supply alternatives.

Between 1978 and 2000, the largest estimated annual load for all constituents occurred in 1997 when annual runoff for the Red River at Emerson, Manitoba, was 9,285,000 acre-ft (table 14). Annual runoff for the Red River at Emerson during water year 1997 was the highest on record. The smallest estimated annual load for sulfate and sodium occurred in 1981 when annual runoff for the Red River at Emerson was 875,900 acre-ft, and the smallest estimated annual load for total dissolved solids, chloride, and total phosphorus occurred in 1990 when annual runoff for the Red River at Emerson was 727,000 acre-ft. The annual runoffs for 1981 and 1990 were each almost double the annual runoff of 436,700 acre-ft for 1977. The long-term mean annual runoff for the Red River at Emerson is 2,897,000 acre-ft, and the lowest annual runoff between 1912 and 2005 occurred in 1934. A comparison of estimated loads for 1981 and 1990 and simulated loads for 1976-77 indicates the simulated loads for the water-supply alternatives generally are within the range of historical loads and, thus, seem reasonable. Total phosphorus loads for the alternatives are noticeably higher than the upper limit 95-percent confidence interval for 1990, but total phosphorus loads are well below the average estimated annual load for 1978-2001.

Simulated results for the six water-supply alternatives are affected by return flow concentrations. This is illustrated by the total phosphorus loads and concentrations for the No-Action Alternative relative to those for the action alternatives for the Red River at Emerson, Manitoba (table 13, fig. 13). Total phosphorus loads are much greater for the No-Action Alternative relative to those for the action alternatives as a result of the

Table 13. Annual constituent loads for the Red River of the North at Emerson, Manitoba, for water-supply alternatives.

[Simulated annual runoff for 1976-77 was 471,600 acre-feet for the No-Action Alternative, 457,100 acre-feet for the North Dakota In-Basin Alternative, 475,600 acre-feet for the Red River Basin Alternative, 535,600 acre-feet for the Garrison Diversion Unit Import to Sheyenne River Alternative, 515,000 acre-feet for the Garrison Diversion Unit Import Pipeline Alternative, and 527,200 acre-feet for the Missouri River Import Pipeline to Red River Valley Alternative]

Constituent	Annual load[1] (tons)					
	No-Action Alternative	North Dakota In-Basin Alternative	Red River Basin Alternative	Garrison Diversion Unit Import to Sheyenne River Alternative	Garrison Diversion Unit Import Pipeline Alternative	Missouri River Import Pipeline to Red River Valley Alternative
Total dissolved solids	291,000	278,000	290,000	351,000	335,000	328,000
Dissolved sulfate	108,000	84,600	93,800	149,000	150,000	133,000
Dissolved chloride	28,500	29,500	28,700	33,400	32,300	28,900
Dissolved sodium	32,800	31,700	31,000	47,000	46,000	40,100
Total phosphorus	1,110	744	856	740	640	741

[1] Simulated concentrations and streamflows from the Red River model were used to estimate annual constituent loads.

assumption that, for the No-Action Alternative, source water to Grand Forks, N. Dak., is dominated by return flows for Fargo, N. Dak., and Moorhead, Minn. Thus, the native-water-to-return-flow ratio was smaller for the action alternatives than for the No-Action Alternative, causing return flows for Grand Forks to have elevated total phosphorus concentrations. Effects of the water-supply alternatives on water quality in the Red River and Sheyenne River can be grouped by the source of the water transfer. For instance, alternatives that involve the transfer of water from within the Red River Basin (the North Dakota In-Basin Alternative and the Red River Basin Alternative) tended to have total dissolved solids, sulfate, sodium, and total phosphorus loads and concentrations that were about the same or less than those for the No-Action Alternative (table 13, figs. 10 through 15). In contrast, alternatives that involve the transfer of water from the Missouri River Basin (the Garrison Diversion Unit Import to Sheyenne River Alternative, the Garrison Diversion Unit Import Pipeline Alternative, and the Missouri River Import to Red River Valley Alternative) tended to have higher sulfate and sodium loads and concentrations than those for the No-Action Alternative (table 13, figs. 10 through 15). These tendencies seem reasonable because the Missouri River tends to have higher sulfate and sodium concentrations than the Red River. The historical median sulfate concentration of 172 mg/L for the Missouri River at Bismarck, N. Dak., is much larger than the historical median sulfate concentration of 61 mg/L for the Red River at Fargo (M. Deutschman, Houston Engineering, written commun., 2006). The historical median sodium concentration for the Missouri River at Bismarck is 59 mg/L, and the historical median for the Red River at Fargo is 14 mg/L (M. Deutschman, Houston Engineering, written commun., 2006).

