CALIBRATION, VERIFICATION, AND USE OF A WATER-QUALITY MODEL TO SIMULATE EFFECTS OF DISCHARGING TREATED WASTEWATER TO THE RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA

By Edwin A. Wesolowski

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4058

Prepared in cooperation with the
NORTH DAKOTA STATE DEPARTMENT OF HEALTH
AND CONSOLIDATED LABORATORIES

Bismarck, North Dakota
1994

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
821 East Interstate Avenue
Bismarck, ND 58501-1199

Copies of this report can be purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, CO 80225-0425

CONTENTS

ILLUSTRATIONS

Page

ILLUSTRATIONS, Continued

ILLUSTRATIONS, Continued

Page

TABLES

Page

CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
British thermal unit per square foot per hour [(BTU/ft^2)/hr]	0.2712	calorie per square centimeter per hour
British thermal unit per square foot per minute [(BTU/ft^2)/min]	0.2712	calorie per square centimeter per minute
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	1	meter per meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square foot (ft^2)	0.09290	square meter
square foot per second (ft^2/s)	0.0929	square meter per second
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 9/5°C + 32.

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °C = 5/9 (°F-32).

The following terms and abbreviations also are used in this report: gram (g), liter (L), meter (m), micrograms per liter (µg/L), microsiemens per centimeter (µS/cm), milligram (mg), milligrams per liter (mg/L), milliliter (mL), millimeter (mm), and nephelometric turbidity unit (NTU).

Calibration, Verification, and Use of a Water-Quality Model to Simulate Effects of Discharging Treated Wastewater to the Red River of the North at Fargo, North Dakota

By Edwin A. Wesolowski

Abstract

A 30.8-mile reach of the Red River of the North receives treated wastewater from plants at Fargo, North Dakota, and Moorhead, Minnesota, and streamflows from the Sheyenne River. A one-dimensional, steady-state, stream water-quality model, the Enhanced Stream Water Quality Model (QUAL2E), was calibrated and verified for summer streamflow conditions to simulate some of the biochemical processes that result from discharging treated wastewater into this reach of the river.

Data obtained to define the river's transport conditions are measurements of channel geometry, streamflow, traveltime, specific conductance, and temperature. Data obtained to define the river's water-quality conditions are measurements of concentrations of selected water-quality constituents and estimates of various reaction coefficients. Most of the water-quality data used to calibrate and verify the model were obtained during two synoptic samplings in August 1989 and August 1990.

The water-quality model simulates specific conductance, water temperature, dissolved oxygen, ultimate carbonaceous biochemical oxygen demand, total nitrite plus nitrate as nitrogen, total ammonia as nitrogen, total organic nitrogen as nitrogen, total phosphorus as phosphorus, and algal biomass as chlorophyll a. Of the nine properties and constituents that the calibrated model simulates, all except algae were verified. When increases in dissolved-oxygen concentration are considered, model sensitivity analyses indicate that dissolved-oxygen concentration is most sensitive to maximum specific algal growth rate. When decreases in dissolved-oxygen concentration are considered, model sensitivity analyses indicate that dissolved-oxygen concentration is most sensitive to point-source ammonia. Model simulations indicate nitrification and sediment oxygen demand consume most of the dissolved oxygen in the study reach.

The Red River at Fargo Water-Quality Model and the verification data set, including associated reaction-coefficient values as input, were used to simulate total ammonia as nitrogen, total nitrite plus nitrate as nitrogen, 5-day carbonaceous biochemical oxygen demand, and dissolved oxygen for water-quality conditions that result from three hypothetical boundary conditions. The model was applied to various combinations of three hypothetical waste loads when the headwater streamflow was either 50 or 75 cubic feet per second, when Fargo's wastewater-treatment plant outflow was either 15 or 37.8 cubic feet per second, and when total ammonia as nitrogen concentration of the outflow was either 5, 9, or 15 milligrams per liter. For each hypothetical waste load, at least one water-quality standard for either total ammonia as nitrogen, total nitrite plus nitrate as nitrogen, or dissolved oxygen was contravened, and, for one scenario, all three standards were contravened.

INTRODUCTION

Pursuant to Section 303(d) of the Clean Water Act, both North Dakota and Minnesota have identified the Red River of the North (hereafter referred to as the Red River) from Wahpeton, N. Dak., to its confluence with the Buffalo River near Georgetown, Minn.,--a distance of about 131 river miles (fig. 1)--as water-quality limited (Michael Ell, North Dakota State Department of Health and Consolidated Laboratories, oral commun., 1989). When a reach of a river has been identified as water-quality limited, the state is required to determine the total maximum daily load that can be discharged to that reach of the river from point and nonpoint sources without contravening water-quality standards (U.S. Environmental Protection Agency, Assessment and Watershed Protection Division, 1991). Within the reach of the Red River from Wahpeton to Georgetown, both point- and nonpoint-source discharges, including urban stormwater runoff, affect the water quality of the river. Currently (1992), both North Dakota and Minnesota require pollution discharge elimination system permits for point-source discharges. Permits currently (1992) are not required for nonpoint-source discharges, including stormwater runoff from municipalities with less than 100,000 population, such as Fargo. The single or combined effect of these sources on the water quality of the Red River in the Fargo-Moorhead area is unknown.

The potential of failing to meet water-quality standards is greatest during lower streamflows, higher stream temperatures, or both. Also, the potential of failing to meet water-quality standards is greatest in the downstream end of the water-quality limited reach in the Fargo-Moorhead area because of the point and nonpoint sources that discharge to the river. In the Fargo-Moorhead area, point sources include outflow from the wastewater-treatment plant at Fargo, N. Dak., the wastewater-treatment plant at Moorhead, Minn., and the American Crystal Sugar processing plant at Moorhead, Minn. Numerous storm sewers from Fargo and Moorhead also have outfalls to the river.

The city of Fargo is planning to expand and improve its wastewater-treatment plant. This expansion and improvement could result in a continuous discharge of treated wastewater to the Red River. Currently (1992), the city discharges treated wastewater to the river only during the open-water season. The potential change of operation could affect the city's future North Dakota Pollution Discharge Elimination System permit and gradually could change the biology of the river in the study reach.

In an attempt to develop a method to compare water quality before and after continuous wastewater discharge, the North Dakota State Department of Health and Consolidated Laboratories entered into a cooperative agreement with the U.S. Geological Survey to study the effects of discharging treated wastewater on a 30.8-mi reach of the Red River. A water-quality model was used as a tool to evaluate the effects of discharging treated wastewater from Fargo and other wastewater sources, including those from Minnesota, on the water quality of the Red River. Use of the water-quality model helped identify the biological, chemical, and physical processes that played a role in determining the water quality of the river. In addition, the water-quality model can be used to help determine potential effects of future discharges of treated wastewater on the water quality of the Red River.

Purpose and Scope

This report describes the results of a study to simulate the effects of discharging treated wastewater on a 30.8-mi reach of the Red River during low-streamflow conditions. The effects were simulated using a model that integrates water-quality conditions and processes involved with waste-assimilation capacities and reaction coefficients. Specific objectives of the study were to: (1) Define hydraulic characteristics, including traveltime and dispersion; (2) define reaeration-rate coefficients; (3) determine ultimate carbonaceous biochemical and sediment oxygen demands; and (4) calibrate and verify a water-quality

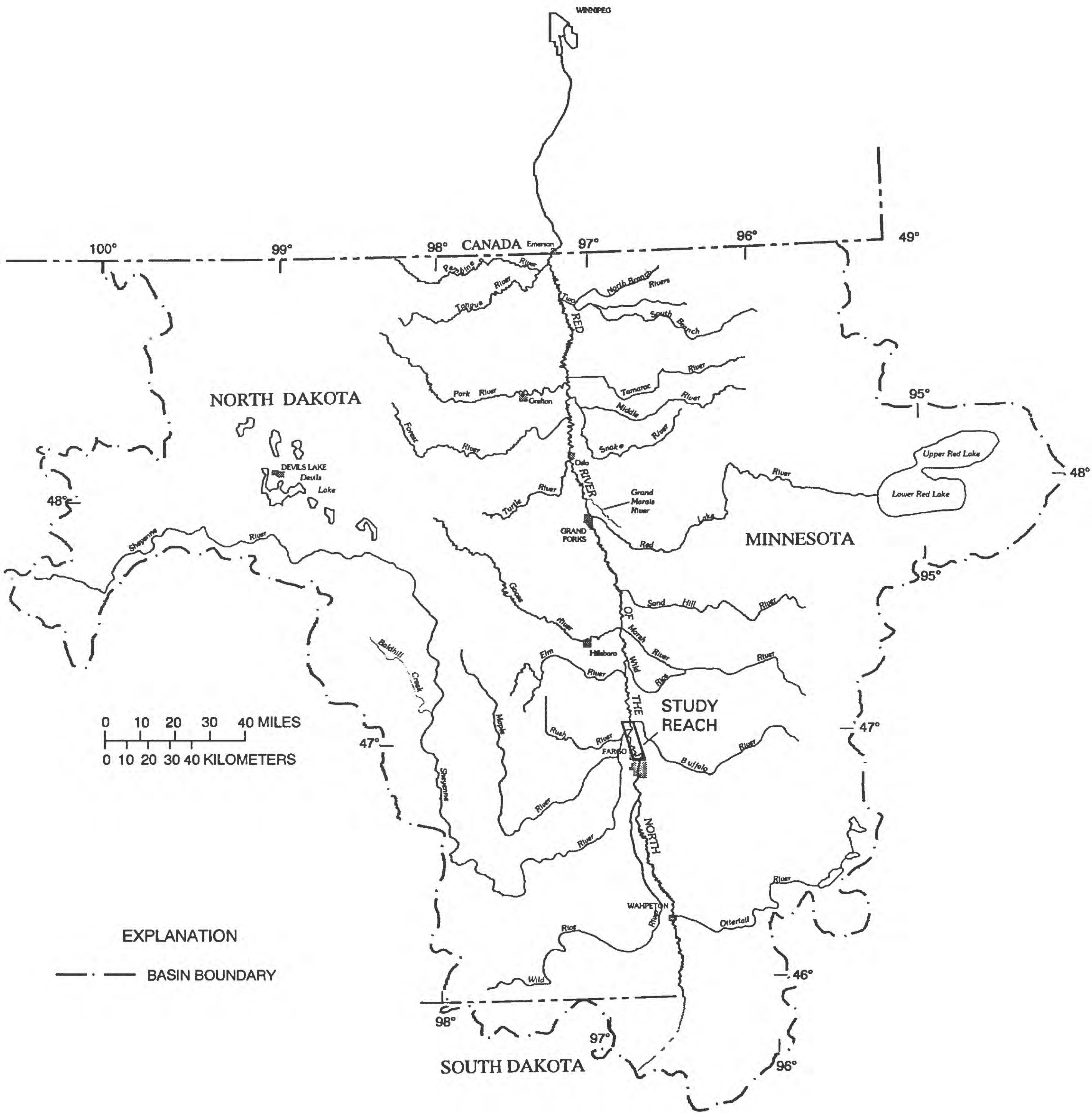


Figure 1. Red River of the North Basin in the United States.

model for the 30.8-mi reach of the Red River. The scope of this study included stream cross-section measurements to define channel geometry, conservative and nonconservative tracer measurements to determine traveltime and dispersion characteristics to define reaeration-rate coefficients, and collection of water-quality data needed to calibrate and verify the water-quality model.

Previous Water-Quality Investigations

Early water-quality investigations of the Red River, through about 1974, included the entire United States part of the basin because of the river's interstate and international significance. Interest in the water quality of the Red River by state health agencies has at least a 60-year history. In 1931-33, an investigation to define the water quality of the Red River was conducted by the North Dakota and Minnesota State Boards of Health. In 1938, after drought years when the Red River had periods of no streamflow during the summer months, the two State Boards of Health conducted another investigation of the Red River and concluded that it would be necessary to require treatment for municipal and industrial waste discharged to the river (U.S. Department of Health, Education, and Welfare, Public Health Service, 1965, p. 13).

Two reports--one by the U.S. Public Health Service, Division of Water Pollution Control, Missouri Drainage Basin Office (1952) and the other by the U.S. Department of Health, Education, and Welfare, Public Health Service (1965)--laid the groundwork and included recommendations that ultimately were developed into water-quality standards for the Red River.

In 1967, one of the first mathematical models of the Red River Basin was discussed in a report by the Federal Water Pollution Control Administration, Division of Technical Control, Comprehensive Planning and Programs (1967). This general river-basin model was used to simulate monthly mean streamflows for water years 1951-60 and monthly mean dissolved solids for water years 1956-60 at selected sites on tributaries and the main stem of the Red River.

In 1972, the Souris-Red-Rainy River Basins Commission (1972a, 1972b) published a report that included the analysis of existing water-quality conditions and potential pollution-control needs and problems from a regional perspective. Water-quality conditions were closely checked with water-quality standards, and areas, including Fargo-Moorhead, were noted where water-quality conditions contravened with water-quality standards. Water-quality management needs also were developed.

In 1974, a waste-load allocation study of 135 mi of the Red River from its source to its confluence with the Buffalo River was conducted by the Minnesota Pollution Control Agency (HICKOK-RCM International, 1974). Existing water-quality conditions were summarized, problems were identified, and recommendations for water-quality standards were presented.

In 1976, the Minnesota Pollution Control Agency conducted water-quality surveys on the Red River from the Fargo-Moorhead area to Georgetown, Minn., to obtain data for the waste-load allocation study for this area (Minnesota Pollution Control Agency, Division of Water Quality, Section of Surface and Ground Waters, 1977). Data collected included streamflow and stage, traveltime, and dissolved oxygen. Samples were collected for chemical analysis of wastewater from point sources and for chemical analysis of streamflow.

On March 13-14, 1989, the U.S. Geological Survey conducted a 24-hour survey of the dissolved oxygen in a 12-mi reach of the Red River under ice conditions. The 12-mi reach began at the Moorhead wastewater outfall. All dissolved-oxygen concentrations were above 11 mg/L during this survey.

Water-Quality Standards

In order to maintain or improve the water quality of streams, the North Dakota State Department of Health and Consolidated Laboratories and the Minnesota Pollution Control Agency have established water-quality standards for all streams throughout their respective states. These standards were determined on the basis of a stream-classification system. Water-quality standards for the Red River for constituents considered in this report are listed in table 1. Limitations on the discharge of treated wastewater from Fargo and Moorhead to the Red River to maintain these stream water-quality standards also are listed in table 1.

Acknowledgments

Appreciation is extended to the landowners who allowed access to sampling sites on the Red River. The author is grateful to Peter Bilstad, Superintendent of the wastewater-treatment plant at Fargo, for his cooperation and help throughout the entire study. A special thank you is extended to Kenneth Kary and his staff at the North Dakota State Department of Health and Consolidated Laboratories for conducting the lengthy and time-consuming ultimate carbonaceous biochemical oxygen demand analyses for the many samples collected during this study.

HYDROLOGIC SETTING AND DESCRIPTION OF STUDY REACH

General Hydrology

The United States part of the Red River Basin includes parts of North Dakota, South Dakota, and Minnesota (fig. 1). Of the total drainage area of 39,200 mi^2 in the United States at the international boundary, the drainage area is only about 6,800 mi^2 at the Red River of the North at Fargo, N. Dak., gaging station (05054000). The gaging station is located at river mile 453, which is 4.1 mi upstream of the beginning of the study reach.

The Ottertail River and the Bois de Sioux River join at Wahpeton, N. Dak., and Breckenridge, Minn., to form the Red River. Streamflow in the Ottertail River is regulated by Orwell Reservoir, which is located 42 mi upstream from the mouth of the Ottertail River and has a capacity of 14,100 acre-ft. Streamflow in the Bois de Sioux River is regulated by Lake Traverse, which is located 28 mi upstream from the mouth of the Bois de Sioux River and has a capacity of 137,000 acre-ft. Generally, there is very little streamflow in the Bois de Sioux River except during a few weeks in the spring.

The study reach is located in the upper one-third of the basin; however, the following data for the United States part of the basin probably are reflective of the land use that influences the water quality of the reach. More than 91 percent of the land area of the Red River Basin is used for agricultural purposes. About 73 percent of the agricultural land is cropland, 9 percent is pasture and range, 13 percent is forest and woodland, and 5 percent is devoted to farmsteads and miscellaneous uses. Irrigated agriculture is insignificant (Souris-Red-Rainy River Basins Commission, 1972a, 1972b).

The Red River flows northward 394 mi to the United States-Canada boundary. The river, a low-sloped, prairie river, flows through a tight, meandering channel that is entrenched in lacustrine deposits of the broad, very flat bed of glacial Lake Agassiz. Slope through the study reach is 0.5 ft/mi. The Red River Valley varies in width from 30 to 50 mi.

Table 1. Selected water-quality standards for the Red River of the North and selected wastewater-discharge limitations for wastewater-treatment plants at Fargo, North Dakota, and Moorhead, Minnesota

[--, not calculated]

	pH (standard units)	Temperature, water (degrees Fahrenheit)	Oxygen, dissolved (milligrams per liter)	Biochemical oxygen demand, 5-day (milligrams per liter)	Nitrate, dissolved as N (milligrams per liter)	Ammonia, dissolved as N (milligrams per liter)	Un-ionized ammonia, dissolved as N (milligrams per liter)	Phosphorus, total as P (milligrams per liter)
Red River of the North[1]	7.0-9.0	[2]85	5	--	[3]1	Formula	Formula	[3]0.1
Red River of the North[4]	6.0-9.0	[5]86	5	--	10	--	0.04	[6]1
Wastewater-treatment plant effluent at Fargo, N. Dak.[7]	6.0-9.0	--	--	[8]25	--	--	--[9]	--
Wastewater-treatment plant effluent at Moorhead, Minn.[10]	6.0-9.0	--	--	[11]15	--	[12]19-22	--	--

[1]North Dakota State Department of Health and Consolidated Laboratories, 1991.

[2]Maximum increase shall not be greater than 5 degrees Fahrenheit above natural background condition.

[3]Intended as interim guideline limit. However, in no case shall standard for nitrogen (N) exceed 10 milligrams per liter for any water used as a municipal or domestic supply.

[4]Minnesota Pollution Control Agency, 1990.

[5]Maximum increase shall not be greater than 5 degrees Fahrenheit above natural conditions in streams.

[6]Wastewater-discharge limitation for municipal point sources and other point sources.

[7]North Dakota Pollution Discharge Elimination System permit for Fargo, N. Dak. (ND002287C, effective 1/01/89).

[8]Standard for 30-consecutive-day period. Standard for 7-consecutive-day period is 45 milligrams per liter.

[9]No standard exists; however, wastewater discharge ammonia concentrations are evaluated on a case-by-case basis to ensure the instream water-quality standard for un-ionized ammonia is not exceeded.

[10]Minnesota Pollution Discharge Elimination System permit for Moorhead, Minn. (MN0049069, effective 6/30/92) interim effluent limitation.

[11]Average for 30 calendar months. Average for 1 calendar week shall not exceed 25 milligrams per liter.

[12]Calendar-month average. Applicable value within range depends on season.

Although there are no reservoirs for flood control on the main stem of the Red River, there are several low-head dams upstream of the study reach. Two of these low-head dams are located between the Red River of the North at Fargo, N. Dak., gaging station and the beginning of the study reach (fig. 2). The water behind these low-head dams provides the water supply for Fargo and Moorhead and for irrigation of golf courses and suburban yards near the river.

Streamflow in the Red River is quite variable from year to year and from season to season. The variability and duration of streamflow in the Red River is an important water-quality consideration when treated wastewater is discharged intermittently or continuously to the river.

The Wild Rice and Sheyenne Rivers enter the Red River from North Dakota and are the only principal tributaries that affect the water quality in the study reach (fig. 1). The Wild Rice River enters the Red River upstream of the study reach at about river mile 470. The median annual mean streamflow for water years 1932-90 at the Wild Rice River near Abercrombie, N. Dak., gaging station (05053000) is 36 ft^3/s (26,100 acre-ft/yr). There is no streamflow at times in most years. The Sheyenne River enters the Red River within the study reach at about river mile 428. The median annual mean streamflow for water years 1904, 1905, and 1930-90 at the Sheyenne River at West Fargo, N. Dak., gaging station (05059500) is 146 ft^3/s (106,000 acre-ft/yr). Using the entire record for the Sheyenne River at West Fargo, N. Dak., gaging station, the 7-day 10-year low streamflow is 8.1 ft^3/s. The lowest daily mean streamflow, which was caused by diversion, was 1.0 ft^3/s on September 23, 1976. The streamflow values for the Sheyenne River at West Fargo, N. Dak., gaging station do not include diversions to the Red River or to Fargo.

Annual streamflow at the Red River of the North at Fargo, N. Dak., gaging station generally reflects the variability in streamflow for the Red River. July, August, and September monthly mean and annual mean streamflows for selected water years for 1902-90 are listed in table 2. The lowest annual mean streamflow was 18 ft^3/s (13,000 acre-ft/yr) for water year 1934, and the highest annual mean streamflow was 1,930 ft^3/s (1,397,000 acre-ft/yr) for water year 1986. The median annual mean streamflow for water years 1902-90 is 449 ft^3/s (325,000 acre-ft/yr). Using the entire record for water years 1902-90, the 7-day 10-year low streamflow is zero.

Table 2. Selected monthly and annual mean streamflows for the Red River of the North at Fargo, North Dakota, gaging station (05054000), water years 1902-90

Water year	Monthly mean streamflow (cubic feet per second)			Annual mean streamflow[1]	
	July	August	September	Cubic feet per second	Acre-feet per year
1932	7.7	0	8.8	52	37,600
1933	15	1.6	.1	42	30,400
1934	0	0	0	18	13,000
1935	184	32	8.4	82	59,400
1936	0	0	0	59	42,700
1939	85	12	0	179	130,000
1940	15	3.2	0	94	68,000
1962	5,690	2,690	845	1,760	1,274,000
1986	2,010	911	1,710	1,930	1,397,000
1989	320	156	227	802	581,000
1990	399	227	175	285	206,400

[1]Does not include diversions to Fargo and Moorhead or diversions from the Sheyenne River except when streamflow was diverted from the Sheyenne River through an open channel to the Red River of the North upstream of the wastewater-treatment plant at Fargo.

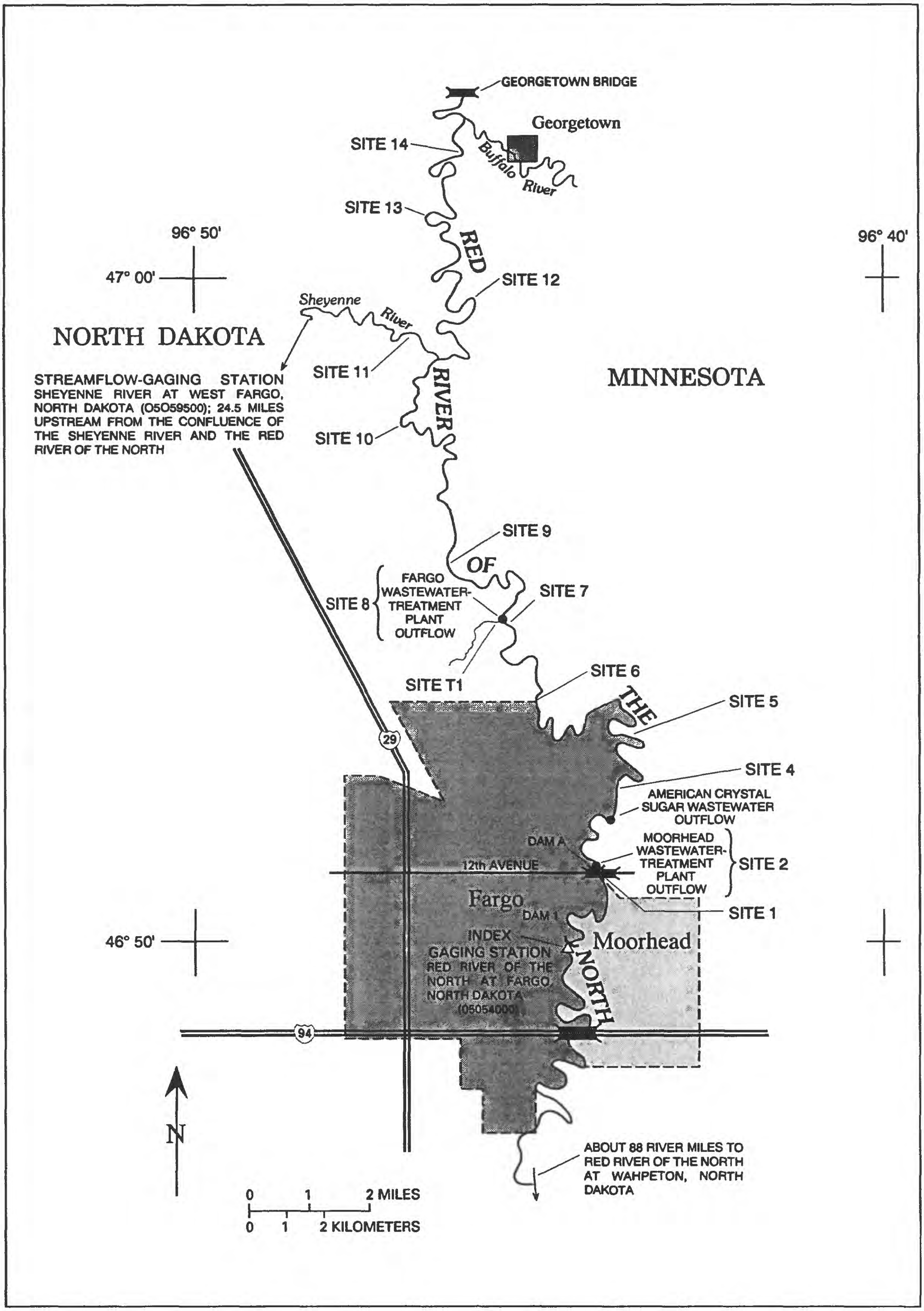


Figure 2. Location of study reach on the Red River of the North and data-collection sites from Fargo, North Dakota, to Georgetown, Minnesota.

Although North Dakota was in a drought during the study (1989-90), the extreme low streamflows in the rivers in most of the State were not evident in the Red River at Fargo area. Much of the streamflow in the Red River during water-quality sampling in August 1989 and August 1990 was the result of releases from Orwell Reservoir.

In order to take into consideration the effect of the various water developments that have occurred in the basin upstream of Fargo on the streamflow in the Fargo-Moorhead area during July-September, streamflow data for the Red River of the North at Fargo, N. Dak., gaging station was compiled for water years 1960-90 (table 3). The lowest annual mean streamflow was 65 ft^3/s (47,100 acre-ft/yr) for water year 1977. The median annual mean streamflow for water years 1960-90 is 580 ft^3/s (420,000 acre-ft/yr). The 7-day 10-year low streamflow for water years 1960-90 is about 11 ft^3/s.

Table 3. Selected monthly and annual mean streamflows for the Red River of the North at Fargo, North Dakota, gaging station (05054000), water years 1960-90

Water year	Monthly mean streamflow (cubic feet per second)			Annual mean streamflow[1]	
	July	August	September	Cubic feet per second	Acre-feet per year
1976	91	35	12	344	249,000
1977	75	18	178	65	47,100
1988	63	69	66	228	165,100

[1]Does not include diversions to Fargo and Moorhead or diversions from the Sheyenne River except when streamflow was diverted from the Sheyenne River through an open channel to the Red River of the North upstream of the wastewater-treatment plant at Fargo.

More importantly for water-quality considerations is the seasonal flow variability during July, August, and September when stream temperatures are the highest. Using the entire record (1902-90) for the Red River of the North at Fargo, N. Dak., gaging station, the lowest monthly mean streamflow for July, August, and September was zero for water years 1934 and 1936 (table 2). The lowest monthly mean streamflow for September also was zero for water years 1939 and 1940. For water year 1932, the lowest monthly mean streamflow for July was 7.7 ft^3/s, the lowest monthly mean streamflow for August was zero, and the lowest monthly mean streamflow for September was 8.8 ft^3/s. The highest monthly mean streamflow for July was 5,690 ft^3/s for water year 1962, the highest monthly mean streamflow for August was 2,690 ft^3/s for water year 1962, and the highest monthly mean streamflow for September was 1,710 ft^3/s for water year 1986.

An analysis of streamflow at the Red River of the North at Fargo, N. Dak., gaging station for water years 1960-90 (table 3) indicates the lowest monthly mean streamflow for July was 63 ft^3/s for water year 1988, the lowest monthly mean streamflow for August was 18 ft^3/s for water year 1977, and the lowest monthly mean streamflow for September was 12 ft^3/s for water year 1976. During July through September for water years 1960-90, the 7-day 10-year low streamflow is about 14 ft^3/s.

Physical Description of Study Reach

The study reach begins just downstream of Dam A (locally referred to as North Dam; B. Montgomery, U.S. Army Corps of Engineers, oral commun., 1990), which is about 0.1 mi downstream of the 12th

Avenue North bridge in Fargo, and extends 30.8 mi downstream to a site 0.8 mi upstream of the confluence of the Buffalo and Red Rivers (fig. 2). About one-third of the study reach is urban-suburban and two-thirds is rural.

The river channel and the riverbanks primarily consist of silts and clays although gravel and rocks are present in riffles. The streambed consists of shallow pools and riffles. The meandering river channel, which gradually becomes wider and deeper downstream, is fairly uniform in shape. In some places within the city of Fargo, the river has been rechanneled to permit higher streamflows to bypass the meanders. During lower streamflows, like those that existed during the study, the streamflow follows the natural channel. The riffles were submerged for the streamflows that existed during this study.

The riverbanks, which are fairly stable, are lined with deciduous trees. Tree density varies and, in places, open areas do exist. The open, treeless area is covered with grass or crop. The shading of the river is related to the changing vegetation along the riverbanks.

Sources of Wastewater

Within the study reach, the Red River receives wastewater that affects the river's water quality from both point and nonpoint sources. The point sources include the wastewater-treatment plant at Fargo, N. Dak., the wastewater-treatment plant at Moorhead, Minn., and the American Crystal Sugar processing plant at Moorhead, Minn. The effect of the American Crystal Sugar processing plant wastewater on the water quality of the Red River is not considered in this report because their Minnesota Pollution Discharge Elimination System permit does not allow discharge of treated wastewater to the river when streamflow is less than 250 ft^3/s (Gary G. Rott, Minnesota Pollution Control Agency, oral commun., 1991). Numerous storm sewers from Fargo and Moorhead also outfall to the Red River. Most of the storm sewers have been separated from the wastewater sewers, and runoff from streets discharges directly to the Red River through a separate system of underground pipes (Peter Bilstad, Superintendent, wastewater-treatment plant at Fargo, N. Dak., and Robert Zimmerman, Superintendent, wastewater-treatment plant at Moorhead, Minn., oral commun., 1991).

The wastewater-treatment plant at Fargo discharges treated wastewater intermittently from a waste-stabilization pond to the Red River at varying rates of as much as 25 Mgal/d from April to November. The wastewater-treatment plant has a capacity of 9.5 Mgal/d and provides secondary treatment to the wastewater. The treated wastewater is held in one of six waste-stabilization ponds, which cover about 90 acres each, for final treatment until it is ready to be discharged to the Red River through a closed 4-mi pipe.

The population of Fargo increased from about 61,400 in 1980 to about 73,000 in 1990 (Fargo Chamber of Commerce, oral commun., 1991), and the amount of wastewater being treated is nearing the design capacity of the wastewater-treatment plant. Studies and plans are underway to expand and improve the plant to an ultimate capacity of 15 Mgal/d. The planned improvement is to remove nitrogenous material and eventually to discharge wastewater continuously to the Red River (Peter Bilstad, Superintendent, wastewater-treatment plant at Fargo, N. Dak., oral commun., 1991).

The wastewater-treatment plant at Moorhead discharges treated wastewater continuously from a waste-stabilization pond to the Red River at varying rates of as much as 6 Mgal/d. The wastewater-treatment plant provides advanced secondary treatment to the wastewater by introducing high-purity oxygen into the activated-sludge process. The treated wastewater is held in a three-cell, 4.9-acre waste-stabilization pond for final treatment until it is ready to be discharged to the river through a closed 2-mi pipe (Robert Zimmerman, Superintendent, wastewater-treatment plant at Moorhead, Minn., oral commun., 1991).

The population of Moorhead increased from about 30,000 in 1980 to about 30,700 in 1990 (Moorhead Chamber of Commerce, oral commun., 1991). The wastewater-treatment plant at Moorhead also services Dilworth, Minn., which had a population of about 2,700 in 1990. The design of the existing plant includes the capability to upgrade the capacity to 12 Mgal/d as the need arises.

The nonpoint sources of wastewater are mainly from agricultural cropland use. Small numbers of cattle graze near the river in some areas (Gary Haberstroh, North Dakota State Department of Health and Consolidated Laboratories, and Dave Anderson, Minnesota Pollution Control Agency, oral commun., 1991); however, no North Dakota Pollution Discharge Elimination System permits have been issued for livestock operations near the Red River in the study reach. Wastewater from livestock probably is insignificant relative to wastewater from point sources.

SIMULATION OF EFFECTS OF DISCHARGING TREATED WASTEWATER

Description of Model

The Enhanced Stream Water Quality Model, QUAL2E (version 3.0), a computer program written by Brown and Barnwell (1987), was calibrated and verified to simulate biochemical processes in the study reach, and its companion program, QUAL2E-UNCAS, was used for uncertainty analysis. The QUAL2E model is a one-dimensional, steady-state, stream water-quality model. The basic equation solved by the QUAL2E model is the one-dimensional, advection-dispersion, mass-transport equation, which is numerically integrated over space and time for each water-quality constituent. For this study, the QUAL2E model was modified to include five additional equations to calculate reaeration-rate coefficients.

To apply the QUAL2E model, a study reach is divided into subreaches, each of which is considered to have uniform characteristics. A conceptual representation of the study reach is shown in figure 3. The segmentation of the study reach into subreaches was dictated by QUAL2E limitations and by the location of the data-collection sites. The study reach consists of 11 subreaches. Each subreach consists of one or more computational elements, which are assumed to be completely mixed and linked to one another by advection and dispersion. For this study, each computational element is 0.2 mi in length. For each computational element, the model computes the streamflow and the mass balance of each water-quality constituent on the basis of: (1) Inflow at the upstream end of the element, (2) inputs to or withdrawals from the element, (3) outflow at the downstream end of the element, and (4) appropriate reaction coefficients for each water-quality constituent (Brown and Barnwell, 1987).

For calibration purposes, in this study the QUAL2E model included a boundary component, a transport component, and a water-quality component. Hereafter, the calibrated QUAL2E model will be referred to as the Red River at Fargo Water-Quality Model (RRatFGO QW) to distinguish the uncalibrated model from the calibrated model and to specify the reach of the Red River that was modeled.

Data Collection for Calibration and Verification of Model

Before the RRatFGO QW model was used to simulate transport and water-quality conditions in the study reach, it was calibrated and verified with independent sets of measured data. The model was calibrated so that simulated data for one data set were in acceptable agreement with measured data of that data set. A second set of measured data was used to verify the calibrated constituent reaction coefficients. Ideally, measured data should be used to determine the value of all reaction coefficients of the boundary,

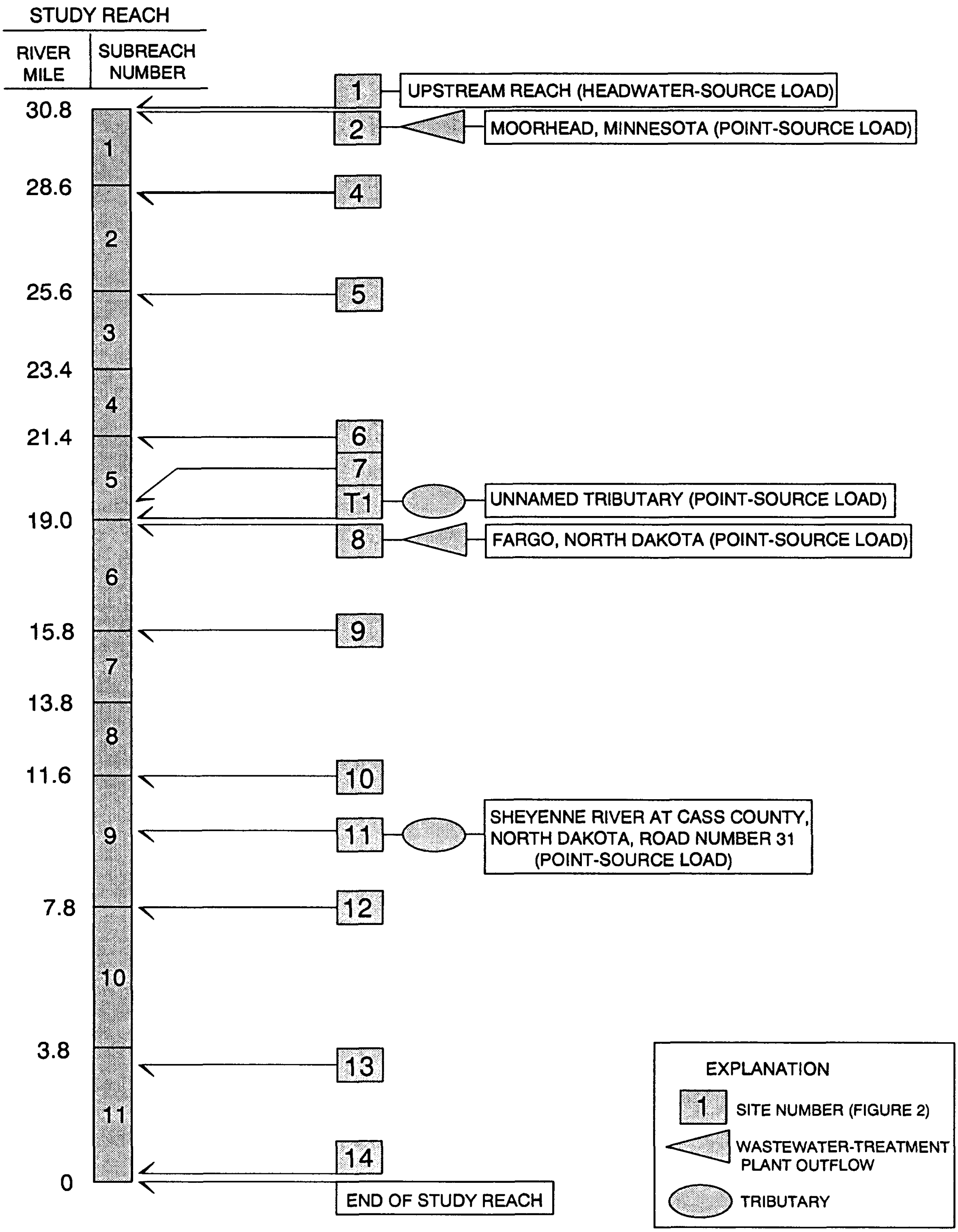


Figure 3. Model input sites and subreaches for the Red River of the North at Fargo study reach.

transport, and water-quality components. In this study, budget limitations only allowed measurement of some reaction coefficients of the transport and water-quality components. Unmeasured reaction coefficients were estimated from literature.

In order to obtain the independent data sets needed to calibrate and verify the RRatFGO QW model, a network of 14 data-collection sites was established. The 14 sites (fig. 2 and table 4) are numbered in downstream order and generally represent the upstream and downstream ends of subreaches for the RRatFGO QW model. Of the 14 sites, 10 represent the Red River. The remaining four sites represent wastewater outflow from the Moorhead wastewater-treatment plant (site 2), inflow from an unnamed tributary (site T1), wastewater outflow from the Fargo wastewater-treatment plant (site 8), and inflow from the Sheyenne River (site 11). In addition to the numbered sites, two unnumbered sites are discussed in this report. The first unnumbered site represents the Red River of the North at Fargo, N. Dak., gaging station, which was used as an index gaging station for streamflow in the Red River. The second unnumbered site was used for tracer injection during one of the tracer measurements.

Data obtained to define the transport conditions are measurements of channel geometry, streamflow, traveltime, specific conductance, and temperature. Data obtained to define the water-quality conditions are measurements of concentrations of selected water-quality constituents and estimates of various reaction coefficients. The measured concentrations of selected water-quality constituents represent the model's boundary and initial conditions.

Channel Geometry

Two methods are provided in the QUAL2E model to characterize the channel and calculate streamflow. Manning's equation, which requires channel slope and trapezoidal cross sections, is used in one method, and discharge coefficients and exponents are used in the other method (Brown and Barnwell, 1987). In this study, Manning's equation was used in the RRatFGO QW model to calculate streamflow, and the trapezoidal cross sections were used to characterize the channel. The slope of the streambed was initially determined from 7.5-minute topographic maps. The slope then was verified from a thalweg water-surface profile (U.S. Army Corps of Engineers, 1970). The average slope through the study reach is slightly greater than 0.5 ft/mi.

Stream cross-section measurements of width and depth were made to define channel geometry. Cross-section measurements were made at about 1-mi intervals from the beginning of the study reach (site 1) to site 14, 0.1 mi upstream of the end of the study reach. The top width of the river was measured by stretching a tagline across the river, and the depth of the river was measured at 5-ft intervals along this tagline. Cross-section measurements were made at various times during the study and at various streamflows. The daily mean streamflows at the index gaging station, Red River of the North at Fargo, N. Dak. (fig. 2), are listed in table 5. These streamflows were adjusted to include wastewater-treatment plant outflow from Fargo (site 8; fig. 2) and inflow from the Sheyenne River (site 11; fig. 2) as represented by the daily mean streamflow at the Sheyenne River at West Fargo, N. Dak., gaging station.

Widths and depths obtained at the 5-ft intervals were entered into a computer program for analyzing channel geometry (Regan and Schaffranek, 1985). The computer program calculates hydraulic depth and cross-section area. The cross sections were plotted by using a digitizer and were modified to conform to a trapezoidal shape, which approximately equalled the measured cross-section area.

Cross-section data obtained when streamflow at the index gaging station ranged from 140 to 400 ft^3/s indicate the mean top width of the river was about 85 ft (range 62 to 109 ft), the mean maximum depth of the river was 4.6 ft (range 2.3 to 6.8 ft), the mean hydraulic depth of the river was 2.8 ft (range 1.6 to 3.9 ft), and the mean cross-section area was about 234 ft^2 (range 119 to 355 ft^2; table 5).

Table 4. Site number, description, and location of data-collection sites

[--, unnumbered sites]

Site number	Description	Miles upstream or downstream from site 1	Location
--	Index gaging station, Red River of the North at Fargo, N. Dak. (05054000).	4.1	At city water plant on 4th Street South in Fargo, N. Dak., and at river mile 453[1].
1	Synoptic and sediment oxygen demand sampling and tracer injection.	0	Beginning of study reach. Immediately downstream from Dam A (locally referred to as North Dam), which is about 0.1 mile below 12th Avenue North Bridge.
2	Synoptic sampling.	.1	At Moorhead, Minn., wastewater-treatment plant outflow (buried pipe).
4	Synoptic, tracer, and sediment oxygen demand sampling.	2.3	At intersection of about 25th Avenue North.
5	Synoptic, tracer, and sediment oxygen demand sampling.	5.2	At intersection of about 35th Avenue North east of Cardinal Muench Seminary.
6	Synoptic, tracer, and sediment oxygen demand sampling and dye injection.	9.4	At bridge on Cass County, N. Dak., Road No. 20.
7	Synoptic, tracer, and sediment oxygen demand sampling.	11.8	Immediately upstream from Fargo, N. Dak., wastewater-treatment plant outflow.
T1	Synoptic sampling.	11.85	At unnamed tributary and former Fargo, N. Dak., wastewater-treatment plant outflow channel.
8	Synoptic sampling.	11.9	At Fargo, N. Dak., wastewater-treatment plant outflow (buried pipe).
9	Synoptic, tracer, and sediment oxygen demand sampling.	15.0	East of Cass County, N. Dak., Road No. 31 and 2.5 miles north of Cass County, N. Dak., Road No. 20.
10	Synoptic, tracer, and sediment oxygen demand sampling.	19.2	East of Cass County, N. Dak., Road No. 31 and about 5 miles north of Cass County, N. Dak., Road No. 20.
--	Tracer injection.	19.8	At Everett Frieberg farm.
11	Synoptic and tracer sampling.	20.8	At bridge over Sheyenne River on Cass County, N. Dak., Road No. 31.
12	Synoptic, tracer, and sediment oxygen demand sampling.	23.0	At intersection with Clay County, Minn., ditch no. 28, 3.5 miles south of Georgetown, Minn.
13	Synoptic sampling, 1989 only.	27.5	East of Cass County, N. Dak., Road No. 31 and about 9 miles north of Cass County, N. Dak., Road No. 20.
14	Synoptic, tracer, and sediment oxygen demand sampling.	30.7	Near end of study reach. About 1 mile west of Georgetown, Minn., and 1.5 miles upstream from Georgetown bridge.

[1]U.S. Army Corps of Engineers, 1970.

Table 5. Cross-section measurements of the Red River of the North at Fargo, North Dakota

Cross-section number	Distance downstream from site 1 (miles)	Date	Daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000) (cubic feet per second)	Top width of river (feet)	Maximum depth of river (feet)	Hydraulic depth of river (feet)	Cross-section area (square feet)	Channel slope (feet per foot)
10	0	8/29/89	140	79	2.3	1.6	126	1.136×10^{-4}
11	1.0	9/20/89	190	74	3.4	1.6	119	1.136×10^{-4}
12	2.0	9/20/89	190	68	5.4	3.2	217	1.136×10^{-4}
13	3.0	9/20/89	190	80	3.4	2.6	204	1.136×10^{-4}
14	4.0	9/20/89	190	81	5.8	3.3	271	1.136×10^{-4}
15	5.0	9/20/89	190	81	5.2	3.1	250	1.136×10^{-4}
16	6.0	9/20/89	190	79	4.5	2.7	211	1.136×10^{-4}
17	7.0	9/20/89	190	82	5.7	3.0	244	1.136×10^{-4}
18	8.0	9/20/89	190	101	3.7	2.5	253	1.136×10^{-4}
19	9.0	9/20/89	190	72	5.8	3.3	238	1.136×10^{-4}
20	10.0	9/20/89	190	85	4.1	2.6	223	1.136×10^{-4}
21	11.0	9/20/89	190	62	4.4	2.6	162	1.136×10^{-4}
22	12.0	8/31/90	300	85	5.6	3.1	262	1.136×10^{-4}
23	13.0	8/31/90	300	98	4.0	2.7	269	1.345×10^{-4}
24	14.0	8/31/90	300	100	4.0	2.7	269	1.345×10^{-4}
25	15.0	8/31/90	300	88	4.3	3.0	266	1.345×10^{-4}
26	16.0	8/31/90	300	76	5.3	3.4	255	1.345×10^{-4}
27	17.0	9/04/90	240	107	2.9	2.0	211	1.345×10^{-4}
28	18.0	9/04/90	240	78	4.2	2.3	178	1.345×10^{-4}
29	19.0	9/04/90	240	80	4.0	2.5	200	1.345×10^{-4}
30	20.0	9/04/90	240	64	6.6	3.9	248	$.758 \times 10^{-4}$
31	21.0	9/04/90	280	98	4.2	2.7	265	$.758 \times 10^{-4}$
32	22.0	9/04/90	280	72	5.2	3.3	236	$.758 \times 10^{-4}$
33	23.0	8/29/90	400	99	4.6	2.9	285	$.758 \times 10^{-4}$
34	24.0	8/29/90	400	88	5.6	3.1	272	$.758 \times 10^{-4}$
35	25.0	8/29/90	400	109	4.3	2.4	258	$.758 \times 10^{-4}$
36	26.0	8/29/90	400	87	4.8	3.1	269	$.758 \times 10^{-4}$
37	27.0	8/29/90	400	91	4.2	2.5	227	$.758 \times 10^{-4}$
38	28.0	8/29/90	400	88	4.6	3.2	284	$.758 \times 10^{-4}$
39	29.0	8/29/90	400	83	4.9	2.3	193	$.758 \times 10^{-4}$
40	30.0	8/29/90	400	100	2.6	1.7	170	$.758 \times 10^{-4}$
41	30.7	8/29/90	400	97	6.8	3.7	355	$.758 \times 10^{-4}$
Mean			277	85	4.6	2.8	234	1.040×10^{-4}

Traveltime, Longitudinal-Dispersion Coefficient, and Reaeration-Rate Coefficient

Traveltime measurements provide transport velocity values that integrate all of the physical variation between two points. Traveltime measurements were made in August 1989, April 1990, and October 1990 (table 6) when streamflow ranged from about 60 to 523 ft^3/s. Two important factors in determining the effects of discharging treated wastewater to the Red River are the river's capacity for reaeration and the effect of the wastewater on the dissolved-oxygen concentration. The major source of oxygen to a river is the atmosphere. Reaeration measurements were made in April and October 1990 when streamflow ranged from about 104 to 523 ft^3/s (table 7). Equipment malfunction during the August 1989 reaeration measurements precluded the use of the 1989 reaeration measurements.

