Prepared in cooperation with the North Dakota Department of Health, the Minnesota Pollution Control Agency, and the cities of Fargo, North Dakota, and Moorhead, Minnesota

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Scientific Investigations Report 2008–5007

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

Cover photograph: Injecting dye at a site downstream from the Moorhead, Minnesota, wastewater-treatment plant outfall on the Red River of the North, September 24, 2003.

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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound per day (lb/d)	0.4536	kilogram per day (kg/d)

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

$$°F=(1.8\times°C)+32$$

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

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

Calibration of a Water-Quality Model for Low-Flow Conditions on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota, 2003

By Robert F. Lundgren and Rochelle A. Nustad

Abstract

A time-of-travel and reaeration-rate study was conducted by the U.S. Geological Survey, in cooperation with the North Dakota Department of Health, the Minnesota Pollution Control Agency, and the cities of Fargo, North Dakota, and Moorhead, Minnesota, to provide information to calibrate a water-quality model for streamflows of less than 150 cubic feet per second. Data collected from September 24 through 27, 2003, were used to develop and calibrate the U.S. Environmental Protection Agency Water Quality Analysis Simulation Program model (hereinafter referred to as the Fargo WASP water-quality model) for a 19.2-mile reach of the Red River of the North.

The Fargo WASP water-quality model was calibrated for the transport of dye by fitting simulated time-concentration dye curves to measured time-concentration dye curves. Simulated peak concentrations were within 10 percent of measured concentrations. Simulated traveltimes of the dye cloud centroid were within 7 percent of measured traveltimes. The variances of the simulated dye concentrations were similar to the variances of the measured dye concentrations, indicating dispersion was reproduced reasonably well.

Average simulated dissolved-oxygen concentrations were within 6 percent of average measured concentrations. Average simulated ammonia concentrations were within the range of measured concentrations. Simulated dissolved-oxygen and ammonia concentrations were affected by the specification of a single nitrification rate in the Fargo WASP water-quality model.

Data sets from August 1989 and August 1990 were used to test traveltime and simulation of dissolved oxygen and ammonia. For streamflows that ranged from 60 to 407 cubic feet per second, simulated traveltimes were within 7 percent of measured traveltimes. Measured dissolved-oxygen concentrations were underpredicted by less than 15 percent for both data sets. Results for ammonia were poor; measured ammonia concentrations were underpredicted by as much as 70 percent for both data sets. Overall, application of the Fargo WASP water-quality model to the 1989 and 1990 data sets resulted in poor agreement between measured and simulated concentrations. This likely is a result of changes in the waste-load composition for the Fargo and Moorhead wastewater-treatment plants as a result of improvements to the wastewater-treatment plants since 1990. The change in waste-load composition probably resulted in a change in decay rates and in dissolved oxygen no longer being substantially depressed downstream from the Moorhead and Fargo wastewater-treatment plants. The Fargo WASP water-quality model is valid for the current (2008) treatment processes at the wastewater-treatment plants.

Introduction

The Clean Water Act requires all States to develop and implement total maximum daily loads (TMDLs) for surface water where existing controls are not adequate to achieve instream water-quality standards (U.S. Environmental Protection Agency, Assessment and Watershed Protection Division, 1991). In the early 1990s, the North Dakota Department of Health (NDDH) and Minnesota Pollution Control Agency (MPCA) determined that TMDLs for dissolved oxygen (DO) and ammonia needed to be developed for a 30.8-mi reach of the Red River of the North (hereinafter referred to as the Red River) that includes Fargo, N. Dak., and Moorhead, Minn. (fig. 1). The NDDH currently (2008) lists this reach of the Red River as impaired for DO and ammonia (North Dakota Department of Health, 2007), and the MPCA currently (2008) lists this reach as impaired for ammonia (Minnesota Pollution Control Agency, 2007). Actions that prompted the impaired listings were the planned expansion of the Fargo wastewater-treatment plant (WWTP; fig. 2), the beginning of year-round effluent discharges from the Fargo WWTP, and the likely need for stricter controls for the Moorhead WWTP (fig. 2) to reduce effluent ammonia concentrations (Wesolowski, 1996c). In June 1994, Red River TMDL work group members from Federal, State, and local agencies began developing TMDLs for DO and ammonia for the 30.8-mi reach. Since that time, both the Fargo and Moorhead WWTPs made improvements to their wastewater processes to reduce effluent ammonia concentrations.

In the 1990s, the U.S. Geological Survey calibrated and verified a water-quality model (QUAL2E) to simulate water quality in the Red River from just upstream from the Moorhead WWTP effluent discharge to downstream at the confluence of the Buffalo and Red Rivers near Georgetown, Minn. (Wesolowski, 1994, 1996a, 1996b, 1996c). Data used to calibrate this model were collected during 1989 and 1990 at streamflows that ranged from 150 to 250 ft^3/s. Because of uncertainties in the model for streamflows of less than 150 ft^3/s, Red River TMDL work group members noted that a time-of-travel and reaeration-rate study should be completed for streamflows that ranged from 20 to 100 ft^3/s and that the water-quality model should be recalibrated for those flows. A model calibrated for low-flow conditions would enable the NDDH and the MPCA to conduct the necessary waste-load allocations for the two municipal WWTPs, to develop TMDLs for the 30.8-mi reach, and to evaluate the Fargo and Moorhead WWTPs current effluent quality and potential impact to the Red River. A proposal and work plan to conduct a water-quality modeling study during drought conditions when headwater streamflow ranged from about 20 to 100 ft^3/s were prepared by Wesolowski (2000).

In 2003, the USGS, in cooperation with the NDDH, MPCA, and cities of Fargo and Moorhead, conducted a time-of-travel and reaeration-rate study during low-flow conditions to provide information to calibrate a water-quality model for streamflows of less than 150 ft^3/s. Because of resource limitations, data collection was limited to a 19.2-mi reach of the Red River from just downstream from Dam A to about 2 mi upstream from the confluence of the Sheyenne and Red Rivers (fig. 2). Traveltime, reaeration-rate, and water-quality data were collected from the 19.2-mi reach from September 24 through 27, 2003. During that period, daily mean streamflow was about 60 ft^3/s at the USGS Red River of the North at Fargo gaging station (05054000; fig. 3). In the 19.2-mi reach, streamflow ranged from about 80 to 100 ft^3/s because of additional discharge from the Fargo and Moorhead WWTP outfalls.

In January 2006, Red River TMDL work group members met to discuss TMDL goals for the NDDH and MPCA, to determine which water-quality model should be used with the September 24 through 27, 2003 data, and to review the September 2003 study data-collection activities and current and future modeling requirements. During the meeting, TMDL work group members made the decision to use the U.S. Environmental Protection Agency (USEPA) Water Quality Analysis Simulation Program (WASP) model because that model can be used for unsteady streamflows, is widely accepted by regulatory agencies, simulates concentrations for a variety of constituents, and is well documented and supported. The model developed during this study, which was conducted in cooperation with the NDDH, the MPCA, and the cities of Fargo and Moorhead, will, hereinafter, be referred to as the Fargo WASP water-quality model. The model was developed and calibrated using data collected from September 24 through 27, 2003, and tested using data collected during 1989 and 1990 as part of the Wesolowski (1994) study.

Purpose and Scope

The purpose of this report is to document the development, calibration, and testing of the Fargo WASP water-quality model for low-flow conditions. Specific objectives of the study were to analyze the data collected during September 2003 and provide estimates for stream velocities, traveltimes, and reaeration-rate coefficients and to calibrate the Fargo WASP water-quality model.