Model Limitations

Although the Red River model includes several limitations and assumptions, the model provides insight into the effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River. Stochastically generated concentrations for upstream and tributary boundary conditions were used in the Red River model because a time series of historical data was unavailable and because too few historical data were available to develop water-quality boundary conditions deterministically through flow-concentration relations. The use of stochastically generated concentrations introduced certain limitations relative to interpretation of the results. The time series of simulated concentrations for the modeled alternatives was not used in the analysis of the effects of the various water-supply alternatives, and conclusions could not be made about the seasonal effects of the various alternatives on concentrations. As a result, the simulated annual median concentrations for each alternative were compared to determine if a selected alternative was expected to result in a change relative to the No-Action Alternative.

Table 14. Maximum, minimum, and average estimated annual constituent loads for the Red River of the North at Emerson, Manitoba, for 1978-2001.

[Annual runoff was 727,000 acre-feet for water year 1990, 875,900 acre-feet for water year 1981, and 9,285,000 acre-feet for water year 1997]

Constituent	Year in which maximum occurred	Year in which minimum occurred	Maximum annual load (tons)			Minimum annual load (tons)			Average annual load (tons)		
			Annual load	Lower limit 95-percent confidence interval	Upper limit 95-percent confidence interval	Annual load	Lower limit 95-percent confidence interval	Upper limit 95-percent confidence interval	Annual load	Lower limit 95-percent confidence interval	Upper limit 95-percent confidence interval
Total dissolved solids	1997	1990	5,070,000	4,490,000	5,720,000	486,000	494,000	544,000	2,170,000	2,120,000	2,210,000
Dissolved sulfate	1997	1981	1,570,000	1,210,000	2,000,000	109,000	97,800	122,000	570,000	544,000	597,000
Dissolved chloride	1997	1990	276,000	211,000	354,000	60,200	54,000	69,800	144,000	138,000	150,000
Dissolved sodium	1997	1981	327,000	266,000	398,000	51,200	47,500	57,000	152,000	147,000	157,000
Total phosphorus	1997	1990	6,330	3,510	10,500	192	224	312	1,740	1,540	1,940

Total phosphorus concentrations for the ungaged local inflows were estimated in the same manner as the concentrations for the conservative constituents (eq. 4). Because equation 4 does not take into account first-order decay, total phosphorus concentrations for the ungaged local inflows were slightly underestimated. To account for first-order decay, equation 4 could have been modified to the following equation:

$$C = \frac{DS_{X+L}\,C_{DS} - (US_X C_{US} e^{-kL} + I_{X+T} C_I e^{-k(L-T)} - W_X C_W)}{Q_{X+A} e^{-k(L-A)}} \qquad (6)$$

where

k is the first-order decay coefficient as in equation 5.

Equation 6 accounts for the decay of total phosphorus according to the various lag times. The available time for the upstream input to decay before reaching the downstream point is L days. Similarly, the available times for known tributary inputs and ungaged inputs to decay before reaching the downstream point are $L - T$ and $L - A$, respectively. If all lag times are zero or if no decay occurred, $k = 0$; then, e^0 is equal to 1.0 and equation 6 reverts to equation 4. A difficulty in using equation 6 is that an iterative process would be required because the calibrated value of k must be known before the concentrations for the ungaged local inflows are estimated. Also, equation 6 noticeably increases the estimated concentrations only if the lag times are substantial in relation to the reactive time scale of the nonconservative constituent. For total phosphorus in these simulations, a reasonable reactive time scale can be approximated by its first-order half-life. If, for example, a decay coefficient of 0.2 d^{-1} was applied, the first-order half-life would be 3.5 days. This reactive time scale is substantial in comparison to a typical lag time $(L - A)$ of 2 days (table 6). In equation 6, if a decay coefficient of 0.2 d^{-1} and a lag time of 2 days are used, the $e^{-k(L-A)}$ in the denominator alone would cause the concentrations for the ungaged local inflows to be underestimated by 50 percent. However, for the Red River model, where decay coefficients of 0.01 d^{-1} and 0.05 d^{-1} were applied, the first-order half-life of phosphorus was 69 and 14 days, respectively. Those values are not substantial relative to the typical lag time of 2 days. As a result, for decay coefficients of 0.01 d^{-1} and 0.05 d^{-1} and a lag time of 2 days in equation 6, $e^{-k(L-A)}$ in the denominator causes the concentrations for the ungaged local inflows to be slightly underestimated at 2 and 10 percent, respectively. These percentages are considered to be within the acceptable error for a measured sample.