Generally, the study reach was divided into two test reaches for collecting traveltime and reaeration data. During the April and October 1990 measurements, automatic samplers were used to collect some dye samples. These samples were collected in addition to the dye samples that were collected manually. During each traveltime and reaeration measurement, streamflow measurements were made at selected sites by wading or by using a boat.

Conservative (fluorescent-dye; 20-percent solution of rhodamine WT) and nonconservative (propane-gas; commercial grade) tracers were used for traveltime and reaeration measurements. Measurements were made after the fluorescent-dye tracer was slug injected into the stream. The propane-gas tracer was constant-rate injected into the stream at the same location so that both tracers underwent identical dispersion and dilution before reaching downstream tracer-collection sites. Traveltime calculations require only fluorescent-dye concentration data, but reaeration calculations require fluorescent-dye and propane-gas concentration data. Traveltime measurements were made by using fluorometric procedures discussed by Kilpatrick and Wilson (1989). Reaeration measurements were made by using a steady-state propane-gas tracer method, and reaeration calculations were made as discussed by Kilpatrick and others (1989). Propane samples were analyzed at the U.S. Geological Survey laboratory in Ocala, Fla., using methods described by Shultz and others (1976).

Time-concentration curves are used to interpret traveltime and longitudinal dispersion (Kilpatrick and Wilson, 1989). After the fluorescent dye was slug injected into the stream, samples of dye were collected at downstream sites at varying frequencies to define the time-concentration curves. Generally, sampling began before the leading edge of the dye cloud arrived, continued through the peak dye concentration, and ended when the dye concentration receded to 2 percent of the peak. Time-concentration curves were prepared for each data-collection site by plotting the measured dye concentration against the elapsed traveltime after injection (supplement 1). A smooth curve was drawn through the plotted points. These curves represent the passage of the entire dye cloud at the sites. The shapes of the curves indicate traveltime and velocity characteristics for a channel. Where necessary, because of missing data, the curves were extrapolated to include the leading and trailing edges.

The main features of time-concentration curves are the leading edge, peak, centroid, and trailing edge. The centroid is a point that represents the center of the area under the time-concentration curve (Kilpatrick and Wilson, 1989). The main features of time-concentration curves are described in terms of elapsed traveltime after dye injection. Data for these and other features of the curves are listed in table 6. Theoretically, when summing the traveltimes between sites, only the data for the traveltime of the centroid are truly additive. The mean streamflow transport velocities of the dye-cloud peak and centroid are listed in table 6. The mean area under the time-concentration curve, the location of the centroid, and the percent of dye recovery were calculated by a program developed by D. A. Stedfast (U.S. Geological Survey, written commun., 1987).

Table 6. Summary of data collected during traveltime measurements of the Red River of the North at Fargo, North Dakota

[--, not calculated]

Site number	Distance downstream from dye injection (miles)	Streamflow (cubic feet per second)	Elapsed traveltime after dye injection (hours)				Dye cloud passage time (hours)	Measured peak dye concentration[1] (micrograms per liter)	Mean streamflow transport velocity of dye cloud (feet per second)		Mean area under time-concentration curve (micrograms-hour per liter)	Dye recovery (percent)
			Leading edge	Peak	Centroid	Trailing edge			Peak	Centroid		
Slug injection of dye at 1935 hours on August 7, 1989, 0.6 mile downstream from site 10; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 200 cubic feet per second												
12	3.2	220	3.75	4.50	4.76	6.75	3.00	6.05	--	--	6.65	--
14	10.9	220	14.25	16.25	16.51	20.75	6.50	2.85	0.94	0.96	5.98	--
Slug injection of dye at 1900 hours on August 8, 1989, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 188 cubic feet per second												
4	2.3	195	[2]3.00	[2]3.65	--	7.38	[2]4.38	[2]8.20	--	--	--	--
5	5.2	195	7.50	9.08	9.43	12.25	4.75	6.50	--	--	11.93	--
6	9.4	195	15.00	17.33	17.76	21.75	6.75	4.50	0.75	0.74	10.98	--
7	11.8	195	19.50	22.17	22.58	27.00	7.50	3.75	.73	.73	10.38	--
9	15.0	195	24.50	27.50	28.10	33.50	9.00	3.10	.88	.85	9.89	--
10	19.2	195	31.50	34.50	35.23	42.25	10.75	2.30	.88	.86	8.94	--
12	23.0	225	37.08	40.75	41.26	49.00	11.92	1.70	.89	.92	7.08	--
Slug injection of dye at 0930 hours on August 17, 1989, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 55 cubic feet per second												
4	2.3	60	5.00	6.08	6.48	8.75	3.75	17.30	--	--	28.90	--
5	5.2	60	12.08	14.67	15.36	20.00	7.92	8.85	0.50	0.48	28.67	--
6	9.4	60	27.00	30.75	31.39	38.50	11.50	5.80	.38	.38	26.20	--
7	11.8	60	34.17	[3]38.00	[3]38.89	[3]46.00	[3]11.83	[3]5.20	[3].49	[3].47	[3]26.20	--

See footnotes at end of table.

Table 6. Summary of data collected during traveltime measurements of the Red River of the North at Fargo, North Dakota--Continued

[--, not calculated]

Site number	Distance downstream from dye injection (miles)	Streamflow (cubic feet per second)	Elapsed traveltime after dye injection (hours)				Dye cloud passage time (hours)	Measured peak dye concentration[1] (micrograms per liter)	Mean streamflow transport velocity of dye cloud (feet per second)		Mean area under time-concentration curve (micrograms-hour per liter)	Dye recovery (percent)
			Leading edge	Peak	Centroid	Trailing edge			Peak	Centroid		
Slug injection of dye (4 liters) at 0640 hours on April 23, 1990, at site 6; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 409 cubic feet per second												
7	2.4	390	2.66	3.08	3.28	5.25	2.59	37.00	--	--	20.40	85
9	5.6	420	6.08	6.83	7.11	10.53	4.45	15.80	1.25	1.23	17.40	86
10	9.8	461	10.73	11.83	12.16	15.33	4.60	11.80	1.23	1.22	18.10	89
12	13.6	523	14.33	16.00	16.29	20.16	5.83	7.60	1.34	1.35	14.70	82
Slug injection of dye (4 liters) at 0630 hours on April 25, 1990, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 410 cubic feet per second												
4	2.3	407	2.25	2.83	3.02	5.17	2.92	27.80	--	--	19.11	83
5	5.2	[4]413	5.43	6.40	6.75	10.50	5.07	14.50	1.13	1.14	17.64	77
6	9.4	418	10.75	12.33	12.66	16.61	5.86	10.50	1.04	1.04	18.02	79
7	11.8	[2]420	13.94	15.83	16.09	19.83	5.89	9.20	1.01	1.03	17.12	75
Slug injection of dye (2 liters) at 0830 hours on October 16, 1990, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 128 cubic feet per second												
4	2.3	104	3.58	4.50	4.82	7.25	3.67	32.30	--	--	34.52	77
7	11.8	160	22.00	25.08	25.33	30.33	8.33	8.15	0.68	0.68	21.81	75
14	30.7	270	48.75	52.75	53.25	63.25	14.50	3.25	1.00	.99	13.07	76

[1]Sampled at 50-percent streamline.
[2]Estimated.
[3]Estimated; study interrupted by rain.
[4]Prorated between adjacent sites.

Table 7. Reaeration-rate coefficients for the Red River of the North determined by the steady-state method and using a constant-rate injection of propane

[--, not calculated]

Site number	Distance downstream from propane injection (miles)	Streamflow (cubic feet per second)	Mean water temperature (degrees Fahrenheit)	Traveltime of dye-cloud centroid (hours)	Mean concentration of propane at 50-percent streamlines (micrograms per liter)	Reaeration-rate coefficient at measured water temperature (per day)[1]	Reaeration-rate coefficient adjusted to 68-degree Fahrenheit water temperature (per day)	Residence time (streamflow-weighted ratio of upstream to downstream propane concentrations)
Monitoring continuous propane injection from 0640 hours on April 23, 1990								
6	0	--	--	--	--	--	--	--
7	2.4	390	60.0	3.28	86.5	--	--	--
10	9.8	461	64.5	12.16	63.7	0.37	0.57	1.15
12	13.6	523	61.0	16.29	51.5	.50	.76	1.09
7 to 12	--	460	--	--	--	.42	.63	1.25
Monitoring continuous propane injection from 0630 hours on April 25, 1990								
1	0	--	--	--	--	--	--	--
4	2.3	407	63.5	3.02	62.0	--	--	--
6	9.4	418	62.5	12.66	52.7	0.40	0.60	1.15
7	11.8	[2]420	64.5	16.09	49.0	.51	.75	1.07
4 to 7	--	415	--	--	--	.43	.64	1.23
Monitoring continuous propane injection from 0830 hours on October 16, 1990[3]								
1	0	--	--	--	--	--	--	--
4	2.3	104	50.0	4.82	[4]172.8	--	--	--
7	11.8	[5]150	44.5	25.33	74.0	0.78	1.03	1.62
14	30.7	[5]215	39.0	53.25	24.4	.91	[6]1.29	2.12
4 to 14	--	160	--	--	--	.86	1.17	3.42
[7]4 to 14	--	190	--	--	--	.56	.92	2.53

[1]Calculations were made as discussed by Kilpatrick and others (1989).

[2]Streamflow was estimated.

[3]During the course of this procedure, the study area received rain that increased streamflow from about 100 to 270 cubic feet per second. Consequently, the reaeration-rate coefficients calculated for these unsteady streamflow conditions are considered an estimate.

[4]Another propane sample collected at this site after the rain had a concentration of 78.0 micrograms per liter when streamflow was estimated at 170 cubic feet per second. See footnote 6.

[5]Streamflow was estimated using velocities from present tracer study and streamflow versus velocities from previous tracer studies.

[6]This value is influenced by the effect of rain on the water surface during the course of this procedure.

[7]Using propane concentration (78.0 micrograms per liter) of sample collected after the rain when streamflow at site 4 was 170 cubic feet per second. See footnote 3.

Longitudinal-dispersion coefficients (table 8) were calculated for selected sites as defined by the variance of the time-concentration curve. The longitudinal-dispersion coefficient represents the rate at which a stream dilutes a soluble substance by longitudinal mixing. Calculations were based on the following change-of-moment method described by Fischer (1966):

$$K_x = \left[\frac{(\bar{U})^2}{2}\right]\left(\frac{\sigma^2 t_2 - \sigma^2 t_1}{\bar{t}_2 - \bar{t}_1}\right) \quad (1)$$

where

K_x is longitudinal-dispersion coefficient, in square feet per second;

$\bar{U}$ is mean streamflow transport velocity, in feet per second;

$\sigma^2 t_2$ is variance of time-concentration curve data at downstream sampling cross section, in hours squared;

$\sigma^2 t_1$ is variance of time-concentration curve data at upstream sampling cross section, in hours squared;

$\bar{t}_2$ is mean traveltime of dye-cloud centroid past downstream sampling cross section, in hours; and

$\bar{t}_1$ is mean traveltime of dye-cloud centroid past upstream sampling cross section, in hours.

The variance used in Fischer's equation (1966) was computed by a program provided by R. E. Rathbun (U.S. Geological Survey, written commun., 1985).

The only restriction for using equation 1 to calculate longitudinal-dispersion coefficients is that the first sampling cross section needs to be sufficiently downstream so that the dye concentration is laterally mixed. An approximation of the longitudinal-dispersion coefficient resulted from equation 1 if the mixing time (in hours) was greater than the mixing time obtained with the following equation (Fischer, 1968):

$$M > (1.8)\,\frac{W^2}{HU*} \quad (2)$$

where

M is theoretical mixing time to obtain approximate uniform dye concentration in sampling cross section, in hours;

W is distance from point of maximum surface velocity to farthest bank (about one-half the width of the river), in feet;

H is hydraulic depth, in feet; and

$U*$ is shear velocity, in feet per second.

Shear velocity is defined as

$$U* = gHS$$

where

g is acceleration because of gravity, in (feet per second) per (second); and

S is channel slope, in foot per foot.

Table 8. Channel geometry, shear velocity, variance of time-concentration curve data, longitudinal-dispersion coefficients, and theoretical mixing times for selected sites

[--, not calculated]

Site number	Distance downstream from dye injection (miles)	Channel geometry: One-half of width of river (feet)	Channel geometry: Mean hydraulic depth of river (feet)	Shear velocity (foot per second)	Variance of time-concentration curve data (hours squared)	Longitudinal-dispersion coefficient (square feet per second)	Theoretical mixing time (hours)
Slug injection of dye at 1935 hours on August 7, 1989, 0.6 mile downstream from site 10; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 200 cubic feet per second							
12	3.2	47	2.8	0.10	0.25	--	4.0
14	10.9	--	--	--	.94	100	--
Slug injection of dye at 1900 hours on August 8, 1989, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 188 cubic feet per second							
5	5.2	39	2.6	0.09	0.65	--	3.3
7	11.8	--	--	--	1.58	20	--
12	23.0	--	--	--	4.04	40	--
Slug injection of dye at 0930 hours on August 17, 1989, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 55 cubic feet per second							
4	2.3	34	1.4	0.07	0.51	--	5.9
7	11.8	--	--	--	[1]4.79	[1]10	--
Slug injection of dye at 0640 hours on April 23, 1990, at site 6; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 409 cubic feet per second							
7	2.4	42	2.7	0.10	0.10	--	3.4
12	13.6	--	--	--	.81	50	--
Slug injection of dye (4 liters) at 0630 hours on April 25, 1990, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 410 cubic feet per second							
4	2.3	44	3.6	0.11	0.15	--	2.4
7	11.8	--	--	--	.79	30	--
Slug injection of dye (2 liters) at 0830 hours on October 16, 1990, at site 1; daily mean streamflow at index gaging station, Red River of the North at Fargo, N. Dak. (05054000), was 128 cubic feet per second							
4	2.3	35	2.0	--	0.35	--	4.0
7	11.8	--	--	--	1.45	10	--
14	30.7	--	--	--	5.38	80	--

[1]Estimated; study interrupted by rain.

The theoretical mixing time required to obtain lateral mixing between selected sites is listed in table 8. The leading edge elapsed traveltime after dye injection (table 6) was less than the theoretical mixing time at all of the first downstream sampling sites except for site 5 on August 8, 1989. In two cases, August 7, 1989, and April 25, 1990, the theoretical mixing time exceeded the leading edge elapsed traveltime by about 6 percent. In the remaining three cases, the theoretical mixing time exceeded the leading edge elapsed traveltime by 11.7 to 28 percent. Plots of the variance of time-concentration curve data versus the traveltime of the dye-cloud centroid indicate that the slope is about the same for all relations except on October 16, 1990 (supplement 2). During the October 16, 1990, dye study, the change in streamflow from precipitation probably caused the difference in dispersion characteristics between sites 4 and 7. Although the theoretical mixing time exceeded the leading edge elapsed traveltime in five of six cases, the fairly uniform slopes of the variance versus traveltime of dye-cloud centroid plots indicate the uniformity of the dispersion characteristics of the river channel in the study reach.

The rate at which reaeration occurs in a river usually is expressed as a reaeration-rate coefficient. In order to define a range of reaeration-rate coefficients that would be applicable to the range of streamflow for which the RRatFGO QW model would be calibrated and verified, reaeration measurements were scheduled for late spring and early fall 1990 when streamflow conditions would coincide with the high and low flows. Propane-sample collection began at downstream cross sections when the dye concentration receded to 2 percent of the peak concentration and continued at 30-minute intervals for 3 hours. The April 1990 tracer samples were collected at the 17-, 50-, and 83-percent streamlines. Analysis of selected samples indicated that the tracers were uniformly mixed in the cross section. Thus, only concentrations for the samples collected at the 50-percent streamline were used in traveltime and reaeration-rate coefficient calculations.

Measured reaeration-rate coefficients in the study reach in April 1990, adjusted to a 68°F water temperature, ranged from 0.57 per day at about 461 ft^3/s to 0.76 per day at about 523 ft^3/s and averaged 0.63 per day. The reaeration-rate coefficient increased in the downstream direction (table 7).

The reaeration measurements scheduled for early fall 1990 were delayed until October because streamflows in the Red River through the study reach were greater than 100 ft^3/s throughout the summer and early fall. Rain began about 12 hours after the beginning of the October 1990 measurement and continued throughout the night, and streamflow in the study reach increased about two and one-half times. Reaeration-rate coefficients, adjusted to a 68°F water temperature, ranged from 1.03 per day at about 150 ft^3/s to 1.29 per day at about 215 ft^3/s and averaged 1.17 per day. The reaeration-rate coefficient increased in the downstream direction (table 7). Because rain occurred during about one-half of the traveltime, the reaeration-rate coefficient calculated for site 7 may be larger than it would have been had it not rained. According to Banks and Wickramanayake (1984), the effect of rain on the surface of a stream is to increase the rate of reaeration. Streamflow values used in the equation to calculate the reaeration-rate coefficient are estimates taken from preliminary stage-discharge relations developed for sites 7 and 14 and from current-meter measurements.

Because of the unsteady streamflow conditions caused by the rain during the October 1990 reaeration measurement, an analysis of the possible error in all of the reaeration measurements was made. Yotsukura and others (1983) stated there is no commonly accepted method for evaluating the accuracy of reaeration-rate coefficients and developed the following equation to evaluate the effect of measurement errors on calculations:

$$\frac{\sigma(K)}{K} = \frac{1}{K(\bar{t}_2 - \bar{t}_1)} \sqrt{\frac{\sigma^2(\bar{C}_{p1})}{(\bar{C}_{p1})^2} + \frac{\sigma^2(\bar{Q}_1)}{(\bar{Q}_1)^2} + \frac{\sigma^2(\bar{C}_{p2})}{(\bar{C}_{p2})^2} + \frac{\sigma^2(\bar{Q}_2)}{(\bar{Q}_2)^2}} \quad (3)$$

where

$\sigma(K)$ is standard deviation of propane desorption coefficient, base e, in per day;

$\sigma^2(\overline{C}_{p1})$ is variance of propane concentration at upstream sampling cross section, in (milligrams per liter) squared;

$\sigma^2(\overline{Q}_1)$ is variance of mean streamflow at upstream sampling cross section, in (cubic feet per second) squared;

$\sigma^2(\overline{C}_{p2})$ is variance of propane concentration at downstream sampling cross section, in (milligrams per liter) squared;

$\sigma^2(\overline{Q}_2)$ is variance of mean streamflow at downstream sampling cross section, in (cubic feet per second) squared;

K is propane desorption coefficient, base e, in per day;

$\overline{C}_{p1}$ is mean propane concentration at upstream sampling cross section, in micrograms per liter;

$\overline{Q}_1$ is mean streamflow at upstream sampling cross section, in cubic feet per second;

$\overline{C}_{p2}$ is mean propane concentration at downstream sampling cross section, in micrograms per liter; and

$\overline{Q}_2$ is mean streamflow at downstream sampling cross section, in cubic feet per second.

The reciprocal of the reaeration-rate coefficient and traveltime product means that the larger the nonobservance of the residence time the larger the relative error. The right side of equation 3 represents the composite error in propane concentration and streamflow measurements. The composite error is influenced predominantly by the error in streamflow measurements. During the April 1990 reaeration measurements, in all cases, the residence-time requirement given by Kilpatrick and others (1989) was not met. Ideally, the streamflow-weighted ratio of upstream to downstream propane concentrations should be equal to or greater than 2.72. Applying equation 3 to the reaeration measurements for April 1990 indicates relative error could be about 35 percent (about 12 percent of the composite error is because of errors in propane concentration and streamflow measurements and the remaining relative error probably is caused by inadequate residence time).

An error analysis also was performed on the October 1990 reaeration data. The residence time was met from site 4 to site 14 for the "before" rain sampling and not met for the "after" rain sampling. The reciprocal of the reaeration-rate coefficient and traveltime product is 1.14, which compares to an ideal 1.0. The relative error in calculations from site 4 to site 7 is 34 percent (about 30 percent of the composite error could be because of errors in propane concentration and streamflow measurements). The residence time was not met from site 7 to site 14 but apparently was sufficiently improved to reduce the relative error because the reciprocal of the reaeration-rate coefficient and traveltime product was less than 1.0. The relative error in calculations from site 7 to site 14 is 39 percent (about 58 percent of the composite error could be because of errors in propane concentration and streamflow measurements).

Water-Quality Data

The QUAL2E model can simulate three conservative constituents, water temperature, dissolved oxygen, ultimate carbonaceous biochemical oxygen demand (CBODu), the nitrogen cycle, the phosphorus cycle, fecal coliform, fecal streptococci, and algae as chlorophyll a. The water-quality properties and constituents simulated in this study are: (1) Specific conductance, (2) water temperature, (3) dissolved oxygen, (4) CBODu, (5) nitrite plus nitrate, (6) ammonia, (7) organic nitrogen, (8) phosphorus, and (9) algae as chlorophyll a.

Most water-quality data used to calibrate and verify the RRatFGO QW model were obtained at the data-collection sites (table 4) during two synoptic--intensive sampling within 24 hours or less--samplings in August 1989 and August 1990. Sediment oxygen demand (SOD) data were collected in August and September 1990. Water-quality samples were collected about every 4 hours except for chlorophyll, which was collected about every 12 to 16 hours in August 1989 and about every 12 hours in August 1990, and CBODu, which was collected about every 8 hours in August 1989. Water-quality data obtained during this study are listed in supplement 3.

Water temperatures listed in supplement 3 are in degrees Celsius. However, in the text of this report, degrees Fahrenheit is used. This inconsistency results from using degrees Fahrenheit in QUAL2E. Onsite measurements of streamflow, specific conductance, pH, water and air temperature, barometric pressure, and dissolved oxygen were made when each sample was collected. Dissolved-oxygen monitors were installed at two sites to continuously record dissolved-oxygen concentration and water temperature during each synoptic sampling.

CBODu samples were analyzed by the North Dakota State Department of Health and Consolidated Laboratories using a method described by Ray Whittemore (oral commun., 1989). Samples were analyzed for total nitrite plus nitrate as nitrogen, total ammonia as nitrogen, total ammonia plus organic nitrogen, total phosphorus as phosphorus, chlorophyll a, and chlorophyll b at the U.S. Geological Survey laboratory in Lakewood, Colo., using methods described by Fishman and Friedman (1989) and Britton and Greeson (1989). (Hereafter, total nitrite plus nitrate as nitrogen will be referred to as nitrite plus nitrate, total ammonia as nitrogen will be referred to as ammonia, total organic nitrogen as nitrogen will be referred to as organic nitrogen, and total phosphorus as phosphorus will be referred to as phosphorus.) *In-situ* SOD for the Red River was measured at nine data-collection sites using methods described by Murphy and Hicks (1986).

The CBODu samples for 1989 were incubated for 75 days, and the samples for 1990 were incubated for 82 days. The samples from site 2 represented treated wastewater from the Moorhead wastewater-treatment plant, and the samples from site 8 represented treated wastewater from the Fargo wastewater-treatment plant. During incubation of the 1989 samples, near-anaerobic conditions were reached for some samples before the samples were reaerated because the samples were not diluted before incubation. However, because of the long incubation time, it was assumed that periodic low dissolved-oxygen concentrations did not adversely affect CBODu concentrations.

In order to average out analytical and procedural inconsistencies, CBODu and 5-day carbonaceous biochemical oxygen demand (CBOD5) concentrations were recalculated by nonlinear least squares fits as described by Jennings and Bauer (1976). The recalculated CBODu concentrations were used as model input. The CBODu and CBOD5 concentrations generated by the nonlinear least squares fits were used to determine a conversion factor so the RRatFGO QW model could simulate CBOD5. CBOD5 rather than CBODu usually is used in the North Dakota Pollution Discharge Elimination System permit program (Michael Ell, North Dakota State Department of Health and Consolidated Laboratories, oral commun., 1989).

Nitrite plus nitrate concentrations were determined for both the 1989 and 1990 samplings. In addition, nitrite concentrations were determined for the 1990 samples, and nitrate concentrations were determined by subtracting nitrite from nitrite plus nitrate concentrations. Organic nitrogen concentrations were determined by subtracting ammonia from ammonia plus organic nitrogen.

Phosphorus concentrations were determined for both the 1989 and 1990 samples. Total hydrolyzable plus orthophosphate phosphorus as phosphorus concentrations also were determined for the 1990 samples so that organic phosphorus concentrations could be calculated by subtracting total hydrolyzable plus orthophosphate phosphorus as phosphorus concentrations from total phosphorus concentrations. However, in about 50 percent of the samples analyzed, the total phosphorus concentration was less than the total hydrolyzable plus orthophosphate phosphorus as phosphorus concentration. The assumption was made that for the study reach organic phosphorus exists only in very small concentrations.

SOD, which was suspected to be a significant dissolved-oxygen sink in the study reach, was measured at nine sites during August and September 1990. Three SOD chambers and one control chamber, which was used to account for the water-column respiration rate, were used at each site. In case of a control chamber failure, two samples were collected in dark biochemical oxygen demand (BOD) bottles for analysis. Each SOD test was run for at least 2 hours or until a 0.5-mg/L decrease in dissolved oxygen was detected. SOD data obtained for the nine sites are listed in supplement 3.

Calibration and Verification of Model

The RRatFGO QW model was calibrated and verified in the steady-state mode. Input data required for calibration and verification are grouped into the following categories: (1) Boundary component, which consists of user-specified input data for the forcing functions that drove the model; (2) transport component, which consists of channel geometry and streamflow, traveltime simulation, specific-conductance simulation, and temperature simulation and correction factor; and (3) water-quality component, which consists of reaeration-rate coefficients and reaction coefficients and simulations of algae, nutrients, and dissolved-oxygen concentrations.

To calibrate the QUAL2E model, adjustments were made to various reaction coefficients until simulated output agreed with average values of measured data obtained during synoptic sampling. Some reaction coefficients were adjusted by model subreach, and others were applied to the entire study reach.

During calibration and verification of the transport and water-quality components, water-quality property or constituent concentrations simulated by the RRatFGO QW model were compared to maximum, average, and minimum concentrations obtained from field measurements or from laboratory analysis of samples obtained in the field. The property or constituent concentrations obtained from field measurements and laboratory analyses are associated with a particular data-collection site (supplement 3). Simulated water-quality property or constituent concentrations were compared to measured concentrations for sites 1, 4 to 7, 9, 10, 12, and 13 for calibration of the model and sites 1, 4 to 7, 9, 10, 12, and 14 for verification of the model.

For this study, the water-quality component of the RRatFGO QW model generally is considered adequately calibrated if simulated concentrations are within one standard deviation of average measured concentrations. The measured concentrations against which the simulated concentrations are compared are listed in supplement 3 for the August 29-30, 1989, calibration data and for the August 14-15, 1990, verification data. The input data used for calibration and verification of the RRatFGO QW model are listed in supplement 4.

Boundary Component

Measured input data for the boundary component are unaffected by internal conditions and calculations of the model and retain constant values. Input data for the forcing functions that drive the RRatFGO QW model are streamflow, water-quality properties or constituents, and climatology. Boundary conditions for the input data are: (1) The headwater-source streamflow and water-quality condition at site 1 (supplement 3); (2) the point-source streamflow and water-quality conditions at sites 2 and 8; (3) the point-source streamflow and water-quality conditions at sites T1 and 11; and (4) wet and dry bulb air temperature, atmospheric pressure, wind velocity, and cloud cover (supplement 4).

Measured initial conditions, which are not required for the steady-state mode operation, were input into the RRatFGO QW model so that the model also can be operated in the dynamic (diurnal) mode. To operate the model in the dynamic mode, however, additional data are required. Measured initial conditions are specified by subreach. Water-quality data for all sites are listed in supplement 3. The sites and the subreaches that the sites represent in the model are shown in figure 3. For example, the average concentration of water-quality properties and constituents for site 4 represents the upstream condition for subreach 2, the average concentration of water-quality properties and constituents for site 5 represents the upstream condition for subreaches 3 and 4, and so forth.

Transport Component

"The understanding of how water moves in rivers and what volume of water is contained in various reaches is important because this factor alone can explain much of the observed variation in river quality" (McCutcheon, 1989, p. 85). Consequently, the degree of success in calibrating the water-quality component of the RRatFGO QW model depends largely on how well the transport component of the model is calibrated. Traveltime measurements discussed previously in this report provide some information, including transport velocity, on how water moves in the study reach. However, to estimate transport velocities in the study reach when streamflows are different from measured streamflows, a relation between streamflow at the index gaging station, Red River of the North at Fargo, N. Dak., and traveltime was developed (fig. 4). The RRatFGO QW model uses Manning's equation to calculate streamflow. Manning's equation requires, among other cross-section properties, cross-section area of the channel for which streamflow is to be calculated.

Channel Geometry and Streamflow

To begin calibration of the transport component of the RRatFGO QW model, measured 1-mi cross-section shapes were modified to trapezoidal shapes. The trapezoidal shape is required by the model to calculate cross-section area. Cross sections were grouped by subreach (fig. 3), and cross-section data collected were averaged to obtain one representative value for each subreach. These representative values are referred to as modified in table 9.

To simulate a trapezoidal shape, channel geometry was calibrated in a trial-and-error manner by adjusting widths, depths, and areas until the calibrated values matched the modified values. The average calibrated top width is about the same as the average modified top width, the average calibrated depth is about 11 percent larger than the average modified depth, and the average calibrated area is about 9 percent larger than the average modified area (table 9).

To calibrate the response of transport velocities to the modified channel geometry, streamflows that existed during the various cross-section measurements were entered into the RRatFGO QW model. Transport velocities that are associated with the streamflows that existed during the various cross-section measurements were estimated from the relation in figure 4 and were compared to simulated transport velocities. Adjustments were made as necessary to channel-geometry values and to Manning's roughness coefficient (n) values until the model satisfactorily simulated transport velocities (table 9).

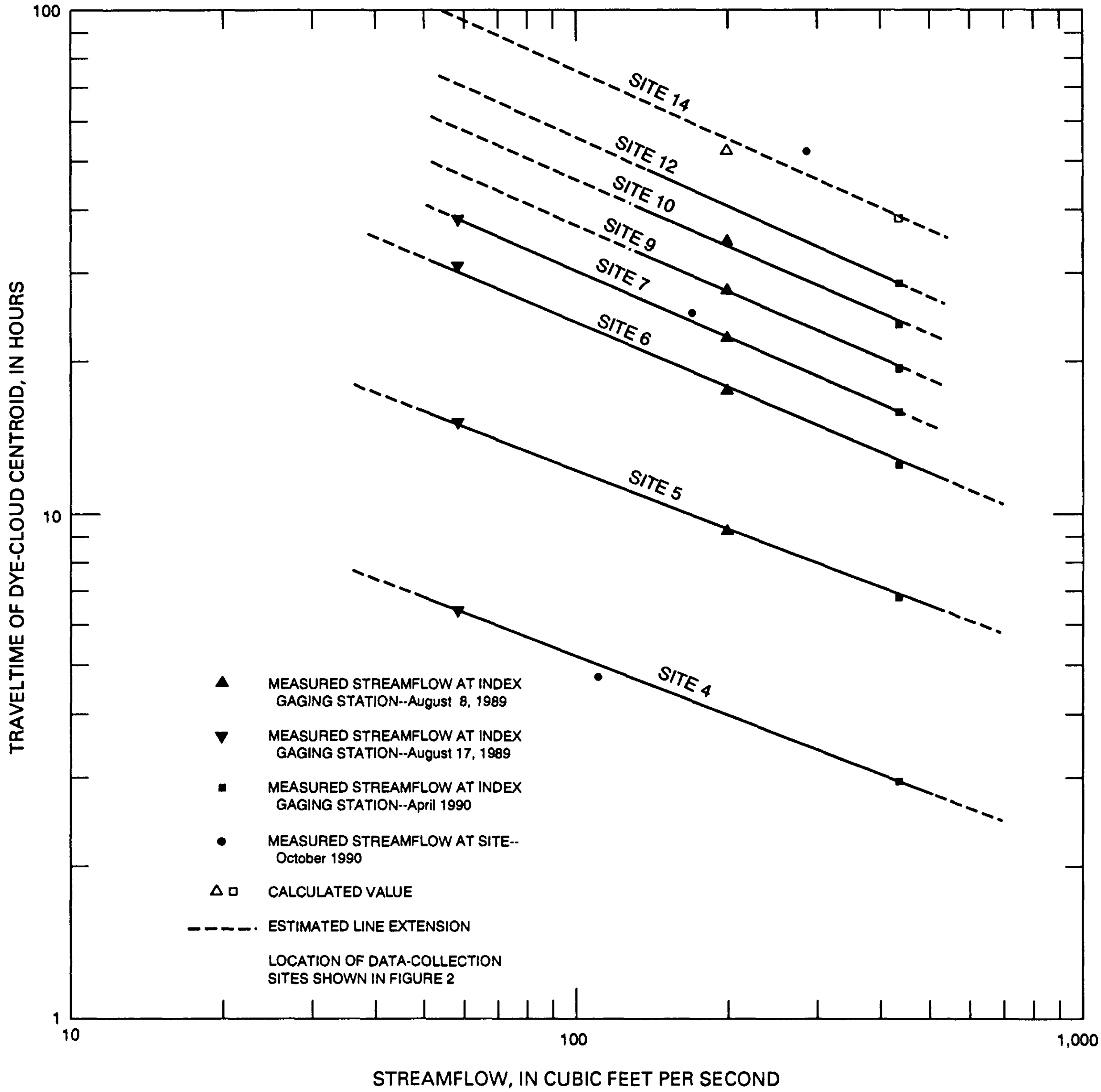


Figure 4. Traveltime of dye-cloud centroid versus streamflow at the index gaging station, Red River of the North at Fargo, North Dakota (05054000).

Table 9. Modified and calibrated channel-geometry and hydraulic data

[--, not calculated]

Subreach	Study reach river mile at upstream end of subreach	Average streamflow (cubic feet per second)	Average top width of river (feet)		Average depth of river (feet)		Average channel area (square feet)	
			Modified	Calibrated	Modified	Calibrated	Modified	Calibrated
1	30.8	190	74	92	2.1	2.4	150	220
2	28.6	190	81	81	3.0	2.9	240	230
3	25.6	190	80	77	2.8	3.1	200	240
4	23.4	190	86	87	2.9	2.9	240	250
5	21.4	190	74	90	2.6	2.7	190	240
6	19.0	250	94	85	[1]2.8	3.0	270	260
7	15.8	250	82	77	[1]3.0	3.2	260	250
8	13.8	250	92	91	2.2	2.7	190	250
9	11.6	250	78	77	3.1	3.2	240	250
10	7.8	350	96	92	[2]2.9	3.2	270	290
11	3.8	350	92	88	[2]2.7	3.3	250	290
Average	--	--	84	85	2.7	3.0	230	250

See footnotes at end of table.

Table 9. Modified and calibrated channel-geometry and hydraulic data--Continued

[--, not calculated]

Subreach	Study reach river mile at upstream end of subreach	Average streamflow (cubic feet per second)	Average channel side slope (run/rise) (foot per foot)				Average channel slope (foot per foot)		Manning's roughness coefficient (*n*)		Average transport velocity of river (feet per second)	
			Left side		Right side							
			Modified	Calibrated	Modified	Calibrated	Initial	Calibrated	Initial	Calibrated	Measured	Calibrated
1	30.8	190	4.94	6.94	8.55	6.15	0.0001136	0.0001136	0.040	0.030	0.86	0.91
2	28.6	190	6.35	6.33	2.03	2.03	.0001136	.0001136	.033	.033	.80	.87
3	25.6	190	6.13	6.13	1.96	1.96	.0001136	.0001136	.040	.037	.76	.82
4	23.4	190	3.53	3.53	3.21	3.21	.0001136	.0001136	.040	.037	.76	.80
5	21.4	190	4.36	6.36	3.52	5.52	.0001136	.0001136	.040	.037	.75	.83
6	19.0	250	5.16	5.16	5.10	5.10	.0001345	.0001136	.040	.033	1.0	1.0
7	15.8	250	5.80	5.80	5.00	5.00	.0001345	.0001136	.040	.030	1.0	1.0
8	13.8	250	5.78	5.78	4.31	4.31	.0001345	.0001136	.040	.028	1.0	1.0
9	11.6	250	4.19	4.19	4.76	4.76	.0000750	.0000943	.040	.028	1.0	1.0
10	7.8	350	4.10	4.10	6.00	6.00	.0000750	.0001136	.040	.028	1.2	1.2
11	3.8	350	3.04	3.04	6.66	6.66	.0000750	.0001136	.040	.028	1.2	1.2
Average	--	--	4.85	5.21	4.65	4.61	.0001087	.0001118	.039	.032	.94	.97

[1]At 300 cubic feet per second.
[2]At 400 cubic feet per second.

Traveltime Simulation

To verify the response of the RRatFGO QW model to a range of streamflows other than those that existed during cross-section measurements, streamflows from the traveltime measurements were entered into the model and simulations of traveltime were made. For a streamflow of 60 ft^3/s in subreaches 1-5, the calibrated RRatFGO QW model simulates traveltime that is 12.6 percent shorter than measured traveltime for the same streamflow. For streamflows of about 390 to 523 ft^3/s in subreaches 5-9, the model simulates traveltimes that are about 8 percent longer than measured traveltimes for the same streamflows. For streamflows of about 195 to 225 ft^3/s in subreaches 1-9, the model simulates traveltimes that are 6.1 percent shorter than measured traveltimes (table 10). The accuracy of the RRatFGO QW model will decrease if it is applied to streamflows outside the range of streamflows that existed during calibration and verification.

Specific-Conductance Simulation

Specific conductance was simulated to determine how well the model is calibrated for stream transport velocities because specific conductance is assumed to be a conservative constituent and a change in its value during transport in the study reach is caused only by a change in dilution. Simulated specific-conductance values that are larger or smaller than measured values indicate that the model is not simulating stream transport accurately. Consequently, the water-quality component of the model will simulate values that are erroneous.

Simulated specific-conductance values for the calibration and verification data sets were compared with average measured values for sites 1, 4 to 7, 9, 10, 12, and 13 or 14 (fig. 5). Simulated values for the calibration data set are within one standard deviation, which ranges from 8 to 22 μS/cm at 25°C, of the corresponding average measured values. Simulated values for the verification data set are within one standard deviation, which ranges from 6 to 20 μS/cm at 25°C, of the corresponding average measured values for all data-collection sites except sites 7, 10, and 14. Specific-conductance values for the verification data set decrease from site 6 to site 7, from site 9 to site 10, and from site 12 to site 14. The decrease in values may be due to some unaccounted-for dilution, incomplete mixing, or sampling error. These decreases also are present in the calibration data set but are larger in the verification data set. Although the transport component of the RRatFGO QW model is calibrated satisfactorily according to the less-than-one standard deviation criteria, the possibility of some error in transport should be noted.

Temperature Simulation and Correction Factor

Although the water temperature range was not large and was not considered significant during synoptic sampling, temperature was simulated so that the model might be used in the diurnal mode. In addition, many of the reaction coefficients are temperature dependent, and temperature simulation gives flexibility for the RRatFGO QW model to be used for other open-water times of the year.

Temperatures calculated in the model are used to correct the reaction coefficients in the source-sink terms for water-quality properties or constituents listed in table 11. The reaction coefficients associated with these properties or constituents were input at a temperature of 68°F and then were corrected to the appropriate temperature using the following Streeter-Phelps type equation:

$$X_T = X_{68}\Theta^{(T-68)} \tag{4}$$

Table 10. Measured and simulated traveltimes for streamflows that existed during traveltime measurements

Site numbers	Subreaches	Date of dye injection	Streamflow (cubic feet per second)	Transport velocity of dye-cloud centroid (feet per second)		Traveltime of dye-cloud centroid (hours)		Absolute value of percent error between measured and simulated traveltime
				Measured	Simulated	Measured[1]	Simulated	
1- 7	1- 5	August 17, 1989	60	0.44	0.51	38.9	34.0	12.6
1- 7	1- 5	April 25, 1990	407-420	1.07	1.04	16.1	16.7	3.7
1-12	1- 9	August 8, 1989	195-225	.82	.87	41.3	38.8	6.1
1-14	1-11	October 16, 1990	104-270	.86	.85	53.2	53.8	1.1
6-12	5- 9	April 23, 1990	390-523	1.26	1.14	16.3	17.6	8.0
12-14	10-11	August 7, 1989	220	.96	.95	16.5	16.2	1.8

[1]Measured values were rounded from the values shown in table 6 to compare with simulated values.

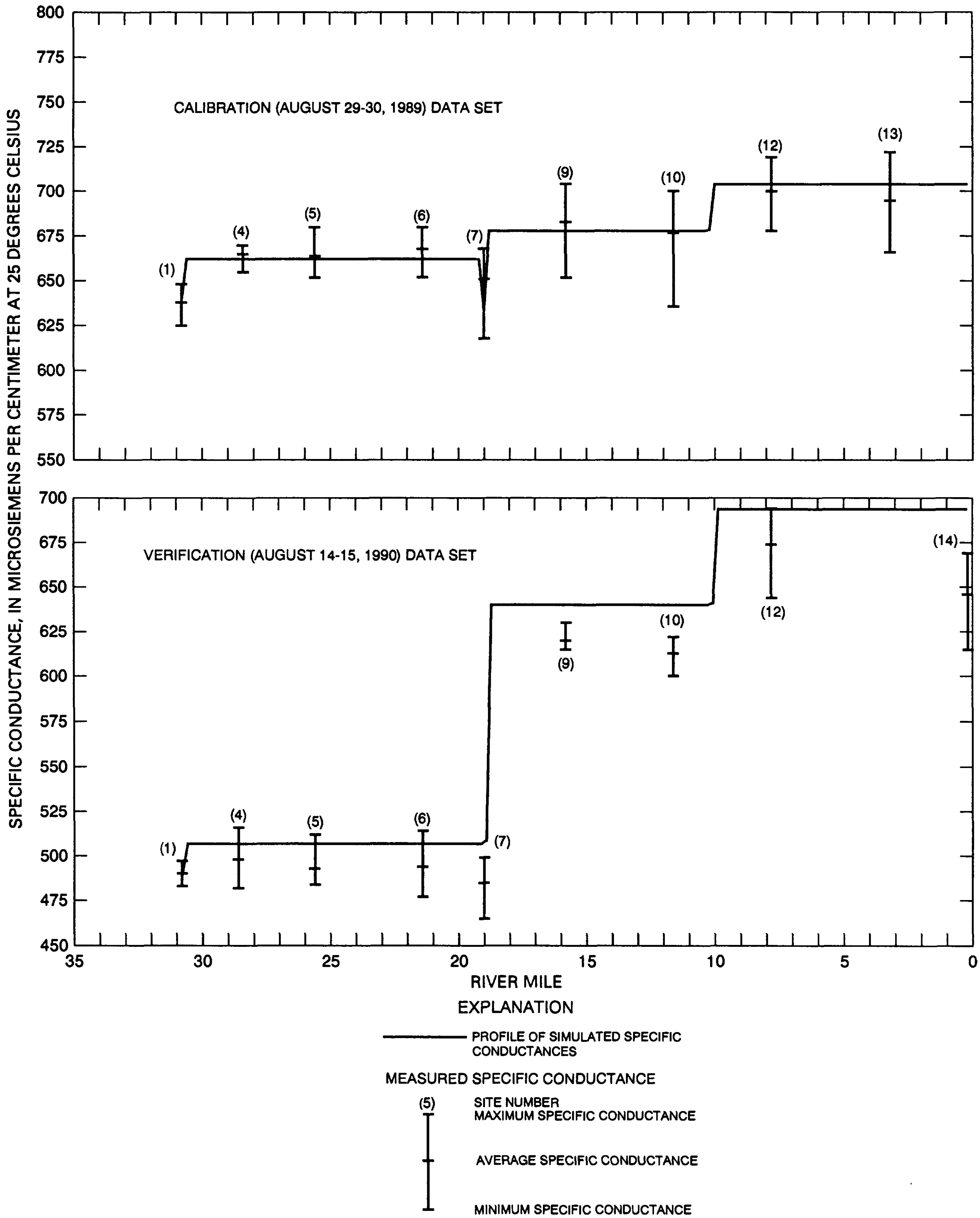


Figure 5. Maximum, average, and minimum measured specific-conductance values for calibration (August 29-30,1989) and verification (August 14-15, 1990) data sets and profiles of simulated specific-conductance values (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

where

X_T is value of coefficient at local temperature,

X_{68} is value of coefficient at standard temperature of 68 degrees Fahrenheit, and

Θ is empirical constant for each temperature-dependent reaction coefficient.

Table 11. Default temperature correction values for the Red River at Fargo Water-Quality Model

Rate coefficient	Symbol	Default temperature correction values[1] (degrees Fahrenheit)
Ultimate carbonaceous biochemical oxygen demand decay rate, in per day	K_1	1.047
Rate of loss of ultimate carbonaceous biochemical oxygen demand caused by settling, in per day	K_3	1.024
Reaeration-rate coefficient, in per day	K_2	1.024
Sediment oxygen demand rate, in (grams oxygen per square foot) per (day)	K_4	1.060
Instream reaction rate for hydrolysis of organic nitrogen to ammonia, in per day	β_3	1.047
Organic nitrogen settling rate, in per day	σ_4	1.024
Instream reaction rate for biological decay of ammonia to nitrite, in per day	β_1	1.083
Benthos source rate for ammonia, in (milligrams ammonia per square foot) per (day)	σ_3	1.074
Instream reaction rate for biological decay of nitrite to nitrate, in per day	β_2	1.047
Instream reaction rate for biological decay of organic phosphorus to phosphorus, in per day	β_4	1.047
Organic phosphorus settling rate, in per day	σ_5	1.024
Benthos source rate for phosphorus, in (milligrams phosphorus per square foot) per (day)	σ_2	1.074
Local specific algal growth rate, in per day	μ	1.047
Local algal respiration rate, in per day	ρ	1.047
Local algal settling rate, in feet per day	σ_1	1.024

[1]From Brown and Barnwell, 1987.

The temperature correction factor may be specified by the user. For calibration and verification of the RRatFGO QW model, the default temperature correction values (table 11) reported by Brown and Barnwell (1987, p. 53) are used.

Temperature is simulated by performing a heat balance on each computational element in the model system. The heat balance accounts for temperature gains and losses from the forcing functions as well as the heat exchanged between the water surface and the atmosphere (Brown and Barnwell, 1987). Although the input variables for temperature simulation can be varied by subreach, the variables were kept constant through the study reach.

Simulated temperature values for the calibration and verification data sets were compared with average measured values (fig. 6). Simulated temperatures for both data sets are within one standard deviation, which ranges from 1.0 to 2.0°F, of the average measured values for all data-collection sites. Temperature was calibrated by adjusting windspeed, and, before verification, climatological data pertinent to August 14-15, 1990, were entered into the RRatFGO QW model and windspeed was again adjusted.

Water-Quality Component

Reaeration-Rate Coefficients

An important consideration in evaluating the effect of wastewater on the water quality of a receiving stream is to determine the stream's ability to maintain an adequate dissolved-oxygen concentration. The water-quality component of the RRatFGO QW model emulates major constituent interactions that occur in the stream and affect dissolved-oxygen concentration (fig. 7). The processes and their major constituent interactions are defined in the model by several reaction coefficients. These reaction coefficients were specified to best describe the constituent interactions in the Red River at Fargo study reach.

Of the major reaction coefficients that affect dissolved-oxygen concentration, the reaeration-rate coefficient probably is the most important. Calculation of the reaeration-rate coefficient is the first step in calibration of the water-quality component. The reaeration-rate coefficient is a measure of the ability of a stream to absorb oxygen from the atmosphere. From a wastewater-assimilation standpoint, the more oxygen a stream can absorb, the more oxygen-depleting waste the stream can assimilate.

Three methods are provided in the QUAL2E model to calculate stream reaeration-rate coefficients. These methods are: (1) As a power function of streamflow, (2) on the basis of measured reaeration-rate coefficients, and (3) on the basis of 11 predictive equations. In this study, the reaeration-rate coefficients used to calibrate and verify the RRatFGO QW model are based on measured reaeration-rate coefficients. In addition, 11 predictive equations were evaluated for possible use in the RRatFGO QW model or for use in other water-quality models for other reaches of the Red River.

Empirically, from predictive equations, a decrease in the reaeration-rate coefficient is expected with an increase in streamflow because the reaeration-rate coefficient is directly proportional to stream velocity and inversely proportional to stream depth. When comparing the April 1990 reaeration-rate coefficients, which were measured at streamflows of about 400 to 500 ft^3/s, with the October 1990 reaeration-rate coefficients, which were measured at streamflows of about 100 to 200 ft^3/s, the reaeration-rate coefficient, as expected from the predictive equations, increases with a decrease in streamflow. However, both the April and October 1990 data sets indicate that the reaeration-rate coefficient within the study reach increases about 20 to 30 percent in the downstream direction at the same time the streamflow increases (table 7). This could result from measurement error or indicate that the effect of a downstream increase in velocity is greater than the effect of a downstream increase in depth.