The Fargo WASP water-quality model was calibrated for streamflow, transport, DO, and ammonia during steady-state conditions. Data collected during low-flow conditions from September 24 through 27, 2003, were used to calibrate the model, while data collected during 1989 and 1990 (Wesolowski, 1994) were used to test the model. The data used to calibrate the model were collected within the 19.2-mi reach from just downstream from Dam A to about 2 mi upstream from the confluence of the Sheyenne and Red Rivers (fig. 2).

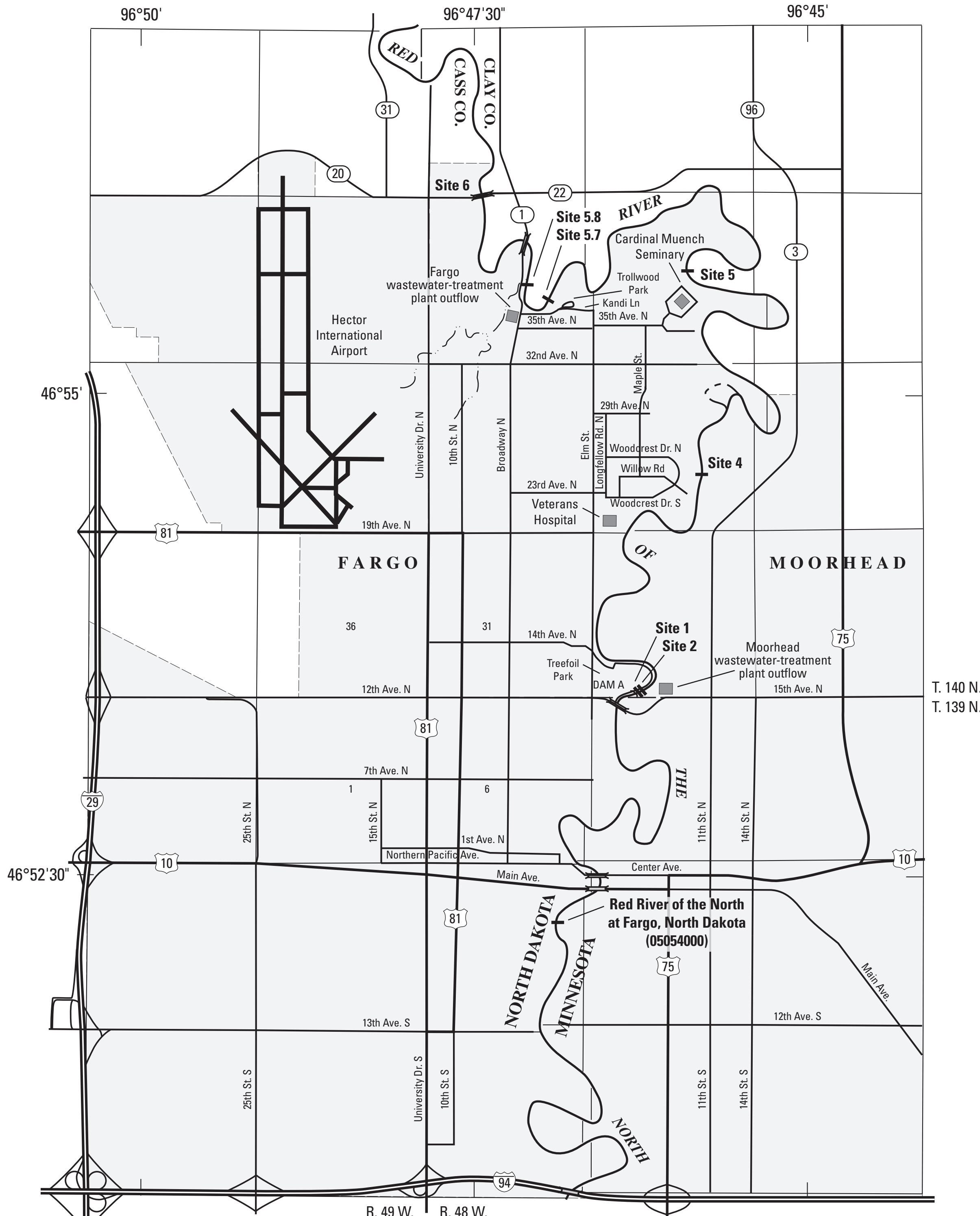
Study Reach

The study reach begins just downstream from Dam A (locally referred to as North Dam), which is located about 0.1 mi downstream from the 12th Avenue North bridge in Fargo (fig. 2). From site 1 at about river mile 448.9, the study reach extends 19.2 mi downstream to site 10 at about river mile 429.7. Site 10 is about 2 mi upstream from the confluence of the Sheyenne and Red Rivers. About one-third of the land use in the study reach is urban-suburban and two-thirds is rural (Wesolowski, 1994).

The Wild Rice River enters the Red River in North Dakota upstream from the study reach at about river mile 470 and is the only major tributary that affects water quality in the study reach (fig. 1). The USGS Red River of the North at Fargo gaging station (05054000) is located at river mile 453, about 4.1 mi upstream from the beginning of the study reach. The Sheyenne River enters the Red River downstream from the study reach at about river mile 428.

The river channel and the riverbanks along the study reach primarily consist of silts and clays, and the streamflow in the river is primarily controlled by the river channel. During low streamflows, such as those that existed from September 24 through 27, 2003, the streamflow follows the natural channel. The meandering river channel, which gradually becomes wider and deeper in a downstream direction, is fairly uniform in shape. In some places within Fargo, the river has been rechanneled to permit high streamflows to bypass the meanders. The riverbanks, which are fairly stable, are lined with deciduous trees. Tree density varies and, in places, open areas exist. The open, treeless areas are covered with grass or crops.

Figure 1. Location of Red River of the North Basin.



Base from U.S. Geological Survey
Georgetown, Minn.-N. Dak. 1:24,000, 1963
Fargo North, N. Dak.-Minn. 1:24,000, 1959
Photorevised 1971 and 1976, revised 1993

Figure 2. Location of sites used in study.