Many of the Red River model limitations that have been discussed could be eliminated by a consistent long-term water-quality data set that could be used to provide known boundary conditions for the model. This data set could allow for more constituents to be simulated and could allow for more realistic simulation of the transport of nonconservative constituents.

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, the Dakota Water Resources Act of 2000 authorized a comprehensive study of 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. Of those eight alternatives, two were removed from consideration for this study. Of the remaining six alternatives, three include the interbasin transfer of water.

To address concerns of stakeholders and to provide information for an environmental impact statement, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, developed and applied a water-quality model to simulate the transport of total dissolved solids, sulfate, chloride, sodium, and total phosphorus during unsteady-flow conditions and to simulate the effects of the six water-supply alternatives on water quality in the Red River and the Sheyenne River. The model, hereinafter referred to as the Red River model, was developed using the RIV1 modeling system, which is a one-dimensional (cross-sectionally averaged), hydrodynamic, water-quality model originally released in 1991 by the U.S. Army Corps of Engineers, Waterways Experiment Station, as CE-QUAL-RIV1. The RIV1 modeling system was updated to run in a Windows environment in 2002 and subsequently was called EPD-RIV1. The EPD-RIV1 modeling system, which includes a pre- and post-processor to facilitate model application and data analysis, was used in this study.

The physical domain of the Red River model includes the Red River from Wahpeton, North Dakota, to Emerson, Manitoba, and the Sheyenne River from below Baldhill Dam, North Dakota, to the confluence with the Red River. Inputs to the model included gaged inflows from the Sheyenne River and 12 tributaries to the Red River, ungaged local inflows for 10 ungaged areas, return flows from 6 point-source wastewater-treatment facilities, and withdrawals from 3 water-treatment facilities.

Boundary conditions were specified for May 15 through October 31, 2003, and January 15 through June 30, 2004. The first 2.5 months were used as an initialization period. Data obtained from long-term records of streamflow for 27 stream gage sites were used as boundary conditions for model calibration and testing. Water-quality data for model calibration and testing were collected at selected stream gage sites as well as at six ungaged sites during September 2003 when streamflows were low and steady and May 2004 when streamflows were medium and unsteady. Measured streamflow data were available for August 1 through October 31, 2003, and April 1 through June 30, 2004 (the calibration periods), but water-quality data were available only for September 15 through 16, 2003, and May 10 through 13, 2004. The water-quality boundary conditions were assumed to be time invariant for the entire calibration period and to be equal to the measured value.

The Red River model was calibrated by adjusting selected boundary conditions, model parameters, and channel-geometry data to obtain reasonable agreement between measured and simulated streamflows and concentrations. Streamflow was calibrated by adjusting model parameters, channel geometry, estimates of ungaged local inflows, and Manning's *n* to obtain reasonable agreement between measured and simulated values. The estimates (both timing and magnitude) of the ungaged local inflows to the Red River and the Sheyenne River had a large effect on simulated streamflows. Simulated streamflows for selected model calibration points were in reasonable agreement with measured streamflows for the 2003 (low-flow) and 2004 (medium-flow) calibration periods. The average difference between the measured and simulated streamflows was less than 4 percent for both periods, and most differences were less than 2 percent. In general, streamflows for the 2003 calibration period were somewhat underpredicted, and streamflows for the 2004 calibration period were slightly overpredicted. However, the average differences between the measured and simulated streamflows are considered to be acceptable because the differences are less than 5 percent, or the same as the error that would be expected in a typical streamflow measurement. Further refinement of local inflow estimates probably would improve predictions, but these refinements are not justified by the relatively small streamflow prediction errors or by the future intended application of the model.

For the water-quality calibration, constituent concentrations for the ungaged local inflows were estimated and two model variables, the dispersion coefficient and a first-order decay coefficient for total phosphorus, were adjusted. The constituent concentrations for the ungaged local inflows were estimated using a modified version of the equation used to calculate ungaged local inflow. The estimated concentrations for the ungaged local inflows then were compared to ranges of historical measured constituent concentrations. Except for two reaches, the estimated concentrations for the 2003 calibration period generally were within the range of historical concentrations for the tributaries within each reach. For the two exceptions, the median historical measured concentration was used as the estimated concentration for the ungaged local inflow. For the 2004 calibration period, the estimated concentrations also generally were within the range of historical concentrations.