A graphical regression of streamflow and reaeration-rate coefficients was developed for the April and October 1990 data (fig. 8). The average streamflow for the sites being considered was used to determine the streamflow coordinate and to calculate the reaeration-rate coefficients listed in table 7. The propane concentration used to calculate the reaeration-rate coefficient, which was used to determine the reaeration-rate coefficient coordinate in figure 8, also is listed in table 7. The error analysis that was performed on the

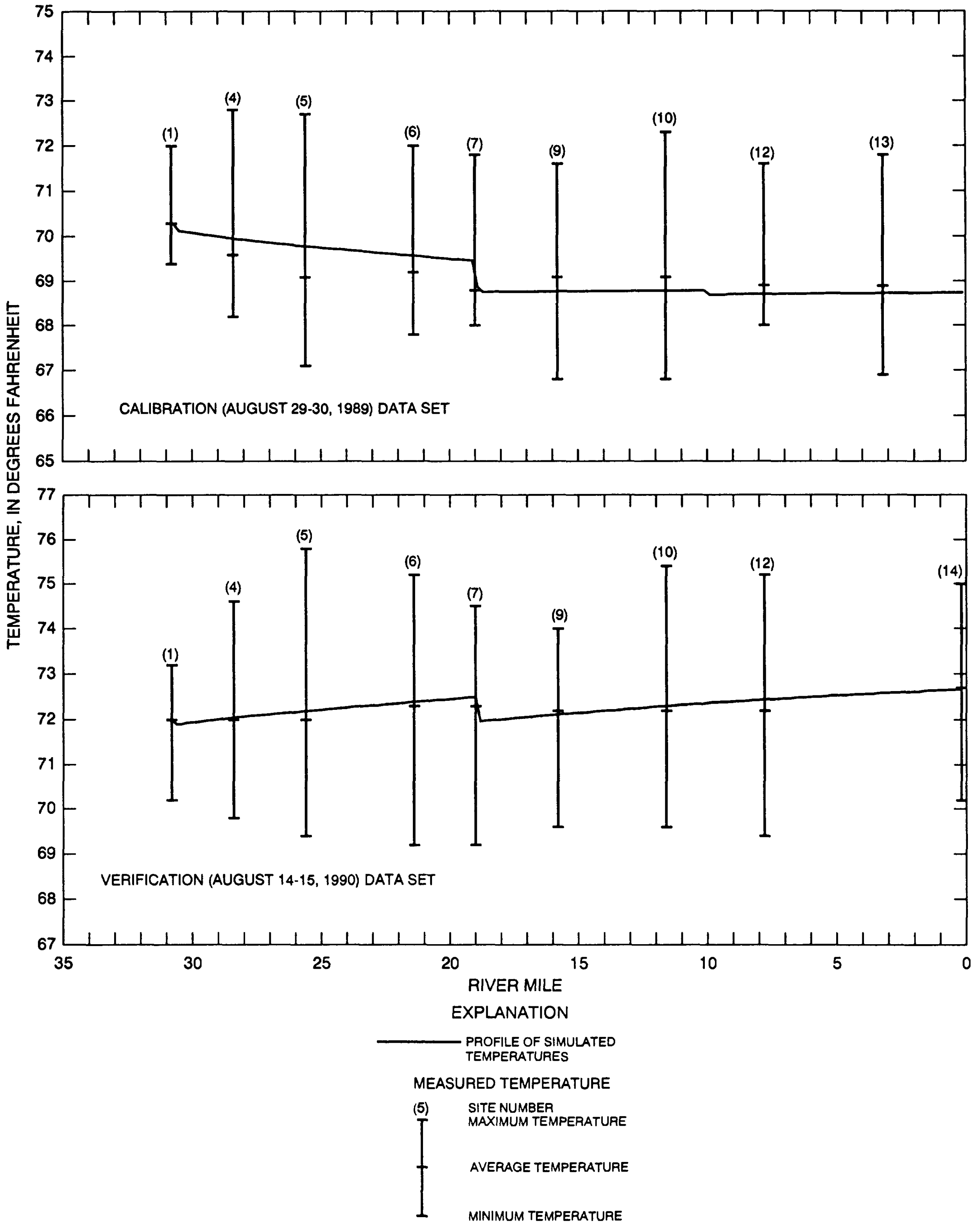


Figure 6. Maximum, average, and minimum measured temperatures for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated temperatures (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

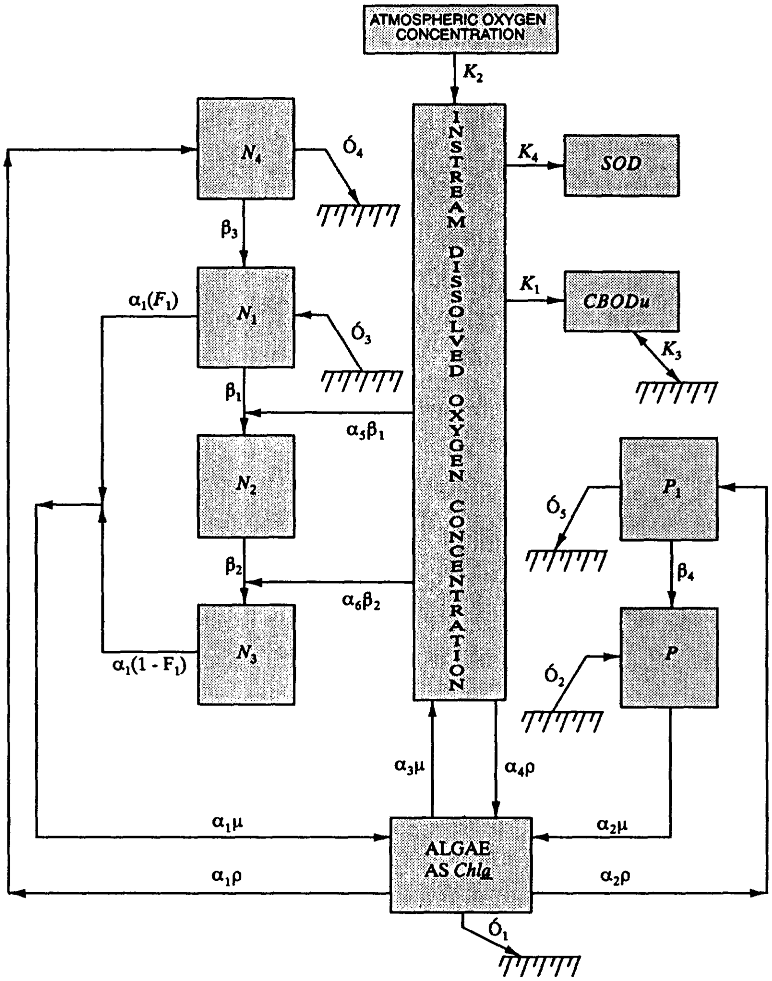


Figure 7. Enhanced Stream Water Quality Model showing major constituent interactions in stream. (Modified from Brown and Barnwell, 1987.)

EXPLANATION (Continued on next page)

CBODu Ultimate carbonaceous biochemical oxygen demand, in milligrams per liter.

Chla Chlorophyll-a concentration, in micrograms per liter.

F_1 Fraction of algal nitrogen uptake from ammonia pool.

K_1 Ultimate carbonaceous biochemical oxygen demand decay rate, in per day.

K_2 Reaeration-rate coefficient, in per day.

K_3 Rate of loss of ultimate carbonaceous biochemical oxygen demand caused by settling, in per day.

K_4 Sediment oxygen demand rate, in (grams oxygen per square foot) per (day).

N_1 Total ammonia concentration as nitrogen, in milligrams per liter.

EXPLANATION (Continued)

N_2 Total nitrite concentration as nitrogen, in milligrams per liter.

N_3 Total nitrate concentration as nitrogen, in milligrams per liter.

N_4 Total organic nitrogen concentration as nitrogen, in milligrams per liter.

P Total inorganic phosphorus concentration as phosphorus, in milligrams per liter.

P_1 Total organic phosphorus concentration as phosphorus, in milligrams per liter.

SOD Sediment oxygen demand, in (grams oxygen per square foot) per (day).

α_1 Fraction of algal biomass that is nitrogen, in (milligrams nitrogen per liter) per (milligrams algal biomass per liter).

α_2 Fraction of algal biomass that is phosphorus, in (milligrams phosphorus per liter) per (milligrams algal biomass per liter).

α_3 Rate of dissolved-oxygen production per unit of algal growth, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter).

α_4 Rate of dissolved-oxygen uptake per unit of algae respired, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter).

α_5 Rate of dissolved-oxygen uptake per unit of total ammonia as nitrogen oxidized to total nitrite as nitrogen, in (milligrams dissolved oxygen per liter) per (milligrams total ammonia as nitrogen per liter).

α_6 Rate of dissolved-oxygen uptake per unit of total nitrite as nitrogen oxidized to total nitrate as nitrogen, in (milligrams dissolved oxygen per liter) per (milligrams total nitrite as nitrogen per liter).

β_1 Instream reaction rate for biological decay of total ammonia as nitrogen to total nitrite as nitrogen, in per day.

β_2 Instream reaction rate for biological decay of total nitrite as nitrogen to total nitrate as nitrogen, in per day.

β_3 Instream reaction rate for hydrolysis of total organic nitrogen as nitrogen to total ammonia as nitrogen, in per day.

β_4 Instream reaction rate for biological decay of total organic phosphorus as phosphorus to total phosphorus as phosphorus, in per day.

μ Local specific algal growth rate, in per day.

ρ Local algal respiration rate, in per day.

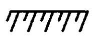
σ_1 Local algal settling rate, in feet per day.

σ_2 Benthos source rate for total phosphorus as phosphorus, in (milligrams total phosphorus as phosphorus per square foot) per (day).

σ_3 Benthos source rate for total ammonia as nitrogen, in (milligrams total ammonia as nitrogen per square foot) per (day).

σ_4 Total organic nitrogen as nitrogen settling rate, in per day.

σ_5 Total organic phosphorus as phosphorus settling rate, in per day.

 Streambed.

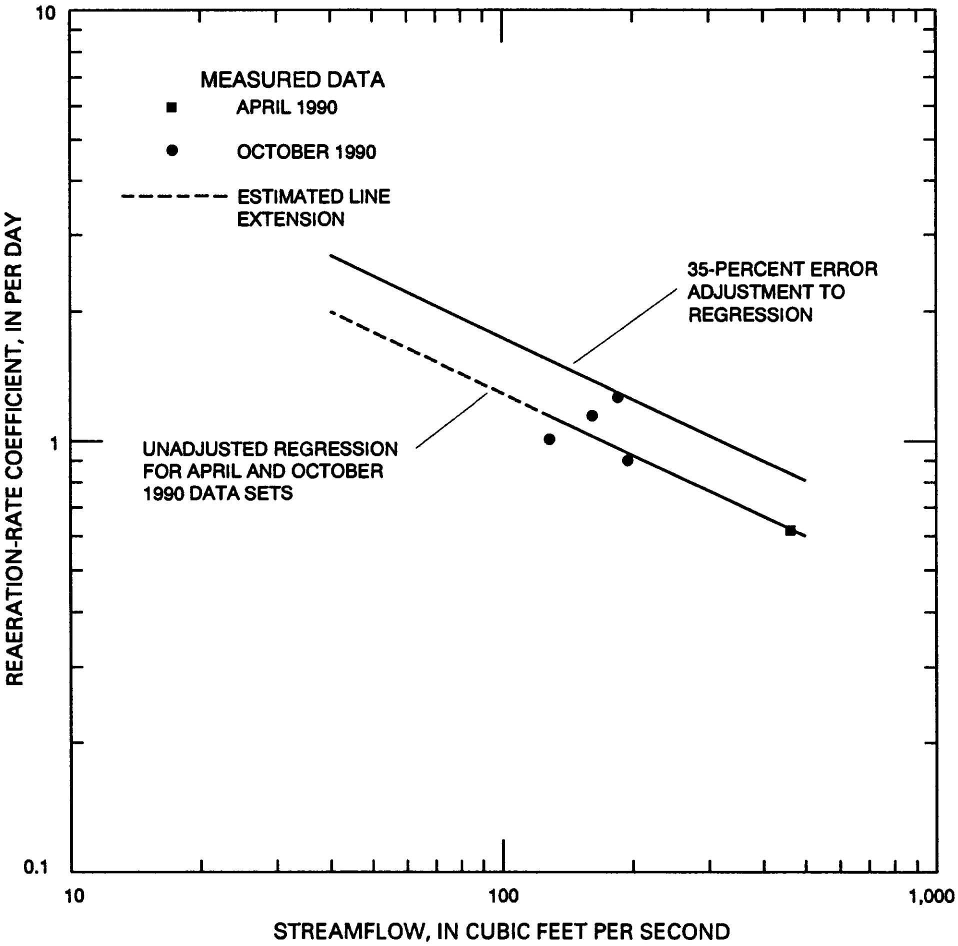


Figure 8. Reaeration-rate coefficient as a function of streamflow for the Red River of the North 30.8-mile reach from Fargo, North Dakota, to Georgetown, Minnesota, April and October 1990.

calculated reaeration-rate coefficients (see Traveltime, Longitudinal-Dispersion Coefficient, and Reaeration-Rate Coefficient section) resulted in error adjusted reaeration-rate coefficients, which were added to the regression shown in figure 8. A 35-percent error adjustment was applied to the regression. The reaeration-rate coefficients used during calibration and verification of the RRatFGO QW model were taken from the adjusted regression shown in figure 8.

The numerous predictive equations developed to estimate reaeration-rate coefficients usually are classified as empirical or semiempirical. Empirical equations are based on velocity-depth relations, whereas semiempirical equations are based on energy dissipation. McCutcheon (1989) presented descriptions of the 11 predictive equations that were evaluated during this study. Because more flexibility may be desired to simulate conditions other than those in this study, some of the existing predictive equations for estimating reaeration-rate coefficients were reviewed, and estimated values were compared with measured values. Of the 11 predictive equations evaluated during this study, only the equations from Bansal (1973) and Velz (1984) produced a dissolved-oxygen concentration that reasonably matched the simulated dissolved-oxygen concentration for the calibration and verification data sets.

The percent difference between estimated reaeration-rate coefficients and measured reaeration-rate coefficients was determined by a computer program written by W. R. Berkas (U.S. Geological Survey, written commun., 1990) called K2. This program consists of 18 predictive equations and includes 6 of the 7 predictive equations given by Brown and Barnwell (1987) plus 4 of the 5 predictive equations added to the computer code, as mentioned during the description of the model. The Velz (1984) equation discussed later in this report was not included in the K2 program. Data needed to drive the K2 program consist of the Froude number, mean depth, elevation change, slope, traveltime, mean velocity, shear velocity, and measured reaeration-rate coefficient. The K2 program was used as a screening tool during this study to retain the predictive equations that provided reaeration-rate coefficients that had percent differences of 20 percent or less in both test reaches (sites 4 to 7 and 7 to 12, tables 12 and 13). The equation screening was not performed at the lower streamflows that occurred during the October 16-20, 1990, reaeration measurements because of the unsteady streamflow condition.

The estimated and measured reaeration-rate coefficients for the two test reaches and the percent difference between the coefficients are listed in tables 12 and 13. The three equations that met the 20-percent criteria are from Cadwallader and McDonnell (1969), Padden and Gloyna (1971), and Bansal (1973). The equation from Cadwallader and McDonnell (1969) was not used in this study because the RRatFGO QW model would need to be modified for this equation.

According to McCutcheon (1989), the equation from Padden and Gloyna (1971) was formulated from regression analysis of data collected in a research flume that had large reaeration-rate coefficients and small velocities--conditions unlike those that existed in the study reach. Only the Bansal (1973) equation

$$K_2 = \frac{4.67U^{0.6}}{D^{1.4}} \qquad (5)$$

where

K_2 is reaeration-rate coefficient, in per day;
U is streamflow transport velocity, in feet per second; and
D is mean depth of subreach, in feet;

and the Velz (1984) equation

$$K_2 = -\frac{ln\left[1-2\left[(1.42)\ (1.1^{T-68})\ (\frac{m}{60})\right]^{\frac{1}{2}}\right]}{\frac{m}{1,440}} \tag{6}$$

where

ln is natural logarithm, base e;

T is temperature, in degrees Fahrenheit; and

m is mixing interval, in minutes ($2.279 + 0.721D$ when $D < 2.26$ feet and $13.94ln(D) - 7.45$ when $D \geq 2.26$ feet);

were tested during calibration and verification. The purpose of these tests was to compare simulated dissolved-oxygen concentrations that were calculated by using reaeration-rate coefficients obtained from these two predictive equations to dissolved-oxygen concentrations that were calculated by using reaeration-rate coefficients obtained from measurements.

Table 12. Estimated and measured reaeration-rate coefficients for sites 4 to 7 when streamflow was between 407 and 420 cubic feet per second

[Reaeration-rate coefficients listed in base e natural logarithm at 68 degrees Fahrenheit per day]

	Estimated reaeration-rate coefficient	Measured reaeration-rate coefficient	Percent difference
Predictive equation from:			
O'Connor and Dobbins (1958)	1.37	0.64	110
Churchill and others #1 (1962)	.96	.64	50
#2 (1962)	.64	.64	0
Krenkel and Orlob (1963)	2.07	.64	220
Owens and others #1 (1964)	1.70	.64	170
#2 (1964)	1.36	.64	110
Langbein and Durum (1967)	1.05	.64	64
Isaacs and Gaudy (1968)	.92	.64	44
Cadwallader and McDonnell (1969)	.77	.64	20
Negulescu and Rojanski (1969)	3.09	.64	380
Padden and Gloyna (1971)	.72	.64	12
Bennett and Rathbun #1 (1972)	1.61	.64	150
#2 (1972)	1.05	.64	64
Lau (1972)	1.48	.64	130
Parkhurst and Pomeroy (1972)	.89	.64	39
Tsivoglou and Wallace (1972)	.44	.64	31
Bansal (1973)	.65	.64	1.6
Tsivoglou and Neal (1976)	.61	.64	4.7

Table 13. Estimated and measured reaeration-rate coefficients for sites 7 to 12 when streamflow was between 390 and 523 cubic feet per second

[Reaeration-rate coefficients listed in base e natural logarithm at 68 degrees Fahrenheit per day]

	Estimated reaeration-rate coefficient	Measured reaeration-rate coefficient	Percent difference
Predictive equation from:			
O'Connor and Dobbins (1958)	1.05	0.63	67
Churchill and others #1 (1962)	.75	.63	19
#2 (1962)	.35	.63	44
Krenkel and Orlob (1963)	1.90	.63	200
Owens and others #1 (1964)	1.27	.63	100
#2 (1964)	.99	.63	57
Langbein and Durum (1967)	.89	.63	41
Isaacs and Gaudy (1968)	.75	.63	19
Cadwallader and McDonnell (1969)	.66	.63	4.8
Negulescu and Rojanski (1969)	2.86	.63	350
Padden and Gloyna (1971)	.57	.63	9.5
Bennett and Rathbun #1 (1972)	1.20	.63	90
#2 (1972)	.81	.63	29
Lau (1972)	1.27	.63	100
Parkhurst and Pomeroy (1972)	.86	.63	36
Tsivoglou and Wallace (1972)	.50	.63	21
Bansal (1973)	.52	.63	17
Tsivoglou and Neal (1976)	1.04	.63	65

According to McCutcheon (1989), development of the Bansal (1973) predictive equation was based on reanalysis of extensive data for numerous rivers. However, it is not known if the channel characteristics, especially slope, of any of these rivers are similar to the channel characteristics of the Red River. The Bansal (1973) equation is a traditional-type equation in that the reaeration-rate coefficient is directly proportional to stream velocity and inversely proportional to stream depth. Stream velocity is not as heavily weighted in the Bansal (1973) equation as in most other traditional-type equations.

The Velz (1984) predictive equation is different from the traditional-type equations because it represents the river segment as if it were quiescent water, which periodically is mixed completely, and reaeration is assumed to occur by molecular diffusion. The mixing interval is related empirically to the effective depth of the river segment (Robert M. Hirsch, written commun., 1979).

Reaction Coefficients and Simulations of Concentrations

Algae and Nutrients

A major part of the water-quality component consists of the processes and interactions of algae and nutrients. The second step in the modeling process was to calibrate the appropriate reaction coefficients to simulate algae as chlorophyll a and nutrient (nitrite plus nitrate, ammonia, organic nitrogen, and phosphorus) kinetics. The appropriate reaction coefficients were estimated from measured data when available. If measured data were not available to estimate reaction coefficients, the reaction coefficients initially were set to a midvalue of the range recommended in the model documentation by Brown and Barnwell (1987) and by recommendations in Bowie and others (1985) and adjusted as necessary until simulated algae and nutrient values matched measured values. The reaction coefficients used in the calibrated model to simulate algae and nutrient kinetics are listed in tables 14 and 15.

Table 14. Reaction coefficients used in the Red River at Fargo Water-Quality Model to calibrate algae and nutrient kinetics

	Recommended reaction coefficient range[1]	Reaction coefficient used
Ratio of chlorophyll a to algal biomass, in (micrograms chlorophyll a per liter) per (milligrams algal biomass per liter)	10 -50	10
Maximum specific algal growth rate, in per day	1.0 - 3.0	1.6
Linear algal selfshading, in (per foot) per (micrograms chlorophyll a per liter)	0.002- 0.02	.0027
Nonlinear algal selfshading, in (per foot) per (micrograms chlorophyll a per liter)$^{2/3}$	0.0165	.0165
Michaelis-Menton light half-saturation, in (British thermal units per square foot) per (minute)	0.02 - 0.10	.1105
Michaelis-Menton nitrogen half-saturation, in milligrams nitrogen per liter	0.01 - 0.30	.03
Michaelis-Menton phosphorus half-saturation, in milligrams phosphorus per liter	0.005- 0.05	.04
Algal preference factor for ammonia	0- 1.0	.9
Fraction of algal biomass that is nitrogen, in (milligrams nitrogen per liter) per (milligrams algal biomass per liter)	0.07 - 0.09	.08
Fraction of algal biomass that is phosphorus, in (milligrams phosphorus per liter) per (milligrams algal biomass per liter)	0.01 - 0.02	.011
Local algal respiration rate, in per day	0.05 - 0.5	.06
Rate of dissolved-oxygen production per unit of algal growth, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter)	1.4 - 1.8	1.6
Rate of dissolved-oxygen uptake per unit of algae respired, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter)	1.6 - 2.3	2.0
Rate of dissolved-oxygen uptake per unit of ammonia oxidized to nitrite, in (milligrams dissolved oxygen per liter) per (milligrams ammonia per liter)	3.0 - 4.0	3.43
Rate of dissolved-oxygen uptake per unit of nitrite oxidized to nitrate, in (milligrams dissolved oxygen per liter) per (milligrams nitrite per liter)	1.0 - 1.14	1.14

[1]From QUAL2E model documentation (Brown and Barnwell, 1987, p. 53-56).

Table 15. Reach-dependent reaction coefficients used in the Red River at Fargo Water-Quality Model to simulate algae and nutrient kinetics

[ft/d, foot per day; 1/ft, per foot; 1/day, per day]

Model subreach	Nonalgal light extinction (1/ft)	Local algal settling rate (ft/d)		Rate of organic nitrogen hydrolysis to ammonia nitrogen (1/day)	Organic nitrogen settling rate (1/day)	Rate of oxidation of ammonia to nitrite (1/day)	Rate of oxidation of nitrite to nitrate (1/day)	Rate of organic phosphorus decay to phosphorus (1/day)
		Calibration 1989	Verification 1990					
1	0.5	1.0	0	0.02	0	1.07	3.08	0.21
2	.5	1.0	0	.02	0	1.07	3.08	.21
3	.5	4.0	0	.02	0	1.07	3.08	.21
4	.5	4.0	0	.02	0	1.07	3.08	.21
5	.5	2.0	0	.02	0	1.07	3.08	.21
6	.5	2.0	1.0	.19	.1	1.07	3.08	.21
7	.5	2.0	1.0	.19	.1	1.07	3.08	.21
8	.5	2.0	1.0	.09	0	1.07	3.08	.21
9	.5	2.0	1.0	.09	0	1.07	3.08	.21
10	.5	2.0	1.5	.09	0	1.07	3.08	.21
11	.5	2.0	1.5	.09	0	1.07	3.08	.21

In the QUAL2E model, phytoplankton concentration (algal biomass) is expressed on the basis of chlorophyll-a concentration. The equation in Brown and Barnwell (1987) that provides conversion between algal biomass and chlorophyll a in the QUAL2E model is:

$$Chl\underline{a} = \alpha_0 A \tag{7}$$

where

$Chl\underline{a}$ is chlorophyll-a concentration, in micrograms per liter;
α_0 is ratio of chlorophyll a to algal biomass, in (micrograms chlorophyll a per liter) per (milligrams algal biomass per liter); and
A is algal biomass concentration, in milligrams per liter.

The coefficient range recommended by Brown and Barnwell (1987) for the ratio of chlorophyll a to algal biomass (α_0) is 10 to 50 (μg Chl<u>a</u>/L)/(mg A/L). The coefficient used in the RRatFGO QW model was 10 (μg Chl<u>a</u>/L)/(mg A/L). A decrease in this ratio caused the model to simulate a larger quantity of biomass for the same chlorophyll-a concentration measured in the water and vice versa.

The Brown and Barnwell (1987) equation that governs the growth and production of chlorophyll a in the QUAL2E model is:

$$\frac{dA}{dt} = \mu A - \rho A - \frac{\sigma_1}{D} A \tag{8}$$

where

$\frac{d}{dt}$ is total derivative with respect to time;
μ is local specific algal growth rate, in per day;
ρ is local algal respiration rate, in per day; and
σ_1 is local algal settling rate, in feet per day.

The local specific algal growth rate is known to be coupled to the availability of required nutrients (nitrogen and phosphorus) and light. The QUAL2E model has three options for expressing multiple nutrient-light limitations of algal growth rate. The limiting nutrient option was used. This option represents the local specific algal growth rate as limited by light and either nitrogen or phosphorus. Thus, the nutrient-light effects are multiplicative, but the nutrient-nutrient effects are alternate. The following formulation follows Liebig's law of the minimum (Brown and Barnwell, 1987, p. 25),

$$\mu = \mu_{max}(FL)\,Min\,(FN, FP) \tag{9}$$

where

μ_{max} is maximum specific algal growth rate, in per day;
FL is algal growth limitation factor for light;
Min is minimum;
FN is algal growth limitation factor for nitrogen; and
FP is algal growth limitation factor for phosphorus.

The coefficient range recommended by Brown and Barnwell (1987) for the maximum specific algal growth rate is 1.0 to 3.0 per day. The coefficient used in the RRatFGO QW model was 1.6 per day. This coefficient was selected after preliminary model simulations of dissolved-oxygen and nutrient concentrations.

Algal growth is limited by light and nutrient availability and by temperature. Light limitation has two components: (1) A relation describing the attenuation of light with depth and including the effect of algal density on light attenuation, and (2) a relation defining the effect of the resulting light levels on algal growth and photosynthesis (Bowie and others, 1985). The first component deals with light intensity at a given depth and the light-extinction coefficient. In the QUAL2E model, photosynthesis occurs throughout the depth of the water column. Light intensity varies with depth according to Beers' law (Brown and Barnwell, 1987) as follows:

$$I_Z = I\ exp\,(-\lambda Z) \tag{10}$$

where

I_Z is light intensity at given depth (Z), in (British thermal units per square foot) per (hour);
I is surface light intensity, in (British thermal units per square foot) per (hour);
exp is the exponential function;
λ is light-extinction coefficient, in per foot; and
Z is depth below surface, in feet.

The light intensity at the water surface is a function of location, time of year, time of day, meteorological conditions, and shading from topographic features or riparian vegetation.

The light-extinction coefficient, which includes algal density and selfshading, is formulated in Brown and Barnwell (1987) by the following nonlinear equation to describe the relation between phytoplankton concentration and light extinction:

$$\lambda = \lambda_0 + \lambda_1 \alpha_0 A + \lambda_2 (\alpha_0 A)^{2/3} \tag{11}$$

where

λ_0 is nonalgal light-extinction coefficient, in per foot;
λ_1 is linear algal selfshading coefficient, in (per foot) per (micrograms chlorophyll a per liter); and
λ_2 is nonlinear algal selfshading coefficient, in (per foot) per (micrograms chlorophyll a per liter)$^{2/3}$.

The coefficient used for linear algal selfshading for this study is 0.0027 (1/ft)/(1/μg Chl<u>a</u>/L). The coefficient used for nonlinear algal selfshading is 0.0165 (1/ft)/(1/μg Chl<u>a</u>/L)$^{2/3}$. The nonalgal light-extinction coefficient, which can be varied by subreach, was estimated from Secchi-disc and turbidity measurements and was set at 0.5 per foot for all subreaches (table 15). A single Secchi-disc measurement (not listed in supplement 3) and two turbidity measurements (listed in supplement 3) were made at nine Red River sampling sites during the August 14-15, 1990, sampling. The nine Secchi-disc measurements were 0.9 ft, and the average of the two turbidity measurements ranged from about 26 to 48 NTU and averaged about 38 NTU for the nine Red River sites.

The following empirical equation was used to estimate the nonalgal light-extinction coefficient (Thomann and Mueller, 1987, p. 422):

$$\lambda_0 = \frac{1.8}{Z_s} \tag{12}$$

where

Z_s is Secchi-disc depth below surface, in feet.

Correlations between Secchi-disc depths and photocell measurements indicate that Secchi-disc depths correspond to the point where 20 percent of the incident light remains. The depth of the euphotic zone, where active photosynthesis takes place, conventionally is considered to extend to the depth where 1 percent of the incident light remains (U.S. Environmental Protection Agency, Office of Water Regulations and Standards Monitoring and Data Support Division, 1983). Thomann and Mueller (1987, p. 421) cited the following equation for which 1 percent of the surface incident light still remains:

$$Z_1 = \frac{4.61}{\lambda} \tag{13}$$

where

Z_1 is depth below surface at which 1 percent of surface radiation still remains, in feet.

For the Red River conditions, incident light greater than 1 percent would be available to a depth of more than 8 ft. Because no depths of this magnitude were measured in the Red River during the study (table 5), incident light probably is available on the river bottom for active photosynthesis for the entire length of the study reach when streamflow is 500 ft^3/s or less.

The second component of light limitation represents the light-limitation factor, which defines the relation between ambient light levels and algal growth rates or rates of photosynthesis. The two relations are: (1) Saturation-type relations in which the algal growth rate increases linearly with light at low intensities but gradually levels off at high intensities to reach a maximum value at the optimum (or saturating) light intensity; and (2) photoinhibition relations, which are similar to the growth curves below the optimum light intensity but which predict decreases in algal growth rates above the optimum light intensity because of the photoinhibition effect.

The QUAL2E model has three options that incorporate the two light-limitation components (Brown and Barnwell, 1987) to calculate the algal growth limitation factor for light (eq. 9). The light-attenuation effects of the algal growth rate are simulated in this study by using the following Monod half-saturation method (Brown and Barnwell, 1987, p. 26):

$$FL_Z = \frac{I_Z}{K_L + I_Z} \tag{14}$$

where

FL_Z is algal growth limitation factor for light intensity at a given depth below surface; and

K_L is Michaelis-Menton light half-saturation coefficient, in (British thermal units per square foot) per (minute).

When equation 10 is combined with equation 14 and equation 14 is integrated over the depth of flow, the depth-averaged light-attenuation factor is obtained as follows:

$$FL_{\bar{Z}} = \left(\frac{1}{\lambda D}\right) ln\left[\frac{K_L + I}{K_L + Ie^{-\lambda D}}\right] \tag{15}$$

where

$FL_{\bar{Z}}$ is algal growth attenuation factor for light, depth averaged; and

e is base of natural logarithms, approximately 2.71828.

Coupled to the selection of the Monod method for calculating the light-attenuation factor is the light half-saturation coefficient. The coefficient range recommended by Brown and Barnwell (1987) for light half-saturation is 0.02 to 0.10 (BTU/ft^2)/min. The coefficient used in the RRatFGO QW model was 0.1105 (BTU/ft^2)/min, which is outside the recommended range.

Steady-state algal simulations in the QUAL2E model require calculation of an average value of the algal growth attenuation factor for light throughout the diurnal cycle. There are four options in the QUAL2E model for calculating this average. The options arise from combinations of situations regarding two factors: (1) The source of the solar radiation used in the calculation (i.e., whether solar radiation is supplied externally by the user or calculated internally in the temperature heat balance); and (2) the nature of the averaging process (i.e., whether hourly values of the algal growth attenuation factor for light are averaged or whether a single daylight average solar radiation value is used to estimate the average algal growth attenuation factor for light).

To calibrate and verify the RRatFGO QW model, the average algal growth attenuation factor for light was calculated from an externally supplied single daylight average solar radiation value and the number of daylight hours per day using equations 16, 17, and 18 (Brown and Barnwell, 1987, p. 29-30):

$$FL_A = (AFACT)\ (f)\ (FL_1) \tag{16}$$

where

FL_A is algal growth attenuation factor for light, adjusted for daylight hours and averaging method;

$AFACT$ is light-averaging factor in QUAL2E model used to provide similarity between calculations using a single average value of solar radiation and calculations using the hourly average values of the algal growth limitation factor for light;

f is fraction of daylight hours; and

FL_1 is algal growth limitation factor for light based on daylight average light intensity;

$$FL_1 = \frac{1}{\lambda D} ln\left[\frac{K_L + \bar{I}_{alg}}{K_L + \bar{I}_{alg}e^{-\lambda D}}\right] \tag{17}$$

where

$\bar{I}_{alg}$ is daylight average light intensity, in (British thermal units per square foot) per (hour);

and

$$\bar{I}_{alg} = \frac{I_{tot}}{h} \qquad (18)$$

where

I_{tot} is total daily solar radiation, in British thermal units per square foot; and

h is number of daylight hours per day, in hours.

The selection of the option that uses a single daylight average solar radiation value or the option that uses diurnal light averaging depends largely on the detail to which one wants the model to account for diurnal variation in light intensity. The option that uses the simpler, single daylight average solar radiation value was chosen for the RRatFGO QW model primarily for easier use of the model at some future date. Also, the present calibration allows the model to simulate algae without the requirement to simulate temperature as well.

The local specific algal growth rate also is limited by nutrients. Michaelis-Menton kinetics are used in the QUAL2E model and it is assumed that algal growth rates are determined by external concentrations of available nutrients. The Michaelis-Menton half-saturation coefficients for nitrogen and phosphorus serve to decrease the algal growth rate in simulations for growth limitations by nutrients. The algal growth rate is decreased on the basis of the following equations (Brown and Barnwell, 1987, p. 34):

$$FN = \frac{N_e}{N_e + K_n} \qquad (19)$$

where

N_e is effective concentration of available inorganic nitrogen, in milligrams per liter; and

K_n is Michaelis-Menton nitrogen half-saturation coefficient, in milligrams nitrogen per liter;

and

$$FP = \frac{P}{P + K_p} \qquad (20)$$

where

P is inorganic phosphorus concentration as phosphorus, in milligrams per liter; and

K_p is Michaelis-Menton phosphorus half-saturation coefficient, in milligrams phosphorus per liter.

The coefficient range recommended by Brown and Barnwell (1987) for nitrogen half-saturation is 0.01 to 0.30 (mg N)/L, and the range recommended for phosphorus half-saturation is 0.005 to 0.05 (mg P)/L. The coefficient used in the RRatFGO QW model for nitrogen was 0.03 (mg N)/L, and the coefficient used for phosphorus was 0.04 (mg P)/L.

Algae uses two forms of nitrogen, ammonia and nitrate, during uptake and growth (Bowie and others, 1985). The QUAL2E model uses the following equation to calculate the effective concentration of available nitrogen (Brown and Barnwell, 1987, p. 34):

$$N_e = N_1 + N_3 \qquad (21)$$

where

N_1 is ammonia concentration as nitrogen, in milligrams per liter; and

N_3 is nitrate concentration as nitrogen, in milligrams per liter.

The QUAL2E model allows for the selection of the algal preference factor for ammonia when both ammonia and nitrate are simulated. The coefficient range recommended by Brown and Barnwell (1987) for the algal preference factor for ammonia is 0 to 1.0. The coefficient in which all of the nitrogen requirements are obtained from nitrate has a preference factor of zero, and the coefficient in which all of the nitrogen requirements are obtained from ammonia uptake has a preference factor of 1.0. The coefficient used in the RRatFGO QW model was 0.9 because of the relatively greater availability of ammonia as compared to nitrate. This selection also provided an additional means to adjust ammonia concentration in the calibration process to simulate the measured concentration of ammonia and nitrate.

Nutrient concentrations were simulated by considering the effects of algal uptake and respiration, source-sink terms, and, for nitrogen species, nitrification. Reaction coefficients that describe the fraction of algal biomass that is nitrogen and the fraction of algal biomass that is phosphorus were selected. The coefficient range recommended by Brown and Barnwell (1987) for the nitrogen fraction is 0.07 to 0.09 (mg N/L)/(mg A/L), and the coefficient range recommended for the phosphorus fraction is 0.01 to 0.02 (mg P/L)/(mg A/L). The coefficient used in the RRatFGO QW model for the nitrogen fraction was 0.08 (mg N/L)/(mg A/L), and the coefficient used for the phosphorus fraction was 0.011 (mg P/L)/(mg A/L).

In the QUAL2E model, the local algal respiration rate is used to approximate three processes: (1) The endogenous respiration of algae, (2) the conversion of algal phosphorus to organic phosphorus, and (3) the conversion of algal nitrogen to organic nitrogen. The coefficient range recommended by Brown and Barnwell (1987) for the local algal respiration rate is 0.05 to 0.5 per day and is about 5 percent of the maximum specific algal growth rate. The coefficient used in the RRatFGO QW model for the local algal respiration rate was 0.06 per day, about 4 percent of the maximum specific algal growth rate.

The local algal settling rate is the principal variable used to adjust simulated algae concentrations for the calibration and verification data sets. The one-standard-deviation criterion from measured concentrations to simulated concentrations for the calibration and verification data sets was not applied to algae concentrations because only two samples were collected at each site during the synoptic samplings and this limited number of samples may not be representative of algae concentrations in the stream. The coefficient range recommended by Brown and Barnwell (1987) for local algal settling rates is 0.5 to 6.0 ft/d. The local algal settling rates for the calibration data set were adjusted by subreach until the simulated algae concentrations reasonably matched the concentrations measured during the August 29-30, 1989, synoptic sampling. Final local algal settling rates for the calibration data set ranged from 1.0 to 4.0 ft/d (table 15). The local algal settling rates for the calibration data set were inappropriate for simulating algae concentrations for the verification data set because simulated algae concentrations did not match measured concentrations. Therefore, algae (chlorophyll-a) concentrations for the verification data set were simulated from local algal settling rates that ranged from 0 to 1.5 ft/d (table 15). Because the local algae settling rates for the calibration and verification data sets are different, the RRatFGO QW model is not considered verified with respect to algae (chlorophyll-a) concentration. The measured and simulated algae concentrations for the calibration and verification data sets are shown in figure 9.

In addition to the limited number of variables available in the QUAL2E model to adjust simulated algae concentrations and the limited algae data set, the difference in the areal distribution of the algae during the two synoptic samplings may have contributed to nonverification of the RRatFGO QW model with respect to algae concentration. During August 29-30, 1989, the largest algae concentrations were in the upstream part of the study reach. Algae concentrations generally decreased in the downstream direction and there was little contribution of algae from Fargo wastewater. In contrast, during August 14-15, 1990, the smallest algae concentrations were in the upstream part of the study reach, algae concentrations generally increased in the downstream direction, and Fargo wastewater was a major contributor of algae. One possible explanation for these two contrasting algae-concentration conditions may be algae-bloom formation in two ponded areas--the river [about 4 mi upstream from the study area, the river is in backwater from Dam A (U.S. Army Corps of Engineers, 1970)] and the waste-stabilization pond. Both areas have favorable conditions for the formation of algae blooms and the increase of algae concentrations. The August 29-30, 1989, data indicate that significant algae blooms were not occurring in the Fargo waste-stabilization pond that was releasing wastewater. However, during August 14-15, 1990, algae blooms were not occurring upstream of the study reach but were occurring in the Fargo waste-stabilization pond that was releasing wastewater.

Nutrients

In natural aerobic water, there is a stepwise transformation from organic nitrogen to ammonia, to nitrite, and finally to nitrate. Organic phosphorus transforms directly to phosphorus. The following equations are used in the model to simulate the nitrogen transformation and phosphorus transformation processes (Brown and Barnwell, 1987, p. 35-39):

$$\frac{dN_4}{dt} = \alpha_1 \rho A - \beta_3 N_4 - \sigma_4 N_4 \qquad (22)$$

where

N_4 is organic nitrogen concentration as nitrogen, in milligrams per liter;

α_1 is fraction of algal biomass that is nitrogen, in (milligrams nitrogen per liter) per (milligrams algal biomass per liter);

β_3 is instream reaction rate for hydrolysis of organic nitrogen to ammonia, in per day; and

σ_4 is organic nitrogen settling rate, in per day;

$$\frac{dN_1}{dt} = \beta_3 N_4 - \beta_1 N_1 + \frac{\sigma_3}{D} - F_1 \ \alpha_1 \mu A \qquad (23)$$

where

β_1 is instream reaction rate for biological decay of ammonia to nitrite, in per day;

σ_3 is benthos source rate for ammonia, in (milligrams ammonia per square foot) per (day); and

F_1 is fraction of algal nitrogen uptake from ammonia pool;

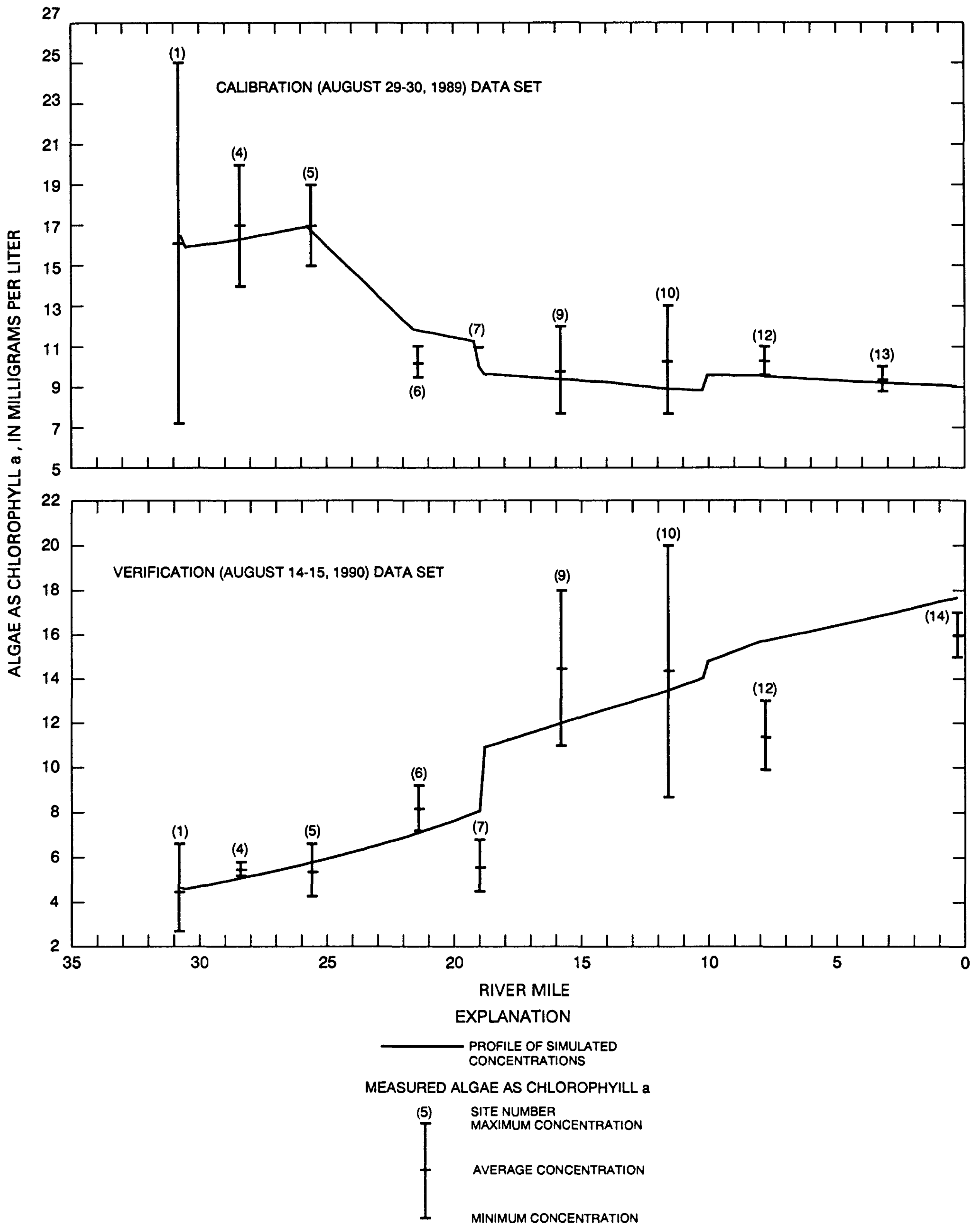


Figure 9. Maximum, average, and minimum measured algae as chlorophyll a concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

$$\frac{dN_2}{dt} = \beta_1 N_1 - \beta_2 N_2 \tag{24}$$

where

N_2 is nitrite concentration as nitrogen, in milligrams per liter; and

β_2 is instream reaction rate for biological decay of nitrite to nitrate, in per day;

$$\frac{dN_3}{dt} = \beta_2 N_2 - (1 - F_1)\,\alpha_1 \mu A \tag{25}$$

$$\frac{dP_1}{dt} = \alpha_2 \rho A - \beta_4 P_1 - \sigma_5 P_1 \tag{26}$$

where

P_1 is organic phosphorus concentration as phosphorus, in milligrams per liter;

α_2 is fraction of algal biomass that is phosphorus, in (milligrams phosphorus per liter) per (milligrams algal biomass per liter);

β_4 is instream reaction rate for biological decay of organic phosphorus to phosphorus, in per day; and

σ_5 is organic phosphorus settling rate, in per day;

and

$$\frac{dP}{dt} = \beta_4 P_1 + \frac{\sigma_2}{D} - \alpha_2 \mu A \tag{27}$$

where

σ_2 is benthos source rate for phosphorus, in (milligrams phosphorus per square foot) per (day).

The beginning of the nitrogen transformation process (ammonification) where organic nitrogen is hydrolyzed to ammonia is shown by equation 22. The coefficient range recommended by Brown and Barnwell (1987) for organic nitrogen hydrolysis to ammonia is 0.02 to 0.4 per day. The coefficients used for calibrating the RRatFGO QW model range from 0.02 to 0.19 per day. In order to simulate the measured organic nitrogen concentrations for the calibration data set, a coefficient of 0.1 per day was used for subreaches 6 and 7 for the organic nitrogen settling rate. This coefficient is within the recommended range of 0.001 to 0.1 per day (Brown and Barnwell, 1987).

The instream reaction rate for measured organic nitrogen was 0.04 per day. This reaction rate was calculated using the following equation (Thomann, 1972, p. 90) for a first-order reaction:

$$N_{4(2)} = N_{4(1)}\ exp\text{-}\left(\frac{\beta_3}{U}\right)X \tag{28}$$

where

$N_{4(2)}$ is downstream organic nitrogen concentration, in milligrams per liter;

$N_{4(1)}$ is upstream organic nitrogen concentration, in milligrams per liter; and

X is distance, in feet.

Instream reaction rates are obtained from semilogarithmic plots of a constituent whose decay rate is assumed to follow a first-order reaction (in this case, organic nitrogen concentration) as a function of traveltime. The coefficient to base e logarithm is given by the slope of a straight line or

$$\beta_3 = \frac{2.3}{t_1 - t_2} ln \frac{N_{4(1)}}{N_{4(2)}} \tag{29}$$

where

t_1 is upstream elapsed traveltime, in hours; and

t_2 is downstream elapsed traveltime, in hours.

The measured and simulated organic nitrogen concentrations for the calibration and verification data sets are shown in figure 10. Except for site 4 of the verification data set, both simulations underpredict organic nitrogen concentrations for sites 1 through 6 but simulated concentrations are within one standard deviation of the corresponding average measured concentrations. Simulated organic nitrogen concentrations for sites 9 through 13 for the calibration data set are within one standard deviation, which ranges from 0.09 to 0.24 mg/L, of the corresponding average measured concentration. Simulated organic nitrogen concentrations for sites 9 through 14 for the verification data set look reasonable and follow the general concentration trend. However, the simulated organic nitrogen concentrations for sites 10 and 12 are greater than one standard deviation, which ranges from 0.08 to 0.24 mg/L, of the corresponding average measured concentration. The reason for the swings in measured organic nitrogen concentrations for the verification data set for sites 10 to 14 is unknown.

Ammonification is a slow process for nitrogen transformation relative to the other processes occurring in the study reach and is quantified by the small instream reaction rate of 0.04 per day for measured organic nitrogen and by the small change in organic nitrogen concentrations in the calibration data set. The calculated instream reaction rate for organic nitrogen for the verification data set is the same as the calculated rate for the calibration data set. The increase in organic nitrogen concentration that occurs downstream of site 7 for the verification data set is attributed to the effects of Fargo wastewater. Because of the slow instream reaction for ammonification, the traveltime through the study reach does not allow enough time for a greater change from organic nitrogen to ammonia.