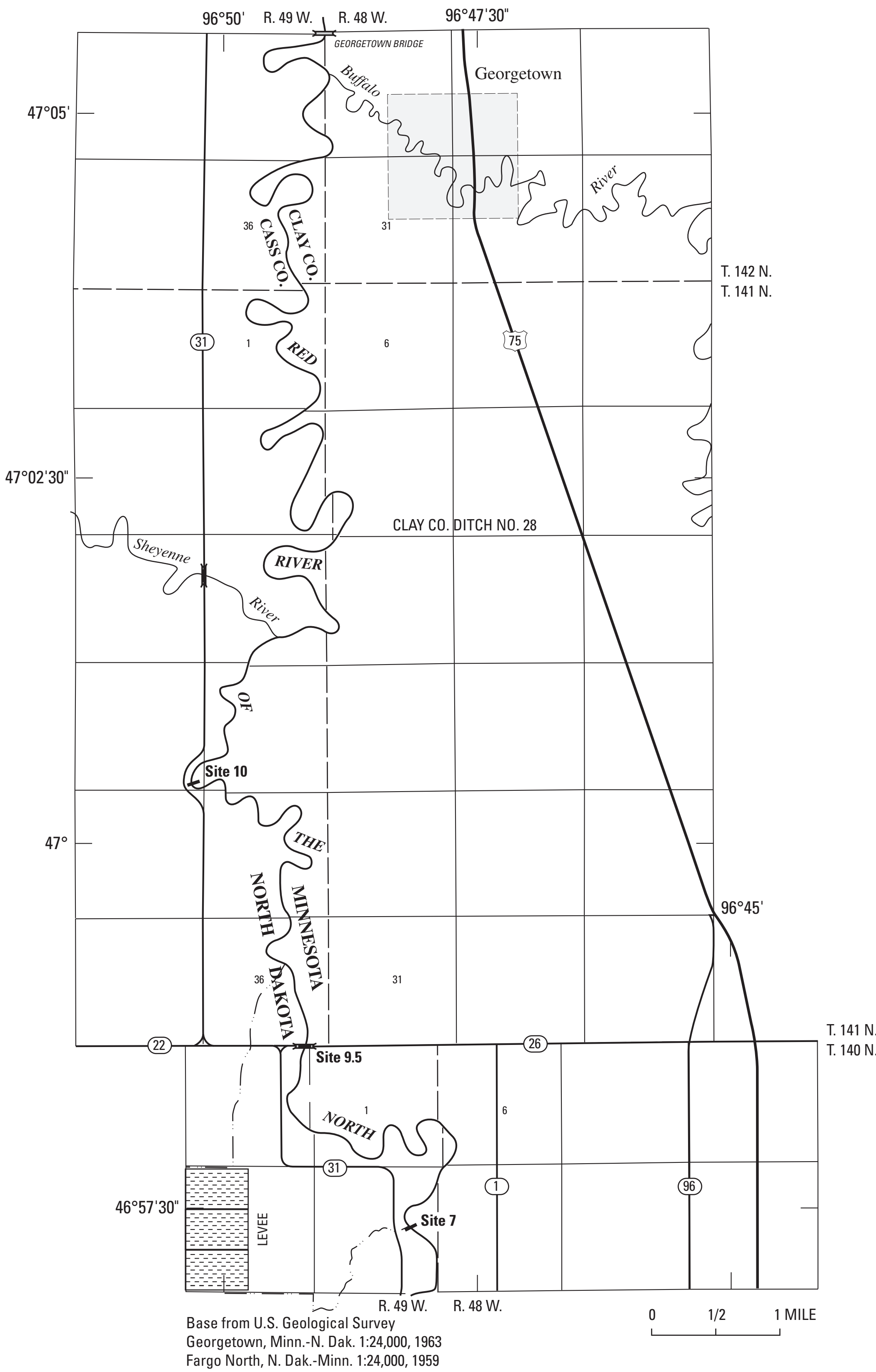


Figure 2. Location of sites used in study.—Continued

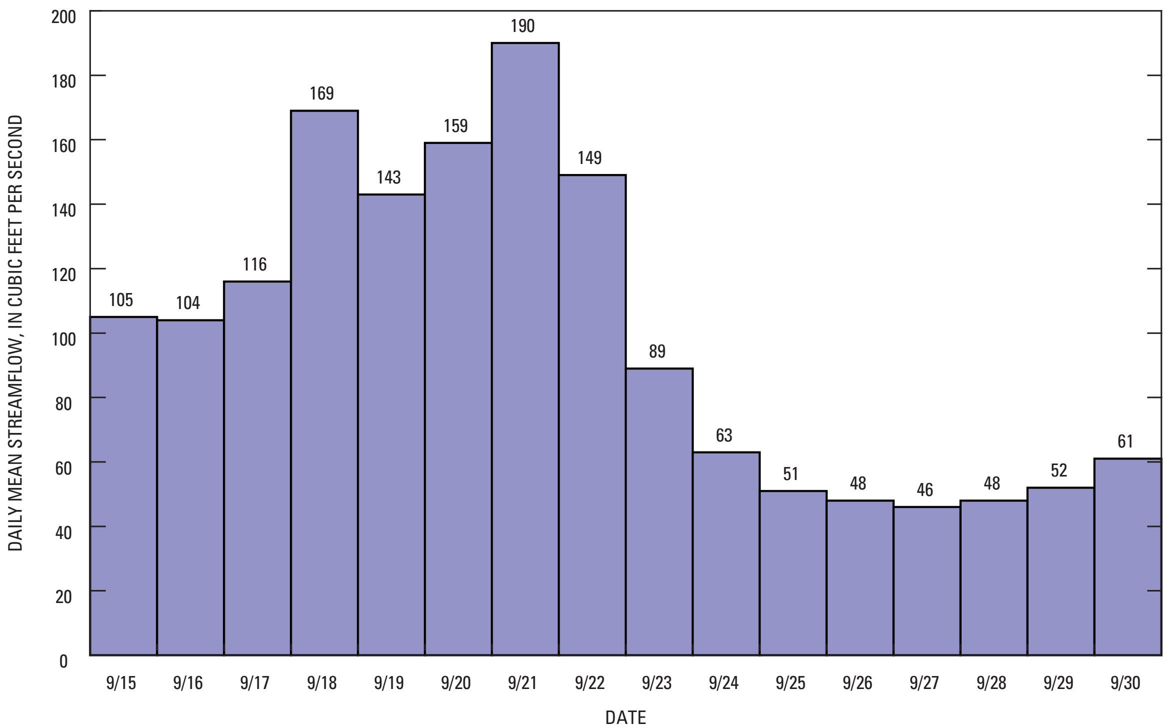


Figure 3. Daily mean streamflow at Red River of the North at Fargo, North Dakota, gaging station (05054000) for September 15 through 30, 2003.

Methods

Input data required to develop the Fargo WASP water-quality model include channel-geometry data, streamflow data, traveltime data, reaeration-rate coefficients, and water-quality data. Methods used to collect or compile the data are summarized in this section. Field property values and constituent concentrations used for the study are on file at the USGS and NDDH offices in Bismarck, N. Dak.

Data-Collection Network

The data-collection network for the 2003 study consisted of 10 sites that were numbered in a downstream order (fig. 2 and table 1). The 10 sites are located on the main stem of the Red River and no sites are located at USGS gaging stations. Of the 10 sites, 6 (sites 1, 4, 5, 5.7, 7, and 10) are located at intervals that were determined on the basis of site access points and 2 (sites 6 and 9.5) are located at existing bridges. The remaining two sites (sites 2 and 5.8) represent point sources from the WWTPs. Of the 10 sites used in the 2003 study, 7 (sites 1, 2, 4, 5, 6, 7, and 10) also were used in the Wesolowski (1994) study.

Channel-Geometry and Streamflow Data

The Fargo WASP water-quality model requires channel-geometry data to characterize the segments between sites. Streamflow was measured with a current-meter according to techniques outlined by Rantz and others (1982). Information from the streamflow measurements were used for model input. Streamflows measured at seven sites (sites 4, 5, 5.7, 6, 7, 9.5, and 10) in the study reach are given in table 2. The study reach slope and bottom roughness were available from the Wesolowski (1994) study. Discharge data included in the model for the two point-source WWTP outfall sites were obtained from the NDDH (Gary Bracht, North Dakota Department of Health, written commun., 2004) and the city of Moorhead (Bob Zimmerman, Moorhead Wastewater Treatment Facility, oral commun., 2004).

Table 1. Description of sites used in 2003 study.