Total dissolved solids concentrations generally were underpredicted for both calibration periods. The average difference between the measured and simulated concentrations was -9.9 percent for the 2003 calibration period and -5.5 percent for the 2004 calibration period. Sulfate concentrations also generally were underpredicted for both calibration periods. The average absolute differences, 19 and 21 percent for the 2003 and 2004 calibration periods, respectively, were about double the average absolute percent differences for total dissolved solids. Chloride and sodium concentrations generally were underpredicted for both calibration periods, and the patterns for both constituents were similar. For the 2003 calibration period, the average absolute difference for chloride, 11 mg/L, was about 27 percent of the average measured concentration, and the average absolute difference for sodium, 12 mg/L, was about 16 percent of the average measured concentration. For the 2004 calibration period, the average absolute difference for chloride, 4 mg/L, was about 16 percent of the average measured concentration, and the average absolute difference for sodium, 6 mg/L, was about 14 percent of the average measured concentration. Total phosphorus was simulated as a nonconservative constituent by assuming that concentrations change according to a first-order decay rate. In RIV1Q, decay coefficients can be specified to vary seasonally and spatially by model branch and model segment. However, because too few data were available to justify varying the decay coefficient seasonally or by model segment, decay coefficients were varied by branch. Decay coefficients of 0.01 $d^{-1}$and 0.05 d^{-1}were determined for branch 1 (Red River) and branch 2 (Sheyenne River), respectively. The smaller decay coefficient for the Red River resulted in a smaller loss of total phosphorus than that for the Sheyenne River. The larger loss of total phosphorus for the Sheyenne River than for the Red River is supported by known physical and biological processes in the rivers. Total phosphorus concentrations generally were underpredicted for both calibration periods. The average difference between the measured and simulated concentrations was 6.2 percent for the 2003 calibration period and -24 percent for the 2004 calibration period.

Model testing was conducted to determine the effects of the small amount of water-quality data on model calibration. Because few water-quality data are available for the gaging locations used for the calibration, water-quality boundary conditions were not known. Therefore, time-invariant boundary conditions were used for the unsteady-flow simulations. The change from time-invariant boundary conditions to unsteady upstream boundary conditions had a large effect on the magnitude of simulated total dissolved solids concentrations for the Red River at Fargo, North Dakota, although the temporal distribution of total dissolved solids was similar for both sets of boundary conditions. Also because of the small amount of water-quality data, constituent concentrations for the ungaged local inflows were not known. Therefore, the concentrations were calculated using a simplified mass-balance approach. Simulations of chemical constituent concentrations during unsteady flow conditions are highly dependent on accurate estimates of the magnitude and timing of chemical loads. The method used to estimate the concentrations for the ungaged local inflows resulted in good agreement between measured and simulated streamflows, but, unlike for the water-quality boundary conditions, continuous records of streamflow were available to develop the estimates.

Model testing indicated that improved point-by-point agreement between measured and simulated concentrations can be obtained by adjusting boundary conditions for rivers, tributaries, and ungaged flows. Such a model, however, would be considered "overtuned" and would be applicable only to the very specific conditions for which the model was calibrated. The Red River model provided good simulations of streamflow throughout the model domain. Therefore, a reasonable assumption is that simulations made using more realistic and complete boundary condition information than used for this study would provide better results than those obtained during the study. Also, the Red River model demonstrates sensitivity to changes in boundary conditions so a reasonable assumption is that the model can be used to compare relative effects of various water-supply alternatives.

The calibrated Red River model was used to simulate the relative effects of the six water-supply alternatives identified by the Bureau of Reclamation on water quality in the Red River and the Sheyenne River. Boundary conditions were specified for April 1, 1976, through August 31, 1977. However, because April 1 through August 31, 1976, was used as an initialization period, simulation results for the alternatives were compared for September 1, 1976, through August 31, 1977. Streamflows throughout the Red River Basin during September 1976 through August 1977 were relatively low. Streamflows for the Red River at Fargo, North Dakota, were less than 17.9 cubic feet per second on 159 days of that 12-month period. Monthly average streamflows for the Red River at Grand Forks, North Dakota, and the Red River at Emerson, Manitoba, were less than 30 percent of the respective long-term average monthly streamflows for 11 of the 12 months between September 1976 and August 1977.