Nitrification is the next step in the nitrogen transformation process. In this step, ammonia is transformed to nitrite, which, in turn, is transformed to nitrate. Nitrification is described in the QUAL2E model by the use of equations 24 and 25.

The coefficient range recommended by Brown and Barnwell (1987) for the biological decay of ammonia to nitrite is 0.10 to 2.00 per day. The calculated reaction coefficient for ammonia to nitrite for the calibration data set is 1.07 per day. A satisfactory calibration of the RRatFGO QW model was achieved by using a coefficient of 1.07 per day for all subreaches. The measured and simulated ammonia concentrations for the calibration and verification data sets are shown in figure 11. Very good agreement is shown between the measured and simulated ammonia concentrations for both the calibration and

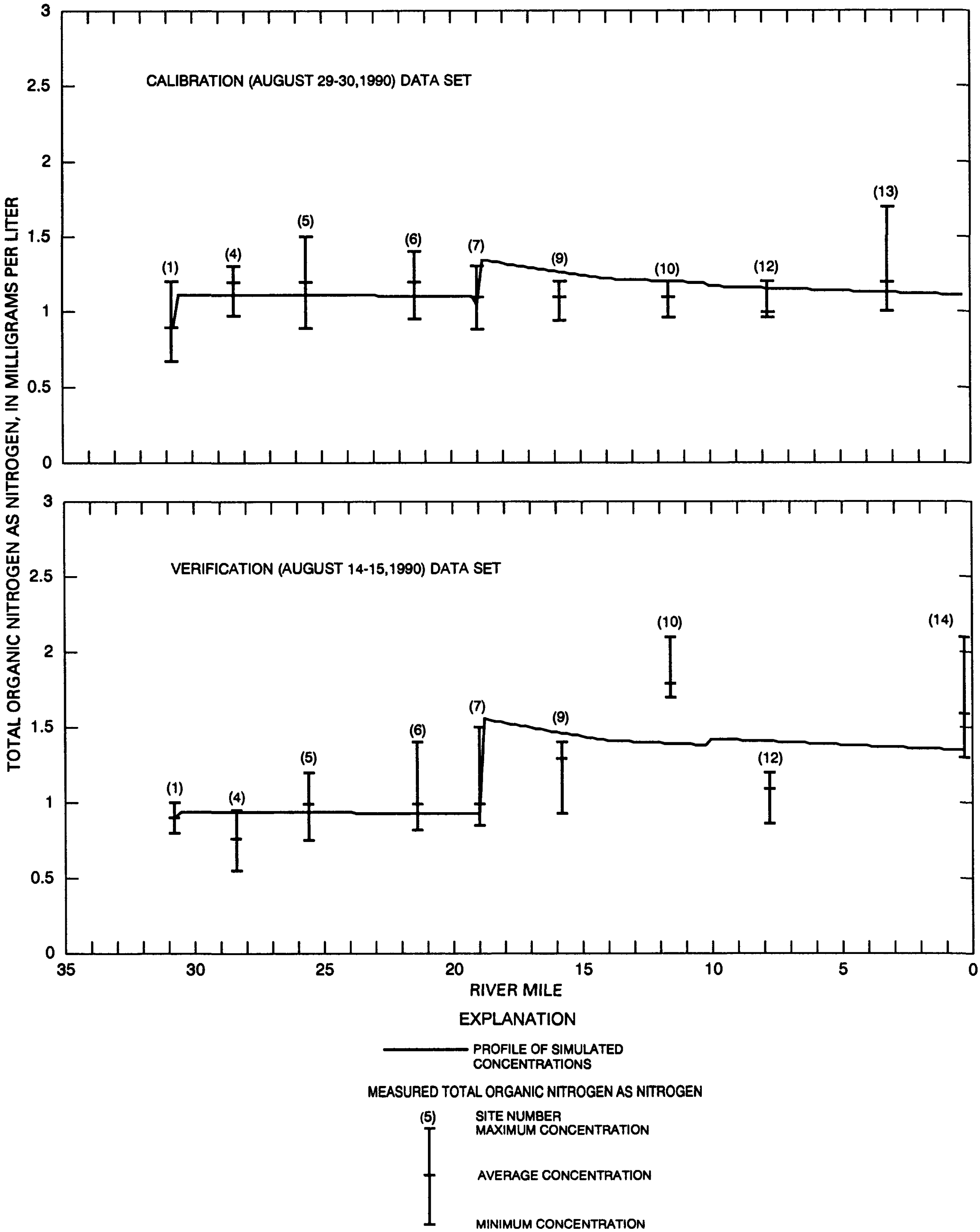


Figure 10. Maximum, average, and minimum measured total organic nitrogen as nitrogen concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

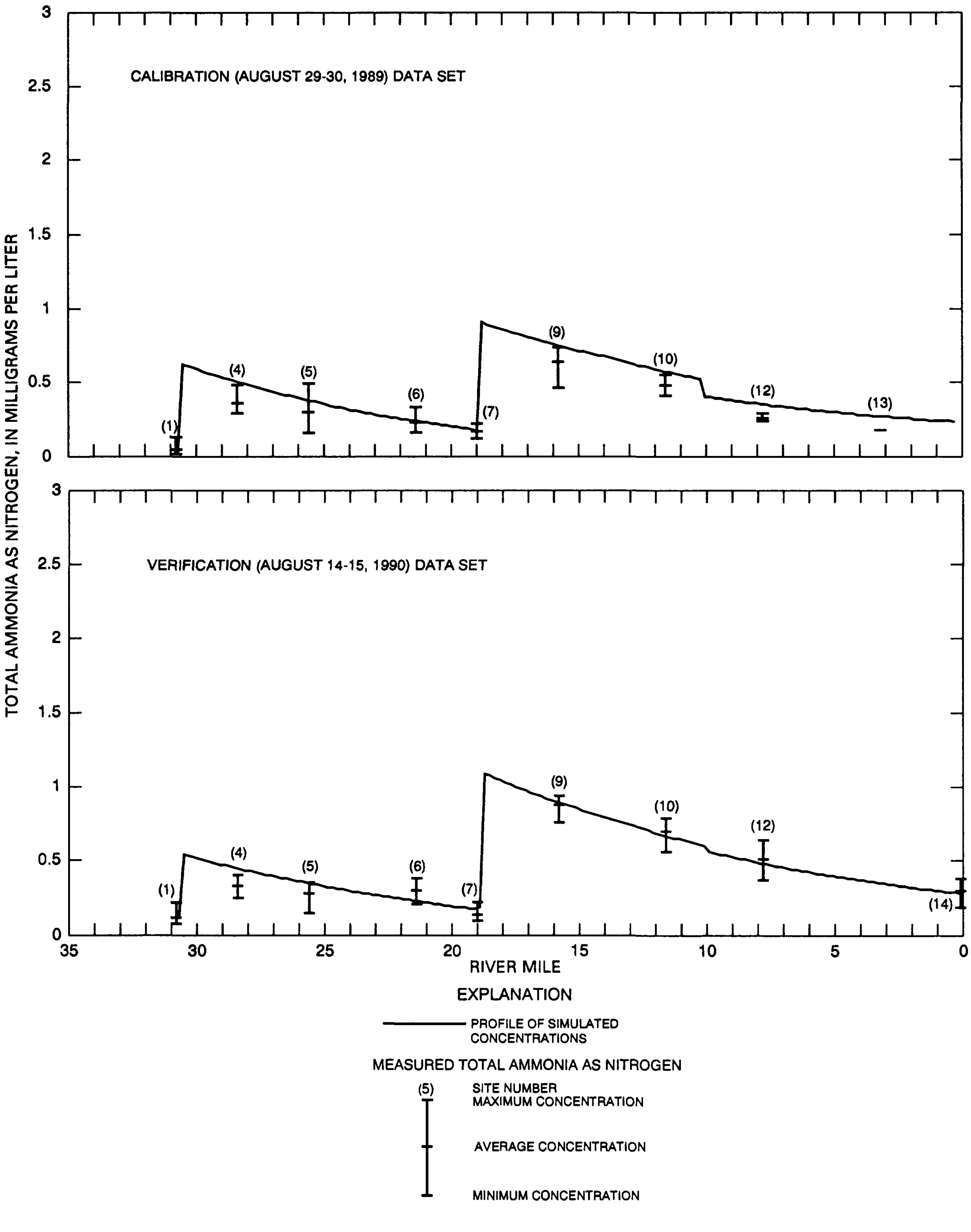


Figure 11. Maximum, average, and minimum measured total ammonia as nitrogen concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

verification data sets. Simulated concentrations are within one standard deviation, which ranges from 0.01 to 0.13 mg/L for the calibration data set and 0.05 to 0.12 mg/L for the verification data set, of the corresponding average measured concentrations.

The coefficient range recommended by Brown and Barnwell (1987) for the biological decay of nitrite to nitrate is 0.20 to 2.00 per day. The calculated reaction coefficient for nitrite to nitrate for the calibration data set is 3.08 per day. This was the largest reaction coefficient calculated for this study and is used in the RRatFGO QW model to assure a quick transformation of nitrite to nitrate. By setting the reaction coefficient larger than the recommended range, simulated nitrate concentrations correspond to nitrite plus nitrate concentrations measured during the 1989 synoptic samplings. Nitrite plus nitrate concentrations also were measured during the 1990 synoptic samplings for verification of the model. This was necessary to verify the reaction coefficient used for nitrite and to verify the simulation of nitrite plus nitrate for the calibration data set.

The measured and simulated nitrite plus nitrate concentrations for the calibration and verification data sets are shown in figure 12. Algal growth, respiration, settling, and nutrient uptake coefficients were used to calibrate the RRatFGO QW model for nitrite plus nitrate concentrations. Simulated nitrite plus nitrate concentrations agree well with measured concentrations for the calibration data set and are within one standard deviation, which ranges from 0 to 0.07 mg/L, of the corresponding average measured concentration. Simulated concentrations for the verification data set are overpredicted from a low of 0.05 mg/L at sites 4 and 5 to a high of 0.3 mg/L at site 14. The simulated concentration at site 14 is 1.2 mg/L, and the average measured concentration is 0.9 mg/L. The standard deviation range for the verification data set is 0 to 0.05 mg/L.

The measured and simulated nitrite concentrations for the verification data set are shown in figure 13. The simulated nitrite concentrations agree well with the measured nitrite concentrations. This agreement supports the use of 3.08 per day for the nitrite to nitrate reaction coefficient. Simulated nitrate concentrations are increased through nitrification and decreased through algal uptake.

Instream phosphorus concentrations are affected by inflow sources to the Red River, by uptake and release through algal photosynthesis and respiration, and by settling to and re-entrainment from the streambed. The coefficient range recommended by Bowie and others (1985, table 5.5) for biological decay of organic phosphorus to phosphorus is 0.01 to 0.7 per day. The calculated reaction coefficient for organic phosphorus to phosphorus for the calibration and verification data sets is 0.21 per day. Total phosphorus was measured during both synoptic samplings. During RRatFGO QW model calibration, it was assumed that organic phosphorus exists only in small concentrations in the Red River. Because both organic and total phosphorus are simulated by the QUAL2E model, the organic phosphorus concentration for the boundary conditions was set at 0.01 mg/L. At this setting, the simulated concentration for the calibration and verification data sets is 0.01 mg/L, and all phosphorus is simulated as total phosphorus.

The measured and simulated total phosphorus concentrations for the calibration and verification data sets are shown in figure 14. Close agreement (within one standard deviation, which ranges from 0.02 to 0.04 mg/L for the calibration data set and 0.02 to 0.05 mg/L for the verification data set, of the corresponding average measured concentration) is shown between the measured and simulated concentrations for sites 1 through 7 for both the calibration and verification data sets. Both simulated data sets were overpredicted downstream of site 8. Simulated concentrations for the verification data set were within 0.10 mg/L for all of the remaining sites except sites 12 and 14. Concentrations at these sites were overpredicted by almost 0.20 mg/L. When the verification data were collected, the Sheyenne River (site 11) did not provide the same dilution as when the calibration data were collected. Rather, in

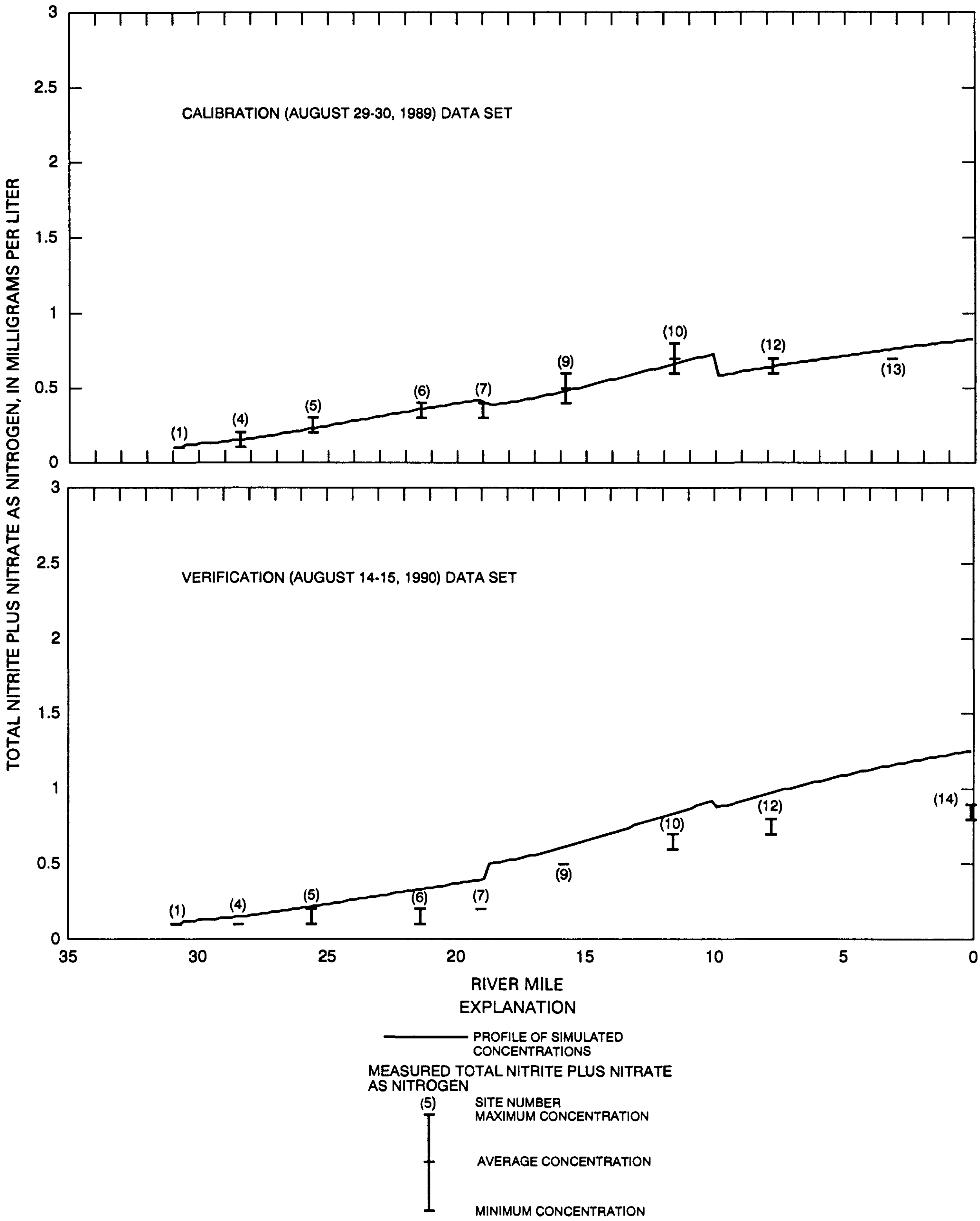


Figure 12. Maximum, average, and minimum measured total nitrite plus nitrate as nitrogen concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

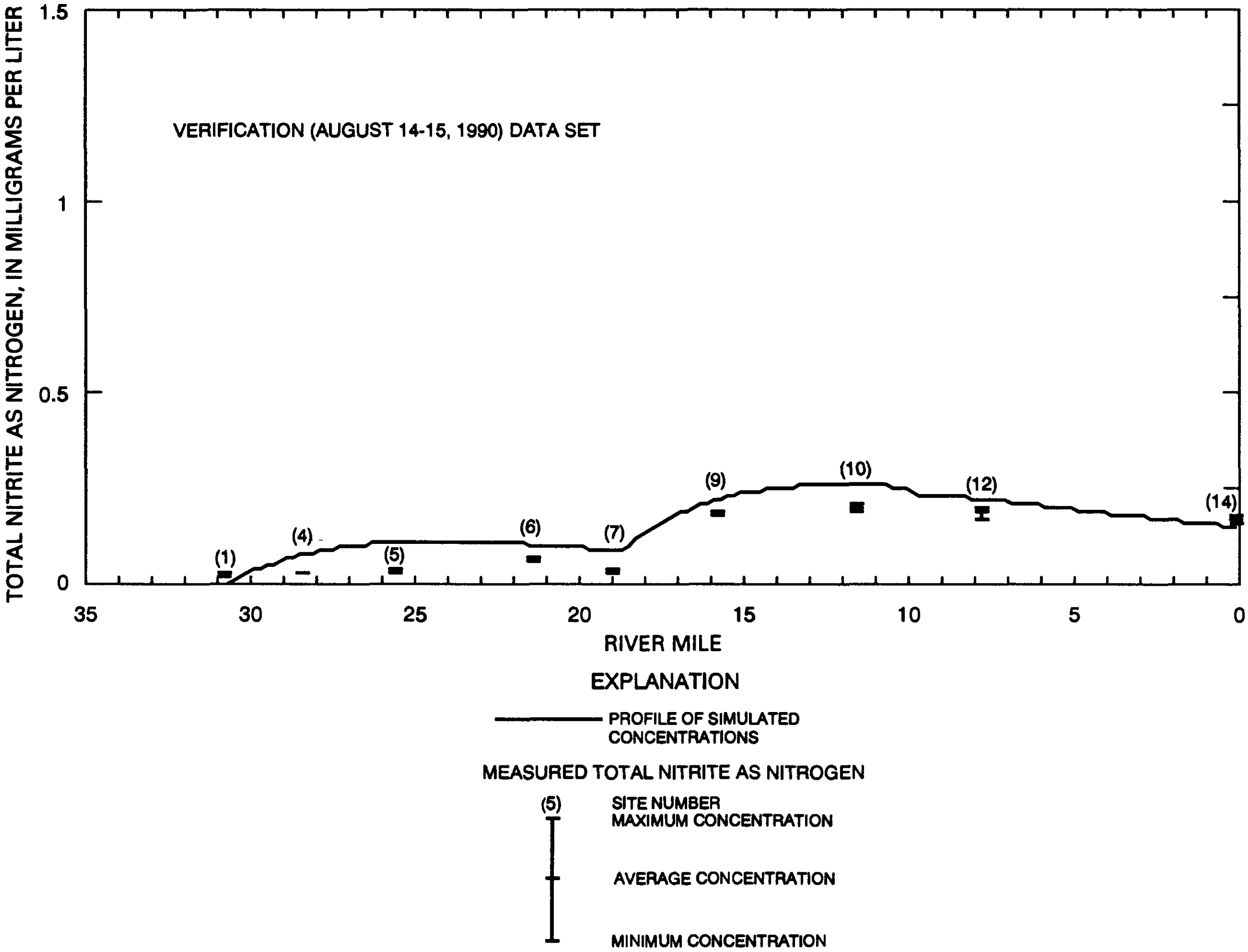


Figure 13. Maximum, average, and minimum measured total nitrite as nitrogen concentrations for verification (August 14-15, 1990) data set and profile of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

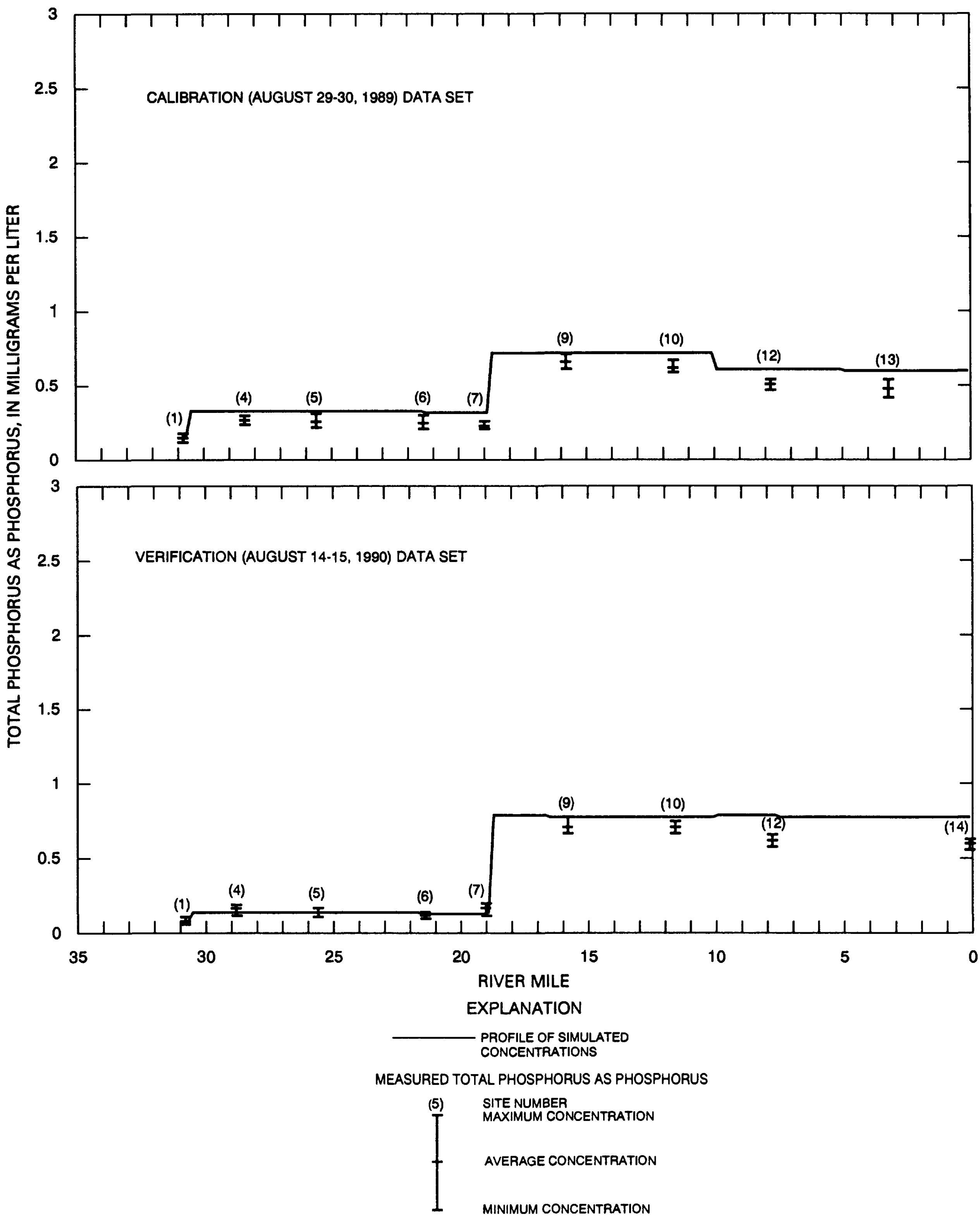


Figure 14. Maximum, average, and minimum measured total phosphorus as phosphorus concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

August 1990, the Sheyenne River had larger total phosphorus concentrations than the Red River. Nonetheless, measured concentrations at the two downstream Red River sites (12 and 14) decrease rather than increase as expected. The reason for this anomaly is unexplained.

Dissolved Oxygen

Dissolved-oxygen concentration was used as the primary indicator of water quality in the Red River at Fargo. Of all the constituents simulated in the water-quality component of the model, dissolved oxygen was the most complex to simulate because most of the calibrated coefficients represent processes that either directly or indirectly affect dissolved-oxygen concentration. The degree to which simulated dissolved-oxygen concentrations compare to measured dissolved-oxygen concentrations of the calibration and verification data sets is an indication of how well the RRatFGO QW model is calibrated.

The change in dissolved-oxygen concentration is estimated using the following equation (Brown and Barnwell, 1987, p. 40):

$$\frac{dO}{dt} = K_2(O^*-O) + (\alpha_3\,\mu - \alpha_4\,\rho)\,A - K_1\,L - \frac{K_4}{D} - \alpha_5\,\beta_1\,N_1 - \alpha_6\,\beta_2\,N_2 \qquad (30)$$

where

O is dissolved-oxygen concentration, in milligrams per liter;

O^* is saturation concentration of dissolved oxygen, in milligrams per liter;

α_3 is rate of dissolved-oxygen production per unit of algal growth, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter);

α_4 is rate of dissolved-oxygen uptake per unit of algae respired, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter);

K_1 is ultimate carbonaceous biochemical oxygen demand decay rate, in per day;

L is ultimate carbonaceous biochemical oxygen demand, in milligrams per liter;

K_4 is sediment oxygen demand rate, in (grams oxygen per square foot) per (day);

α_5 is rate of dissolved-oxygen uptake per unit of ammonia oxidized to nitrite, in (milligrams dissolved oxygen per liter) per (milligrams ammonia per liter); and

α_6 is rate of dissolved-oxygen uptake per unit of nitrite oxidized to nitrate, in (milligrams dissolved oxygen per liter) per (milligrams nitrite per liter).

The α_3 and α_4 variables in equation 30 represent the rate of dissolved-oxygen production by algal photosynthesis and the rate of dissolved-oxygen uptake by algal respiration. The coefficient range recommended by Brown and Barnwell (1987) for dissolved-oxygen production per unit of algal growth is 1.4 to 1.8 (mg O/L)/(mg A/L). The coefficient range recommended for dissolved-oxygen uptake per unit of algae respired is 1.6 to 2.3 (mg O/L)/(mg A/L). The coefficient used in the RRatFGO QW model for dissolved-oxygen production per unit of algal growth was 1.6 (mg O/L)/(mg A/L). The coefficient used for dissolved-oxygen uptake per unit of algae respired was 2.0 (mg O/L)/(mg A/L).

The α_5 and α_6 variables in equation 30 represent the rate of dissolved-oxygen uptake during the nitrification process. For the RRatFGO QW model, these reaction coefficients were set to the stoichiometric equivalent amounts needed to balance the chemical reactions. The coefficient used for dissolved-oxygen uptake per unit of ammonia oxidized to nitrite was 3.43 (mg O/L)/(mg N_1/L), and the coefficient used for dissolved-oxygen uptake per unit of nitrite oxidized to nitrate was 1.14 (mg O/L)/(mg N_2/L) (Brown and Barnwell, 1987).

Before the RRatFGO QW model can execute equation 30, two processes that directly affect the dissolved-oxygen concentration in the Red River need to be considered: (1) CBODu and (2) SOD. In theory, the CBODu decay process takes place in the water column, and the SOD decay process takes place in the benthos. In practice, these processes are difficult to distinguish because they are interrelated. In applying the decay rates to the RRatFGO QW model, a conservative approach, which uses a lower deoxygenation rate, was used in an attempt to avoid double counting deoxygenation.

CBODu is a measure used to quantify biochemical oxidation of organic constituents in water. The QUAL2E model uses a first-order reaction to describe this process with the following equation:

$$\frac{dL}{dt} = K_1 L - K_3 L \qquad (31)$$

where

K_3 is rate of loss of ultimate carbonaceous biochemical oxygen demand caused by settling, in per day.

Factors that influence removal of CBODu from the water column include the water temperature, the hydraulic conditions, and the nature of the carbonaceous material (Bowie and others, 1985, p. 139).

CBODu is reduced by the decay process, with a corresponding decrease in dissolved oxygen, and by the settling of organic matter to the streambed, which reduces BOD without a corresponding decrease in dissolved oxygen. The coefficient range recommended by Brown and Barnwell (1987, p. 55) for the CBODu deoxygenation rate (commonly referred to as "bottle" rate) is 0.02 to 3.4 per day. The coefficient range recommended for BOD settling rate is -0.36 to 0.36 per day. The calculated instream oxygen removal rate (CBODu) for the calibration and verification data sets is 0.08 per day. The instream oxygen removal rate varied from site to site, but no attempt was made to use this variation in the model. Instead, a uniform decay rate was used for all subreaches. The use of a uniform decay rate was justified because of the difficulties experienced in the laboratory during the incubation process in 1989 and because the 1990 calculated instream oxygen removal rates and deoxygenation rates were similar to the 1989 rates.

The CBODu deoxygenation rate caused by decay for the calibration and verification data sets is 0.05 per day (table 16) as calculated using the program developed by Jennings and Bauer (1976). Bowie and others (1985) reported that if unfiltered samples are used in calculating BOD decay, the decay rate calculated is the oxygen removal rate. Because unfiltered water samples were used in determining CBODu, a 0.03 per day BOD settling rate was used in the RRatFGO QW model (table 16).

The measured and simulated CBODu concentrations for the calibration and verification data sets are shown in figure 15. Simulated concentrations for both data sets are underpredicted by the RRatFGO QW model. Simulations for both data sets, however, are within one standard deviation, which ranges from 0.4 to 2.0 mg/L for the calibration data set and 0.2 to 2.0 mg/L for the verification data set, of the corresponding average measured concentrations. The underpredicted concentrations may indicate that the model is not accounting for all processes that are occurring in the water column, that the method of analysis somehow is inflating the CBODu concentration in the water column, or that both of these are occurring.

Table 16. Reach-dependent reaction coefficients used in the Red River at Fargo Water-Quality Model to simulate dissolved-oxygen kinetics

[1/day, per day; (g O/ft^2)/d, grams oxygen per square foot per day]

Model subreach	Ultimate carbonaceous biochemical oxygen demand		Sediment oxygen demand [(g O/ft^2)/d]	Reaeration-rate coefficient (1/day)	
	Deoxygenation rate caused by decay (1/day)	Deoxygenation loss rate caused by settling (1/day)		Calibration 1989	Verification 1990
1	0.05	0.03	0.10	1.7	1.4
2	.05	.03	.10	1.7	1.4
3	.05	.03	.10	1.7	1.4
4	.05	.03	.10	1.7	1.4
5	.05	.03	.10	1.7	1.4
6	.05	.03	.10	1.7	1.4
7	.05	.03	.10	1.7	1.4
8	.05	.03	.10	1.7	1.4
9	.05	.03	.10	1.7	1.4
10	.05	.03	.10	1.7	1.4
11	.05	.03	.10	1.7	1.4

SOD is the final dissolved-oxygen sink term considered during calibration of the RRatFGO QW model. SOD was more uniform from site to site than expected. Larger SOD concentrations were expected immediately downstream of wastewater discharge. The standard deviation of the measured SOD concentrations ranges from 0.02 to 0.07 (g O/ft^2)/d. The mean concentration for the nine sites is 0.10 (g O/ft^2)/d. Although SOD can be varied by subreach in the QUAL2E model, 0.10 (g O/ft^2)/d was used for all subreaches in the RRatFGO QW model (table 16). Because SOD concentrations can be quite variable, no coefficient range was recommended by Brown and Barnwell (1987).

SOD measurements for the calibration data set were obtained during August 28 to September 7, 1990, rather than during August 29-30, 1989. However, SOD measurements also were made at two sites (3 and 5) on September 20, 1989. The mean SOD concentration at site 3 for 1989 was 0.07 (g O/ft^2)/d, and the mean concentration at site 5 was 0.06 (g O/ft^2)/d. The SOD concentrations for 1990 are larger than the SOD concentrations for 1989. It is conceivable that the 1990 concentrations were larger than the 1989 concentrations because the 1990 spring runoff was below normal and the maximum daily mean streamflow was 877 ft^3/s at the Red River of the North at Fargo, N. Dak., gaging station. Velocities at this streamflow are about at the threshold to begin scouring. Krenkel and Novotny (1980) reported that if streamflow transport velocity is less than 0.6 to 1.0 ft/s, deposition occurs, and that if streamflow transport velocity is more than 1.0 to 1.5 ft/s, scouring occurs.

The final oxygen source parameter to be considered before dissolved-oxygen simulation is complete is the stream reaeration rate. Reaeration-rate coefficients are estimated using a streamflow versus measured reaeration-rate coefficient regression as previously described under Reaeration-Rate Coefficients in the

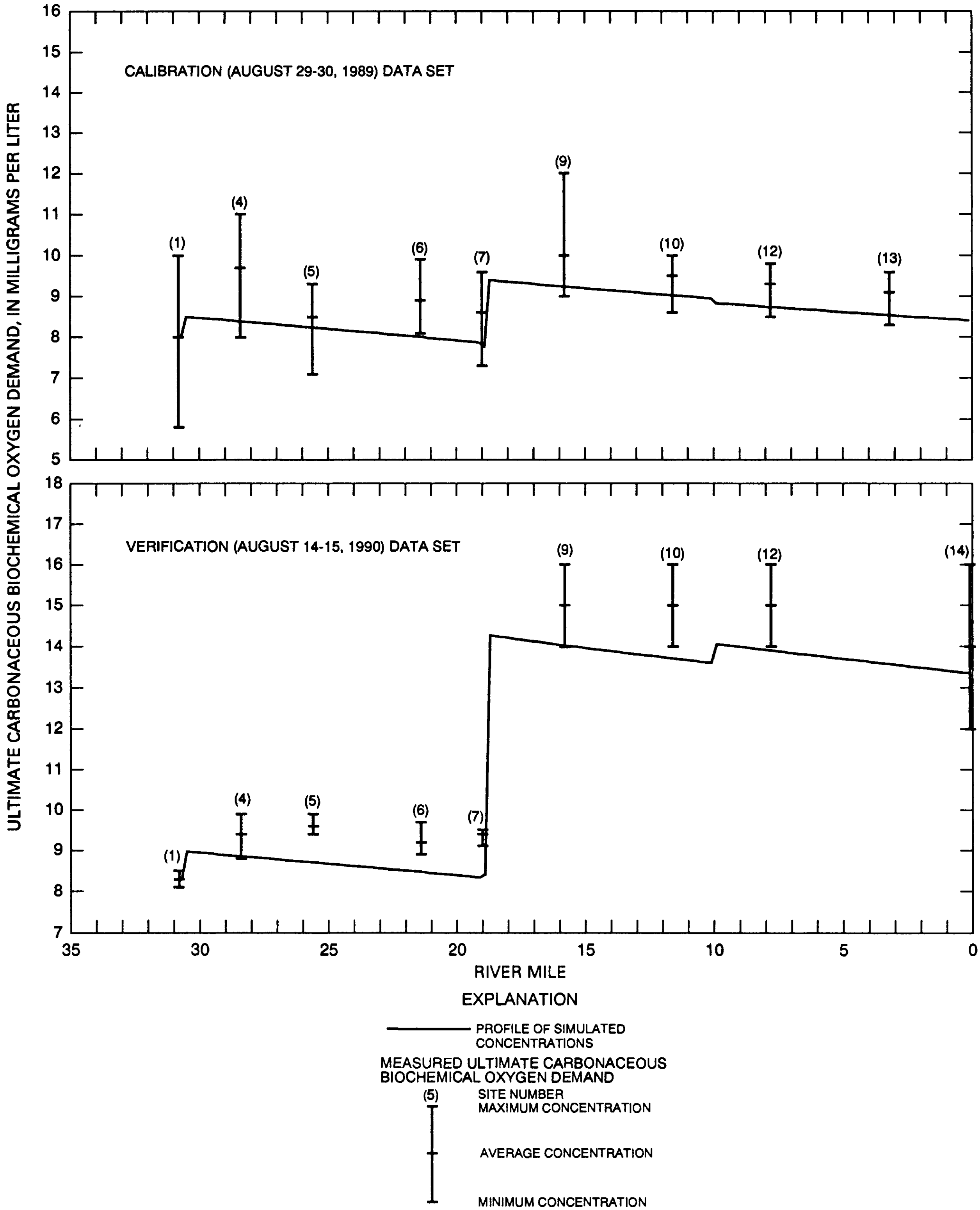


Figure 15. Maximum, average, and minimum measured ultimate carbonaceous biochemical oxygen demand concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

Water-Quality Component section of this report. For the calibration data set, streamflow for the upstream reach is 140 ft^3/s. The reaeration-rate coefficient for this streamflow is 1.7 per day (fig. 8). This coefficient was used in all subreaches for model calibration (table 16). For the verification data set, streamflow in the upstream reach is 200 ft^3/s. The reaeration-rate coefficient for this streamflow is 1.4 per day (fig. 8). This coefficient was used in all subreaches for model verification (table 16).

As previously discussed, the reaeration-rate coefficient increased in the downstream direction with a corresponding increase in streamflow. Although the QUAL2E model has the capability of varying the reaeration-rate coefficient by subreach, using the same reaeration-rate coefficient for all subreaches in the RRatFGO QW model provides a lower estimate of dissolved-oxygen concentrations in the downstream part of the subreach.

Measured and simulated dissolved-oxygen concentrations for the calibration and verification data sets are shown in figure 16. For the calibration data set, the RRatFGO QW model underpredicted dissolved-oxygen concentrations for sites 6 and 7 and overpredicted dissolved-oxygen concentrations for sites 10, 12, and 13. However, the simulated concentrations are within one standard deviation, which ranges from 0.3 to 1.1 mg/L, of the corresponding average measured concentrations. For the verification data set, the RRatFGO QW model underpredicted dissolved-oxygen concentrations for all sites. However, the simulated concentrations are within one standard deviation, which ranges from 0.24 to 0.9 mg/L, of the corresponding average measured concentrations. Thus, the water-quality component reaction coefficients are considered satisfactorily calibrated and verified with the exception of algae settling rates as previously explained under Algae in the Water-Quality Component section of this report.

To test the predictive equations from Bansal (1973) and Velz (1984), simulated dissolved-oxygen concentrations obtained by using these two equations are compared to average measured dissolved-oxygen concentrations for the calibration and verification data sets. The simulated dissolved-oxygen concentrations obtained by using these two equations compare favorably with concentrations for the calibration data set (fig. 17). The average reaeration-rate coefficients obtained by using the Bansal (1973) equation range from 1.0 to 1.5 per day and average 1.2 per day. The average reaeration-rate coefficients obtained by using the Velz (1984) equation range from 1.1 to 2.1 per day and average 1.5 per day. By comparison, the average reaeration-rate coefficient determined from figure 8 is 1.7 per day. The simulated dissolved-oxygen concentrations obtained by using the two equations compare unfavorably with concentrations for the verification data set (fig. 18). Both equations underpredict dissolved-oxygen concentrations throughout the study reach, and the underprediction exceeds 1 mg/L from site 10 through the end of the reach. The average reaeration-rate coefficients obtained by using the Bansal (1973) equation range from 0.87 to 1.2 per day and average 1.0 per day. The average reaeration-rate coefficients obtained by using the Velz (1984) equation range from 0.90 to 1.5 per day and average 1.1 per day. By comparison, the average reaeration-rate coefficient determined from figure 8 is 1.4 per day.

Sensitivity Analyses

Several analyses were conducted to determine the sensitivity of simulated dissolved-oxygen concentrations to selected properties, constituents, and reaction coefficients. The sensitivity was determined for three sites--sites 5, 10, and 14. A total of 20 properties, constituents, and reaction coefficients were selected for use in the sensitivity analyses. These properties, constituents, and reaction coefficients were grouped into six classifications--climate, hydraulics, algae, reaction coefficients, headwater source, and point source (fig. 19). The sensitivity was determined relative to the calibrated value of dissolved-oxygen concentration at each site (fig. 19).

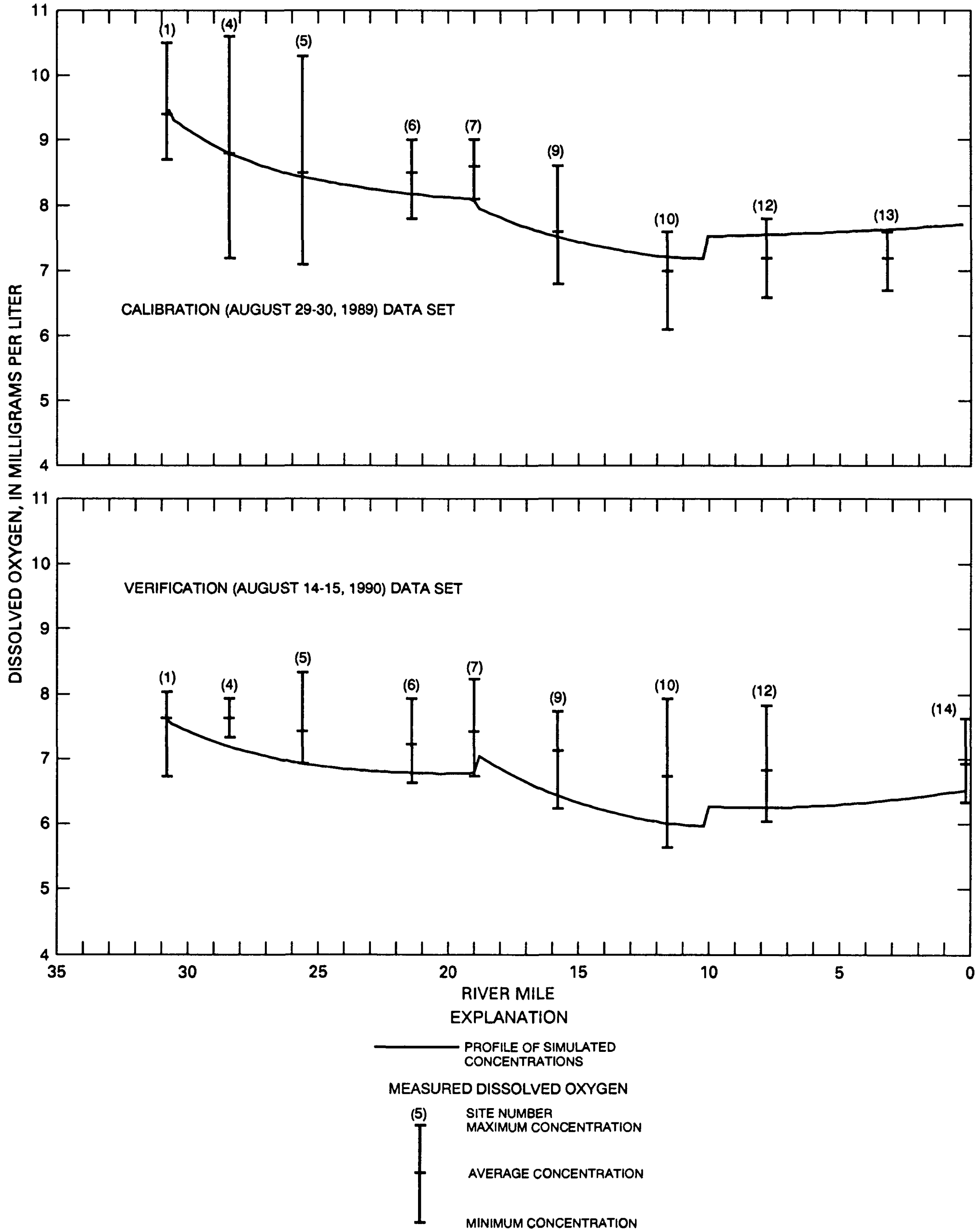


Figure 16. Maximum, average, and minimum measured dissolved-oxygen concentrations for calibration (August 29-30, 1989) and verification (August 14-15, 1990) data sets and profiles of simulated concentrations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

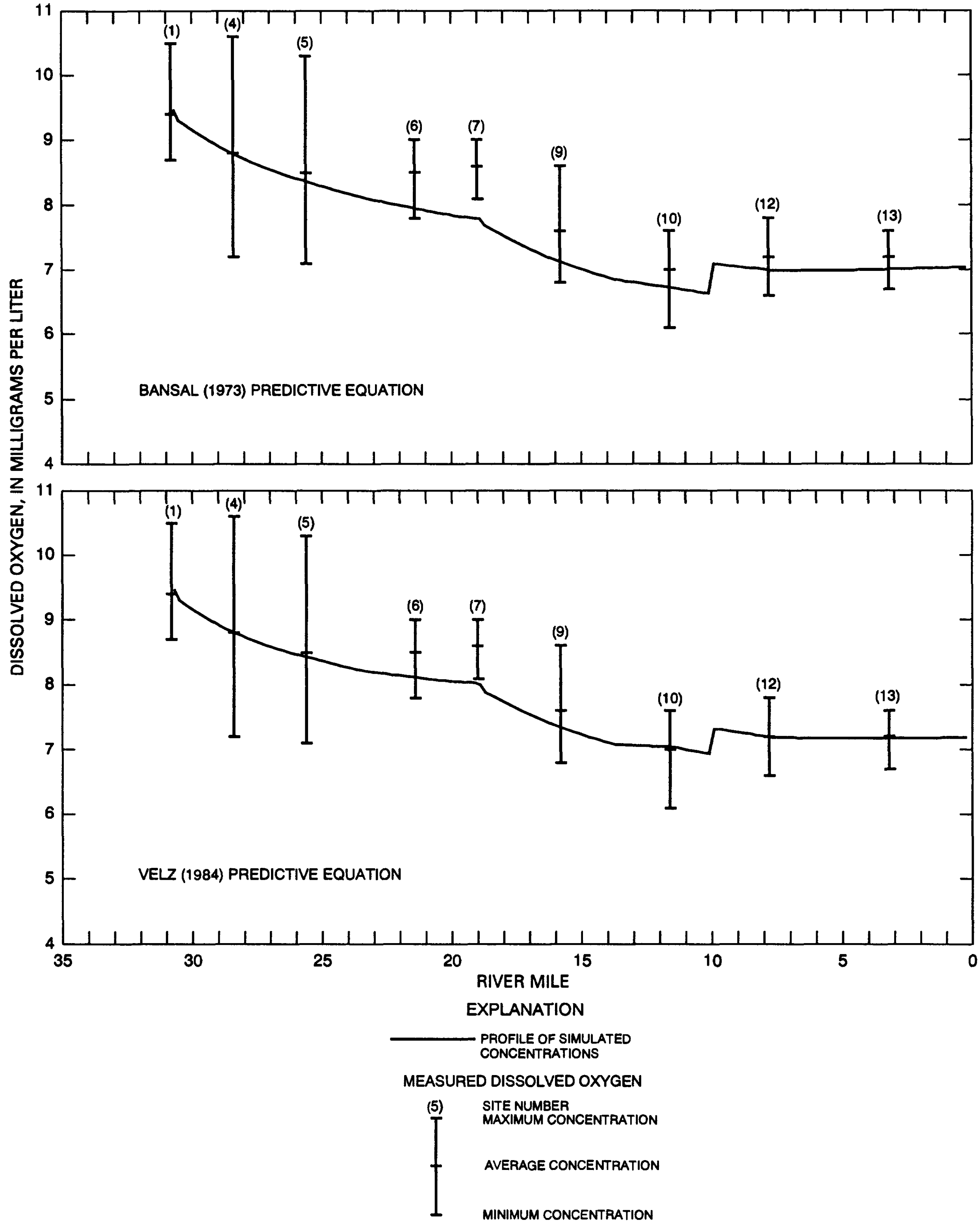


Figure 17. Maximum, average, and minimum measured dissolved-oxygen concentrations for calibration (August 29-30, 1989) data set and profiles of simulated concentrations obtained by using the Bansal (1973) and Velz (1984) predictive equations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

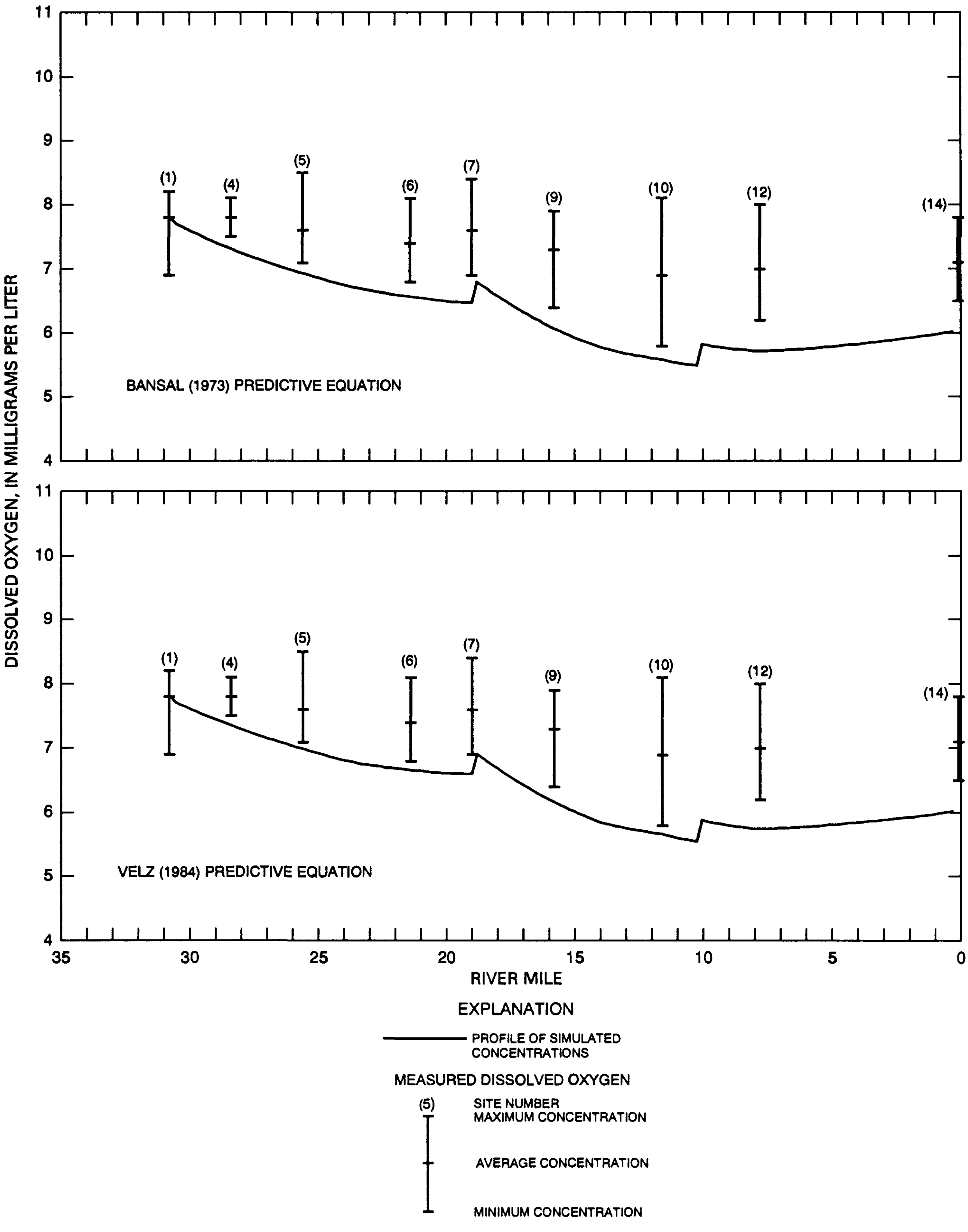
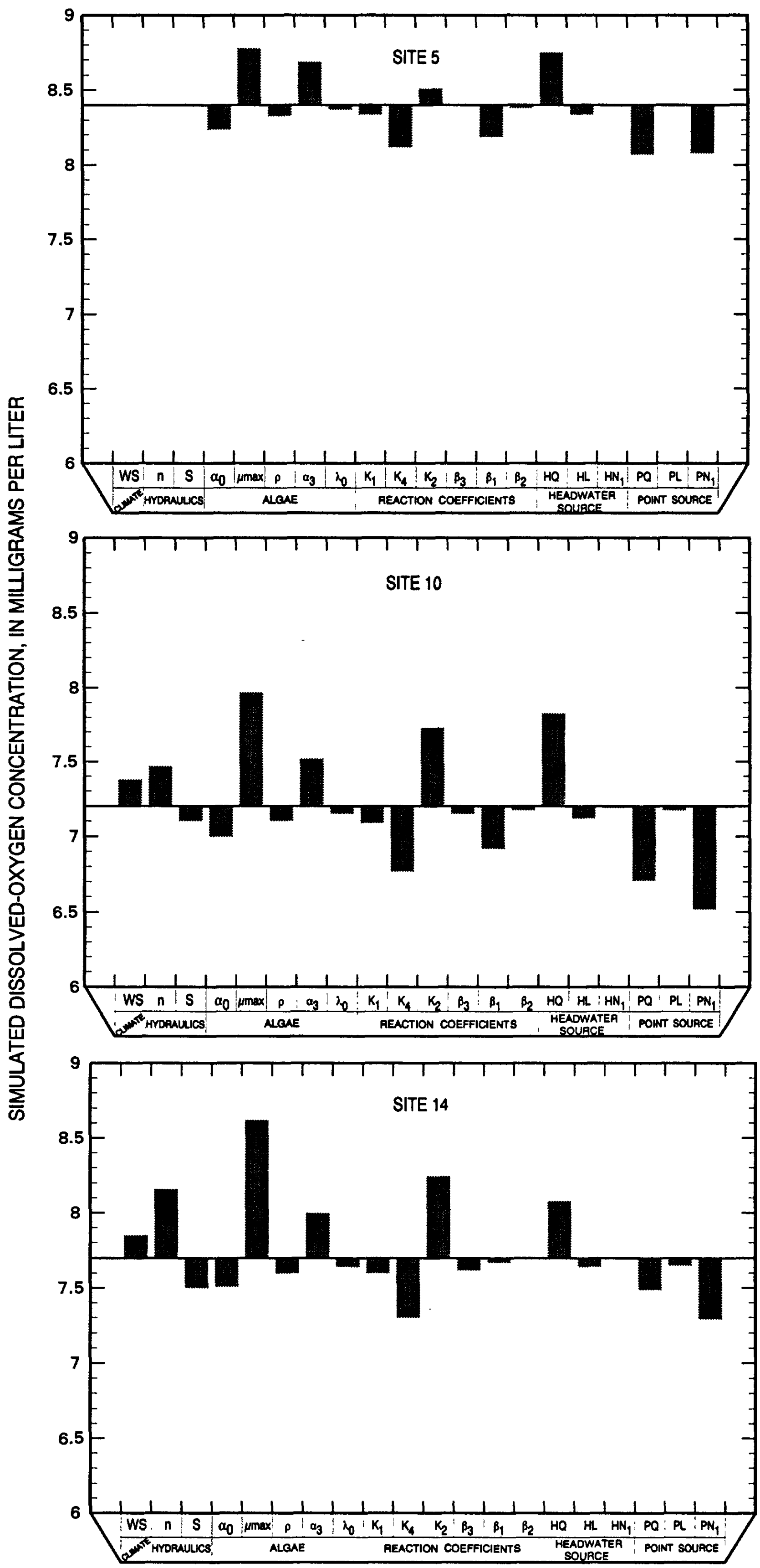


Figure 18. Maximum, average, and minimum measured dissolved-oxygen concentrations for verification (August 14-15, 1990) data set and profiles of simulated concentrations obtained by using the Bansal (1973) and Velz (1984) predictive equations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).