[RM, river mile; WWTP, wastewater-treatment plant]

Site number (fig. 2)	U.S. Geological Survey site number	Site name and location	Description	Miles downstream from site 1
1	465327096461800	Red River of the North 0.1 mile below 12th Avenue North bridge at Fargo, North Dakota (RM448.9)—Beginning of study reach at about 0.1 mile downstream from 12th Avenue North bridge. Immediately downstream from Dam A. Enter Treefoil Park from Elm Street just south of intersection with 14th Avenue North. Dam A is southeast of park entrance.	Site for dye and gas injection and synoptic water-quality sampling	0
2	465328096461200	Red River of the North at WWTP outfall at Moorhead, Minnesota (RM448.89)—At Moorhead, Minnesota, wastewater-treatment plant outflow (buried pipe) on east bank downstream from Dam A.	Point-source site for synoptic water-quality sampling	0.01
4	465431096455000	Red River of the North 2.3 miles below 12th Avenue North bridge at Fargo, North Dakota (RM446.6)—At intersection of Woodcrest Drive and Elm Street (north of Veterans Hospital). From Elm Street, turn east on Woodcrest Drive South. Site is located near 204 Woodcrest Drive. Follow trail to river.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	2.3
5	465544096455300	Red River of the North 2 miles above North Broadway Street bridge at Fargo, North Dakota (RM443.7)—At intersection of Elm Street North and Kandi Lane. From Elm Street North, turn northeast on Golf Course Avenue and follow to river.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	5.2
5.7	465530096465900	Red River of the North 0.6 mile above North Broadway Street bridge at Fargo, North Dakota (RM440.9)—At intersection of Kandi Lane and Broadway Street North. From Broadway Street North, turn east on Kandi Lane and into west end of Trollwood Park parking lot.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	8.0
5.8	465537096470700	Red River of the North at WWTP outfall at Fargo, North Dakota (RM440.5)—At Fargo, North Dakota, outlet end of wastewater-treatment plant outflow. East of Broadway Street North.	Point-source site for synoptic water-quality sampling	8.4
6	465602096472900	Red River of the North at Cass Co. 20 bridge at Fargo, North Dakota (RM439.15—At bridge on Cass County, North Dakota, Road No. 20.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	9.75
7	465721096481100	Red River of the North 1.5 miles below Cass Co. 20 bridge at Fargo, North Dakota (RM437.6)—Immediately upstream from discontinued Fargo, North Dakota, wastewater-treatment plant outflow. About 1.5 miles north of Cass County, North Dakota, Road No. 20.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	11.8
9.5	465836096491300	Red River of the North at Cass Co. 22 bridge below Fargo, North Dakota (RM433.42)—At bridge on Cass County, North Dakota, Road No. 22 (Clay County, Minnesota, Road No. 26).	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	15.48
10	470022096501900	Red River of the North 3.7 miles above Cass Co. 22 bridge below Fargo, North Dakota (RM429.7)—End of study reach. East of Cass County, North Dakota, Road No. 31 and about 2 miles north of Cass County, North Dakota, Road No. 20.	Calibration site for dye, gas, and synoptic water-quality sampling and streamflow measurement	19.2

Table 2. Streamflow data for the Red River of the North, September 24 through 27, 2003.

[ft^3/s, cubic feet per second; ft^2, feet squared; ft/s, feet per second; ft, feet; --, no data]

Site number (fig. 2)	Sampling date	Sampling time	Mean daily discharge (ft^3/s)	Instantaneous streamflow (ft^3/s)	Area (ft^2)	Velocity (ft/s)	Width (ft)
1	--	--	--	--	--	--	--
2	--	--	[1]5.6	--	--	--	--
4	9/24/2003	1040	--	84.3	138	0.61	82
5	9/24/2003	1625	--	82.9	206	.40	70
5.7	9/24/2003	2000	--	83.3	197	.42	95
5.8	--	--	[2]16.3	--	--	--	--
6	9/25/2003	1220	--	95.4	152	.63	68
7	9/25/2003	1500	--	100.8	255	.40	96
9.5	9/26/2003	1110	--	99.8	213	.47	76
10	9/26/2003	1110	--	85.9	131	.65	62
10	9/26/2003	1905	--	84.3	132	.64	62

[1]Mean daily discharge from the Moorhead, Minnesota, wastewater-treatment plant outfall for September 24 through 27, 2003.

[2]Mean daily discharge from the Fargo, North Dakota, wastewater-treatment plant outfall for September 24 through 27, 2004.

Traveltime Data and Reaeration-Rate Coefficients

Traveltime measurements provide transport velocity values that integrate all of the physical variability within the reach between two points. Important factors in determining the effects of discharging treated wastewater to the Red River are the effect of the wastewater on the DO concentration in the river and the river's capacity to reaerate. The major source of oxygen to the Red River is the atmosphere. Traveltime data for the study reach are given in table 3, and reaeration-rate coefficients are given in table 4. The traveltime measurements were made when streamflow ranged from about 80 to 100 ft^3/s. Daily mean streamflow at the USGS Red River of the North at Fargo gaging station (05054000) for September 15 through 30, 2003, is shown in figure 3.

For the Wesolowski (1994) study and the 2003 study, Rhodamine WT (RWT) 20-percent stock solution (a conservative fluorescent dye) and nonconservative propane gas (commercial grade) tracers were used to determine traveltime and to calculate reaeration-rate coefficients. The dye and gas injections were done simultaneously. Traveltime calculations require only fluorescent dye concentration data, but reaeration-rate calculations require fluorescent dye and propane gas concentration data. Methods described by Kilpatrick and Wilson (1989) were used to measure traveltimes. The modified-tracer technique developed by Kilpatrick and others (1989) was used to measure reaeration rates.

Dye concentrations were determined using a fluorometer, which is an instrument that measures fluorescence. Fluorescence readings, when compared to known dye concentrations (standards), can be used to determine dye concentrations in water. The fluorescence of a water sample needs to be measured using the same fluorometer used to determine the known dye concentrations and under the same environmental conditions (Wilson and others, 1986). Otherwise, comparison of the fluorescence readings and the dye concentrations will not be representative.

Before dye injection during the 2003 study, the fluorometer was calibrated to a set of known RWT concentrations, usually 10, 25, and 100 micrograms per liter (μg/L). The prepared concentrations in the samples used to calibrate the fluorometer were mixed using water from the Red River to account for the natural fluorescence effects that might occur in the river. For quality assurance, the calibration of the fluorometer was checked after each dye trace to ensure that it had not drifted during the dye trace.

The RWT dye was slug injected at about the center of the river on September 24, 2003 (table 3). The amount of dye injected into the river was predetermined using the methods described by Kilpatrick and Wilson (1989). The dye was injected in the upstream part of the study reach, about 30 ft downstream from site 1 or 10 ft downstream from site 2 (fig. 4). During the 2003 study, this was the only section of the study reach that transitioned from a pool to a riffle.

At sites downstream from the dye injection, water samples were collected at predetermined intervals before and during the arrival of the dye cloud and until the dye concentration was less than 10 percent of the peak concentration passing the site. Streamflow measurements that were made at all dye-sampling sites were used to determine the location of the centroid of flow, and samples were collected at that location in the river.

Dye concentrations were measured at seven sites along the study reach. At sites 4, 5.7, 7, and 10, the fluorescence (dye concentration) of the water was measured continuously using a Self-Contained Underwater Fluorescence Apparatus (SCUFA) submersible fluorometer (fig. 5; Turner Designs, Inc., 2002a). These sites were selected because of availability and setup time of the SCUFA. A SCUFA measures the fluorescence of the water once per second and is capable of measuring RWT concentrations as small as 0.04 micrograms per liter (μg/L; Turner Designs, Inc., 2002a). For this study, the fluorescence readings obtained every second were averaged over 1-minute intervals and the 1-minute averages were stored for later analysis.