Streamflow boundary conditions for the water-supply alternative simulations were provided by the Bureau of Reclamation. The streamflows were generated by the Bureau of Reclamation using the surface-water model StateMod. StateMod was used to superimpose projected 2050 water demands on naturalized flows in the Red River Basin. The resulting flows and water-source volumes then were used to develop upstream streamflow boundary conditions and return flow boundary conditions and those results were used in the Red River model with September 1976 through August 1977 streamflows to simulate the effects of the alternatives on water quality in the Red River and the Sheyenne River. StateMod-generated monthly streamflows were disaggregated into daily streamflows for the Red River model by using daily patterns for 2006 withdrawals and streamflow. Monthly streamflow gains and losses produced by StateMod for each reach were used to represent ungaged local inflows. Because StateMod-generated streamflows were sometimes equal to zero, a minimal amount of streamflow was added upstream from the withdrawals on the Red River and the Sheyenne River to maintain numerical stability of the model. Limited sensitivity analysis indicated the additional water caused concentrations immediately downstream from where the additional streamflows were input to be reduced by about 1 to 5 percent.

Constituent concentrations for upstream boundary conditions, tributaries, and return flows for all water-supply alternatives were provided by an engineering consulting firm under contract to the Bureau of Reclamation. Water-quality boundary conditions were generated using a stochastic approach in which probability distributions derived from all available historical data on instream concentrations were used to produce daily concentrations for model boundaries. Return flow concentrations were estimated from source concentrations and current (2006) wastewater-treatment technology. Because no historical information on ungaged local inflow concentrations is available to estimate those boundary conditions, time-invariant concentrations for the low-flow 2003 calibration period were used as the ungaged local inflow boundary conditions.

The effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River were evaluated by comparing the effects of five of the alternatives relative to the No-Action Alternative. Simulated annual median concentrations for the Red River at river mile 536.3, downstream from Wahpeton, North Dakota, are noticeably greater for the action alternatives than for the No-Action Alternative for all simulated constituents. This results from the combination of smaller return flows and lower return flow concentrations for Wahpeton Industrial with the No-Action Alternative than with the action alternatives. Simulated annual median concentrations for the Red River at Fargo, North Dakota, are statistically greater for the action alternatives than for the No-Action Alternative for all constituents except sodium. The relatively high sodium concentrations contributed from ungaged local inflows to the Red River at Fargo resulted in median concentrations that are similar for all alternatives.

Return flows for Fargo, North Dakota, and Moorhead, Minnesota, and inflow from the Red Lake River affect simulated concentrations for the Red River at Grand Forks, North Dakota. In general, the interquartile ranges for the Red River at Grand Forks are small and maximum concentrations are low relative to those for other sites largely because of the inflow of relatively good quality water from the Red Lake River. For the Red River at Grand Forks, simulated annual median total dissolved solids, sulfate, chloride, and sodium concentrations for the Garrison Diversion Unit Import to Sheyenne River, Garrison Diversion Unit Import Pipeline, and Missouri River Import to Red River Valley Alternatives are greater than the corresponding annual median concentrations for the No-Action Alternative. For the Red River Basin Alternative, simulated annual median total dissolved solids, sulfate, sodium, and total phosphorus concentrations are either not statistically different from or are less than those for the No-Action Alternative. For the North Dakota In-Basin Alternative, simulated annual median total dissolved solids, sulfate, and total phosphorus concentrations are less than those for the No-Action Alternative. The differences between the action alternatives and the No-Action Alternative are largely the result of return flows for Fargo and Moorhead.

For the Red River at Emerson, Manitoba, the three interbasin alternatives resulted in an increase in simulated annual median total dissolved solids, sulfate, and sodium concentrations relative to those for the No-Action Alternative. In contrast, the North Dakota In-Basin and Red River Basin Alternatives either had no effect on the simulated annual median total dissolved solids, sulfate, and sodium concentrations or caused a reduction in the concentrations relative to those for the No-Action Alternative. The interquartile ranges for chloride and the annual median chloride concentrations for all alternatives are similar, probably as a result of poor quality water from tributaries between Grand Forks, North Dakota, and Emerson. Because of assumptions about the return flow concentrations for Grand Forks, simulated annual median total phosphorus concentrations for the Red River at Emerson for all action alternatives are significantly less than that for the No-Action Alternative.

For the Sheyenne River below Baldhill Dam, North Dakota, simulated annual median constituent concentrations for the Red River Basin, Garrison Diversion Unit Import Pipeline, and Missouri River Import to Red River Valley Alternatives are the same as those for the No-Action Alternative because those alternatives have no effect on Lake Ashtabula water quality. The North Dakota In-Basin Alternative resulted in a statistically significant increase in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative. The Garrison Diversion Unit Import to Sheyenne River Alternative either had no effect on or caused a decrease in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative.