EXPLANATION

WS WINDSPEED, IN FEET PER SECOND

n MANNING'S ROUGHNESS COEFFICIENT

S CHANNEL SLOPE, IN FOOT PER FOOT

α_0 RATIO OF CHLOROPHYLL a TO ALGAL BIOMASS, IN (MICROGRAMS CHLOROPHYLL a PER LITER) PER (MILLIGRAMS ALGAL BIOMASS PER LITER)

μmax MAXIMUM SPECIFIC ALGAL GROWTH RATE, IN PER DAY

ρ LOCAL ALGAL RESPIRATION RATE, IN PER DAY

α_3 RATE OF DISSOLVED-OXYGEN PRODUCTION PER UNIT OF ALGAL GROWTH, IN (MILLIGRAMS DISSOLVED OXYGEN PER LITER) PER (MILLIGRAMS ALGAL BIOMASS PER LITER)

λ_0 NONALGAL LIGHT-EXTINCTION COEFFICIENT, IN PER FOOT

K_1 ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND DECAY RATE, IN PER DAY

K_4 SEDIMENT OXYGEN DEMAND RATE, IN (GRAMS OXYGEN PER SQUARE FOOT) PER (DAY)

K_2 REAERATION-RATE COEFFICIENT, IN PER DAY

β_3 INSTREAM REACTION RATE FOR HYDROLYSIS OF TOTAL ORGANIC NITROGEN AS NITROGEN TO TOTAL AMMONIA AS NITROGEN, IN PER DAY

β_1 INSTREAM REACTION RATE FOR BIOLOGICAL DECAY OF TOTAL AMMONIA AS NITROGEN TO TOTAL NITRITE AS NITROGEN, IN PER DAY

β_2 INSTREAM REACTION RATE FOR BIOLOGICAL DECAY OF TOTAL NITRITE AS NITROGEN TO TOTAL NITRATE AS NITROGEN, IN PER DAY

HQ HEADWATER-SOURCE STREAMFLOW, IN CUBIC FEET PER SECOND

HL HEADWATER-SOURCE ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND, IN MILLIGRAMS PER LITER

HN_1 HEADWATER-SOURCE TOTAL AMMONIA AS NITROGEN, IN MILLIGRAMS PER LITER

PQ POINT-SOURCE STREAMFLOW, IN CUBIC FEET PER SECOND

PL POINT-SOURCE ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND, IN MILLIGRAMS PER LITER

PN_1 POINT-SOURCE TOTAL AMMONIA AS NITROGEN, IN MILLIGRAMS PER LITER

—— CALIBRATED VALUE OF DISSOLVED OXYGEN PRIOR TO 50-PERCENT CHANGE IN SELECTED PROPERTY, CONSTITUENT, OR COEFFICIENT

Figure 19. Simulated dissolved-oxygen concentration at sites 5, 10, and 14 on the Red River of the North at Fargo, North Dakota, resulting from a 50-percent change in selected calibrated properties, constituents, and coefficients.

Dissolved oxygen is considered sensitive to a particular property, constituent, or reaction coefficient when a small change in the concentration of the property, constituent, or reaction coefficient causes a relatively large change in the concentration of dissolved oxygen. Therefore, a sensitivity analysis identifies those properties, constituents, and reaction coefficients that should be measured for model calibration because estimated values will add uncertainty to the dissolved-oxygen simulation. Furthermore, once these properties, constituents, and reaction coefficients are identified, they may be used as a tool to direct areas of research, to gather data more efficiently, or to aid in water-quality management.

The sensitivity was determined by increasing the calibrated value of one property, constituent, or reaction coefficient by 50 percent while the values of other properties, constituents, or reaction coefficients were kept constant. For the next sensitivity sequence, the changed property, constituent, or reaction coefficient was returned to the original value and the next property, constituent, or reaction coefficient was increased by 50 percent, and so on. The amount of change can represent the magnitude of uncertainty or error associated with each property, constituent, or reaction coefficient.

The result of a 50-percent increase in the value of the calibrated property, constituent, or reaction coefficient is an increase or decrease in dissolved-oxygen concentration. The magnitude and rank of the increases in dissolved-oxygen concentration vary from site to site in the downstream direction except for maximum specific algal growth rate (μ_{max}). Dissolved-oxygen concentration is most sensitive to maximum specific algal growth rate (μ_{max}) at all three sites. Excluding maximum specific algal growth rate (μ_{max}), dissolved oxygen at site 5 is most sensitive to headwater-source streamflow (HQ), dissolved-oxygen production per unit of algal growth (α_3), and reaeration-rate coefficient (K_2). Dissolved-oxygen concentration at site 5 is least sensitive to climate and hydraulics. Dissolved oxygen at site 10 is sensitive to headwater-source streamflow (HQ), reaeration-rate coefficient (K_2), and dissolved-oxygen production per unit of algal growth (α_3). Dissolved oxygen is more sensitive to climate and hydraulics at site 10 than at site 5. Dissolved oxygen at site 14 is sensitive to reaeration-rate coefficient (K_2), Manning's roughness coefficient (n), headwater-source streamflow (HQ), and dissolved-oxygen production per unit of algal growth (α_3). In general, dissolved oxygen becomes more sensitive to hydraulics in a downstream direction.

The magnitude and rank of the decreases in dissolved-oxygen concentration also vary in the downstream direction. Dissolved-oxygen sensitivity to SOD (K_4) is substantial and consistent at all three sites although the rank is not the highest. Dissolved-oxygen concentration at site 5 is sensitive to point-source streamflow (PQ), point-source ammonia (PN_1), SOD (K_4), biological decay of ammonia to nitrite (β_1), and ratio of chlorophyll a to algal biomass (α_0). Dissolved-oxygen concentration at site 10 is sensitive to point-source ammonia (PN_1), point-source streamflow (PQ), SOD (K_4), biological decay of ammonia to nitrite (β_1), and ratio of chlorophyll a to algal biomass (α_0). Dissolved-oxygen sensitivity to channel slope (S) is decreasing. Dissolved oxygen at site 14 is sensitive to point-source ammonia (PN_1), SOD (K_4), point-source streamflow (PQ), channel slope (S), and ratio of chlorophyll a to algal biomass (α_0). Dissolved-oxygen concentration at site 14 is not as sensitive to biological decay of ammonia to nitrite (β_1) as at sites 5 and 10. Dissolved-oxygen concentration is not very sensitive to CBODu decay rate (K_1) or to headwater-source (HL) or point-source (PL) CBODu concentrations.

The RRatFGO QW model was calibrated to simulate water temperature, CBODu, algae, and the nitrogen cycle, all of which affect dissolved-oxygen concentration. If a property, constituent, or constituent category that affects dissolved-oxygen concentration is not simulated, its effect is not considered. Therefore, the effect on dissolved-oxygen concentration attributable to a property, constituent, or constituent category can be estimated by eliminating that property, constituent, or constituent category from the simulation. In order to determine which property, constituent, or constituent category caused the largest effect on simulated dissolved-oxygen concentration, modeling sequences were made without simulating, in turn, water temperature, CBODu, algae, and all three nitrogen species (nitrogen cycle). In addition, two modeling sequences were made without including, in turn, reaeration-rate coefficient and SOD. This technique identifies the property, constituent, or constituent category that causes the largest increase or decrease in dissolved-oxygen concentration. Dissolved-oxygen concentrations for each modeling sequence for sites 5, 10, and 14 are shown in figure 20.

When the increases and decreases in dissolved-oxygen concentration are considered separately, the magnitude of the increase or decrease in dissolved-oxygen concentration as a result of not simulating or not including selected properties, constituents, or constituent categories in modeling sequences varies. However, the rank of the increase or decrease stays the same from site to site except at site 5 when not simulating algae results in a lower dissolved-oxygen concentration than when not including reaeration-rate coefficient. Nitrification (the nitrogen cycle) consumes most of the dissolved oxygen at all three sites. SOD is the second largest consumer of dissolved oxygen, and CBODu is the smallest consumer of dissolved oxygen. Reaeration is the largest contributor of dissolved oxygen at sites 10 and 14, and algae is the second largest contributor.

Not simulating water temperature in the modeling sequence also causes a difference in dissolved-oxygen concentration. This difference is caused by the manner in which the model calculates dissolved oxygen depending upon whether or not water temperature is being simulated. When water temperature is simulated, a pressure correction is made because barometric-pressure data are a primary requirement of the heat-balance equation (Brown and Barnwell, 1987).

Simulation of Hypothetical Waste Loads

To demonstrate the potential use of the RRatFGO QW model as a tool for evaluating alternate water-quality management strategies that involve wastewater discharges and water quality in the Red River, the model and the verification data set, including associated reaction-coefficient values as input, were used to simulate total ammonia as nitrogen, total nitrite plus nitrate as nitrogen, CBOD5, and dissolved oxygen for the water-quality conditions that result from three hypothetical boundary conditions. The three hypothetical boundary conditions were incorporated into the verification data set, which was used as input to the RRatFGO QW model. The hypothetical boundary conditions used in the simulations are listed in table 17.

The hypothetical boundary conditions for the upstream reach were selected to represent nontypical low streamflows, typical ammonia concentrations, and typical CBOD5 concentrations. The fixed reaeration-rate coefficients corresponding to the upstream streamflows were determined from figure 8. For the Moorhead wastewater-treatment plant, the outflow rates, the ammonia concentrations, and the CBOD5 concentrations for the three hypothetical conditions are typical. For the Fargo wastewater-treatment plant, the outflow rate and the ammonia concentration for hypothetical condition 1 are typical, but the outflow rates and the ammonia concentrations for hypothetical conditions 2 and 3 are larger than typical. CBOD5 concentrations for the three hypothetical conditions are about typical. For the Sheyenne River, the streamflow, the ammonia concentrations, and the CBOD5 concentrations for the three conditions are typical.

Profiles of simulated ammonia, nitrite plus nitrate, CBOD5, and dissolved-oxygen concentrations are shown in figures 21 through 29. Where applicable, the North Dakota water-quality standard also is shown on the profile. To evaluate the three hypothetical conditions for contravention of the ammonia standard, a maximum pH of 8.2 and a maximum water temperature of 75.5°F, both of which existed at site 5, were used (North Dakota State Department of Health and Consolidated Laboratories, 1991).

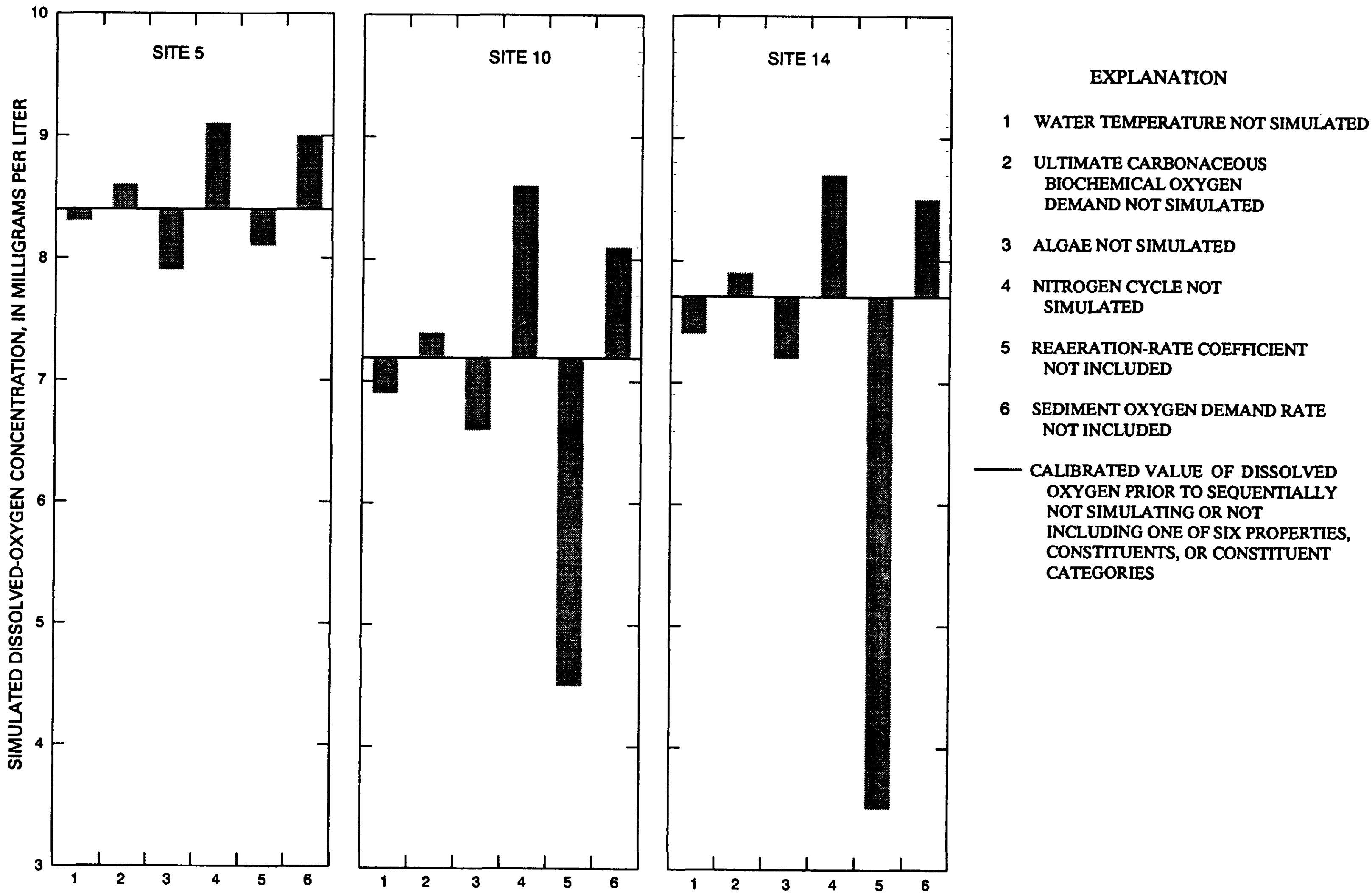


Figure 20. Simulated dissolved-oxygen concentration at sites 5, 10, and 14 on the Red River of the North at Fargo, North Dakota, resulting from sequentially not simulating or not including one of six properties, constituents, or constituent categories.

Table 17. Hypothetical streamflow and water-quality conditions

Constituent	Hypothetical condition 1	Hypothetical condition 2	Hypothetical condition 3
Site 1, Upstream reach			
Streamflow (cubic feet per second)	50	75	75
Total ammonia as nitrogen (milligrams per liter)	[1].12	[1].12	[1].12
5-day carbonaceous biochemical oxygen demand (milligrams per liter)	[1]1.5	[1]1.5	[1]1.5
Fixed reaeration coefficient (per day)	2.5	2.2	2.2
Site 2, Moorhead wastewater-treatment plant			
Outflow (cubic feet per second)	[1]5	[1]5	[1]5
Total ammonia as nitrogen (milligrams per liter)	[1]17.7	[1]17.7	[1]17.7
5-day carbonaceous biochemical oxygen demand (milligrams per liter)	[1]20	[1]20	[1]20
Site 8, Fargo wastewater-treatment plant			
Outflow (cubic feet per second)	15	37.8	37.8
Total ammonia as nitrogen (milligrams per liter)	5	9	15
5-day carbonaceous biochemical oxygen demand (milligrams per liter)	20	20	20
Site 11, Sheyenne River			
Streamflow (cubic feet per second)	[1]16	[1]16	[1]16
Total ammonia as nitrogen (milligrams per liter)	[1].08	[1].08	[1].08
5-day carbonaceous biochemical oxygen demand (milligrams per liter)	[1]5.7	[1]5.7	[1]5.7

[1]Verification data set.

For hypothetical condition 1 (figs. 21 to 23), only the nitrite plus nitrate standard[1] was exceeded. The effect of the ammonia load from Moorhead wastewater-treatment plant outflow at site 2 and Fargo wastewater-treatment plant outflow at site 8 on the ammonia concentration in the Red River is shown in figure 21. The maximum simulated nitrite plus nitrate concentration was 2.2 mg/L at about study reach river mile 10 (fig. 21). The maximum simulated instream CBOD5 concentration resulting from Moorhead wastewater-treatment plant outflow at site 2 was 1.7 mg/L at about study reach river mile 30.7, and the maximum concentration resulting from Fargo wastewater-treatment plant outflow at site 8 was 3.8 mg/L at about study reach river mile 18.9 (fig. 22). The minimum simulated dissolved-oxygen concentration obtained by using a constant reaeration-rate coefficient was 5.9 mg/L at about study reach river mile 25 (fig. 22). The profile of the dissolved-oxygen concentrations for hypothetical condition 1 is typical and resembles the profile of the dissolved-oxygen concentrations for verified conditions shown in figure 16. Dilution from Sheyenne River streamflow at site 11 causes an increase in dissolved-oxygen concentration at about study reach river mile 10. The minimum simulated dissolved-oxygen concentration obtained by using the Bansal (1973) predictive equation was 5.5 mg/L at about study reach river mile 24, and the minimum simulated concentration obtained by using the Velz (1984) predictive equation was 6.5 mg/L at about study reach river mile 25 (fig. 23).

For hypothetical condition 2 (figs. 24 to 26), nitrite plus nitrate and dissolved-oxygen standards were contravened. The maximum simulated ammonia concentration was 3.0 mg/L at about study reach river mile 19 (fig. 24). The maximum simulated nitrite plus nitrate concentration was 3.1 mg/L at study reach river mile zero (fig. 24). The nitrite plus nitrate concentration was still increasing at the end of the study reach but the rate of increase was decreasing. The maximum simulated instream CBOD5 concentration

[1]The North Dakota water-quality standard is defined for nitrate as nitrogen. The calibrated RRatFGO QW model rapidly converts nitrite as nitrogen to nitrate as nitrogen. The 1.0-mg/L standard, which is shown in figures 21, 24, and 27 is intended as an interim guideline limit but in no case shall the standard for nitrate as nitrogen exceed 10 mg/L for any water used as a municipal or domestic water supply (North Dakota State Department of Health and Consolidated Laboratories, 1991).

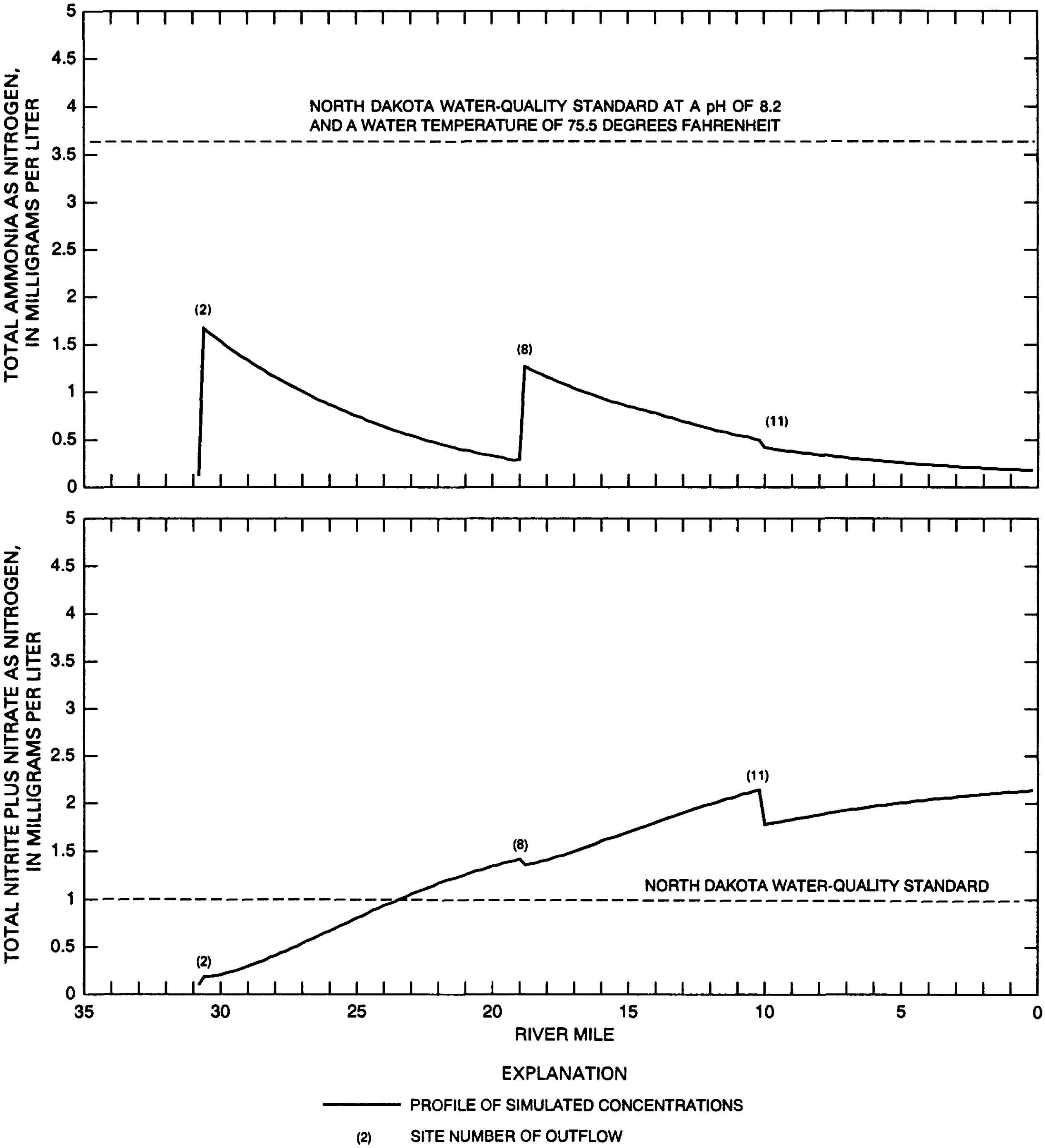


Figure 21. Profiles of simulated total ammonia as nitrogen and total nitrite plus nitrate as nitrogen concentrations for hypothetical condition 1 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

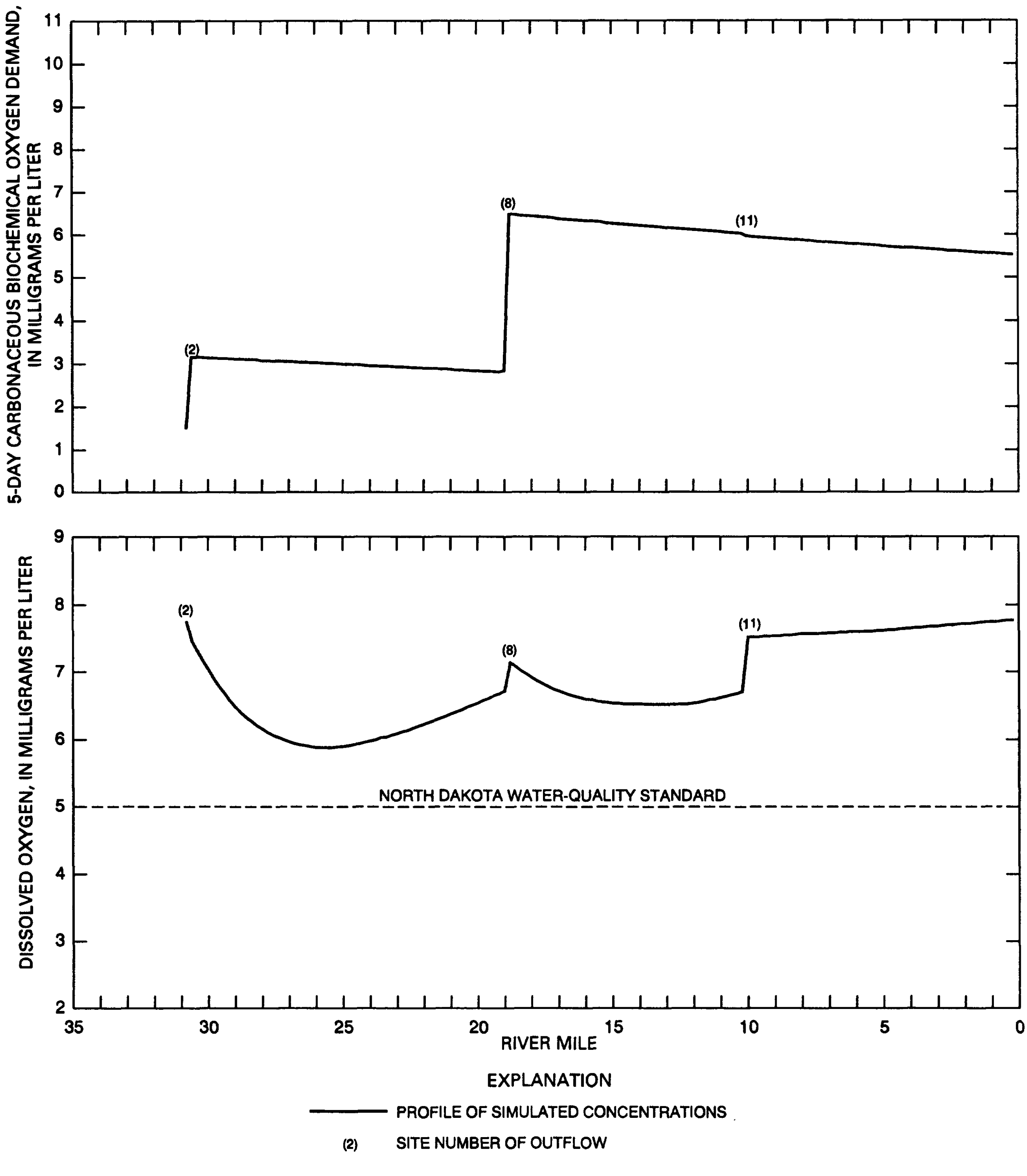


Figure 22. Profiles of simulated 5-day carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for hypothetical condition 1 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

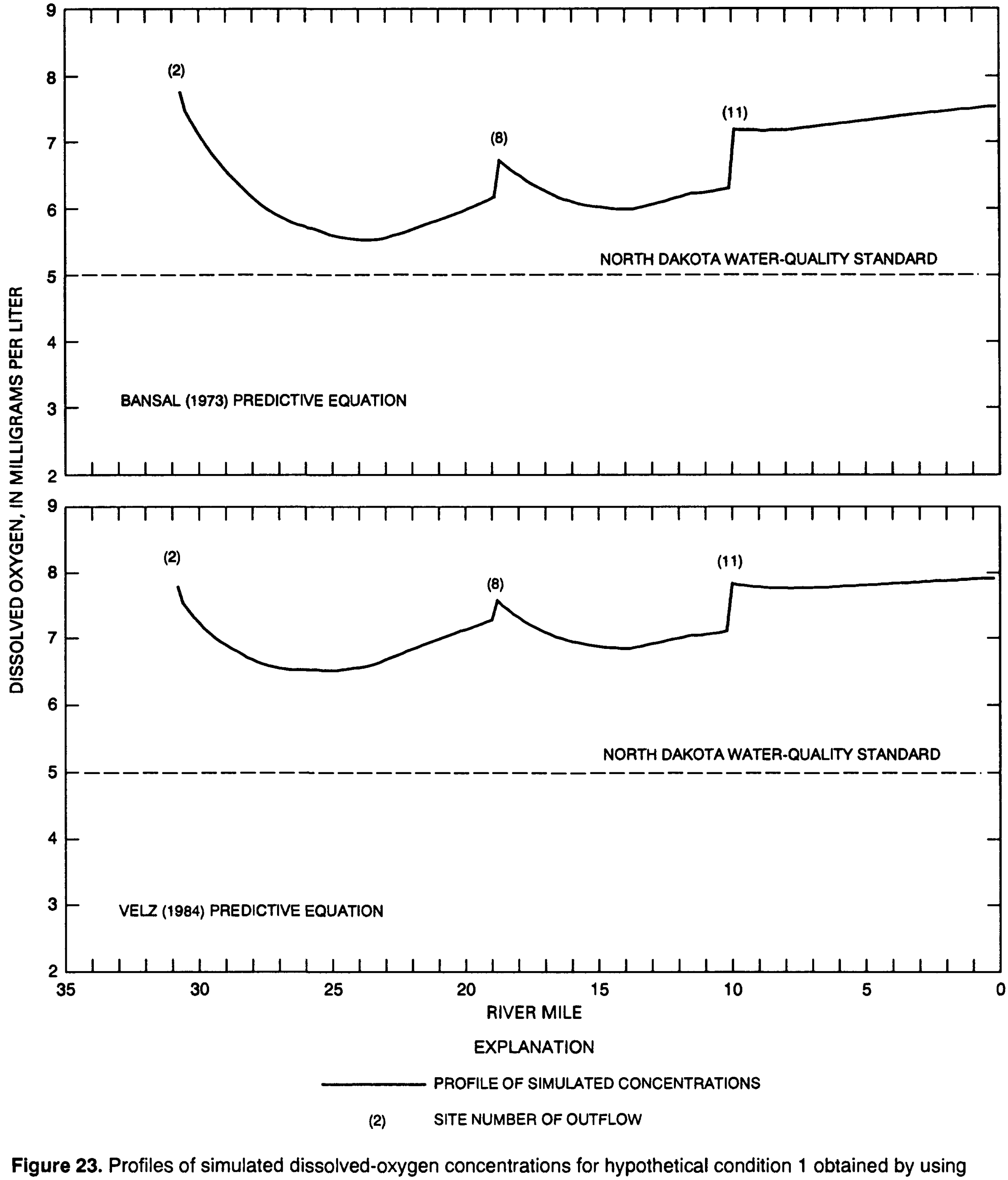


Figure 23. Profiles of simulated dissolved-oxygen concentrations for hypothetical condition 1 obtained by using reaeration-rate coefficients determined from the Bansal (1973) and Velz (1984) predictive equations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

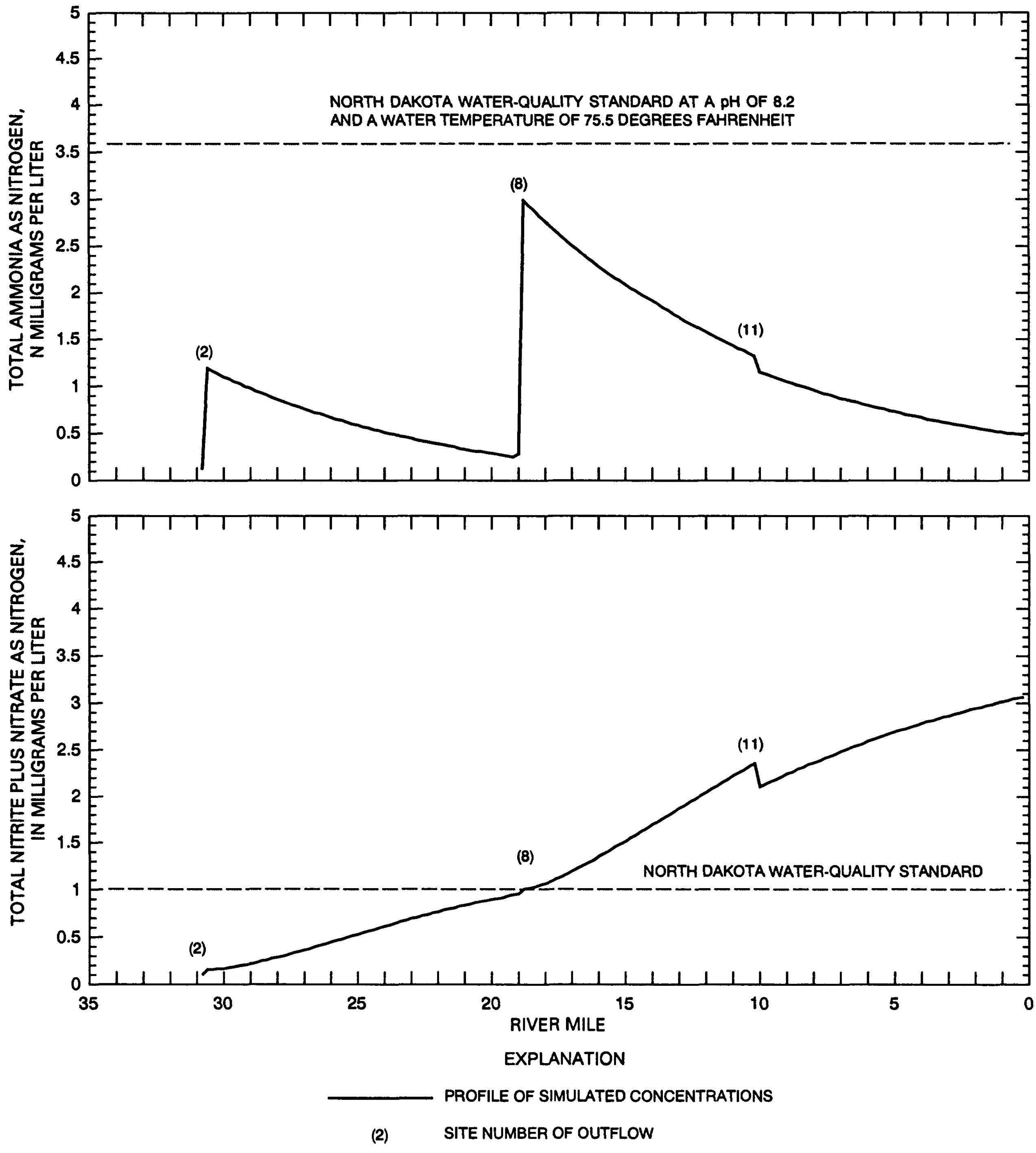


Figure 24. Profiles of simulated total ammonia as nitrogen and total nitrite plus nitrate as nitrogen concentrations for hypothetical condition 2 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

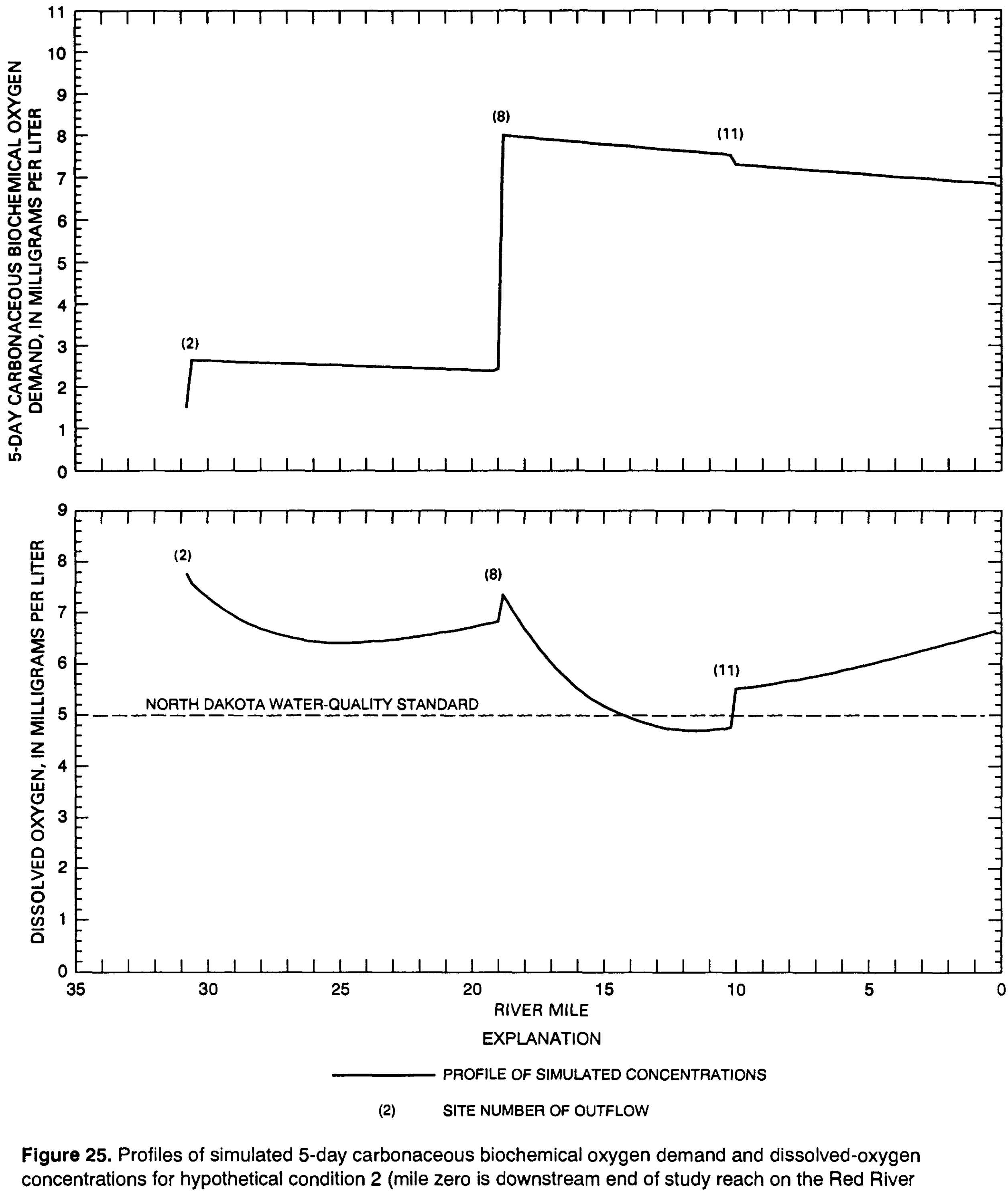


Figure 25. Profiles of simulated 5-day carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for hypothetical condition 2 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

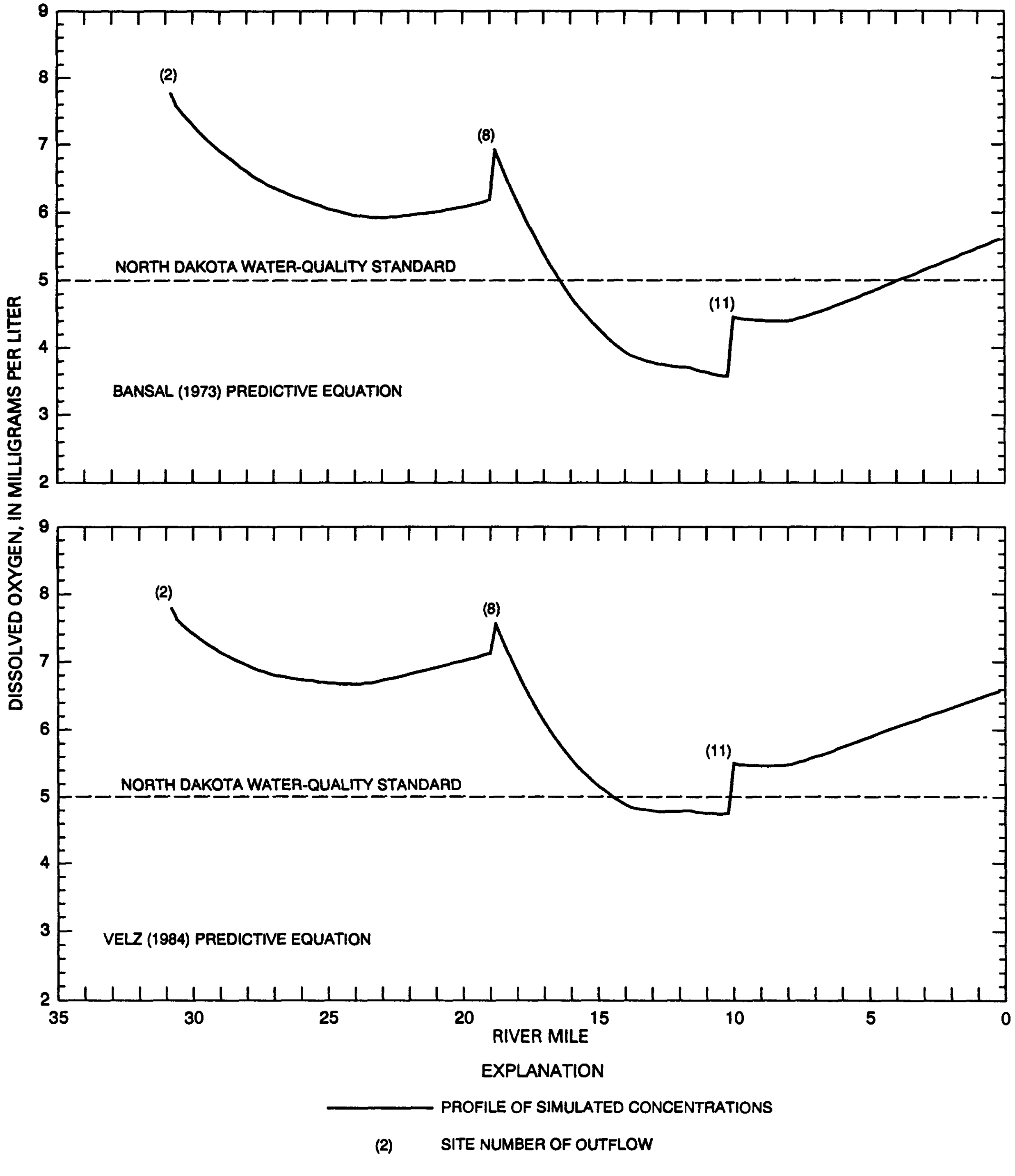


Figure 26. Profiles of simulated dissolved-oxygen concentrations for hypothetical condition 2 obtained by using reaeration-rate coefficients determined from the Bansal (1973) and Velz (1984) predictive equations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