At sites 5, 6, and 9.5, the dye concentrations were measured in discrete water samples using a Turner Designs model 10 fluorometer. Samples were collected and later analyzed in the USGS laboratory in Bismarck, N. Dak. As with the SCUFA, the Turner Designs model 10 fluorometer was calibrated using standards mixed with river water to account for natural fluorescence effects. However, samples were not at ambient stream temperature when they were analyzed. Therefore, because fluorescence is affected by temperature, the dye concentrations for sites measured with the Turner Designs model 10 fluorometer were corrected to a temperature of 20°C (Turner Designs, Inc., 2002b).

Time-concentration curves are used to interpret traveltime and longitudinal dispersion (Kilpatrick and Wilson, 1989). For the 2003 study, time-concentration curves for seven sites (sites 4, 5, 5.7, 6, 7, 9.5, and 10) were prepared by plotting the measured dye concentration in relation to the elapsed traveltime after injection (fig. 6). A smooth curve was drawn through the plotted points. These curves represent the passage of the dye cloud at the sites. Traveltime and velocity are determined by comparing upstream and downstream curves. At sites 5, 6, and 9.5 where the fluorescence was measured in discrete samples, the leading and trailing edge of the time-concentration curve were not captured. As a result, time-concentration curves were more accurate for sites where the dye concentration was measured continuously using a SCUFA than for sites where dye concentrations were measured from discrete water samples.

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. The main features of the time-concentration curves are described in terms of elapsed traveltime after dye injection. Data for these and other features of the curves are given in table 3. The leading edge, centroid, and trailing edge for the discrete sample locations were estimated.

Wesolowski (1994) developed a relation between measured streamflow at the Red River of the North at Fargo gaging station (05054000) and traveltime of the dye cloud centroid (fig. 7) on the basis of data collected on two dates in August 1989, and one in April and October 1990. This relation is intended to be used to estimate flow velocities in the study reach. Except for site 4, the traveltime of the dye cloud centroid for each of the sites in the 2003 study plotted close to the lines shown in figure 7, verifying the relations developed by Wesolowski (1994). The traveltime of the dye cloud centroid measured for site 4 is much faster than the traveltime measured in previous studies (fig. 7). There is some uncertainty regarding the traveltime data for site 4 (table 3). Traveltime was used to calculate mean streamflow transport velocities for each of the sites (table 3). The mean streamflow transport velocity of the dye cloud at the centroid of 1.35 ft/s for site 4 (table 3) is much greater than the mean measured velocity of 0.61 ft/s for site 4 from the streamflow measurement (table 2). For other sites, the mean streamflow transport velocity of the dye cloud at the centroid (table 3) and the mean measured velocity (table 2) are much closer. Also, the mean streamflow transport velocity for site 4 is much greater than the mean streamflow transport velocity for other sites (table 3). These differences may be an indication of different channel characteristics between site 1 and site 4 as compared to the channel characteristics downstream from site 4 or it may be an indication of sampling error. In addition, there is some uncertainty as to whether the dye was 100-percent laterally mixed before reaching site 4. The actual channel length between site 1 and site 4 is 2.3 mi. Using equations from Kilpatrick and Wilson (1989), the length necessary for the dye to be 95-percent laterally mixed is between 2.1 and 2.5 mi, depending on how width is estimated. However, the channel length required to obtain 100-percent lateral mixing may be twice that required for 95-percent mixing (Kilpatrick and Wilson, 1989). When lateral mixing is still taking place, the tracer cloud typically moves faster than the mean stream velocity (Funkhouser and Barks, 2004). Thus, if the dye had been 100-percent laterally mixed, the traveltime would likely have been greater than the 2.3 hours estimated from the 2003 study.

For the 2003 study, propane gas was injected at a constant rate into the river, at the same location as the dye injection, through small-pore diffusers. The gas is not readily absorbed into water, and only 20 to 50 percent of the amount that is injected is ultimately absorbed, the rest being lost to the atmosphere (Wesolowski, 2000). Absorption efficiency is related to water depth, and about 2 ft of depth is required for efficient absorption. For the 2003 study, the propane gas was injected at a constant rate until the gas arrived at the most downstream site. Because continuous injection was used, longitudinal dispersion was not a factor in decreased concentration; therefore, the concentration decreased only by desorption and dilution.

Propane gas samples were collected for this study from the study reach after the gas concentration reached a plateau. The gas plateau is reached when the dye concentration returns to background concentrations (Kilpatrick and others, 1989). For the 2003 study, background concentrations were defined as less than 10 percent of the peak concentration. Discrete gas samples were collected at seven sites within a 3-hour period at 30-minute intervals. To meet residence time requirements between sampling sites, gas samples were collected only at sites 4, 5, 5.7, 6, 7, 9.5, and 10. Residence time (unitless) is the ratio of upstream to downstream gas concentration and should be greater than 2.72 to ensure accurate computation of the reaeration-rate coefficient (Kilpatrick and others, 1989). The gas samples were analyzed for propane concentration at Severn Trent Laboratories in Denver, Colo. The average of the propane concentrations for each site was used to calculate the reaeration-rate coefficient for the site.

The rate of reaeration in a river usually is expressed as a reaeration-rate coefficient (Friedman and Blanc, 1991). Calculated reaeration-rate coefficients for the study reach, adjusted to a 20°C water temperature, ranged from 1.18 to 1.58 per day when streamflow ranged from 80 to 100 ft^3/s (table 4) with an average of 1.4 per day. The reaeration-rate coefficient increased in the downstream direction. The residence time ranged from 1.89 to 6.89. The calculated average reaeration-rate coefficient from site 4 to site 10 should be an accurate estimate of the reaeration-rate coefficient for the study reach because the residence time is greater than 2.72.

To estimate reaeration-rate coefficients when streamflows differ from measured streamflows, a graphical regression of streamflows and reaeration-rate coefficients was developed by Wesolowski (1994). The reaeration-rate coefficient of 1.4 per day computed for the reach from site 4 to site 10, at an average streamflow of 85.1 ft^3/s, for the 2003 study was added to the original regression and the regression equation was recomputed (fig. 8). From the regression, an R-squared value of 0.949 was determined, indicating that 95 percent of the variability in the reaeration coefficient can be explained by streamflow. The R-squared value is large despite the fact that the reaeration coefficients were computed on the basis of data from different sites. For example, the reaeration-rate coefficient from the 2003 data was computed from data for sites 4 and 10, whereas the reaeration-rate coefficient for the April 1990 data point was computed from data for sites 4 and 7 (Wesolowski, 1994, table 7). The regression is valid for streamflows of 85 to 415 ft^3/s.

Table 3. Traveltime data for the Red River of the North, September 24 through 27, 2003.