Because boundary conditions within the Sheyenne River below Baldhill Dam, North Dakota, to Sheyenne River at West Fargo, North Dakota, reach were the same for all alternatives, simulated annual median total dissolved solids, sulfate, chloride. and sodium concentrations for the Sheyenne River at West Fargo for the Red River Basin, Garrison Diversion Unit Import Pipeline, and Missouri River Import to Red River Valley Alternatives are not statistically different from those for the No-Action Alternative. In contrast, because of longer traveltime, those alternatives caused a decrease in simulated annual median total phosphorus concentrations. The North Dakota In-Basin Alternative either had no statistically significant effect on or caused a decrease in simulated annual median sulfate, chloride, and sodium concentrations relative to those for the No-Action Alternative, and simulated annual median total dissolved solids and total phosphorus concentrations for the North Dakota In-Basin Alternative are statistically higher than those for the No-Action Alternative. The Garrison Diversion Unit Import to Sheyenne River Alternative either had no effect on or caused a decrease in simulated annual median total dissolved solids, chloride, and total phosphorus concentrations relative to those for the No-Action Alternative. Simulated annual median sulfate and sodium concentrations for that alternative increased relative to those for the No-Action Alternative.

Except for total phosphorus, simulated constituent loads for the Red River at Emerson, Manitoba, for the Garrison Diversion Unit Import to Sheyenne River Alternative were about 20 to 40 percent greater than those for the No-Action Alternative. This difference resulted, in part, from the minimum instream flow for aquatic life that was incorporated into the Garrison Diversion Unit Import to Sheyenne River Alternative. In general, the simulated annual loads for total dissolved solids, sulfate, and sodium were higher for alternatives that include interbasin transfer of water than for the No-Action Alternative. Because of lower streamflows for the North Dakota In-Basin Alternative in relation to those for the No-Action Alternative, loads for all constituents were either less than or about the same as those for the No-Action Alternative.

Annual constituent loads for the Red River at Emerson, Manitoba, were estimated for 1978-2001 using LOADEST and available historical data. Estimated constituent loads for 1981 and 1990, years with little annual runoff, were compared to simulated loads for 1976-77 for the six water-supply alternatives. The comparison indicates the simulated loads generally are within the range of historical loads, and, thus, seem reasonable. Total phosphorus loads for the alternatives are noticeably higher than the upper limit 95-percent confidence interval for 1990, but total phosphorus loads are well below the average estimated annual load for 1978-2001.

Simulated results for the six water-supply alternatives are affected by return flow concentrations. This is illustrated by the total phosphorus loads and concentrations for the No-Action Alternative relative to those for the action alternatives for the Red River at Emerson, Manitoba. Effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River can be grouped by the source of water transfer. Alternatives that involve the transfer of water from within the Red River Basin (the North Dakota In-Basin and Re River Basin Alternatives) tended to have total dissolved solids, sulfate, sodium, and total phosphorus concentrations that were about the same or less than those for the No-Action Alternative. In contrast, consistent with median sulfate and sodium loads and concentrations in the Missouri River, alternatives that involve the transfer of water from the Missouri River Basin (the Garrison Diversion Unit Import to Sheyenne River, Garrison Diversion Unit Import Pipeline, and Missouri River Import to Red River Valley Alternatives) tended to have higher sulfate and sodium loads and concentrations than those for the No-Action Alternative.

The Red River model includes several limitations and assumptions; however, the model provides insight into the effects of the water-supply alternatives on water quality in the Red River and the Sheyenne River. Because of few historical data, stochastically generated concentrations were used in the Red River model for boundary conditions. The use of stochastically generated concentrations limited interpretation of the results. The time-series of simulated concentrations for the modeled alternatives was not used in the analysis of the effects of the various water-supply alternatives, and conclusions could not be made about the seasonal effects of the various alternatives on concentrations. As a result, the simulated annual median concentrations for each alternative were compared to determine if a selected alternative was expected to result in a change relative to the No-Action Alternative. Total phosphorus concentrations for the ungaged local inflows were estimated in the same manner as the concentrations for the conservative constituents. As a result, total phosphorus concentrations for the ungaged local inflows were slightly underestimated at 2 and 10 percent. However, those percentages are considered to be within the acceptable error for a measured sample. A long-term water-quality data set could eliminate many of the Red River model limitations and could allow for more constituents to be simulated and for more realistic simulation of the transport of nonconservative constituents.

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