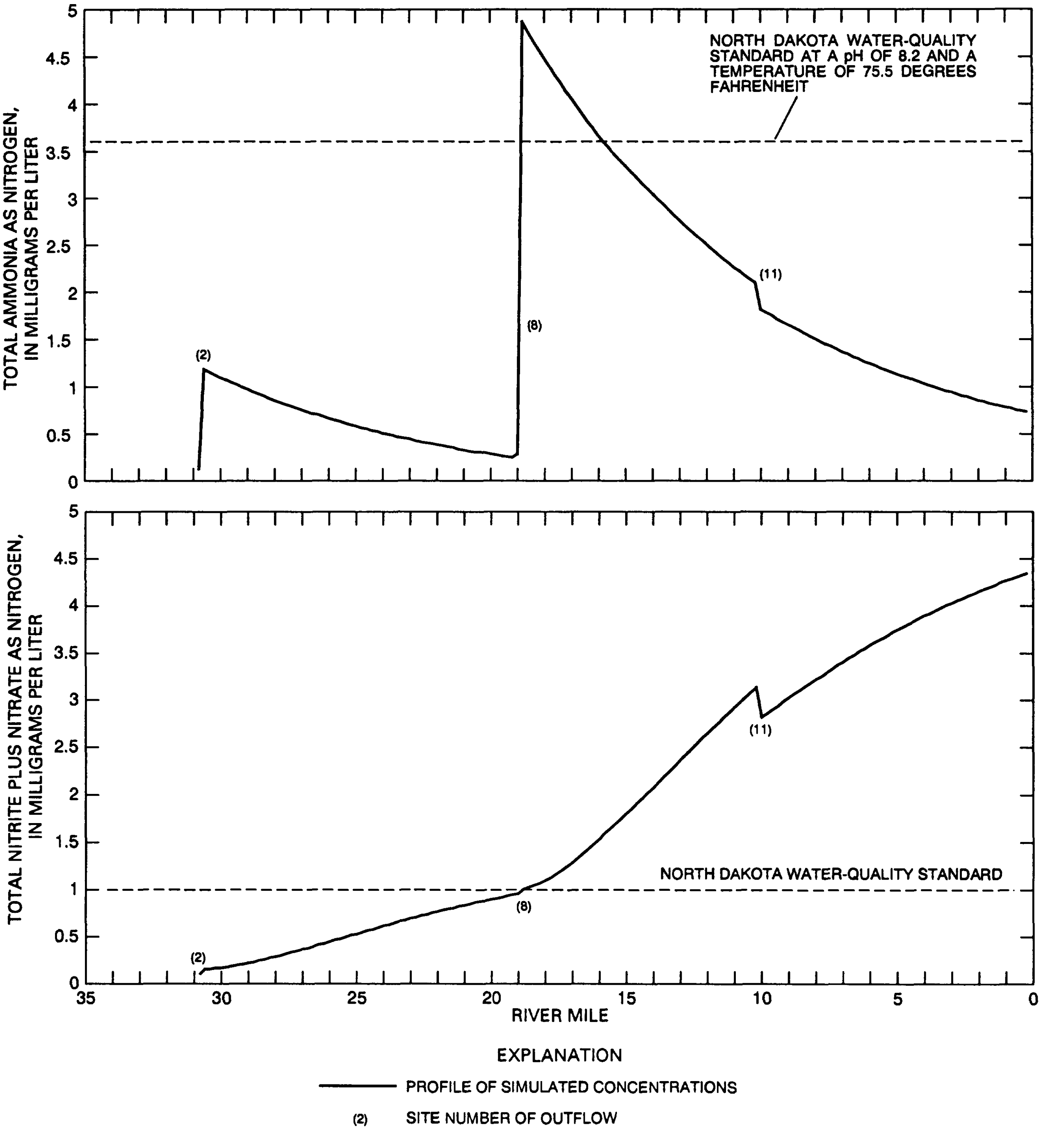


Figure 27. Profiles of simulated total ammonia as nitrogen and total nitrite plus nitrate as nitrogen concentrations for hypothetical condition 3 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

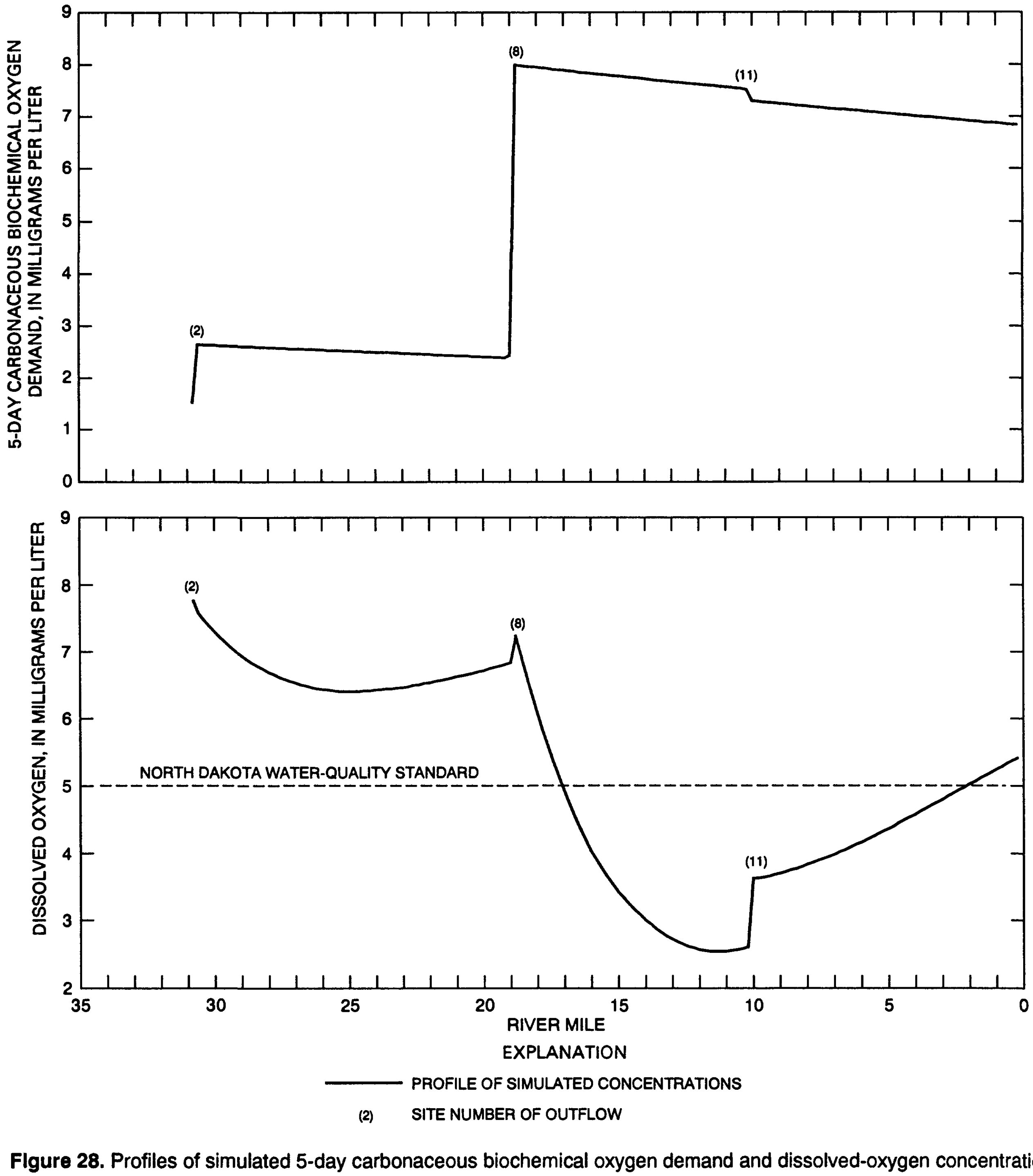


Figure 28. Profiles of simulated 5-day carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for hypothetical condition 3 (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

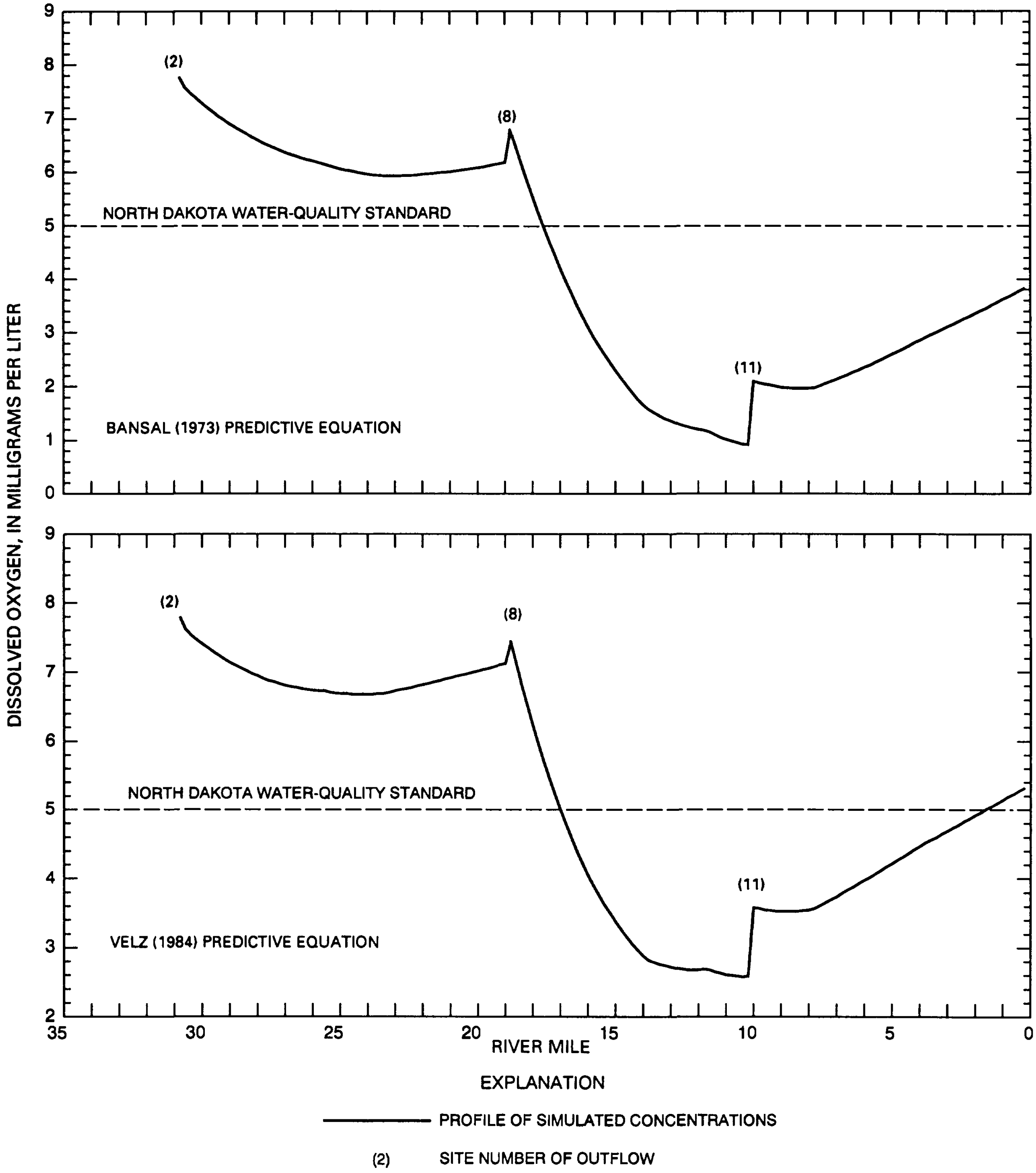


Figure 29. Profiles of simulated dissolved-oxygen concentrations for hypothetical condition 3 obtained by using reaeration-rate coefficients determined from the Bansal (1973) and Velz (1984) predictive equations (mile zero is downstream end of study reach on the Red River of the North at Fargo, North Dakota).

resulting from Moorhead wastewater-treatment plant outflow at site 2 was 1.1 mg/L at about study reach river mile 30.7, and the maximum concentration resulting from Fargo wastewater-treatment plant outflow at site 8 was 5.6 mg/L at about study reach river mile 19 (fig. 25). The minimum simulated dissolved-oxygen concentration resulting from Moorhead wastewater-treatment plant outflow at site 2 was 6.5 mg/L at about study reach river mile 25 (fig. 25). This dissolved-oxygen concentration is larger than for hypothetical condition 1 because of the increased headwater streamflow.

The increased ammonia load from Fargo wastewater-treatment plant outflow at site 8 is evident in the dissolved-oxygen concentration downstream of site 8. The ammonia load from Fargo wastewater-treatment plant outflow causes the dissolved-oxygen concentration to decrease to 4.7 mg/L at about study reach river mile 11 before recovery begins. Dilution from Sheyenne River streamflow at site 11 is evident at about study reach river mile 10 where dissolved-oxygen recovery is accelerated. Dissolved-oxygen recovery is still taking place at the end of the study reach.

Dissolved-oxygen concentrations obtained by using the Bansal (1973) predictive equation generally are lower than dissolved-oxygen concentrations obtained by using a constant reaeration-rate coefficient. The minimum simulated dissolved-oxygen concentration obtained by using the Bansal (1973) predictive equation was 3.6 mg/L at about study reach river mile 10 (fig. 26). Generally, dissolved-oxygen concentrations obtained by using the Velz (1984) predictive equation (fig. 26) are about the same as dissolved-oxygen concentrations obtained by using a constant reaeration-rate coefficient except between sites 2 and 8 where concentrations obtained by using the Velz (1984) predictive equation are larger. The minimum simulated dissolved-oxygen concentration obtained by using the Velz (1984) predictive equation was 4.8 mg/L at about study reach river mile 10 (fig. 26).

For hypothetical condition 3 (figs. 27 to 29), ammonia, nitrite plus nitrate, and dissolved-oxygen standards were contravened. The maximum simulated ammonia concentration was 4.9 mg/L at about study reach river mile 19 (fig. 27). Ammonia decays at a fairly rapid rate and is approaching upstream (headwater) concentrations at study reach river mile zero. The maximum simulated nitrite plus nitrate concentration was 4.4 mg/L at study reach river mile zero (fig. 27). The nitrite plus nitrate concentration increased rapidly throughout the study reach and was still increasing at the end of the study reach. The maximum simulated instream CBOD5 concentration resulting from Moorhead wastewater-treatment plant outflow at site 2 was 1.1 mg/L at about study reach river mile 30.7, and the maximum concentration resulting from Fargo wastewater-treatment plant outflow at site 8 was 5.6 mg/L at about study reach river mile 19 (fig. 28). The minimum simulated dissolved-oxygen concentration obtained by using a constant reaeration-rate coefficient was 2.6 mg/L at about study reach river mile 11 (fig. 28). The dissolved-oxygen sag at study reach river mile 25 is less than the corresponding sag for hypothetical condition 1 because headwater streamflow is 25 ft^3/s greater for hypothetical condition 3 than for hypothetical condition 1.

The large ammonia load from Fargo wastewater-treatment plant outflow at site 8 is very evident in the ammonia, nitrite plus nitrate, and dissolved-oxygen profiles (figs. 27 and 28). The ammonia load from Fargo wastewater-treatment plant outflow causes the dissolved-oxygen concentration to decrease to 2.6 mg/L at about study reach river mile 11 before recovery begins. Dilution from Sheyenne River streamflow at site 11 is evident at about study reach river mile 10 where dissolved-oxygen recovery is accelerated. Dissolved-oxygen recovery is still taking place at the end of the study reach.

Dissolved-oxygen concentrations obtained by using the Bansal (1973) predictive equation generally are lower than dissolved-oxygen concentrations obtained by using a constant reaeration-rate coefficient. The minimum simulated dissolved-oxygen concentration obtained by using the Bansal (1973) predictive equation was 1.0 mg/L at about study reach river mile 11 (fig. 29). Generally, dissolved-oxygen concentrations obtained by using the Velz (1984) predictive equation are about the same as dissolved-oxygen concentrations obtained by using a constant reaeration-rate coefficient. The minimum simulated dissolved-oxygen concentration obtained by using the Velz (1984) predictive equation was 2.5 mg/L at about study reach river mile 11 (fig. 29).

SUMMARY

A 30.8-mile reach of the Red River of the North receives treated wastewater from plants at Fargo, North Dakota, and Moorhead, Minnesota, and streamflows from the Sheyenne River. The 30.8-mile reach begins about 0.1 mile downstream of the 12th Avenue North bridge in Fargo and extends downstream to a site 0.8 mile upstream of the confluence of the Buffalo and Red Rivers. This reach of the river receives wastewater from both point and nonpoint sources.

The Enhanced Stream Water Quality Model, QUAL2E, was calibrated and verified for summer streamflow conditions to simulate some of the biochemical processes that result from discharging treated wastewater into the study reach. Its companion program, QUAL2E-UNCAS, was used for uncertainty analysis. To apply the QUAL2E model, the study reach was divided into 11 subreaches. The calibrated QUAL2E model is referred to as the Red River at Fargo Water-Quality Model (RRatFGO QW) to distinguish the uncalibrated model from the calibrated model. Before the RRatFGO QW model was used to simulate transport and water-quality conditions, it was calibrated and verified with independent sets of measured data. To obtain the independent data sets needed to calibrate and verify the model, a network of 14 data-collection sites was established. The model simulates streamflow, specific conductance, water temperature, ultimate carbonaceous biochemical oxygen demand, chlorophyll a as an indicator of algal biomass, and nitrogen and phosphorus.

Model calibration was performed in two steps. First, the transport component of the model was calibrated to simulate transport conditions in the river, and second, the water-quality component of the model was calibrated to simulate water-quality conditions of the river. To define the river's transport characteristics and reaeration-rate coefficients, width, depth, streamflow, traveltime, and reaeration measurements were made. Cross-section data obtained when streamflow ranged from 140 to 400 cubic feet per second indicate the mean top width of the river was about 85 feet, the mean maximum depth of the river was 4.6 feet, the mean hydraulic depth of the river was 2.8 feet, and the mean cross-section area was about 234 square feet. Traveltime measurements indicate mean streamflow transport velocities ranged from 0.38 to 1.35 feet per second when streamflows ranged from 60 to 523 cubic feet per second. Measured reaeration-rate coefficients, adjusted to a 68-degree Fahrenheit water temperature, ranged from 0.57 per day at 461 cubic feet per second to 1.29 per day at 215 cubic feet per second.

To define the river's water-quality characteristics and reaction coefficients, two synoptic (24-hour) water-quality samplings were performed in August 1989 and August 1990. Samples were analyzed onsite for streamflow, specific conductance, pH, water and air temperature, barometric pressure, and dissolved oxygen. In addition, samples were collected for laboratory analysis of ultimate carbonaceous biochemical oxygen demand, nitrite plus nitrate, ammonia, organic nitrogen, phosphorus, chlorophyll a, and chlorophyll b. Sediment oxygen demand was measured in place at nine sites in the study reach during August and September 1990.

To begin calibration of the transport component of the model, measured 1-mile cross-section shapes were modified to trapezoidal shapes. Cross sections were grouped by subreach, and cross-section data were averaged to obtain one representative value, referred to as modified, for each subreach. To simulate a trapezoidal shape, channel geometry was calibrated in a trial-and-error manner by adjusting widths, depths, and areas until the calibrated values matched the modified values. The average calibrated top width is about the same as the average modified top width, the average calibrated depth is about 11 percent larger than the average modified depth, and the average calibrated area is about 9 percent larger than the average modified area. For a streamflow of 60 cubic feet per second, the model simulates traveltime that is 12.6 percent shorter (faster streamflow transport velocity) than measured traveltime for the same streamflow. For streamflows of about 390 to 523 cubic feet per second, the model simulates traveltimes that are about 8 percent longer (slower streamflow transport velocities) than measured traveltimes for the same streamflows.

Specific conductance was simulated to determine how well the model was calibrated for stream transport velocities. Simulated specific-conductance values are in acceptable agreement of the measured values for the calibration and verification data sets except for three sites. Thus, the transport component of the model is satisfactorily calibrated. Satisfactory temperature simulations were accomplished at all sites by adjusting windspeed. Because climatic conditions at the time of synoptic sampling are taken into consideration during temperature simulations, the windspeed adjustments necessarily are different for model calibration and verification.

A graphical regression of streamflow and reaeration-rate coefficients was developed. After an error analysis was performed on the calculated reaeration-rate coefficients, a 35-percent error adjustment was applied to the regression. Of the 11 predictive equations evaluated during this study, only the equations from Bansal (1973) and Velz (1984) produced a dissolved-oxygen concentration that reasonably matched the simulated dissolved-oxygen concentration for the calibration and verification data sets.

To calibrate the water-quality component of the model to simulate algae, nutrient, and dissolved-oxygen concentrations, the appropriate reaction coefficients were estimated from measured data when available. If measured data were not available, the reaction coefficients initially were set to a midvalue of the range recommended in model documentation and adjusted as necessary until simulated data matched measured data. Most of the properties, constituents, and coefficients to simulate algae were not measured. The model was calibrated to simulate algae concentration for the calibration data set by using local algal settling rates ranging from 1.0 to 4.0 feet per day. It was not possible to verify the model with respect to algae kinetics, however, because it was necessary to readjust the local algal settling rates ranging from 0 to 1.5 feet per day for the verification data set in order to simulate algae concentrations that reasonably matched measured concentrations.

Simulated organic nitrogen concentrations for the calibration data set are within one standard deviation of the average measured concentrations at all data-collection sites, and simulated concentrations for the verification data set are within one standard deviation except at sites 10 and 12. Simulated ammonia concentrations are within one standard deviation of the average measured concentrations for both data sets. Although simulated nitrite plus nitrate concentrations for the calibration data set are within one standard deviation of the average measured concentrations, simulated concentrations for the verification data set are overpredicted from a low of one standard deviation (0.05 milligram per liter) at sites 4 and 5 to a high of 0.3 milligram per liter at site 14. Simulated phosphorus concentrations for both data sets are in close agreement with measured concentrations for sites 1 through 7; however, for both data sets, simulations overpredict phosphorus concentrations downstream of site 8.

Dissolved-oxygen concentration was used as the primary indicator of water quality in the Red River. Two processes that directly affect dissolved-oxygen concentration are ultimate carbonaceous biochemical oxygen demand and sediment oxygen demand. Simulated ultimate carbonaceous biochemical oxygen demand concentrations for the calibration and verification data sets are underpredicted but are within one standard deviation of the average measured concentrations. A sediment oxygen demand concentration of

0.10 gram oxygen per square foot per day was used for calibration and verification. When using a constant reaeration-rate coefficient throughout the study reach, simulations of dissolved oxygen for both data sets are within one standard deviation of the average measured concentrations. Thus, the water-quality component reaction coefficients of the RRatFGO QW model are considered satisfactorily calibrated except for algae settling rate.

The calibrated model was used to conduct several analyses to determine the sensitivity of simulated dissolved-oxygen concentrations to 20 selected properties, constituents, and reaction coefficients. The sensitivity was determined for sites 5, 10, and 14. When increases in dissolved-oxygen concentration are considered, dissolved-oxygen concentration is most sensitive to maximum specific algal growth rate at all three sites. When decreases in dissolved-oxygen concentration are considered, dissolved-oxygen concentration is most sensitive to point-source streamflow followed by point-source ammonia at site 5 and to point-source ammonia at the two remaining sites. Model simulations indicate nitrification and sediment oxygen demand consume most of the dissolved oxygen in the study reach.

To demonstrate the potential use of the RRatFGO QW model as a tool for evaluating alternate water-quality management strategies that involve wastewater discharges and water quality in the Red River, the model and the verification data set, including associated reaction-coefficient values as input, were used to simulate total ammonia as nitrogen, total nitrite plus nitrate as nitrogen, CBOD5, and dissolved oxygen for the water-quality conditions that result from three hypothetical boundary conditions. The three hypothetical boundary conditions were incorporated into the verification data set, which was used as input to the RRatFGO QW model. The model was applied to various combinations of three hypothetical waste loads when the headwater streamflow was either 50 or 75 cubic feet per second, when Fargo's wastewater-treatment plant outflow was 15 or 37.8 cubic feet per second, and when total ammonia as nitrogen concentration of the outflow was 5, 9, or 15 milligrams per liter. For each hypothetical waste load, at least one water-quality standard for either total ammonia as nitrogen, total nitrite plus nitrate as nitrogen, or dissolved oxygen was contravened, and, for one scenario, all three standards were contravened. When dissolved-oxygen concentrations for three hypothetical waste loads were simulated, the dissolved-oxygen concentrations obtained by using the Bansal (1973) predictive equation consistently are lower than the concentrations obtained by using the Velz (1984) predictive equation. The dissolved-oxygen concentrations obtained by using the Velz (1984) predictive equation are about the same as concentrations obtained by using the constant reaeration-rate coefficient.

SELECTED REFERENCES

Banks, R.B., and Wickramanayake, G.B., 1984, Effect of rain on surface reaeration: Journal of Environmental Engineering, v. 110, no. 1, p. 1-13.

Bansal, M.K., 1973, Atmospheric reaeration in natural streams: Water Research, v. 7, no. 5, p. 769-782.

Bennett, J.P., and Rathbun, R.E., 1972, Reaeration in open-channel flow: U.S. Geological Survey Professional Paper 737, 75 p.

Bowie, G.L., Mills, W.B., Porcella, D.B., Campbell, C.L., Pagenkopf, J.R., Rupp, G.L., Johnson, K.M., Chan, P.W.H., Gherini, S.A., and Chamberlin, C.E., 1985, Rates, constants, and kinetics formulation in surface water quality modeling, second edition: U.S. Environmental Protection Agency, EPA/600/3-85/040, 455 p.

Britton, L.J., and Greeson, P.E., eds., 1989, Methods for collection and analysis of aquatic biological and microbiological samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A4, 363 p.

Brown, L.C., and Barnwell, T.O., Jr., 1987, The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS--Documentation and user manual: Athens, Georgia, U.S. Environmental Protection Agency, Environmental Research Laboratory, EPA/600/3-87/007, 189 p.

Cadwallader, T.E., and McDonnell, A.J., 1969, A multivariate analysis of reaeration data: Water Research, v. 3, p. 731-742.

Churchill, M.A., Elmore, H.L., and Buckingham, R.A., 1962, The prediction of stream reaeration rates: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 88, no. SA4, p. 1-46.

Federal Water Pollution Control Administration, Division of Technical Control, Comprehensive Planning and Programs, 1967, Fitting the Red River of the North Basin to the general river basin simulation program: 23 p.

Fischer, H.B., 1966, A note on the one-dimensional model: Great Britain, Air and Water Pollution International Journal, Great Britain, v. 10, p. 443-452.

___1968, Dispersion predictions in streams: American Society of Civil Engineers, Journal of Sanitary Engineering Division, v. 94, no. SA5, p. 927-943.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

HICKOK-RCM International, 1974, Load allocation study for the Minnesota Pollution Control Agency, Red River of the North river segment: Wayzata, Minnesota, 72 p.

Hovis, J.S., and Whittemore, R.C., 1982, The mathematical water-quality model QUAL-II and guidance for its use--Revised version: National Council of the Paper Industry for Air and Stream Improvement, Technical Bulletin no. 391, one volume.

Isaacs, W.P., and Gaudy, A.F., 1968, Atmospheric oxygenation in a simulated stream: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 94, no. SA2, p. 319-344.

Jennings, M.E., and Bauer, D.P., 1976, Determination of biochemical oxygen demand parameters: Computer Program Documentation User's Manual, Bay St. Louis, Mississippi, U.S. Geological Survey, Gulf Coast Hydroscience Center, 55 p.

Kilpatrick, F.A., Rathbun, R.E., Yotsukura, N., Parker, G.W., and DeLong, L.L., 1989, Determination of stream reaeration coefficients by use of tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A18, 52 p.

Kilpatrick, F.A., and Wilson, J.F., Jr., 1989, Measurement of time of travel in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A9, 27 p.

Krenkel, P.A., and Novotny, V., 1980, Water quality management: New York, New York, Academic Press, Inc., 671 p.

Krenkel, P.A., and Orlob, G.T., 1963, Turbulent diffusion and the reaeration coefficient: American Society of Civil Engineers Transactions, v. 128, Part III, Paper no. 3491, p. 293-334.

Langbein, W.B., and Durum, W.H., 1967, The aeration capacity of streams: U.S. Geological Survey Circular 542, 6 p.

Lau, Y.L., 1972, Prediction equations of reaeration in open-channel flow: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 98, no. SA6, p. 1063-1068.

McCutcheon, S.C., 1989, Water quality modeling, volume 1, Transport and surface exchange in rivers: Boca Raton, Florida, CRC Press, Inc., 334 p.

Minnesota Pollution Control Agency, Division of Water Quality, Section of Surface and Ground Waters, 1977, Red River of the North low flow investigations, August-September 1976: Roseville, Minnesota, 28 p.

Minnesota Pollution Control Agency, 1990, Standards for the protection of the quality and purity of the water of the State, Rules chapter 7050 (rule as adopted by Minnesota Pollution Control Agency on July 24, 1990, and amended in August 1990): St. Paul, Minnesota, 133 p.

Murphy, P.J., and Hicks, D.B., 1986, *In-situ* method for measuring sediment oxygen demand, *in* Hatcher, K.J., ed., Sediment oxygen demand--Processes, modeling, and measurement: 56th Annual Conference of the Water Pollution Control Federal, Athens, Georgia, University of Georgia, October 2-7, 1983, p. 307-322.

Negulescu, M., and Rojanski, V., 1969, Recent research to determine reaeration coefficient: Water Research, v. 3, no. 3, p. 189-202.

Nordin, C.F., Jr., and Sabol, G.V., 1974, Empirical data on longitudinal dispersion in rivers: U.S. Geological Survey Water-Resources Investigations 74-20, 332 p.

North Dakota State Department of Health and Consolidated Laboratories, 1991, Standards of water quality for State of North Dakota, Rule 33-16-02: Bismarck, North Dakota, 29 p.

O'Connor, D.J., and Dobbins, W.E., 1958, Mechanism of reaeration in natural streams: American Society of Civil Engineers Transactions, v. 123, p. 641-684.

Owens, M., Edwards, R.W., and Gibbs, J.W., 1964, Some reaeration studies in streams: International Journal of Air and Water Pollution, v. 8, no. 819, p. 469-486.

Padden, T.J., and Gloyna, E.F., 1971, Simulation of stream processes in a model river: Austin, Texas, University of Texas, Report No. EHE-70-23.

Parkhurst, J.D., and Pomeroy, R.D., 1972, Oxygen absorption in streams: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 98, no. SA1, p. 101-124.

Red River Basin Committee League of Women Voters of Minnesota and North Dakota, 1959, Red River Basin of the North water resources and needs: Fergus Falls, Minnesota, 39 p.

Regan, R.S., and Schaffranek, R.W., 1985, A computer program for analyzing channel geometry: U.S. Geological Survey Water-Resources Investigations Report 85-4335, 49 p.

Shultz, D.J., Pankow, J.F., Tai, D.Y., Stephens, D.W., and Rathbun, R.E., 1976, Determination, storage, and preservation of low molecular weight hydrocarbon gases in aqueous solution: U.S. Geological Survey Journal of Research, v. 4, no. 2, p. 247-251.

Skarheim, H.P., 1973, Tables of the fraction of ammonia in the undissociated form for pH 6 to 9, temperature 0-30 degrees Celsius, total dissolved solids 0-3000 mg/L, and salinity 5-35 g/kg: Berkeley University of California, Sanitary Engineering Research Laboratory, SERL Report No. 73-5, 33 p.

Souris-Red-Rainy River Basins Commission, 1972a, Souris-Red-Rainy River Basins comprehensive study: v. 2, appendices A-C, 353 p.

Souris-Red-Rainy River Basins Commission, 1972b, Souris-Red-Rainy River Basins comprehensive study: v. 4, appendices F-H, 266 p.

Thomann, R.V., 1972, Systems analysis and water quality management: New York, New York, Environmental Research and Applications, Inc., 286 p.

Thomann, R.V., and Mueller, J.A., 1987, Principles of surface water quality modeling and control: New York, New York, Harper and Row, 644 p.

Thurston, R.V., Russo, R.C., and Emerson, K., 1979, Aqueous ammonia equilibrium-tabulation of percent of un-ionized ammonia: Duluth, Minnesota, U.S. Environmental Protection Agency, EPA-600/3-79-091, 427 p.

Tsivoglou, E.C., and Neal, L.A., 1976, Tracer method of reaeration, III. Predicting the reaeration capacity of inland streams: Journal of Water Pollution Control Federation.

Tsivoglou, E.C., and Wallace, J.R., 1972, Characterization of stream reaeration capacity: U.S. Environmental Protection Agency EPA-R3-72-012, Washington, D.C.

U.S. Army Corps of Engineers, 1970, Red River of the North water surface profiles, mile 358 to 549: St. Paul District, U.S. Army Corps of Engineers River Profile Map, 2 sheets.

U.S. Department of Health, Education, and Welfare, Public Health Service, 1965, Report on pollution of the interstate waters of the Red River of the North (Minnesota-North Dakota): Cincinnati, Ohio, 169 p.

U.S. Environmental Protection Agency, Office of Water Regulations and Standards Monitoring and Data Support Division, 1983, Technical guidance manual for performing waste load allocations, Book II, Streams and rivers, chapter 2, Nutrient/eutrophication impacts: EPA-440/4-84-021, November 1983, Final, 126 p.

U.S. Environmental Protection Agency, Assessment and Watershed Protection Division, 1991, Guidance for water-quality-based decision: The TMDL process: EPA 440/4-91-002, April 1991, 50 p.

U.S. Geological Survey, 1990, Water resources data, North Dakota, Water year 1989: U.S. Geological Survey Water-Data Report ND-89-1, 386 p.

U.S. Public Health Service, Division of Water Pollution Control, Missouri Drainage Basin Office, 1952, Missouri-Souris development area water pollution investigation, A cooperative state-Federal report on water pollution, November 1951: Water Pollution Series No. 32, 254 p.

Velz, C.J., 1984, Applied stream sanitation: New York, John Wiley and Sons, 800 p.

Wesolowski, E.A., and Nelson, R.A., 1987, Low-flow traveltime, longitudinal-dispersion, and reaeration characteristics of the Souris River from Lake Darling Dam to J. Clark Salyer National Wildlife Refuge, North Dakota: U.S. Geological Survey Water-Resources Investigations Report 87-4241, 66 p.

Whittemore, R.C., 1985, Modifications to the QUAL-2 water-quality model and user manual for QUAL-2E version 2.2: National Council of the Paper Industry for Air and Stream Improvement, Technical Bulletin no. 457, one volume.

Yotsukura, N., Stedfast, D.A., Draper, R.E., and Brutsaert, W.H., 1983, An assessment of steady-state propane-gas tracer method for reaeration coefficients--Cowaselon Creek, New York: U.S. Geological Survey Water-Resources Investigations Report 83-4183, 88 p.

GLOSSARY OF TERMS

A. Algal biomass concentration, in milligrams per liter.

$AFACT$. Light-averaging factor in QUAL2E model used to provide similarity between calculations using a single average value of solar radiation and calculations using the hourly average values of the algal growth limitation factor for light.

BOD. Biochemical oxygen demand, in milligrams per liter.

$CBOD5$. 5-day carbonaceous biochemical oxygen demand, in milligrams per liter.

$CBODu$. Ultimate carbonaceous biochemical oxygen demand, in milligrams per liter. ($CBODu$ is used when referring to ultimate carbonaceous biochemical oxygen demand in text. L is used when referring to ultimate carbonaceous biochemical oxygen demand in equations.)

$Chl\underline{a}$. Chlorophyll-a concentration, in micrograms per liter.

$\overline{C}_{p1}$. Mean propane concentration at upstream sampling cross section, in micrograms per liter.

$\overline{C}_{p2}$. Mean propane concentration at downstream sampling cross section, in micrograms per liter.

$\frac{d}{dt}$. Total derivative with respect to time.

D. Mean depth of subreach, in feet.

e. Base of natural logarithms, approximately 2.71828.

exp. Exponential function.

f. Fraction of daylight hours.

F_1. Fraction of algal nitrogen uptake from ammonia pool.

FL. Algal growth limitation factor for light.

FL_1. Algal growth limitation factor for light based on daylight average light intensity.

FL_A. Algal growth attenuation factor for light, adjusted for daylight hours and averaging method.

FL_Z. Algal growth limitation factor for light intensity at a given depth below surface.

$FL_{\overline{Z}}$. Algal growth attenuation factor for light, depth averaged.

FN. Algal growth limitation factor for nitrogen.

FP. Algal growth limitation factor for phosphorus.

g. Acceleration because of gravity, in (feet per second) per (second).

h. Number of daylight hours per day, in hours.

H. Hydraulic depth, in feet.

HL. Headwater-source ultimate carbonaceous biochemical oxygen demand, in milligrams per liter.

HN_1. Headwater-source ammonia as nitrogen, in milligrams per liter.

HQ. Headwater-source streamflow, in cubic feet per second.

I. Surface light intensity, in (British thermal units per square foot) per (hour).

$\bar{I}_{alg}$. Daylight average light intensity, in (British thermal units per square foot) per (hour).

I_{tot}. Total daily solar radiation, in British thermal units per square foot.

I_Z. Light intensity at given depth (Z), in (British thermal units per square foot) per (hour).

K. Propane desorption coefficient, base e, in per day.

K_1. Ultimate carbonaceous biochemical oxygen demand decay rate, in per day.

K_2. Reaeration-rate coefficient, in per day.

K_3. Rate of loss of ultimate carbonaceous biochemical oxygen demand caused by settling, in per day.

K_4. Sediment oxygen demand rate, in (grams oxygen per square foot) per (day). (K_4 is used when referring to sediment oxygen demand rate in equations. SOD is used when referring to sediment oxygen demand rate in text.)

K_L. Michaelis-Menton light half-saturation coefficient, in (British thermal units per square foot) per (minute).

K_n. Michaelis-Menton nitrogen half-saturation coefficient, in milligrams nitrogen per liter.

K_p. Michaelis-Menton phosphorus half-saturation coefficient, in milligrams phosphorus per liter.

K_x. Longitudinal-dispersion coefficient, in square feet per second.

L. Ultimate carbonaceous biochemical oxygen demand, in milligrams per liter. (L is used when referring to ultimate carbonaceous biochemical oxygen demand in equations. $CBODu$ is used when referring to ultimate carbonaceous biochemical oxygen demand in text.)

ln. Natural logarithm, base e.

m. Mixing interval, in minutes ($2.279 + 0.721D$ when $D < 2.26$ feet and $13.94 ln(D) - 7.45$ when $D \geq 2.26$ feet).

M. Theoretical mixing time to obtain approximate uniform dye concentration in sampling cross section, in hours.

Min. Minimum.

n. Manning's roughness coefficient.

N_1. Ammonia concentration as nitrogen, in milligrams per liter.

N_2. Nitrite concentration as nitrogen, in milligrams per liter.

N_3. Nitrate concentration as nitrogen, in milligrams per liter.

N_4. Organic nitrogen concentration as nitrogen, in milligrams per liter.

$N_{4(1)}$. Upstream organic nitrogen concentration, in milligrams per liter.

$N_{4(2)}$. Downstream organic nitrogen concentration, in milligrams per liter.

N_e. Effective concentration of available inorganic nitrogen, in milligrams per liter.

O. Dissolved-oxygen concentration, in milligrams per liter.

$O*$. Saturation concentration of dissolved oxygen, in milligrams per liter.

P. Inorganic phosphorus concentration as phosphorus, in milligrams per liter.

P_1. Organic phosphorus concentration as phosphorus, in milligrams per liter.

PL. Point-source ultimate carbonaceous biochemical oxygen demand, in milligrams per liter.

PN_1. Point-source ammonia as nitrogen, in milligrams per liter.

PQ. Point-source streamflow, in cubic feet per second.

$\overline{Q}_1$. Mean streamflow at upstream sampling cross section, in cubic feet per second.

$\overline{Q}_2$. Mean streamflow at downstream sampling cross section, in cubic feet per second.

$QUAL2E$. Enhanced Stream Water Quality Model.

$RRatFGO\ QW$. Red River at Fargo Water-Quality Model.

S. Channel slope, in foot per foot.

SOD. Sediment oxygen demand rate, in (grams oxygen per square foot) per (day). (SOD is used when referring to sediment oxygen demand rate in text. K_4 is used when referring to sediment oxygen demand rate in equations.)

T. Temperature, in degrees Fahrenheit.

t_1. Upstream elapsed traveltime, in hours.

t_2. Downstream elapsed traveltime, in hours.

$\bar{t}_1$. Mean traveltime of dye-cloud centroid past upstream sampling cross section, in hours.

$\bar{t}_2$. Mean traveltime of dye-cloud centroid past downstream sampling cross section, in hours.

U. Streamflow transport velocity, in feet per second.

$\overline{U}$. Mean streamflow transport velocity, in feet per second.

$U*$. Shear velocity, in feet per second.

W. Distance from point of maximum surface velocity to farthest bank (about one-half the width of the river), in feet.

WS. Windspeed, in feet per second.

X. Distance, in feet or in miles (depending on use in equation).

X_{68}. Value of coefficient at standard temperature of 68 degrees Fahrenheit.

X_T. Value of coefficient at local temperature.

Z. Depth below surface, in feet.

Z_1. Depth below surface at which 1 percent of surface radiation still remains, in feet.

Z_s. Secchi-disc depth below surface, in feet.

α_0. Ratio of chlorophyll a to algal biomass, in (micrograms chlorophyll a per liter) per (milligrams algal biomass per liter).

α_1. Fraction of algal biomass that is nitrogen, in (milligrams nitrogen per liter) per (milligrams algal biomass per liter).

α_2. Fraction of algal biomass that is phosphorus, in (milligrams phosphorus per liter) per (milligrams algal biomass per liter).

α_3. Rate of dissolved-oxygen production per unit of algal growth, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter).

α_4. Rate of dissolved-oxygen uptake per unit of algae respired, in (milligrams dissolved oxygen per liter) per (milligrams algal biomass per liter).

α_5. Rate of dissolved-oxygen uptake per unit of ammonia oxidized to nitrite, in (milligrams dissolved oxygen per liter) per (milligrams ammonia per liter).

α_6. Rate of dissolved-oxygen uptake per unit of nitrite oxidized to nitrate, in (milligrams dissolved oxygen per liter) per (milligrams nitrite per liter).

β_1. Instream reaction rate for biological decay of ammonia to nitrite, in per day.

β_2. Instream reaction rate for biological decay of nitrite to nitrate, in per day.

β_3. Instream reaction rate for hydrolysis of organic nitrogen to ammonia, in per day.

β_4. Instream reaction rate for biological decay of organic phosphorus to phosphorus, in per day.

Θ. Empirical constant for each temperature-dependent reaction coefficient.

λ. Light-extinction coefficient, in per foot.

λ_0. Nonalgal light-extinction coefficient, in per foot.

λ_1. Linear algal selfshading coefficient, in (per foot) per (micrograms chlorophyll a per liter).

λ_2. Nonlinear algal selfshading coefficient, in (per foot) per (micrograms chlorophyll a per liter)$^{2/3}$.

μ. Local specific algal growth rate, in per day.

μ_{max}. Maximum specific algal growth rate, in per day.

ρ. Local algal respiration rate, in per day.

σ_1. Local algal settling rate, in feet per day.

σ_2. Benthos source rate for phosphorus, in (milligrams phosphorus per square foot) per (day).

σ_3. Benthos source rate for ammonia, in (milligrams ammonia per square foot) per (day).

σ_4. Organic nitrogen settling rate, in per day.

σ_5. Organic phosphorus settling rate, in per day.

$\sigma^2 (\overline{C}_{p1})$. Variance of propane concentration at upstream sampling cross section, in (milligrams per liter) squared.

$\sigma^2 (\overline{C}_{p2})$. Variance of propane concentration at downstream sampling cross section, in (milligrams per liter) squared.

$\sigma (K)$. Standard deviation of propane desorption coefficient, base e, in per day.

$\sigma^2 (\overline{Q}_1)$. Variance of mean streamflow at upstream sampling cross section, in (cubic feet per second) squared.

$\sigma^2 (\overline{Q}_2)$. Variance of mean streamflow at downstream sampling cross section, in (cubic feet per second) squared.

$\sigma^2 t_1$. Variance of time-concentration curve data at upstream sampling cross section, in hours squared.

$\sigma^2 t_2$. Variance of time-concentration curve data at downstream sampling cross section, in hours squared.

Blank Page

SUPPLEMENT 1
PLOTS OF DYE CONCENTRATION VERSUS TRAVELTIME FOR THE RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA

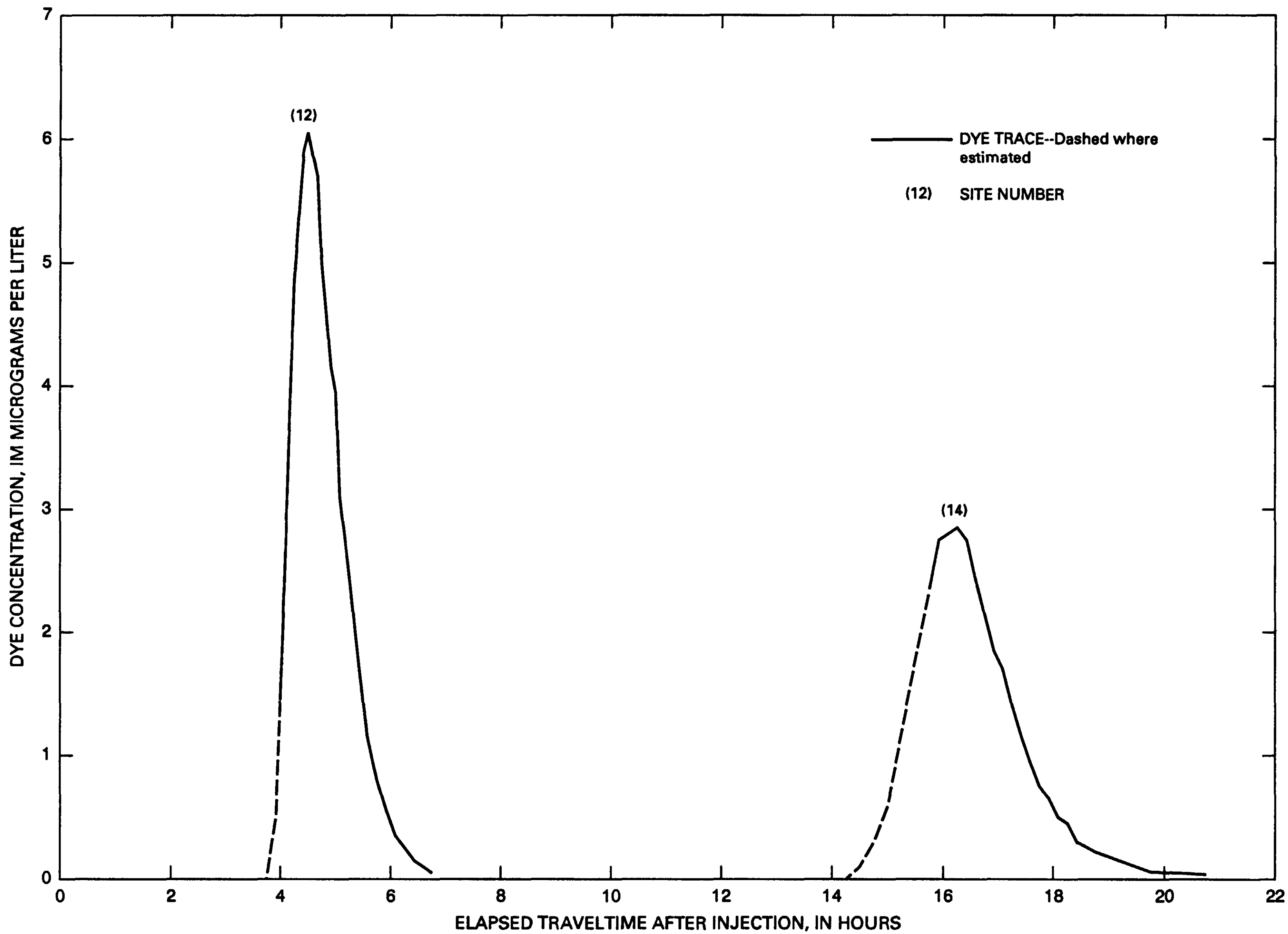


Figure 30. Dye concentration versus traveltime for sites 12 and 14 on the Red River of the North at Fargo, North Dakota. (Dye injected 0.6 mile downstream from site 10, August 7, 1989.)

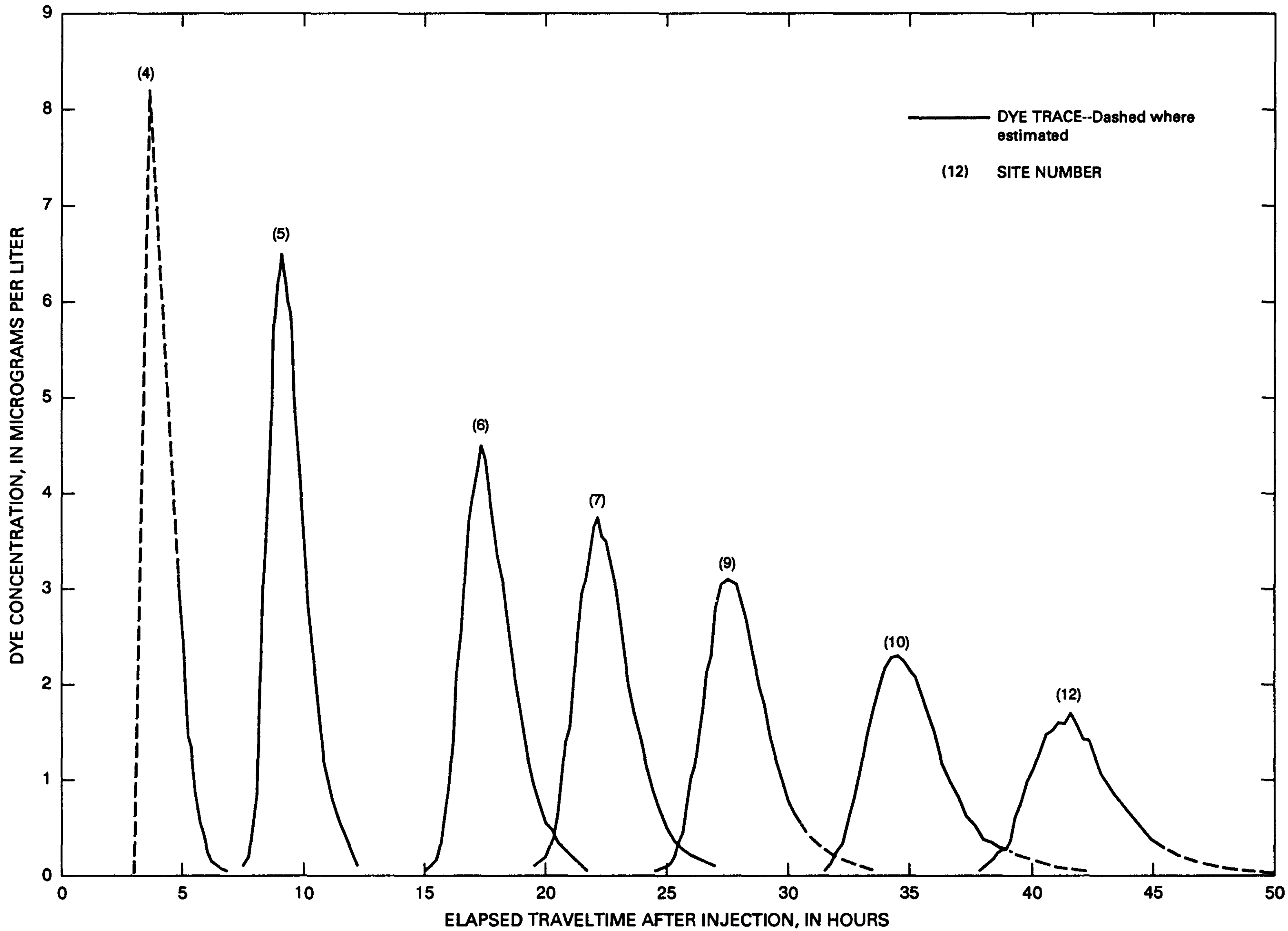


Figure 31. Dye concentration versus traveltime for sites 4 to 7, 9, 10, and 12 on the Red River of the North at Fargo, North Dakota. (Dye injected at site 1, August 8, 1989.)