[ft^3/s, cubic feet per second; µg/L, micrograms per liter; ft/s, feet per second]

Site number (fig. 2)	Distance downstream from dye injection (miles)	Instantaneous streamflow (ft^3/s)	Elapsed traveltime after dye injection (hours)				Time for dye cloud to pass site (hours)	Measured peak dye concentration (µg/L)	Mean streamflow transport velocity of dye cloud (ft/s)	
			Leading edge	Peak	Centroid	Trailing edge			Peak	Centroid
Slug injection of dye (2 liters) at 0916 hours on September 24, 2003, about 10 feet downstream from site 2; daily mean streamflow at Red River of the North at Fargo, N. Dak., gaging station (05054000) was 63 ft^3/s										
[1]4	2.3	84.3	1.88	2.32	2.50	4.58	2.7	27.3	1.46	1.35
[2]5	5.2	82.9	[3]12.00	14.23	[3]15.00	[3]19.00	7.0	6.9	.36	.34
[1]5.7	8.0	83.3	20.77	23.88	24.33	30.17	9.4	5.3	.43	.44
[2]6	9.8	95.4	[3]23.50	28.48	[3]30.00	[3]36.00	12.5	4.0	.56	.45
[1]7	11.8	100.8	30.23	35.37	36.02	41.77	11.5	3.2	.44	.50
[2]9.5	15.48	99.8	[3]38.00	45.73	[3]48.00	[3]60.00	22.0	3.0	.52	.45
[1]10	19.2	85.9	50.48	56.63	58.47	74.00	23.5	2.2	.50	.52

[1]A Self-Contained Underwater Fluorescence Apparatus (SCUFA) submersible fluorometer was used to continuously measure dye concentrations.

[2]A Turner Designs model 10 fluorometer was used to manually measure dye concentrations in discrete samples.

[3]Estimated.

Table 4. Reaeration-rate coefficients for the Red River of the North, September 24 through 27, 2003.

[Coefficients were determined by the steady-state method using a constant-rate injection of propane. ft³/s, cubic feet per second; °C, degrees Celsius; µg/L, micrograms per liter; --, not calculated]

Site number (fig. 2)	Distance downstream from propane injection (miles)	Instantaneous streamflow (ft³/s)	Mean water temperature (°C)	Traveltime of dye cloud centroid (hours)	Mean concentration of propane at 50-percent streamflow lines (µg/L)	Reaeration-rate coefficient at measured water temperature (per day)[1]	Reaeration-rate coefficient adjusted to 20°C water temperature (per day)	Residence time (streamflow-weighted ratio of upstream to downstream propane concentration)
Monitoring continuous propane injection from 0800 hours on September 24, 2003								
4	2.3	84.3	14.1	2.5	33.0	--	--	--
5	5.2	82.9	12.4	--	18.0	--	--	--
5.7	8.0	83.3	11.9	24.3	17.7	0.70	1.18	1.89
6	9.75	95.4	13.2	--	12.7	--	--	--
7	11.80	100.8	12.7	36.0	9.2	.95	1.58	1.59
9.5	15.48	99.8	12.2	--	7.5	--	--	--
10	19.20	85.9	11.9	58.5	4.7	.89	1.50	2.30
4 to 10	--	[2]85.1	--	--	--	.83	1.40	6.89

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

[2]Average of streamflows for sites 4 and 10.

Figure 4. Injecting dye at a site downstream from the Moorhead, Minnesota, wastewater-treatment plant outfall on the Red River of the North, September 24, 2003.

Figure 5. Self-Contained Underwater Fluorescence Apparatus (SCUFA).

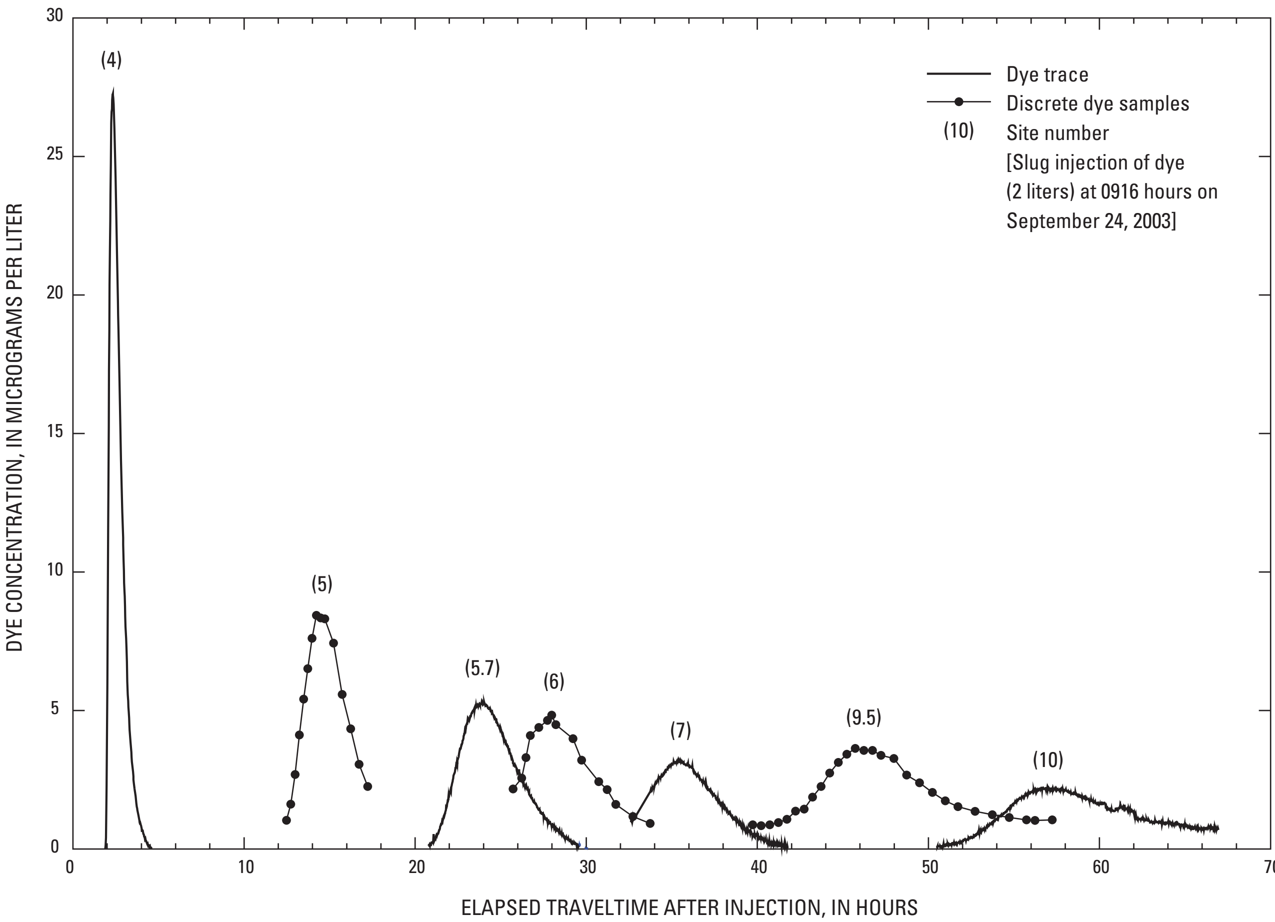
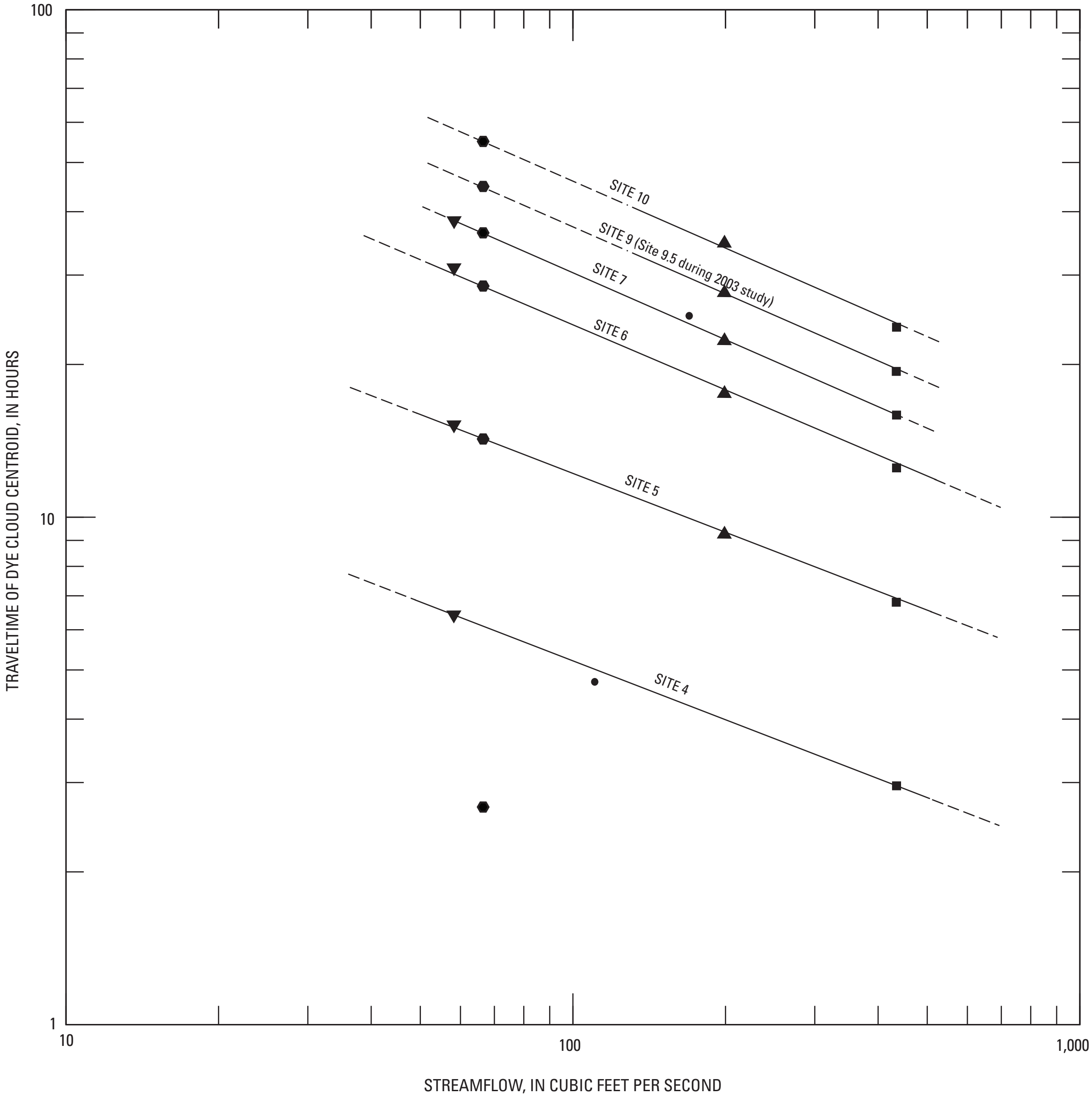