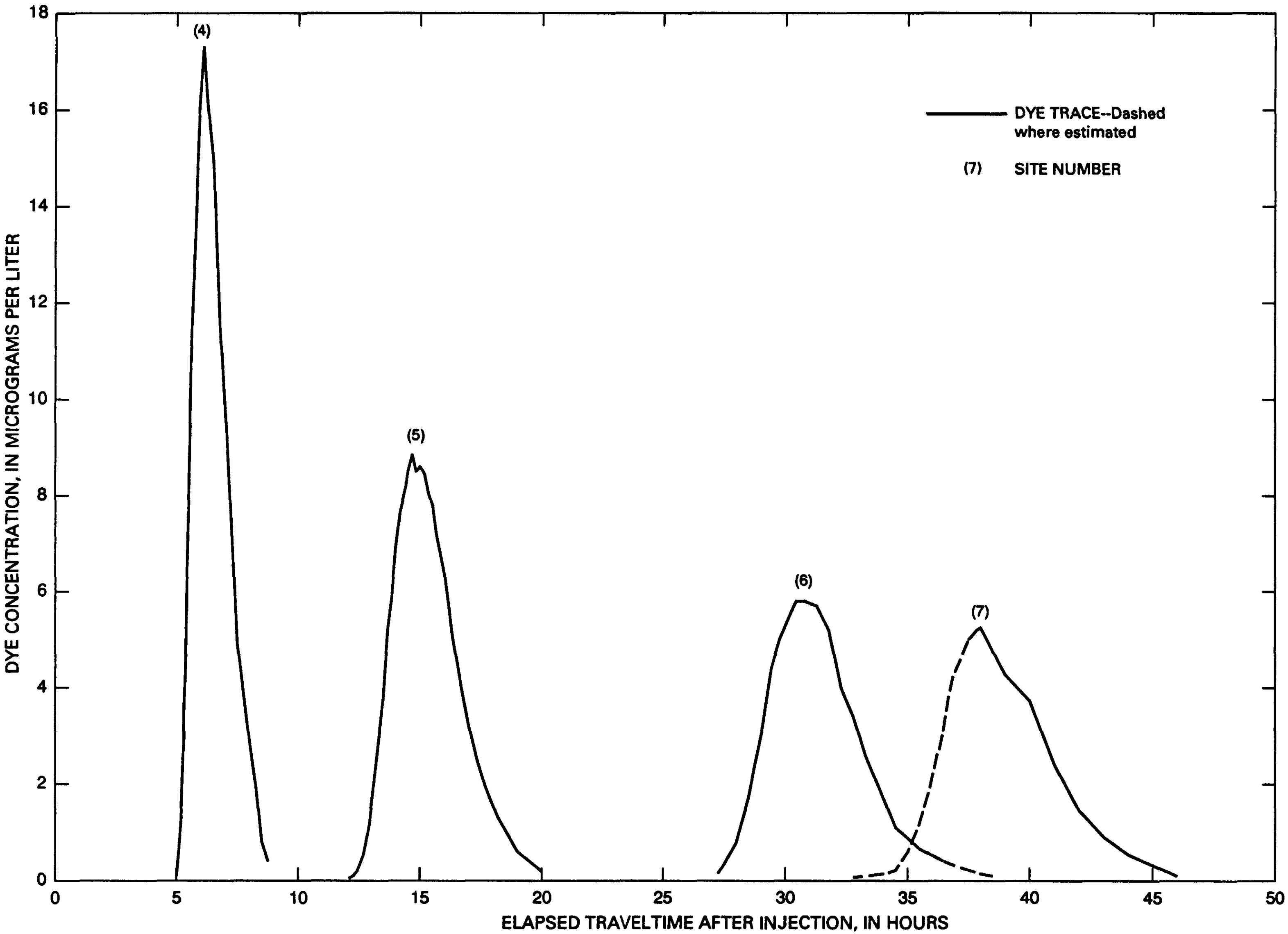


Figure 32. Dye concentration versus traveltime for sites 4 to 7 on the Red River of the North at Fargo, North Dakota. (Dye injected at site 1, August 17, 1989.)

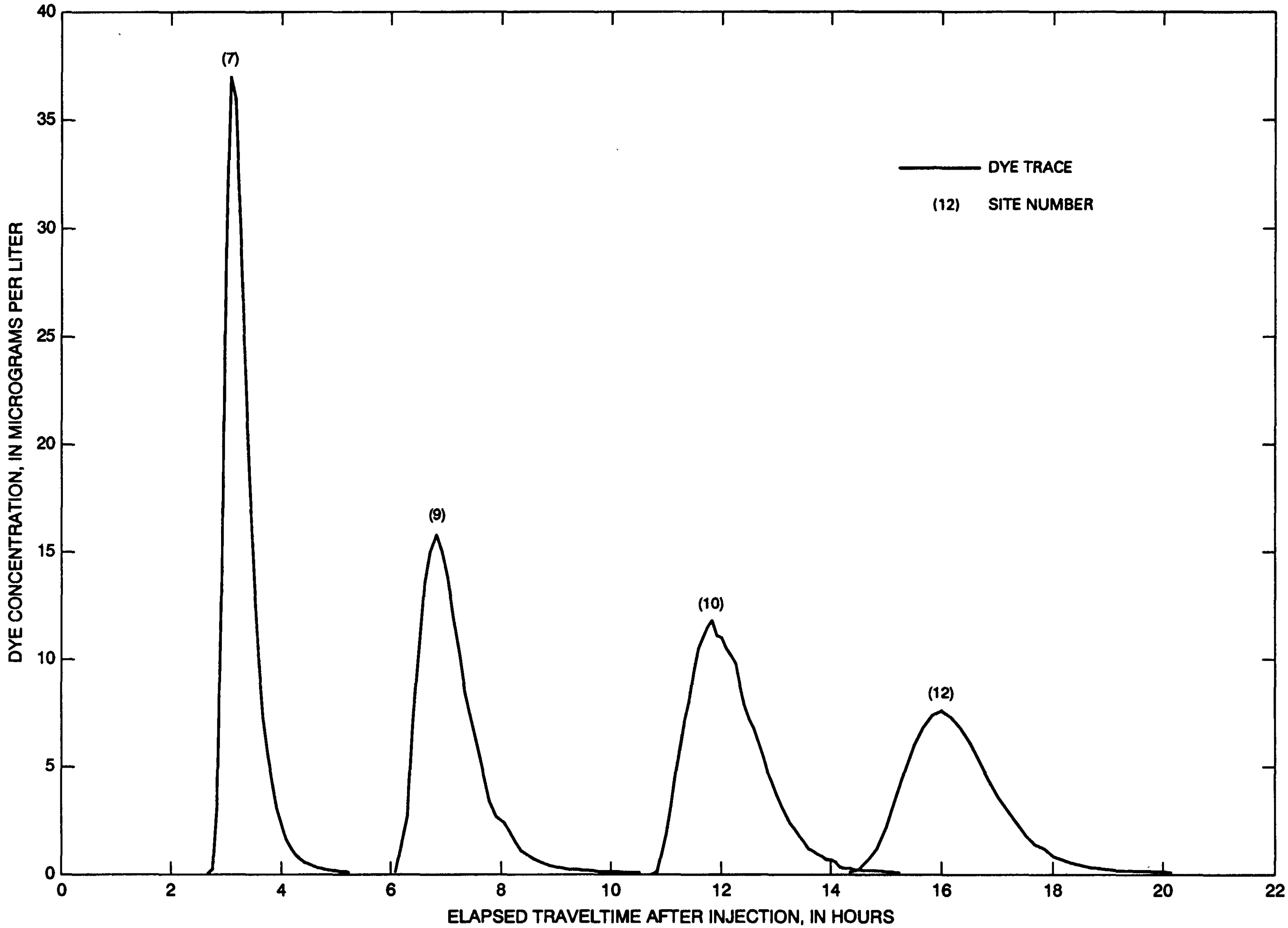


Figure 33. Dye concentration versus traveltime for sites 7, 9, 10, and 12 on the Red River of the North at Fargo, North Dakota. (Dye injected at site 6, April 23,1990.)

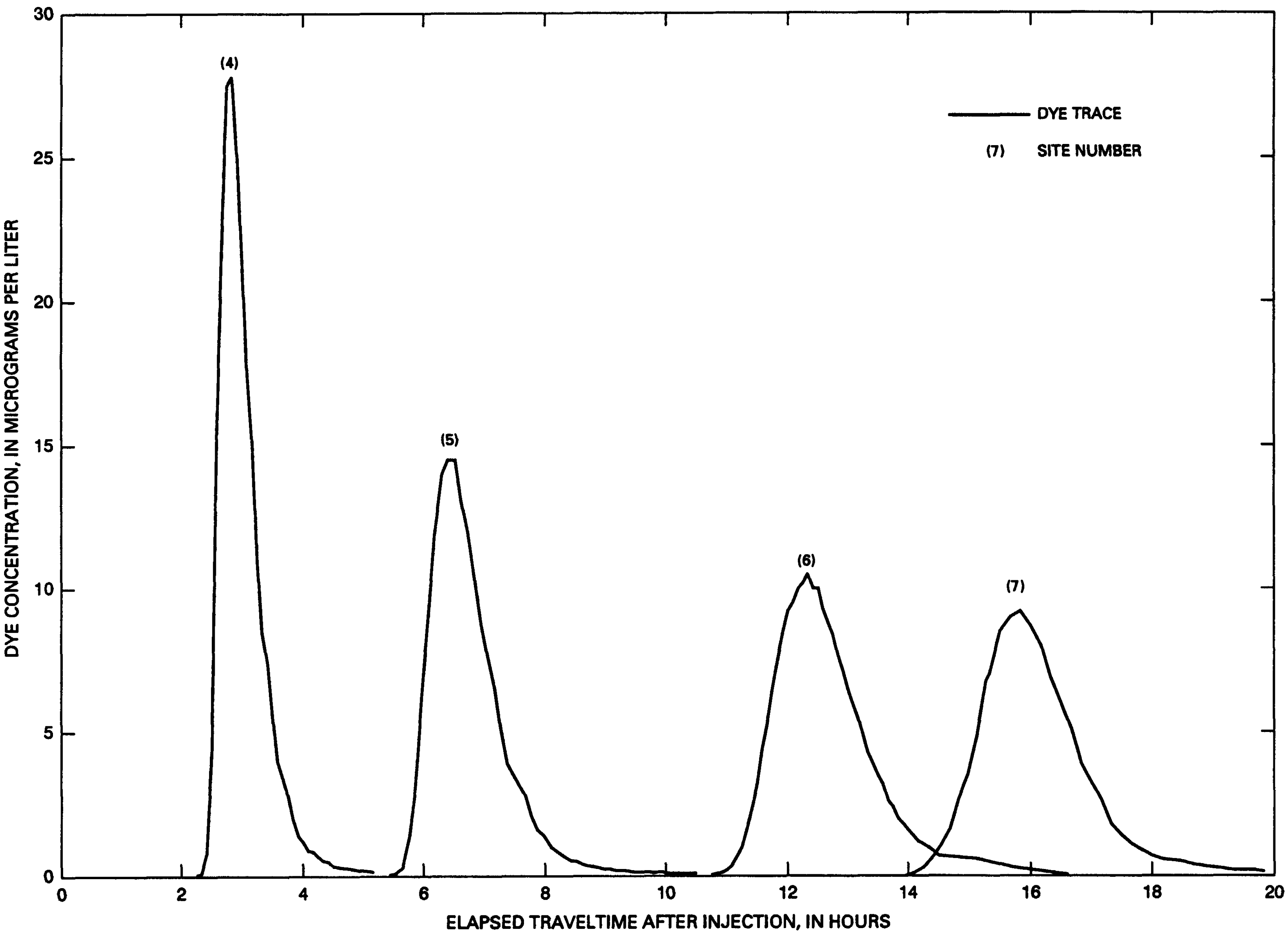


Figure 34. Dye concentration versus traveltime for sites 4 to 7 on the Red River of the North at Fargo, North Dakota. (Dye injected at site 1, April 25, 1990.)

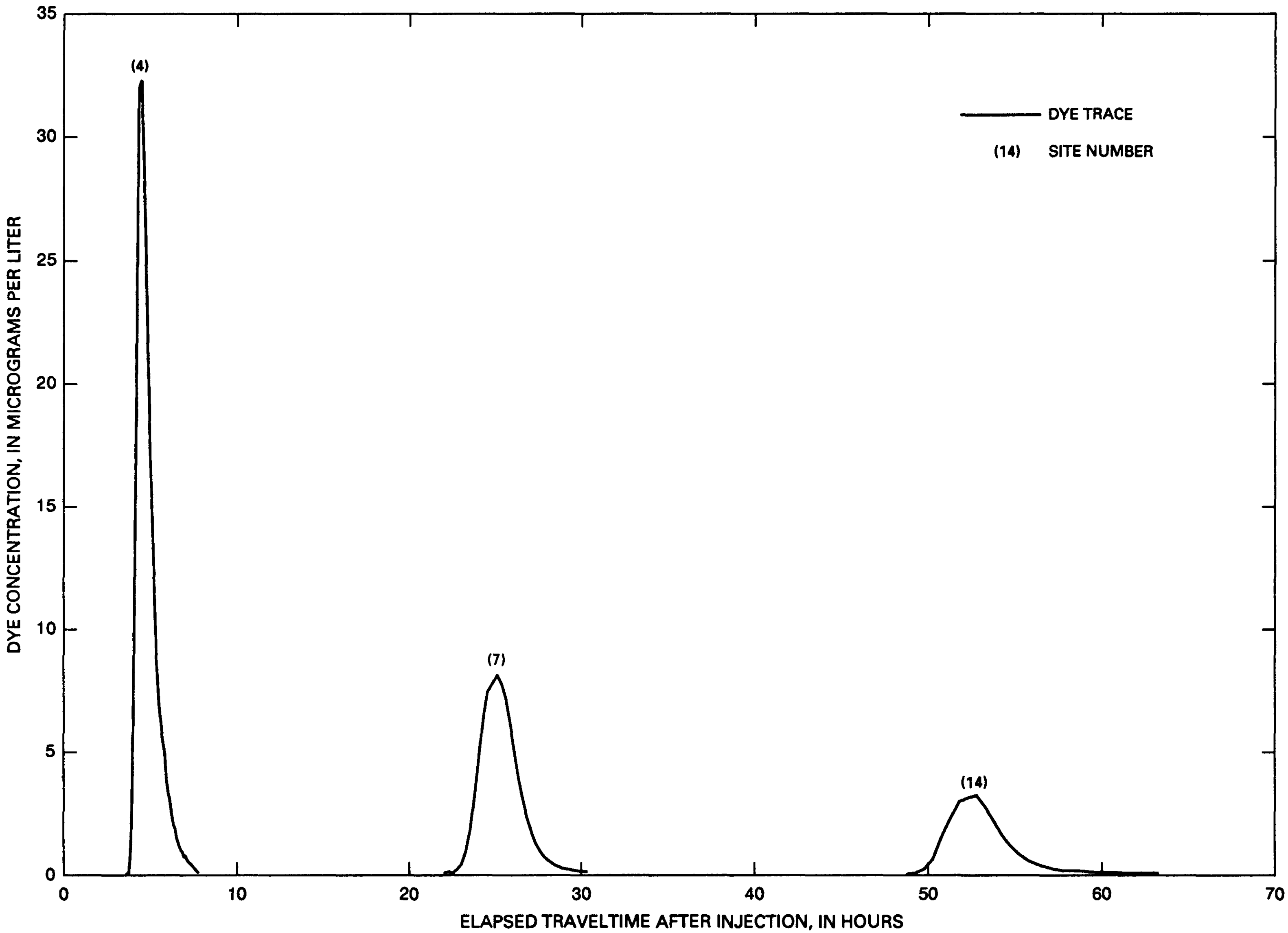


Figure 35. Dye concentration versus traveltime for sites 4, 7, and 14 on the Red River of the North at Fargo, North Dakota. (Dye injected at site 1, October 16, 1990.)

SUPPLEMENT 2
PLOTS OF VARIANCE OF TIME-CONCENTRATION CURVE DATA VERSUS TRAVELTIME OF DYE-CLOUD CENTROID FOR THE RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA

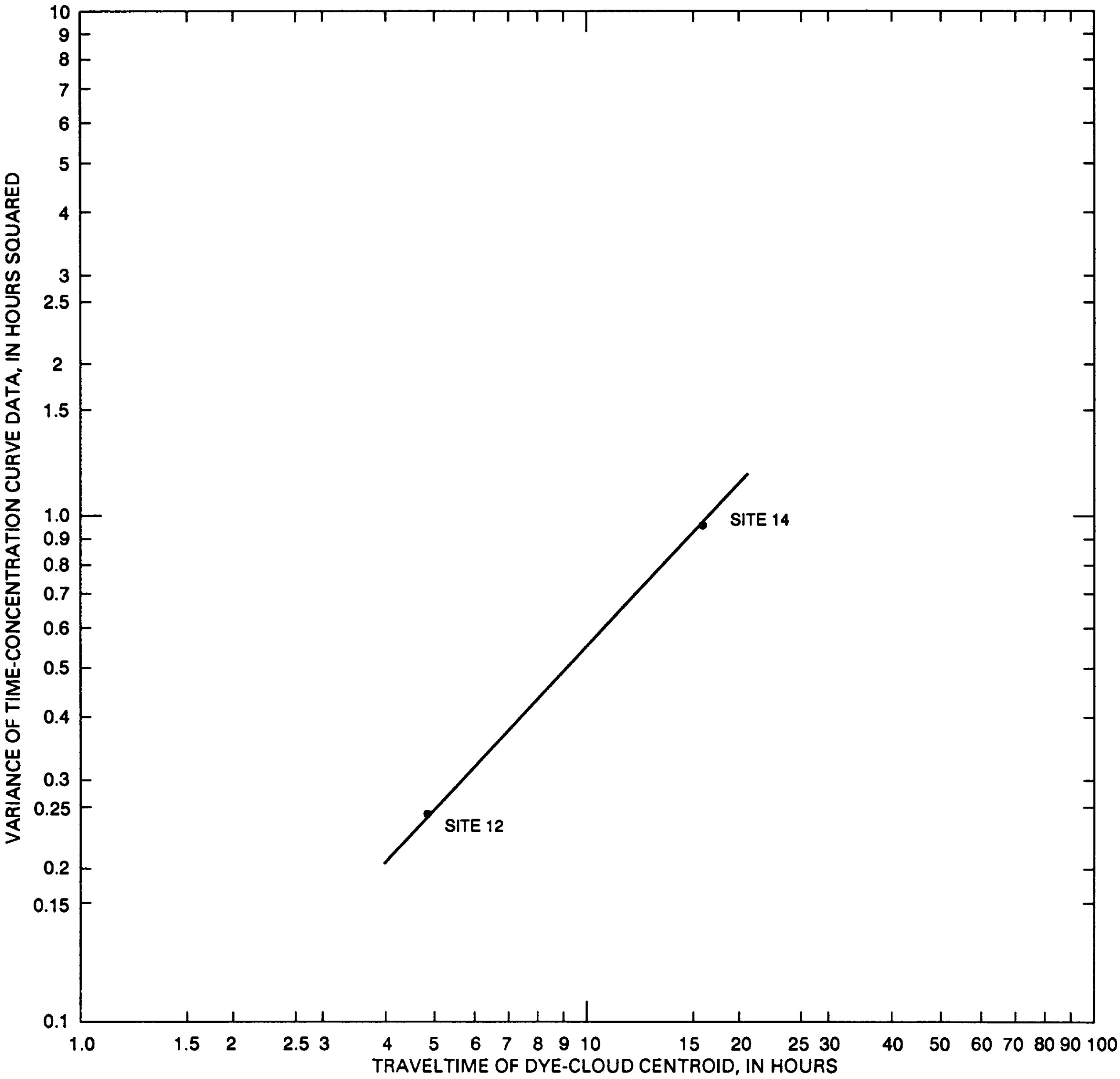


Figure 36. Variance of time-concentration curve data versus traveltime of dye-cloud centroid for sites 12 and 14 on the Red River of the North at Fargo, North Dakota, August 7, 1989.

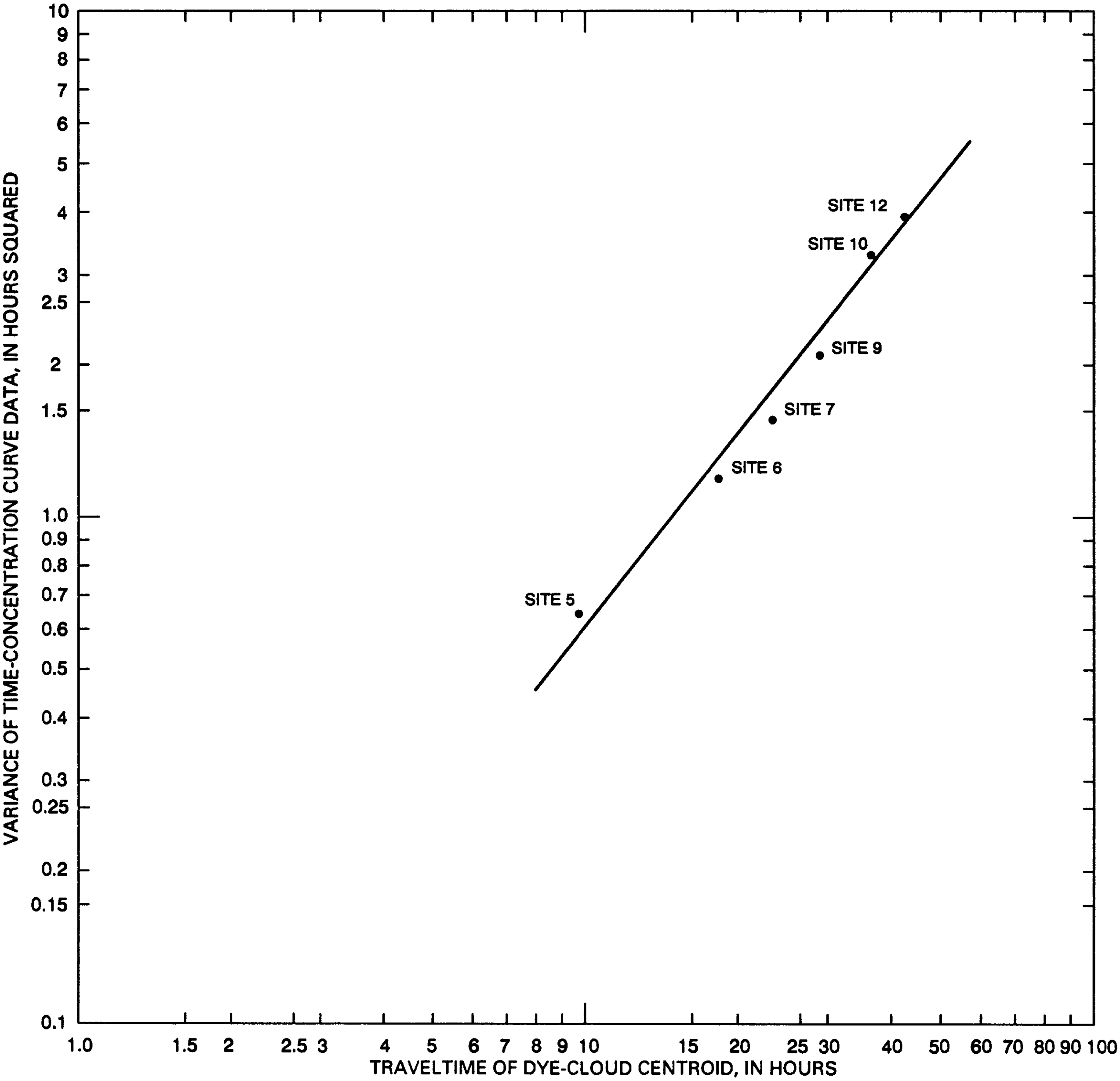


Figure 37. Variance of time-concentration curve data versus traveltime of dye-cloud centroid for sites 5 to 7, 9, 10, and 12 on the Red River of the North at Fargo, North Dakota, August 8, 1989.

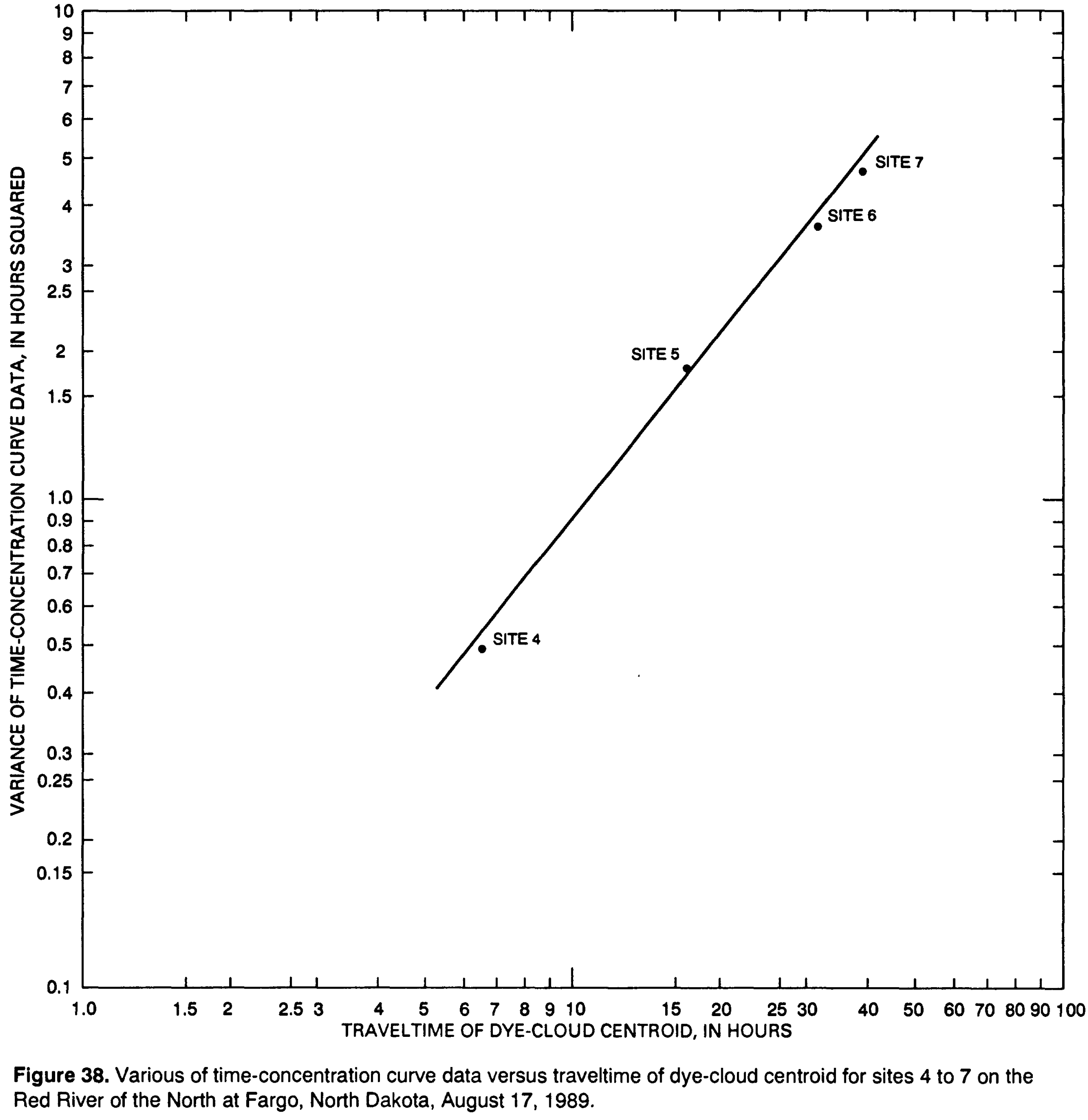


Figure 38. Various of time-concentration curve data versus traveltime of dye-cloud centroid for sites 4 to 7 on the Red River of the North at Fargo, North Dakota, August 17, 1989.

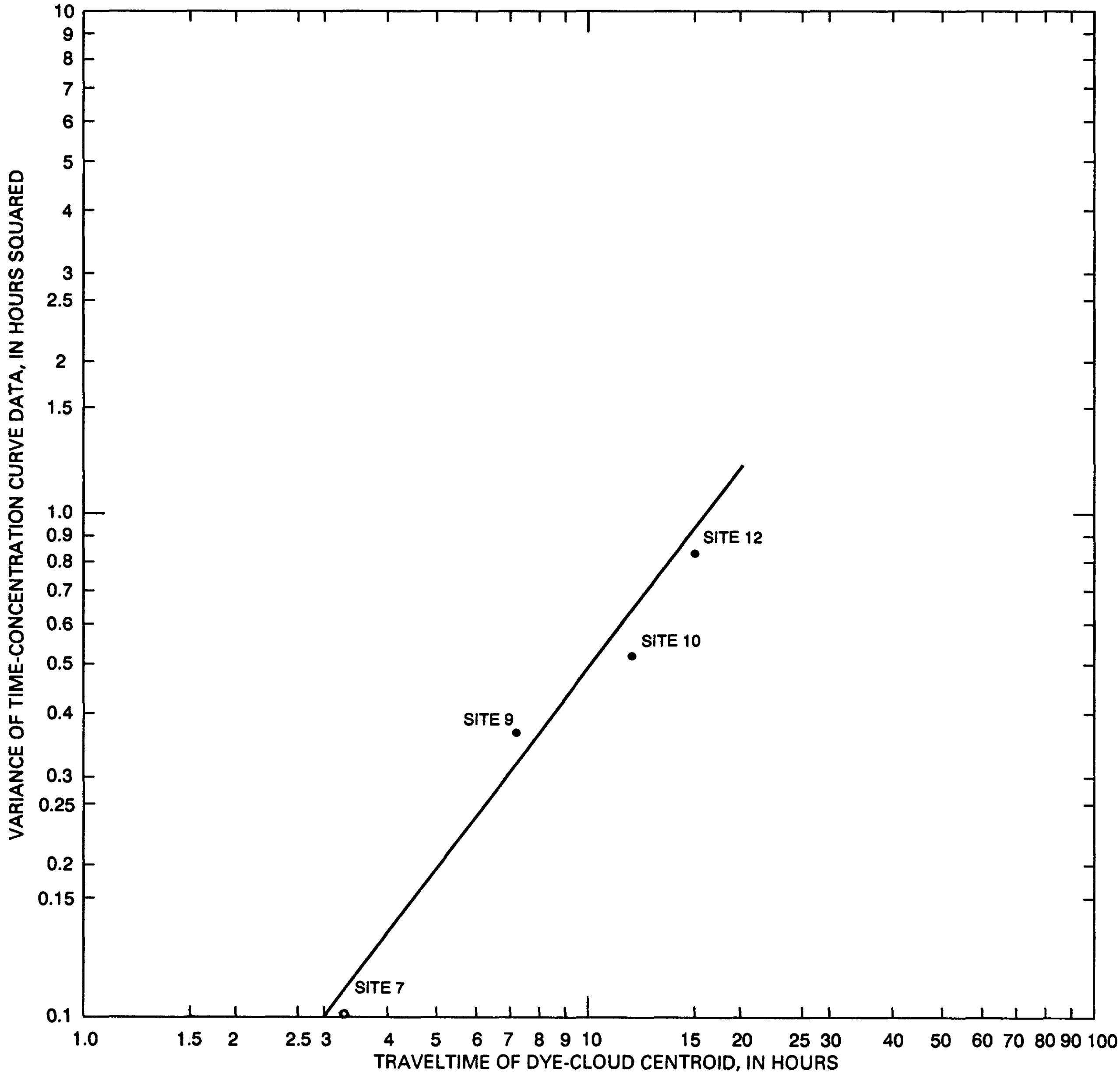


FIGURE 39. Variance of time-concentration curve data versus traveltime of dye-cloud centroid for sites 7, 9, 10, and 12 on the Red River of the North at Fargo, North Dakota, April 23, 1990.

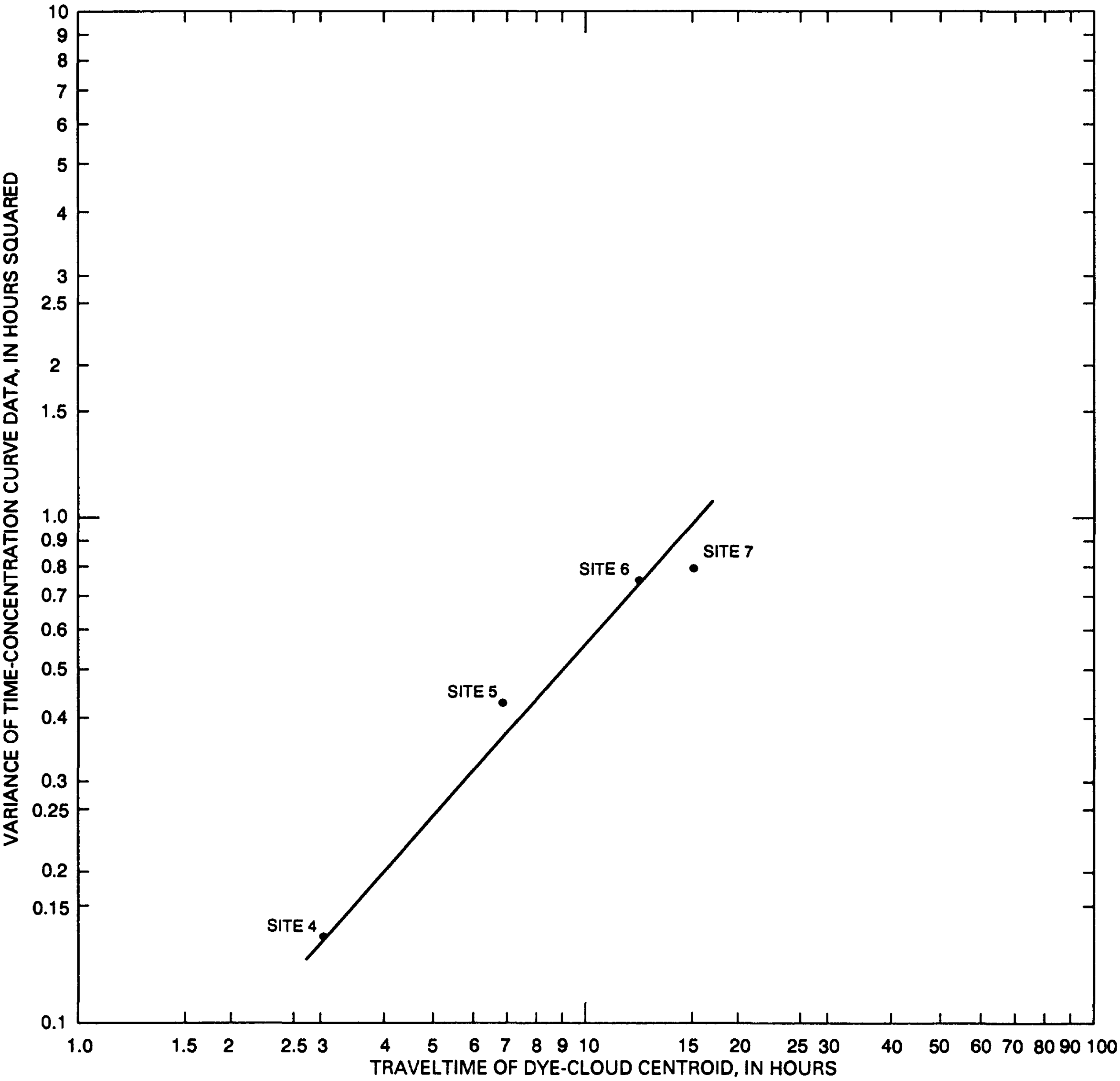


Figure 40. Variance of time-concentration curve data versus traveltime of dye-cloud centroid for sites 4 to 7 on the Red River of the North at Fargo, North Dakota, April 25, 1990.

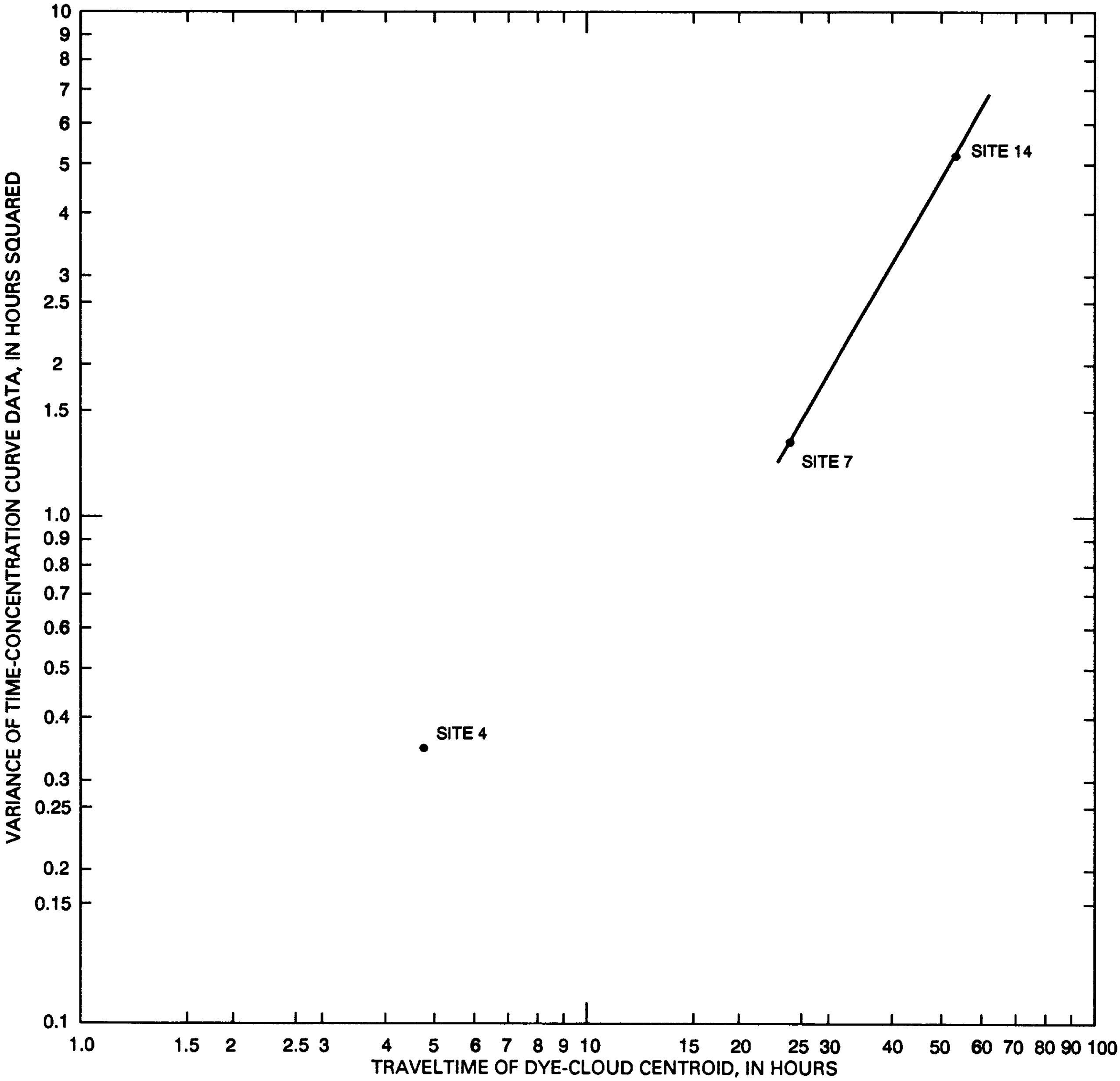


Figure 41. Variance of time-concentration curve data versus traveltime of dye-cloud centroid for sites 4, 7, and 14 on the Red River of the North at Fargo, North Dakota, October 16, 1990.

SUPPLEMENT 3
WATER-QUALITY DATA COLLECTED DURING SYNOPTIC SAMPLINGS ON AUGUST 29-30, 1989, AND AUGUST 14-15, 1990, AND SEDIMENT OXYGEN DEMAND DATA COLLECTED ON AUGUST 28, 1990, AUGUST 30-31, 1990, AND SEPTEMBER 5-7, 1990, RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota

[ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; μg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (μS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 1				
08-29-89	1625	140	645	8.4	24.0	22.0	789	--	10.5
08-29-89	2025	--	648	8.4	17.0	22.0	789	--	10.1
08-30-89	0120	--	635	8.2	14.5	21.5	789	--	8.8
08-30-89	0550	--	640	8.1	16.0	21.0	789	--	9.3
08-30-89	0830	--	640	8.4	15.0	21.0	789	--	9.6
08-30-89	1315	--	630	8.8	22.0	21.0	787	--	8.9
08-30-89	1620	--	625	8.7	23.0	21.0	785	--	8.7
08-14-90	1210	200	497	7.9	23.5	22.0	765	--	8.0
08-14-90	1600	--	496	7.3	27.5	23.0	765	28	8.2
08-14-90	1950	--	491	7.8	24.5	23.0	766	--	8.2
08-15-90	0015	--	483	8.3	16.5	22.5	766	--	7.9
08-15-90	0400	--	486	8.3	14.0	22.0	766	25	7.6
08-15-90	0755	--	488	8.4	15.0	21.0	766	--	6.9
09-05-90	1200	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1515	--	--	--	--	--	--	--	--
					Site 2				
08-29-89	1635	6.0	1,200	6.8	24.0	20.0	789	--	6.9
08-29-89	2035	--	--	6.8	17.0	20.0	789	--	6.8
08-30-89	0130	--	1,240	6.7	14.5	19.5	789	--	7.3
08-30-89	0600	--	1,250	7.4	16.0	19.5	789	--	6.6
08-30-89	0840	--	1,260	6.8	15.0	19.5	789	--	6.5

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota–Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square ıoot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 1, Continued					
08-29-89	1625	9.7	--	--	<0.10	0.03	1.0	0.18	25	4.8
08-29-89	2025	--	--	--	<.10	.02	.90	.18	--	--
08-30-89	0120	5.8	--	--	<.10	.03	.70	.16	--	--
08-30-89	0550	--	--	--	<.10	.02	.80	.13	--	--
08-30-89	0830	6.3	--	--	<.10	.04	.80	.16	7.2	.7
08-30-89	1315	--	--	--	<.10	.13	1.3	.14	--	--
08-30-89	1620	10	--	--	<.10	.05	1.1	.12	--	--
08-14-90	1210	8.4	--	0.03	<.10	.22	1.0	.09	--	--
08-14-90	1600	8.1	--	.03	<.10	.13	1.0	.06	6.6	.3
08-14-90	1950	8.2	--	.03	<.10	.09	1.1	.06	--	--
08-15-90	0015	8.2	--	.02	<.10	.08	1.0	.11	--	--
08-15-90	0400	8.2	--	.03	<.10	.10	.90	.10	2.7	<.3
08-15-90	0755	8.5	--	.03	<.10	.11	1.1	.08	--	--
09-05-90	1200	--	0.07	--	--	--	--	--	--	--
	to	--	.12	--	--	--	--	--	--	--
	1515	--	.08	--	--	--	--	--	--	--
					Site 2, Continued					
08-29-89	1635	23	--	--	0.50	16	21.0	4.4	1.5	<0.2
08-29-89	2035	--	--	--	.50	15	20.0	4.4	--	--
08-30-89	0130	24	--	--	.60	16	21.0	4.7	--	--
08-30-89	0600	--	--	--	.60	16	21.0	4.8	--	--
08-30-89	0840	21	--	--	.60	16	22.0	4.9	.9	<.2

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; μg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (μS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 2, Continued				
08-30-89	1325	--	1,240	7.2	22.0	20.0	787	--	6.6
08-30-89	1630	--	1,200	7.1	23.0	19.0	785	--	6.8
08-14-90	1220	5.0	1,200	6.5	23.5	19.0	765	--	6.1
08-14-90	1605	--	1,170	6.5	27.5	19.5	765	2.7	6.3
08-14-90	1958	--	1,200	6.3	24.5	20.0	766	--	6.0
08-15-90	0030	--	1,180	6.7	16.5	19.5	766	--	6.2
08-15-90	0415	--	1,180	6.5	14.0	19.0	766	5.0	6.3
08-15-90	0805	--	1,170	6.9	15.0	18.5	766	--	6.3
					Site 4				
08-29-89	1730	--	668	8.2	20.5	22.5	789	--	10.6
08-29-89	2140	--	670	8.1	15.0	21.0	789	--	7.6
08-30-89	0250	--	670	8.3	14.0	20.5	789	--	7.2
08-30-89	0650	--	670	8.3	16.0	20.5	789	--	8.4
08-30-89	0945	--	660	8.1	16.0	20.0	789	--	8.5
08-30-89	1415	--	662	8.6	22.0	21.0	787	--	9.1
08-30-89	1700	--	655	8.6	23.0	21.0	785	--	9.0
08-14-90	1245	--	500	7.8	26.0	23.0	765	--	8.0
08-14-90	1640	--	510	7.7	26.5	23.5	765	35	8.1
08-14-90	2015	--	516	7.6	21.5	22.5	766	--	7.8