Figure 6. Dye concentration in relation to traveltime for sites 4, 5, 5.7, 6, 7, 9.5, and 10 on the Red River of the North.



EXPLANATION

Estimated line extension

Measured streamflow at Red River of the North gaging station—August 8, 1989

Measured streamflow at Red River of the North gaging station—August 17, 1989

Measured streamflow at Red River of the North gaging station—April 1990

Measured streamflow at site—October 1990

Measured streamflow at Red River of the North gaging station—September 24–27, 2003

Location of sites shown on figure 2

Figure 7. Traveltime of dye cloud centroid in relation to streamflow at the Red River of the North at Fargo, North Dakota, gaging station (05054000; modified from Wesolowski, 1994).

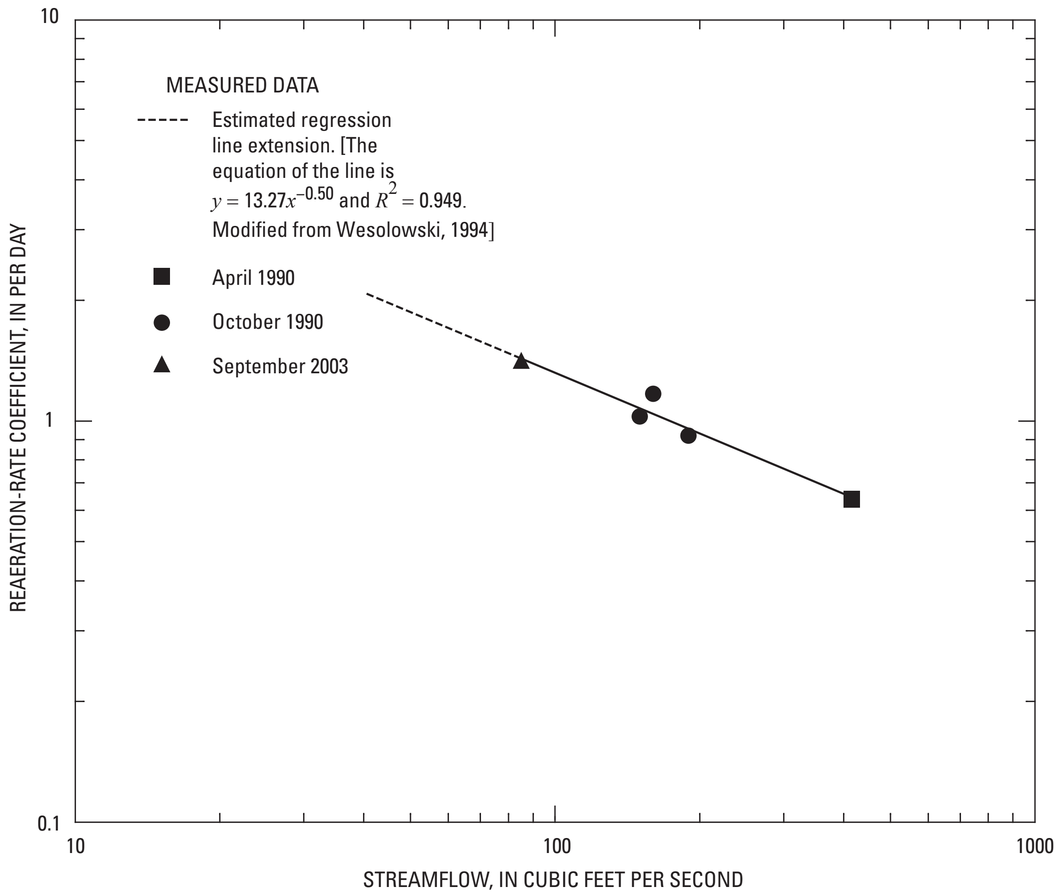


Figure 8. Reaeration-rate coefficient as a function of streamflow for the Red River of the North 30.8-mile reach from Fargo, North Dakota, to Georgetown, Minnesota, April and October 1990 and September 2003.

Water Sample Collection and Analysis

Water samples were collected during low, steady-state streamflow conditions from September 24 through 27, 2003. The samples were collected at 10 sites that included 1 upstream site used for the model boundary condition (site 1), 2 point-source sites (sites 2 and 5.8), and 7 calibration sites (sites 4, 5, 5.7, 6, 7, 9.5, and 10; fig. 2 and table 1). Field properties were measured and samples were collected according to methods described by the U.S. Geological Survey (variously dated). The samples were analyzed by the NDDH Laboratory in Bismarck, N. Dak., for selected properties and constituents (table 5).