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 2, Continued					
08-30-89	1325	--	--	--	0.60	16	29.0	4.7	--	--
08-30-89	1630	16	--	--	.50	16	21.0	4.5	--	--
08-14-90	1220	33	--	0.40	1.1	17	18.0	2.2	--	--
08-14-90	1605	38	--	.39	1.0	17	18.0	2.1	1.5	<0.3
08-14-90	1958	37	--	.42	1.0	17	19.0	2.2	--	--
08-15-90	0030	31	--	.39	1.0	18	22.0	2.4	--	--
08-15-90	0415	38	--	.41	1.0	19	22.0	2.6	.9	<.3
08-15-90	0805	42	--	.43	1.1	18	21.0	2.9	--	--
					Site 4, Continued					
08-29-89	1730	11	--	--	0.10	0.29	1.6	0.26	20	3.2
08-29-89	2140	--	--	--	.20	.48	1.5	.30	--	--
08-30-89	0250	9.8	--	--	.20	.44	1.7	.28	--	--
08-30-89	0650	--	--	--	.10	.33	1.6	.25	--	--
08-30-89	0945	8.0	--	--	.10	.33	1.3	.24	14	1.8
08-30-89	1415	--	--	--	.10	.30	1.5	.29	--	--
08-30-89	1700	9.7	--	--	.20	.34	1.5	.28	--	--
08-14-90	1245	9.4	--	0.03	<.10	.28	.90	.18	--	--
08-14-90	1640	9.9	--	.03	<.10	.25	1.2	.12	5.8	.3
08-14-90	2015	9.7	--	.03	.10	.38	1.2	.16	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 4				
08-15-90	0105	--	492	7.9	16.0	21.5	766	--	7.6
08-15-90	0455	--	486	7.9	12.0	21.0	766	29	7.6
08-15-90	0815	--	482	8.2	14.5	21.0	766	--	7.5
09-06-90	0830	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1000	--	--	--	--	--	--	--	--
					Site 5				
08-29-89	1800	--	655	8.3	23.0	22.5	789	--	10.3
08-29-89	2235	--	665	8.1	16.0	21.5	790	--	8.8
08-30-89	0335	--	675	8.3	15.5	20.0	789	--	7.1
08-30-89	0715	--	680	8.1	16.0	19.5	789	--	7.6
08-30-89	1015	--	670	8.1	16.0	19.5	789	--	8.4
08-30-89	1430	--	647	8.6	22.0	21.0	787	--	8.6
08-30-89	1730	--	656	8.6	23.0	20.0	785	--	8.8
08-14-90	1305	--	493	7.8	27.5	23.0	765	--	7.6
08-14-90	1707	--	495	7.6	25.5	24.5	765	35	8.5
08-14-90	2035	--	512	7.7	20.5	23.5	766	--	7.9
08-15-90	0130	--	490	7.8	14.0	21.5	766	--	7.3
08-15-90	0530	--	484	8.0	13.0	21.0	766	38	7.1
08-15-90	0835	--	486	8.2	15.5	21.0	766	--	7.2
08-30-90	1345	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1600	--	--	--	--	--	--	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 4, Continued					
08-15-90	0105	9.5	--	0.03	<0.10	0.35	0.90	0.18	--	--
08-15-90	0455	8.8	--	.03	.10	.40	1.2	.19	5.2	<0.3
08-15-90	0815	9.2	--	.03	<.10	.33	1.2	.19	--	--
09-06-90	0830	--	0.12	--	--	--	--	--	--	--
	to	--	.08	--	--	--	--	--	--	--
	1000	--	.07	--	--	--	--	--	--	--
					Site 5, Continued					
08-29-89	1800	9.3	--	--	0.20	0.16	1.2	0.24	15	2.2
08-29-89	2235	--	--	--	.20	.21	1.1	.22	--	--
08-30-89	0335	7.1	--	--	.20	.41	1.6	.31	--	--
08-30-89	0715	--	--	--	.30	.49	1.7	.28	--	--
08-30-89	1015	9.3	--	--	.20	.33	1.8	.27	19	3.2
08-30-89	1430	--	--	--	.20	.30	1.7	.31	--	--
08-30-89	1730	8.3	--	--	.20	.23	1.2	.22	--	--
08-14-90	1305	9.9	--	0.04	.10	.27	1.4	.15	--	--
08-14-90	1707	9.5	--	.03	.10	.15	1.3	.12	6.6	.4
08-14-90	2035	9.7	--	.03	.10	.19	1.2	.14	--	--
08-15-90	0130	9.4	--	.04	.20	.32	1.4	.11	--	--
08-15-90	0530	9.4	--	.04	.20	.32	1.4	.15	4.3	<.3
08-15-90	0835	9.4	--	.04	.10	.35	1.1	.17	--	--
08-30-90	1345	--	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--	--
	1600	--	0.10	--	--	--	--	--	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 6				
08-29-89	1910	--	658	8.2	22.0	22.0	787	--	8.9
08-29-89	2230	--	661	8.3	17.0	21.5	788	--	8.7
08-30-89	0200	--	652	8.2	13.5	21.0	788	--	8.6
08-30-89	0754	--	673	8.0	14.5	20.0	787	--	8.3
08-30-89	1137	--	680	7.7	19.0	20.0	786	--	7.8
08-30-89	1420	--	678	8.0	23.0	20.0	785	--	8.3
08-30-89	1810	--	675	7.9	21.5	20.5	783	--	9.0
08-14-90	1415	--	477	7.5	26.0	23.0	764	--	7.7
08-14-90	1840	--	480	7.7	27.0	24.0	763	36	8.1
08-14-90	2150	--	484	7.7	19.0	23.5	765	--	7.6
08-15-90	0237	--	498	7.6	16.5	22.5	765	--	7.1
08-15-90	0707	--	514	7.6	13.5	20.5	766	39	6.8
08-15-90	1007	--	513	7.8	23.5	20.5	766	--	6.8
08-30-90	0915	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1230	--	--	--	--	--	--	--	--
					Site 7				
08-29-89	1830	--	618	8.1	22.5	22.0	789	--	9.0
08-29-89	2310	--	648	7.9	16.5	21.0	790	--	8.1
08-30-89	0415	--	650	8.4	13.5	20.5	789	--	--
08-30-89	0745	--	650	8.1	16.5	20.0	789	--	8.2
08-30-89	1045	--	660	8.2	16.0	20.5	788	--	8.4

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 6, Continued					
08-29-89	1910	8.4	--	--	0.30	0.25	1.2	0.28	9.5	1.4
08-29-89	2230	--	--	--	.30	.18	1.2	.21	--	--
08-30-89	0200	8.1	--	--	.30	.16	1.3	.22	--	--
08-30-89	0754	--	--	--	.30	.19	1.4	.22	11	.9
08-30-89	1137	9.2	--	--	.30	.29	1.5	.28	--	--
08-30-89	1420	--	--	--	.40	.33	1.5	.26	--	--
08-30-89	1810	9.9	--	--	.30	.24	1.5	.30	--	--
08-14-90	1415	9.2	--	0.07	.20	.28	1.2	.11	--	--
08-14-90	1840	9.7	--	.06	.20	.27	1.3	.12	9.2	.4
08-14-90	2150	9.1	--	.06	.10	.29	1.7	.14	--	--
08-15-90	0237	9.1	--	.06	.20	.21	1.3	.10	--	--
08-15-90	0707	9.3	--	.06	.20	.38	1.2	.12	7.2	.3
08-15-90	1007	8.9	--	.06	.20	.35	1.3	.12	--	--
08-30-90	0915	--	--	--	--	--	--	--	--	--
	to	--	0.07	--	--	--	--	--	--	--
	1230	--	.13	--	--	--	--	--	--	--
					Site 7, Continued					
08-29-89	1830	8.2	--	--	0.40	0.22	1.1	0.25	11	1.5
08-29-89	2310	--	--	--	.40	.22	1.5	.23	--	--
08-30-89	0415	7.3	--	--	.30	.15	1.1	.21	--	--
08-30-89	0745	--	--	--	.30	.14	1.2	.22	--	--
08-30-89	1045	9.6	--	--	.30	.12	1.2	.23	11	1.5

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 7, Continued				
08-30-89	1450	--	660	8.6	21.5	20.0	787	--	9.0
08-30-89	1750	--	668	8.6	23.0	20.0	785	--	9.0
08-14-90	1335	--	489	7.8	28.0	22.5	766	--	7.8
08-14-90	1735	--	488	7.7	26.0	23.5	765	35	8.4
08-14-90	2057	--	492	7.6	17.0	23.0	766	--	8.1
08-15-90	0200	--	477	7.9	14.0	22.5	766	--	7.3
08-15-90	0600	--	465	8.1	10.0	21.5	766	40	7.0
08-15-90	0855	--	499	8.2	21.5	21.0	767	--	6.9
08-31-90	0830	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1200	--	--	--	--	--	--	--	--
					Site T1				
08-29-89	1850	19	410	7.6	22.5	20.0	789	--	7.6
08-29-89	2320	--	410	7.6	16.5	18.5	790	--	7.8
08-30-89	0420	--	415	8.4	13.5	18.0	789	--	--
08-30-89	0755	--	400	7.4	16.5	17.5	789	--	7.4
08-30-89	1055	--	400	7.5	16.0	18.0	788	--	8.0
08-30-89	1500	--	380	8.1	21.5	17.0	787	--	7.7
08-30-89	1800	--	380	7.9	23.0	17.0	785	--	8.0

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 7, Continued					
08-30-89	1450	--	--	--	0.40	0.16	1.3	0.26	--	--
08-30-89	1750	9.5	--	--	.40	.21	1.3	.23	--	--
08-14-90	1335	9.1	--	0.04	.20	.15	1.0	.20	--	--
08-14-90	1735	9.4	--	.04	.20	.12	1.2	.12	4.5	<0.3
08-14-90	2057	9.4	--	.04	.20	.13	1.1	.18	--	--
08-15-90	0200	9.4	--	.03	.20	.11	1.1	.18	--	--
08-15-90	0600	9.5	--	.03	.20	.10	1.6	.16	6.8	<.3
08-15-90	0855	9.4	--	.05	.20	.22	1.1	.17	--	--
08-31-90	0830	--	0.17	--	--	--	--	--	--	--
	to	--	.04	--	--	--	--	--	--	--
	1200	--	.10	--	--	--	--	--	--	--
					Site T1, Continued					
08-29-89	1850	7.2	--	--	0.20	0.03	0.50	0.21	0.6	<0.2
08-29-89	2320	--	--	--	.20	.02	.50	.22	--	--
08-30-89	0420	7.0	--	--	.20	.02	.50	.22	--	--
08-30-89	0755	--	--	--	.20	.02	.50	.21	--	--
08-30-89	1055	6.4	--	--	.20	.02	.80	.22	.8	<.2
08-30-89	1500	--	--	--	.20	.02	.60	.23	--	--
08-30-89	1800	7.0	--	--	.20	.02	.60	.23	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 8				
08-29-89	1840	14	1,280	7.7	22.5	21.0	789	--	7.2
08-29-89	2315	--	1,260	7.5	16.5	20.5	790	--	7.3
08-30-89	0425	--	1,230	8.1	13.5	20.0	789	--	--
08-30-89	0805	--	1,280	7.4	16.5	19.5	789	--	7.0
08-30-89	1105	--	1,280	7.7	16.0	19.5	788	--	6.9
08-30-89	1510	--	1,270	8.0	21.5	19.0	787	--	6.8
08-30-89	1810	--	1,220	7.9	23.0	19.0	785	--	6.5
08-14-90	1340	36	1,440	8.0	28.0	21.0	766	--	8.8
08-14-90	1740	--	1,430	8.0	26.0	20.0	765	5.0	10.4
08-14-90	2103	--	1,440	8.0	17.0	21.0	766	--	9.5
08-15-90	0215	--	1,390	8.2	14.0	20.5	766	--	9.3
08-15-90	0615	--	1,390	8.4	10.0	20.0	766	7.3	8.8
08-15-90	0900	--	1,340	8.6	21.5	20.5	767	--	7.2
					Site 9				
08-29-89	1620	--	680	8.1	26.0	22.0	788	--	8.3
08-29-89	2025	--	662	8.1	19.0	21.5	788	--	8.1
08-30-89	2400	--	652	7.9	16.0	21.0	788	--	7.2
08-30-89	0432	--	693	7.7	13.0	20.0	788	--	6.9
08-30-89	0902	--	699	7.2	12.5	19.5	788	--	6.8

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 8, Continued					
08-29-89	1840	32	--	--	0.30	10	16	5.3	8.1	<0.2
08-29-89	2315	--	--	--	.30	10	13	5.5	--	--
08-30-89	0425	43	--	--	.20	9.8	15	6.0	--	--
08-30-89	0805	--	--	--	.20	8.9	18	5.8	--	--
08-30-89	1105	22	--	--	.20	10	14	5.6	2.8	.6
08-30-89	1510	--	--	--	.20	10	14	5.8	--	--
08-30-89	1810	20	--	--	.20	10	14	5.5	--	--
08-14-90	1340	49	--	0.86	1.0	7.4	12	4.5	--	--
08-14-90	1740	48	--	.82	1.1	5.8	12	4.6	22	2.7
08-14-90	2103	46	--	.93	1.1	6.9	12	4.6	--	--
08-15-90	0215	45	--	.95	1.2	6.8	12	4.5	--	--
08-15-90	0615	49	--	.96	1.2	6.5	12	4.4	27	4.1
08-15-90	0900	53	--	.98	1.2	5.3	10	4.2	--	--
					Site 9, Continued					
08-29-89	1620	12	--	--	0.50	0.61	1.8	0.61	12	1.2
08-29-89	2025	--	--	--	.50	.61	1.6	.66	--	--
08-30-89	2400	10	--	--	.60	.68	1.7	.65	--	--
08-30-89	0432	--	--	--	.50	.74	1.9	.64	7.6	.9
08-30-89	0902	9.0	--	--	.40	.74	1.7	.65	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 9, Continued				
08-30-89	1230	--	692	7.6	18.5	20.0	785	--	7.6
08-30-89	1615	--	704	8.2	19.5	20.5	784	--	8.6
08-14-90	1200	--	615	7.2	26.0	22.5	763	--	7.6
08-14-90	1555	--	618	7.5	31.0	23.5	764	31	7.9
08-14-90	1955	--	616	7.6	25.0	23.0	763	--	7.8
08-15-90	0005	--	623	7.6	15.5	22.5	764	--	7.0
08-15-90	0405	--	622	7.9	11.0	21.0	765	39	6.8
08-15-90	0800	--	630	7.7	18.5	21.0	766	--	6.4
09-06-90	1330	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1600	--	--	--	--	--	--	--	--
					Site 10				
08-29-89	1650	--	636	8.0	23.0	22.5	788	--	7.6
08-29-89	2045	--	680	7.9	18.5	21.5	788	--	7.5
08-30-89	0015	--	686	7.9	17.5	21.0	788	--	6.9
08-30-89	0515	--	661	7.8	13.5	20.0	788	--	6.5
08-30-89	0929	--	677	7.3	13.5	19.5	788	--	6.1
08-30-89	1245	--	700	7.4	19.5	20.0	785	--	6.8
08-30-89	1630	--	699	7.9	21.5	20.5	784	--	7.5
08-14-90	1221	--	616	7.2	23.0	22.0	763	--	6.7
08-14-90	1625	--	613	7.6	26.5	24.0	764	49	8.1
08-14-90	2005	--	619	7.7	24.0	23.5	763	--	7.8

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 9, Continued					
08-30-89	1230	--	--	--	0.40	0.63	1.6	0.68	--	--
08-30-89	1615	11	--	--	.40	.46	1.4	.71	--	--
08-14-90	1200	16	--	0.18	.50	.76	2.1	.76	--	--
08-14-90	1555	15	--	.17	.50	.94	2.2	.78	18	1.0
08-14-90	1955	14	--	.19	.50	.89	2.2	.70	--	--
08-15-90	0005	15	--	.19	.50	.92	2.3	.67	--	--
08-15-90	0405	15	--	.19	.50	.92	2.1	.68	11	.7
08-15-90	0800	15	--	.19	.50	.87	1.8	.67	--	--
09-06-90	1330	--	0.18	--	--	--	--	--	--	--
	to	--	.09	--	--	--	--	--	--	--
	1600	--	--	--	--	--	--	--	--	--
					Site 10, Continued					
08-29-89	1650	8.6	--	--	0.60	0.42	1.6	0.59	13	1.3
08-29-89	2045	--	--	--	.70	.41	1.5	.61	--	--
08-30-89	0015	10	--	--	.70	.46	1.5	.61	--	--
08-30-89	0515	--	--	--	.80	.48	1.5	.59	7.6	.5
08-30-89	0929	9.9	--	--	.80	.55	1.7	.67	--	--
08-30-89	1245	--	--	--	.70	.54	1.7	.62	--	--
08-30-89	1630	9.5	--	--	.70	.47	1.7	.64	--	--
08-14-90	1221	14	--	0.19	.60	.79	2.9	.75	--	--
08-14-90	1625	16	--	.19	.60	.56	2.3	.73	20	1.5
08-14-90	2005	15	--	.20	.60	.60	2.4	.74	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--*Continued*

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 10, Continued				
08-15-90	0030	--	622	7.5	15.0	22.0	765	--	6.7
08-15-90	0440	--	600	7.8	11.0	21.0	766	47	6.2
08-15-90	0815	--	610	7.5	18.5	21.0	767	--	5.8
09-07-90	0945	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1400	--	--	--	--	--	--	--	--
					Site 11				
08-29-89	1720	56	787	8.4	26.0	22.0	787	--	9.2
08-29-89	2100	--	826	8.1	17.5	21.0	788	--	8.8
08-30-89	0035	--	840	7.6	15.5	20.5	788	--	8.4
08-30-89	0551	--	814	8.1	12.5	19.5	788	--	8.1
08-30-89	0950	--	787	7.9	14.5	19.0	788	--	7.9
08-30-89	1258	--	800	8.0	19.0	19.5	785	--	8.5
08-30-89	1648	--	793	8.3	21.0	20.0	784	--	9.2
08-14-90	1240	16	1,460	7.8	26.0	21.5	764	--	9.3
08-14-90	1700	--	1,500	8.0	24.5	24.5	764	35	13.3
08-14-90	2020	--	1,520	8.1	26.0	24.0	763	--	13.7
08-15-90	0055	--	1,520	8.1	15.5	22.5	765	--	11.0
08-15-90	0510	--	1,510	8.1	13.0	21.0	766	50	9.2
08-15-90	0835	--	1,500	8.0	23.0	20.5	766	--	7.6

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 10, Continued					
08-15-90	0030	14	--	0.21	0.70	0.75	2.6	0.68	--	--
08-15-90	0440	15	--	.21	.70	.75	2.5	.67	8.7	0.6
08-15-90	0815	15	--	.22	.70	.73	2.4	.68	--	--
09-07-90	0945	--	0.09	--	--	--	--	--	--	--
	to	--	.08	--	--	--	--	--	--	--
	1400	--	.11	--	--	--	--	--	--	--
					Site 11, Continued					
08-29-89	1720	9.1	--	--	<0.10	0.02	1.0	0.28	13	1.5
08-29-89	2100	--	--	--	<.10	.02	1.0	.27	--	--
08-30-89	0035	8.9	--	--	<.10	.02	1.1	.24	--	--
08-30-89	0551	--	--	--	<.10	.05	1.1	.22	11	.6
08-30-89	0950	8.0	--	--	<.10	.02	1.2	.20	--	--
08-30-89	1258	--	--	--	<.10	.02	.90	.19	--	--
08-30-89	1648	8.2	--	--	<.10	.05	1.5	.26	--	--
08-14-90	1240	20	--	0.16	.20	.13	1.9	.89	--	--
08-14-90	1700	22	--	.15	.20	.08	2.0	.88	25	3.8
08-14-90	2020	22	--	.14	.10	.07	2.5	.88	--	--
08-15-90	0055	21	--	.14	.10	.07	2.0	.90	--	--
08-15-90	0510	21	--	.13	.10	.07	2.9	.80	18	2.4
08-15-90	0835	21	--	.15	.20	.09	2.0	.91	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 12				
08-29-89	1845	--	681	8.0	22.0	22.0	788	--	7.8
08-29-89	2200	--	678	8.0	17.0	21.5	788	--	7.3
08-30-89	0130	--	709	7.9	13.5	20.5	788	--	6.9
08-30-89	0715	--	719	7.8	13.5	19.5	788	--	6.6
08-30-89	1108	--	695	7.4	18.0	19.5	788	--	6.7
08-30-89	1347	--	699	7.8	20.5	20.0	786	--	7.0
08-30-89	1740	--	717	7.8	20.5	20.5	784	--	7.8
08-14-90	1340	--	644	7.4	25.5	23.0	765	--	6.9
08-14-90	1805	--	658	7.6	27.0	24.0	764	48	8.0
08-14-90	2115	--	671	7.7	22.0	23.5	765	--	7.7
08-15-90	0204	--	690	7.5	15.5	22.0	766	--	6.8
08-15-90	0627	--	694	7.5	18.5	21.0	766	45	6.2
08-15-90	0934	--	687	7.5	22.0	21.0	767	--	6.2
08-31-90	1000	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1430	--	--	--	--	--	--	--	--
					Site 13				
08-29-89	1750	230	683	7.9	23.0	22.0	788	--	7.6
08-29-89	2125	--	676	7.9	17.5	21.5	788	--	7.3
08-30-89	0100	--	666	7.9	17.0	20.5	788	--	7.0
08-30-89	0628	--	700	7.8	12.5	20.0	788	--	6.8
08-30-89	1032	--	722	7.5	16.5	19.5	788	--	6.7

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2/)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
Site 12, Continued										
08-29-89	1845	9.8	--	--	0.60	0.25	1.5	0.54	11	1.0
08-29-89	2200	--	--	--	.60	.24	1.5	.47	--	--
08-30-89	0130	9.2	--	--	.60	.24	1.2	.51	--	--
08-30-89	0715	--	--	--	.70	.26	1.5	.49	9.6	.8
08-30-89	1108	8.5	--	--	.70	.28	1.4	.51	--	--
08-30-89	1347	--	--	--	.70	.29	1.4	.51	--	--
08-30-89	1740	9.6	--	--	.70	.27	1.3	.52	--	--
08-14-90	1340	14	--	0.18	.70	.64	1.5	.66	--	--
08-14-90	1805	15	--	.17	.70	.49	1.5	.59	13	1.0
08-14-90	2115	16	--	.18	.70	.37	1.6	.58	--	--
08-15-90	0204	16	--	.19	.80	.51	1.7	.63	--	--
08-15-90	0627	15	--	.20	.80	.52	1.7	.62	9.9	.6
08-15-90	0934	15	--	.20	.80	.51	1.5	.66	--	--
08-31-90	1000	--	--	--	--	--	--	--	--	--
	to	--	0.15	--	--	--	--	--	--	--
	1430	--	--	--	--	--	--	--	--	--
Site 13, Continued										
08-29-89	1750	9.2	--	--	0.80	0.22	1.4	0.54	8.8	0.9
08-29-89	2125	--	--	--	.70	.19	1.2	.52	--	--
08-30-89	0100	9.4	--	--	.70	.18	1.2	.47	--	--
08-30-89	0628	--	--	--	.70	.17	1.3	.43	10	1.1
08-30-89	1032	8.3	--	--	.70	.18	1.9	.48	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter; --, no data; <, less than]

Date	Time	Streamflow[1] (ft^3/s)	Specific conductance (µS/cm at 25°C)	pH (standard units)	Temperature, air (°C)	Temperature, water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
					Site 13, Continued				
08-30-89	1316	--	718	7.7	21.0	20.0	786	--	7.3
08-30-89	1707	--	697	7.8	20.5	20.5	784	--	7.6
					Site 14				
08-14-90	1315	270	615	7.4	24.0	22.5	764	--	7.1
08-14-90	1735	--	637	7.6	26.0	24.0	763	41	7.8
08-14-90	2050	--	644	7.6	23.0	23.5	765	--	7.3
08-15-90	0132	--	651	7.5	15.5	22.5	765	--	6.9
08-15-90	0553	--	662	7.6	11.5	21.5	766	35	6.6
08-15-90	0906	--	669	7.5	21.0	21.0	766	--	6.5
08-28-90	0945	--	--	--	--	--	--	--	--
	to	--	--	--	--	--	--	--	--
	1345	--	--	--	--	--	--	--	--

See footnotes at end of supplement.

Supplement 3. Water-quality data collected during synoptic samplings on August 29-30, 1989, and August 14-15, 1990, and sediment oxygen demand data collected on August 28, 1990, August 30-31, 1990, and September 5-7, 1990, Red River of the North at Fargo, North Dakota--Continued

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; (g O/ft^2)/d, grams oxygen per square foot per day; µg/L, micrograms per liter]

Date	Time	Ultimate carbonaceous biochemical oxygen demand (mg/L)	Sediment oxygen demand[2] [(g O/ft^2)/d]	Nitrogen, nitrite, total (mg/L as N)	Nitrogen, nitrite plus nitrate, total (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Chlorophyll a, phytoplankton (µg/L)	Chlorophyll b, phytoplankton (µg/L)
					Site 13, Continued					
08-30-89	1316	--	--	--	0.80	0.17	1.4	0.50	--	--
08-30-89	1707	9.6	--	--	.80	.17	1.2	.43	--	--
					Site 14, Continued					
08-14-90	1315	12	--	0.16	0.80	0.30	1.6	0.56	--	--
08-14-90	1735	14	--	.18	.90	.36	2.2	.63	15	0.7
08-14-90	2050	14	--	.18	.90	.38	1.8	.59	--	--
08-15-90	0132	14	--	.17	.90	.31	1.9	.59	--	--
08-15-90	0553	16	--	.17	.90	.23	1.9	.59	17	.9
08-15-90	0906	16	--	.17	.90	.19	2.3	.61	--	--
08-28-90	0945	--	--	--	--	--	--	--	--	--
	to	--	0.06	--	--	--	--	--	--	--
	1345	--	.10	--	--	--	--	--	--	--

[1]Time indicated may not be actual time when streamflow was measured. Streamflow is average during synoptic sampling period.
[2]Values are from individual *in-situ* chambers.

SUPPLEMENT 4
INPUT DATA USED FOR MODEL CALIBRATION AND VERIFICATION

```
TITLE01          STREAM QUALITY MODEL--QUAL2E/NCASI VERSION--STEADY STATE
TITLE02          CALIBRATION:  AUG 29-30, 1989   RED RIVER NR FARGO, ND
TITLE03  YES     CONSERVATIVE MINERAL  I  SPCN   USCM
TITLE04  NO      CONSERVATIVE MINERAL  II
TITLE05  NO      CONSERVATIVE MINERAL III
TITLE06  YES     TEMPERATURE
TITLE07  YES     ULTIMATE BIOCHEMICAL OXYGEN DEMAND
TITLE08  YES     ALGAE AS CHL-A IN UG/L
TITLE09  YES     PHOSPHORUS CYCLE AS P IN MG/L
TITLE10          (ORGANIC-P; DISSOLVED-P)
TITLE11  YES     NITROGEN CYCLE AS N IN MG/L
TITLE12          (ORGANIC-N; AMMONIA-N; NITRITE-N;' NITRATE-N)
TITLE13  YES     DISSOLVED OXYGEN IN MG/L
TITLE14  NO      FECAL COLIFORM IN NO./100 ML
TITLE15  NO      FECAL STREP IN NO./100 ML  FCSP   100M
ENDTITLE
LIST DATA INPUT
WRITE OPTIONAL SUMMARY
NOFLOW AUGMENTATION
STEADY STATE
TRAPEZOIDAL CHANNELS
PRINT LCD/SOLAR DATA
NPLOT DO AND BOD
FIXED DNSTM CONC (YES=1)=      0.      5D-ULT BOD CONV K COEF  =      0.
INPUT ENGLISH          =     0.      OUTPUT ENGLISH        =     0.
NUMBER OF REACHES      =     11.      NUMBER OF JUNCTIONS    =      0.
NUM OF HEADWATERS      =     1.      NUMBER OF POINT LOADS  =      4.
TIME STEP (HOURS)      =     1.      LNTH. COMP. ELEMENT (MI)=      .2
MAXIMUM ROUTE TIME (HRS)=    30.      TIME INC. FOR RPT2 (HRS)=      0.
LATITUDE OF BASIN (DEG) =  47.00      LONGITUDE OF BASIN      =  96.75
STANDARD MERIDIAN (DEG) =    98.      DAY OF YEAR STAT TIME   =    241
EVAP. COEFF. (AE)      =  .00068     EVAP. COEFF. (BE)      =  .00027
ELEV. OF BASIN (ELEV.) =   900.      DUST ATTENUATION COEFF. =     .05
ENDATA1
O UPTAKE BY NH3 OXID(MG O/MG N)=  3.43  O UPTAKE BY NO2 OXID(MG 0/MG N)=  1.14
O PROD BY ALGAE (MG O/MG A)   =   1.6  O UPTAKE BY ALGAE (MG O/MG A)  =   2.
N CONTENT OF ALGAE (MG N/MG A) =  .080  P CONTNET OF ALGAE (MG P/MG A) =  .011
ALG MAX SPEC GROWTH RATE(1/DAY)=   1.6  ALGAE RESPIRATION RATE(1/DAY)  =   .12
N HALF SATURATION CONST (MG/L) =   .03  P HALF SATURATION CONST (MG/L) =   .04
```

LIN ALG SHADE CO(1/FT-UGCHA/L) = .0027 NLIN SHADE(1/FT-(UGCHA/L)**2/3)= .0165
LIGHT FUNCTION OPTION (LFNOPT) = 1 LIGHT SATURATION COEF (BTU/MIN)= .1105
DAILY AVERAGING OPTION (LAVOPT)= 2 LIGHT AVERAGING FACTOR (AFAACT)= 1.0
NUMBER OF DAYLIGHT HOURS (DLH) = 13.3 TOTAL DAILY SOLAR RADTN (INT) = 1769.6
ALGY GROWTH CALC OPTION(LGROPT)= 2 ALGAL PREF FOR NH3-N (PREFN) = .9
ALG/TEMP SOLR RAD FACTOR(TFACT)= 1.0 NITRICATION INHIBITION COEF = 10.0
ENDATA1A
ENDATA1B

STREAM REACH	1. RCH=SITE NO 1	FROM	30.8	TO	28.6
STREAM REACH	2. RCH=SITE NO 4	FROM	28.6	TO	25.6
STREAM REACH	3. RCH=SITE NO 5-7.4	FROM	25.6	TO	23.4
STREAM REACH	4. RCH=MI:7.4-9.4	FROM	23.4	TO	21.4
STREAM REACH	5. RCH=SITE NO 6	FROM	21.4	TO	19.0
STREAM REACH	6. RCH=SITE NO 7	FROM	19.0	TO	15.8
STREAM REACH	7. RCH=SITE NO 9	FROM	15.8	TO	13.8
STREAM REACH	8. RCH=MI:17.0-19.2	FROM	13.8	TO	11.6
STREAM REACH	9. RCH=SITE NO 10	FROM	11.6	TO	7.8
STREAM REACH	10. RCH=SITE NO 12	FROM	7.8	TO	3.8
STREAM REACH	11. RCH=SITE NO 13	FROM	3.8	TO	0.0

ENDATA2

FLOW AUGMT SOURCES RCH=	1.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	2.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	3.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	4.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	5.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	6.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	7.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	8.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	9.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	10.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	11.	0.	0.	0.	0.	0.	0.	0.	0.

ENDATA3

FLAG FIELD RCH=	1.	11.	1.6.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	2.	15.	2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	3.	11.	2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	4.	10.	2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	5.	12.	2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	6.	16.	6.6.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	7.	10.	2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	8.	11.	2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	9.	19	2.2.2.2.2.2.2.2.6.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	10.	20	2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.

```
FLAG FIELD RCH= 11.     19      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.5.
ENDATA4
HYDRAULICS RCH=  1.    30.    6.94    6.15    77.30 .0001136    .030
HYDRAULICS RCH=  2.    30.    6.33    2.03    68.95 .0001136    .033
HYDRAULICS RCH=  3.    30.    6.13    1.96    64.43 .0001136    .037
HYDRAULICS RCH=  4.    30.    3.53    3.21    77.38 .0001136    .037
HYDRAULICS RCH=  5.    30.    6.36    5.52    73.57 .0001136    .037
HYDRAULICS RCH=  6.    50.    5.16    5.10    69.28 .0001136    .033
HYDRAULICS RCH=  7.    50.    5.80    5.00    60.00 .0001136    .030
HYDRAULICS RCH=  8.    50.    5.78    4.31    76.70 .0001136    .028
HYDRAULICS RCH=  9.    50.    4.19    4.76    62.19 .0000943    .028
HYDRAULICS RCH= 10.    50.    4.10    6.00    76.00 .0001136    .028
HYDRAULICS RCH= 11.    50.    3.04    6.66    71.69 .0001136    .028
ENDATA5
REACT COEF RCH=  1.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  2.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  3.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  4.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  5.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  6.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  7.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  8.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH=  9.   .05  0.03  .100  1   1.7     .0000943
REACT COEF RCH= 10.   .05  0.03  .100  1   1.7     .0001136
REACT COEF RCH= 11.   .05  0.03  .100  1   1.7     .0001136
ENDATA6
N AND P COEF  RCH=  1.  .02   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  2.  .02   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  3.  .02   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  4.  .02   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  5.  .02   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  6.  .19   .1  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  7.  .19   .1  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  8.  .09   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH=  9.  .09   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH= 10.  .09   .0  1.07   .0  3.08  .21   .0   .0
N AND P COEF  RCH= 11.  .09   .0  1.07   .0  3.08  .21   .0   .0
ENDATA6A
ALG/OTHER COEF RCH=  1.  10.  1.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH=  2.  10.  1.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH=  3.  10.  4.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH=  4.  10.  4.0  .5  .8  .8  .0  .0
```

```
ALG/OTHER COEF RCH= 5.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 6.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 7.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 8.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 9.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 10.  10.  2.0  .5  .8  .8  .0  .0
ALG/OTHER COEF RCH= 11.  10.  2.0  .5  .8  .8  .0  .0
ENDATA6B
INITIAL COND-1 RCH= 1. 70.00 8.80 7.90 665. 0.00 0.00 72 1400
INITIAL COND-1 RCH= 2. 69.60 8.80 9.70 665. 0.00 0.00 130 2000
INITIAL COND-1 RCH= 3. 69.10 8.50 8.50 664. 0.00 0.00 180 1400
INITIAL COND-1 RCH= 4. 69.10 8.50 8.50 664. 0.00 0.00 180 1400
INITIAL COND-1 RCH= 5. 69.20 8.50 8.90 668. 0.00 0.00 380 1300
INITIAL COND-1 RCH= 6. 68.90 8.60 8.60 651. 0.00 0.00 210 1000
INITIAL COND-1 RCH= 7. 69.10 7.60 10.40 683. 0.00 0.00 220 1500
INITIAL COND-1 RCH= 8. 69.10 7.60 10.40 683. 0.00 0.00 220 1500
INITIAL COND-1 RCH= 9. 69.10 7.00 9.50 677. 0.00 0.00 200 5600
INITIAL COND-1 RCH= 10. 68.90 7.20 9.30 700. 0.00 0.00 260 1000
INITIAL COND-1 RCH= 11. 68.90 7.20 9.10 695. 0.00 0.00 170 910
ENDATA7
INITIAL COND-2 RCH= 1. 13.40 1.20 .45 .001 .10 .01 .27
INITIAL COND-2 RCH= 2. 17.00 1.20 .36 .001 .10 .01 .27
INITIAL COND-2 RCH= 3. 17.00 1.20 .30 .001 .20 .01 .26
INITIAL COND-2 RCH= 4. 17.00 1.10 .30 .001 .20 .01 .26
INITIAL COND-2 RCH= 5. 10.20 1.10 .23 .001 .30 .01 .25
INITIAL COND-2 RCH= 6. 11.00 1.10 .17 .001 .40 .01 .23
INITIAL COND-2 RCH= 7. 9.80 1.00 .64 .001 .50 .01 .66
INITIAL COND-2 RCH= 8. 9.80 1.10 .64 .001 .50 .01 .66
INITIAL COND-2 RCH= 9. 10.30 1.10 .48 .001 .70 .01 .62
INITIAL COND-2 RCH= 10. 10.30 1.10 .26 .001 .70 .01 .51
INITIAL COND-2 RCH= 11. 9.40 1.20 .18 .001 .70 .01 .48
ENDATA7A
INCR INFLOW-1 RCH= 1.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 2.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 3.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 4.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 5.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 6.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 7.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 8.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 9.  0.  0.  0.  0.  0.  0.  0.  0.  0.
INCR INFLOW-1 RCH= 10.  0.  0.  0.  0.  0.  0.  0.  0.  0.
```

```
INCR INFLOW-1  RCH= 11.   0.   0.   0.   0.   0.   0.   0.   0.   0.
ENDATA8
INCR INFLOW-2  RCH=  1.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  2.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  3.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  4.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  5.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  6.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  7.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  8.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH=  9.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH= 10.   0.   0.   0.   0.   0.   0.   0.
INCR INFLOW-2  RCH= 11.   0.   0.   0.   0.   0.   0.   0.
ENDATA8A
ENDATA9
HEADWTR-1 HDW=  1.RED RIVER        140  70.3  9.5  8.0  638.
ENDATA10
HEADWTR-2 HDW   1.  130  1200  16.5  .90  .02  .001  .10  .01  .15
ENDATA10A
POINTLD-1 PTL=  1.MOREHEAD STP       6.0  67.1  6.8  20.8  1230
POINTLD-1 PTL=  2.TRIB NO 1         19.0  64.4  7.8  6.9   399
POINTLD-1 PTL=  3.FARGO STP         14.0  67.3  7.0  29.0  1220
POINTLD-1 PTL=  4.SHEYENNE R.       56.0  68.4  8.6  8.5   787
ENDATA11
POINTLD-2 PTL   1.  160  290  1.2  6.0  15.0  .001  0.6  .01  4.60
POINTLD-2 PTL   2.  100  630  0.7   .6   .02  .001  0.2  .01  .22
POINTLD-2 PTL   3.    4  200  5.4  5.0   9.8  .001  0.2  .01  5.60
POINTLD-2 PTL   4.  380  2300  12.0  1.1  .03  .001  0.1  .01  .24
ENDATA11A
ENDATA12
DOWNSTREAM BOUNDARY-1    68.9   7.2   9.1   695
ENDATA13
DOWNSTREAM BOUNDARY-2     9.4   1.2   .18   .001   .70  .001   .48
ENDATA13A
LOCAL CLIMATOLOGY08 29 89 1600        .55   61.6   55.8   30.98    5.8
BEGIN  RCH   1
PLOT   RCH   1   2   3   4   5   6   7   8   9   10   11
```

```
TITLE01          STREAM QUALITY MODEL--QUAL2E/NCASI VERSION
TITLE02          VERIFICATION: AUG 14-15 1990  - RED RIVER NR FARGO, ND
TITLE03  YES      CONSERVATIVE MINERAL  I  SPCN   USCM
TITLE04  NO       CONSERVATIVE MINERAL  II
TITLE05  NO       CONSERVATIVE MINERAL III
TITLE06  YES      TEMPERATURE
TITLE07  YES      ULTIMATE BIOCHEMICAL OXYGEN DEMAND
TITLE08  YES      ALGAE AS CHL-A IN UG/L
TITLE09  YES      PHOSPHORUS CYCLE AS P IN MG/L
TITLE10          (ORGANIC-P; DISSOLVED-P)
TITLE11  YES      NITROGEN CYCLE AS N IN MG/L
TITLE12          (ORGANIC-N; AMMONIA-N; NITRITE-N;' NITRATE-N)
TITLE13  YES      DISSOLVED OXYGEN IN MG/L
TITLE14  NO       FECAL COLIFORM IN NO./100 ML
TITLE15  NO       FECAL STREP IN NO./100 ML  FCSP   100M
ENDTITLE
LIST DATA INPUT
WRITE OPTIONAL SUMMARY
NOFLOW AUGMENTATION
STEADY STATE
TRAPEZOIDAL CHANNELS
PRINT LCD/SOLAR DATA
NPLOT DO AND BOD
FIXED DNSTM CONC (YES=1)=     0.      5D-ULT BOD CONV K COEF  =     0.
INPUT ENGLISH        =     0.      OUTPUT ENGLISH      =     0.
NUMBER OF REACHES      =     11.      NUMBER OF JUNCTIONS    =     0.
NUM OF HEADWATERS      =     1.      NUMBER OF POINT LOADS  =     4.
TIME STEP (HOURS)      =     1.      LNTH. COMP. ELEMENT (MI)=     .2
MAXIMUM ROUTE TIME (HRS)=    30.      TIME INC. FOR RPT2 (HRS)=     0.
```

LATITUDE OF BASIN (DEG) = 47.00 LONGITUDE OF BASIN = 96.75

STANDARD MERIDIAN (DEG) = 98. DAY OF YEAR STAT TIME = 226

EVAP. COEFF. (AE) = .00068 EVAP. COEFF. (BE) = .00027

ELEV. OF BASIN (ELEV.) = 900. DUST ATTENUATION COEFF. = .05

ENDATA1

O UPTAKE BY NH3 OXID(MG O/MG N)= 3.43 O UPTAKE BY NO2 OXID(MG 0/MG N)= 1.14

O PROD BY ALGAE (MG O/MG A) = 1.6 O UPTAKE BY ALGAE (MG O/MG A) = 2.

N CONTENT OF ALGAE (MG N/MG A) = .080 P CONTNET OF ALGAE (MG P/MG A) = .011

ALG MAX SPEC GROWTH RATE(1/DAY)= 1.6 ALGAE RESPIRATION RATE(1/DAY) = .06

N HALF SATURATION CONST (MG/L) = .03 P HALF SATURATION CONST (MG/L) = .04

LIN ALG SHADE CO(1/FT-UGCHA/L) = .0027 NLIN SHADE(1/FT-(UGCHA/L)**2/3)= .0165

LIGHT FUNCTION OPTION (LFNOPT) = 1 LIGHT SATURATION COEF (BTU/MIN)= .1105

DAILY AVERAGING OPTION (LAVOPT)= 2 LIGHT AVERAGING FACTOR (AFAACT)= 1.0

NUMBER OF DAYLIGHT HOURS (DLH) = 14.3 TOTAL DAILY SOLAR RADTN (INT) = 1769.6

ALGY GROWTH CALC OPTION(LGROPT)= 2 ALGAL PREF FOR NH3-N (PREFN) = .9

ALG/TEMP SOLR RAD FACTOR(TFACT)= 1.0 NITRICATION INHIBITION COEF = 10.0

ENDATA1A

ENDATA1B

STREAM REACH	1. RCH=SITE NO 1	FROM	30.8	TO	28.6
STREAM REACH	2. RCH=SITE NO 4	FROM	28.6	TO	25.6
STREAM REACH	3. RCH=SITE NO 5-7.4	FROM	25.6	TO	23.4
STREAM REACH	4. RCH=MI:7.4-9.4	FROM	23.4	TO	21.4
STREAM REACH	5. RCH=SITE NO 6	FROM	21.4	TO	19.0
STREAM REACH	6. RCH=SITE NO 7	FROM	19.0	TO	15.8
STREAM REACH	7. RCH=SITE NO 9	FROM	15.8	TO	13.8
STREAM REACH	8. RCH=MI:17.0-19.2	FROM	13.8	T0	11.6
STREAM REACH	9. RCH=SITE NO 10	FROM	11.6	TO	7.8
STREAM REACH	10. RCH=SITE NO 12	FROM	7.8	TO	3.8
STREAM REACH	11. RCH=SITE NO 13	FROM	3.8	TO	0.0

ENDATA2

FLOW AUGMT SOURCES RCH=	1.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	2.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	3.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	4.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	5.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	6.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	7.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	8.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	9.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	10.	0.	0.	0.	0.	0.	0.	0.	0.
FLOW AUGMT SOURCES RCH=	11.	0.	0.	0.	0.	0.	0.	0.	0.

ENDATA3

FLAG FIELD RCH=	1.	11.	1.6.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	2.	15.	2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	3.	11.	2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	4.	10.	2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	5.	12.	2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	6.	16.	6.6.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	7.	10.	2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	8.	11.	2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	9.	19	2.2.2.2.2.2.2.2.6.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	10.	20	2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=	11.	19	2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.5.

ENDATA4

HYDRAULICS RCH=	1.	30.	6.94	6.15	77.30	.0001136	.030
HYDRAULICS RCH=	2.	30.	6.33	2.03	68.95	.0001136	.033
HYDRAULICS RCH=	3.	30.	6.13	1.96	64.43	.0001136	.037
HYDRAULICS RCH=	4.	30.	3.53	3.21	77.38	.0001136	.037

HYDRAULICS RCH= 5. 30. 6.36 5.52 73.57 .0001136 .037

HYDRAULICS RCH= 6. 50. 5.16 5.10 69.28 .0001136 .033

HYDRAULICS RCH= 7. 50. 5.80 5.00 60.00 .0001136 .030

HYDRAULICS RCH= 8. 50. 5.78 4.31 76.70 .0001136 .028

HYDRAULICS RCH= 9. 50. 4.19 4.76 62.19 .0000943 .028

HYDRAULICS RCH= 10. 50. 4.10 6.00 76.00 .0001136 .028

HYDRAULICS RCH= 11. 50. 3.04 6.66 71.69 .0001136 .028

ENDATA5

REACT COEF RCH= 1. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 2. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 3. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 4. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 5. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 6. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 7. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 8. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 9. .05 0.03 .10 1 1.4 .0000943

REACT COEF RCH= 10. .05 0.03 .10 1 1.4 .0001136

REACT COEF RCH= 11. .05 0.03 .10 1 1.4 .0001136

ENDATA6

N AND P COEF RCH= 1. .02 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 2. .02 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 3. .02 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 4. .02 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 5. .02 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 6. .19 .1 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 7. .19 .1 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 8. .09 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 9. .09 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 10. .09 .0 1.07 .0 3.08 .21 .00 .0

N AND P COEF RCH= 11. .09 .0 1.07 .0 3.08 .21 .00 .0

ENDATA6A

ALG/OTHER COEF RCH= 1. 10. 0. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 2. 10. 0. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 3. 10. 0. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 4. 10. 0. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 5. 10. 0. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 6. 10. 1. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 7. 10. 1 .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 8. 10. 1. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 9. 10. 1. .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 10. 10. 1.5 .5 .8 .8 .0 .0

ALG/OTHER COEF RCH= 11. 10. 1.5 .5 .8 .8 .0 .0

ENDATA6B

INITIAL COND-1 RCH= 1. 72.00 7.80 8.06 490. 0.00 0.00 280 0000

INITIAL COND-1 RCH= 2. 72.00 7.80 9.90 498. 0.00 0.00 380 0000

INITIAL COND-1 RCH= 3. 72.00 7.60 10.00 493. 0.00 0.00 270 0000

INITIAL COND-1 RCH= 4. 72.00 7.60 10.00 493. 0.00 0.00 270 0000

INITIAL COND-1 RCH= 5. 72.30 7.40 9.50 494. 0.00 0.00 240 0000

INITIAL COND-1 RCH= 6. 72.30 7.60 9.30 485. 0.00 0.00 170 0000

INITIAL COND-1 RCH= 7. 72.20 7.30 16.70 620. 0.00 0.00 210 0000

INITIAL COND-1 RCH= 8. 72.20 7.30 16.70 620. 0.00 0.00 210 0000

INITIAL COND-1 RCH= 9. 72.20 6.90 16.10 613. 0.00 0.00 200 0000

INITIAL COND-1 RCH= 10. 72.20 7.00 15.90 674. 0.00 0.00 120 0000

INITIAL COND-1 RCH= 11. 72.70 7.10 13.10 646. 0.00 0.00 140 0000

ENDATA7

INITIAL COND-2 RCH= 1. 4.60 .91 .12 .001 .10 .01 .08

INITIAL COND-2 RCH= 2. 5.50 .77 .33 .001 .10 .01 .17

INITIAL COND-2 RCH= 3. 5.40 1.00 .28 .001 .10 .01 .14

INITIAL COND-2 RCH= 4. 5.40 1.00 .28 .001 .10 .01 .14

INITIAL COND-2 RCH= 5. 8.20 1.00 .30 .001 .20 .01 .12

INITIAL COND-2 RCH= 6. 5.60 1.00 .14 .001 .20 .01 .17

INITIAL COND-2 RCH= 7. 14.50 1.30 .88 .001 .50 .01 .71

INITIAL COND-2 RCH= 8. 14.50 1.30 .88 .001 .50 .01 .71

INITIAL COND-2 RCH= 9. 14.40 1.80 .70 .001 .70 .01 .71

INITIAL COND-2 RCH= 10. 11.40 1.10 .51 .001 .80 .01 .61

INITIAL COND-2 RCH= 11. 16.00 1.60 .30 .001 .90 .01 .60

ENDATA7A

INCR INFLOW-1 RCH= 1. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 2. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 3. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 4. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 5. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 6. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 7. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 8. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 9. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 10. 0. 0. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-1 RCH= 11. 0. 0. 0. 0. 0. 0. 0. 0. 0.

ENDATA8

INCR INFLOW-2 RCH= 1. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 2. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 3. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 4. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 5. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 6. 0. 0. 0. 0. 0. 0. 0.

INCR INFLOW-2 RCH= 7. 0. 0. 0. 0. 0. 0. 0.

```
INCR INFLOW-2  RCH=  8.    0.    0.    0.    0.    0.    0.    0.
INCR INFLOW-2  RCH=  9.    0.    0.    0.    0.    0.    0.    0.
INCR INFLOW-2  RCH=  10.    0.    0.    0.    0.    0.    0.    0.
INCR INFLOW-2  RCH=  11.    0.    0.    0.    0.    0.    0.    0.
ENDATA8A
ENDATA9
HEADWTR-1 HDW=   1.RED RIVER            200  72.0   7.8   8.3  490.
ENDATA10
HEADWTR-2 HDW=   1.   280  0000   4.6   .91   .12  .001   .10   .01   .08
ENDATA10A
POINTLD-1 PTL=   1.MOREHEAD STP         5.0  66.6   6.2  36.6  1182
POINTLD-1 PTL=   2.TRIB NO 1          00.0  00.0   0.0   0.0   000
POINTLD-1 PTL=   3.FARGO STP           36.0  68.9   9.0  48.2  1400
POINTLD-1 PTL=   4.SHEYENNE R.         16.0  72.5  11.1  21.2  1500
ENDATA11
POINTLD-2 PTL=   1.    38   000   1.2   2.3  17.7  .001  1.00   .01  2.40
POINTLD-2 PTL=   2.   000   000   0.0    .0    .0  .000  0.00   .00   .00
POINTLD-2 PTL=   3.    40   000  27.0   5.2   6.4  .001  1.10   .01  4.50
POINTLD-2 PTL=   4.   140  0000  25.0   2.1   .08  .001  0.10   .01   .88
ENDATA11A
ENDATA12
DOWNSTREAM BOUNDARY-1     00.0    0.0    0.0    000
ENDATA13
DOWNSTREAM BOUNDARY-2      0.0    0.0    .00   .000    .00   .000    .00
ENDATA13A
LOCAL CLIMATOLOGY08 14 90 1200             .25    68.5    50.0   30.10     4.5
BEGIN  RCH    1
PLOT   RCH    1   2   3   4   5   6   7   8   9  10  11
```