Field quality assurance and quality control for the study described in this report were addressed by using the same data-collection procedures that are used in the USGS National Stream Quality Accounting Network (NASQAN) program (Kelly and others, 2001). Results for blank and replicate samples collected during 2003 for the NASQAN program in North Dakota indicate that no sample contamination was introduced by field activities (data on file at the USGS North Dakota Water Science Center, Bismarck, North Dakota).

Field properties were measured and water samples were collected at each site for a 24-hour period in 3-hour intervals from September 24 through 27, 2003, except for chlorophyll samples, which were collected every 12 hours. Unfiltered samples were collected at the centroid of streamflow where tracer samples were collected. Water-quality sampling began at each site near the time of the dye concentration peak and continued until 10 percent of the peak concentration or a concentration of 0.1 μg/L was reached.

Statistical summaries of field property values and constituent concentrations for each of the sites are given in table 6 for September 24 through 27, 2003. DO ranged from 7.3 milligrams per liter (mg/L) at site 2 to 10.1 mg/L at site 10. Ammonia concentrations ranged from less than 0.01 mg/L at four sites to 11.4 mg/L at the Moorhead WWTP outfall (site 2).

Samples were analyzed for the different forms of biochemical oxygen demand (BOD; table 5). BOD is a measure of the amount of oxygen consumed by decaying organic matter over a specified period of time and is commonly characterized by a two-step process (U.S. Environmental Protection Agency, 1995). Although both steps can occur simultaneously, the first step typically involves oxidation of carbonaceous organic matter by saprophytic organisms and is considered the carbonaceous phase of the BOD reaction. The second step, the nitrogenous phase of the BOD reaction, includes the conversion of organic nitrogen to ammonia by autotrophic organisms and the subsequent oxidation of ammonia. A standardized test that measures the amount of oxygen that has been consumed after incubation of the sample at 20°C for a specific length of time, usually 5 days, is used to determine BOD (U.S. Environmental Protection Agency, 1995). The BOD test, unless it is run with a nitrification inhibitor, measures the oxygen required to carry out both steps of the BOD reaction. This amount commonly is called total BOD (hereinafter referred to as BOD). If a nitrification inhibitor is used, the BOD test measures the oxidation of carbonaceous material only, and the results are reported as carbonaceous biochemical oxygen demand (CBOD). If independent tests are run for BOD and CBOD, NBOD can then be calculated by subtracting CBOD from BOD. For the BOD samples in this study, the NDDH laboratory used Standard Method 5210C (American Public Health Association, American Water Works Association, and Water Environment Federation, 1995). In this method BOD is determined, but in addition, NBOD is determined by analyzing the nitrite plus nitrate concentration within the BOD sample each time DO is measured. The nitrite plus nitrate concentrations are then corrected to compute the oxygen equivalency of the nitrification reaction (American Public Health Association, American Water Works Association, and Water Environment Federation, 1995). These values of NBOD are then subtracted from BOD to determine CBOD. In some instances, the NBOD concentrations were greater than the BOD concentrations, and the resulting CBOD concentrations were negative. These negative CBOD concentrations were reported as zero by the NDDH Laboratory (James Quarnstrom, North Dakota Department of Health Laboratory, written commun., 2006). For the majority of the samples analyzed for this study, the BOD test was run for 5 days to determine 5-day oxygen demand (BOD_5, $NBOD_5$, and $CBOD_5$; table 6). A 96-day test was also run for two samples from each site and results were reported after 5 days and after 96 days. Hereinafter, results reported for 96 days will be referred to as ultimate oxygen demand (BOD_u, $NBOD_u$, and $CBOD_u$).

Field properties were measured and water samples were collected from the Red River immediately downstream from the outfall pipe to determine the water-quality of the discharge from the Moorhead WWTP (site 2). At site 2, the end of the outfall discharge pipe was partially submerged below the water surface (fig. 9). As a result, some mixing of wastewater effluent with Red River water may have occurred, which may have caused the water-quality data for site 2 to be nonrepresentative of pure wastewater effluent. To determine whether water-quality data at site 2 are representative of pure wastewater effluent, data from site 2 for September 24 through 27, 2003, were compared with routine data collected by the Moorhead WWTP staff at the last sampling location inside the Moorhead WWTP (Andy Bradshaw, Moorhead Wastewater Treatment Facility, written commun., 2007; table 7). Average concentrations were consistent between the two sampling locations, which indicates water-quality data collected at site 2 are representative of pure wastewater effluent.

Water samples from the Fargo WWTP (site 5.8) were collected from an open, rock-lined channel that flows from the treatment plant and then discharges into the Red River. At site 5.8, only one set of field properties (table 7) was measured because of safety concerns in accessing the site. The samples were collected before the effluent discharge entered the river, so the constituent concentrations should represent pure wastewater effluent. Comparison of water-quality data from site 5.8 and data collected at the last sampling location inside the Fargo WWTP indicated average concentrations generally are in close agreement except for BOD_5 (table 7). The average BOD_5 concentration for samples collected from site 5.8 was smaller than that for samples collected inside the Fargo WWTP and is most likely related to analysis error at low concentrations.

Table 5. Properties and constituents for which water samples were analyzed.

[Samples were analyzed by the North Dakota Department of Health Laboratory, Bismarck, North Dakota. --, no data; <, less than; mL, milliliter]

Property or constituent	Parameter code	Measurement type	Minimum detection limit	Units
Streamflow	00060	Field	--	Cubic feet per second
Specific conductance	00095	Field	--	Microsiemens per centimeter at 25 degrees Celsius
pH	00400	Field	--	Standard units
Temperature, water	00010	Field	--	Degrees Celsius
Barometric pressure	00025	Field	--	Millimeters of mercury
Dissolved oxygen	00300	Field	--	Milligrams per liter
Biochemical oxygen demand (5th day and [1]ultimate)	([2])	Laboratory	--	Milligrams per liter
Nitrogenous biochemical oxygen demand (5th day and [1]ultimate)	([2])	Calculated	--	Milligrams per liter
Carbonaceous biochemical oxygen demand (5th day and [1]ultimate)	([2])	Calculated	--	Milligrams per liter
Nitrite plus nitrate, unfiltered	00630	Laboratory	<0.02	Milligrams per liter
Ammonia, unfiltered	00610	Laboratory	<.010	Milligrams per liter
Nitrogen, ammonia plus organic (Kjeldahl), unfiltered	00625	Calculated	<.001	Milligrams per liter
Nitrogen, total, unfiltered	00600	Laboratory	<.015	Milligrams per liter
Phosphorus, unfiltered	00665	Laboratory	<.004	Milligrams per liter
Chlorophyll *a*[3]	70951	Laboratory	([3])	Micrograms per liter
Chlorophyll *b*[3]	70952	Laboratory	([3])	Micrograms per liter

[1]Results reported after 96 days were referred to as ultimate oxygen demand.

[2]Parameter code not available.

[3]The detection limit for chlorophyll *a* and *b* depends on the volume of water that is filtered through the media. For chlorophyll *a*, the limit, in micrograms per liter, is 1.5 for 2,000 mL of water, 2.0 for 1,000 mL of water, 6.0 for 500 mL of water, and 12.0 for 250 mL of water. For chlorophyll *b*, the limit, in micrograms per liter, is 0.5 for 2,000 mL of water, 1.0 for 1,000 mL of water, 2.0 for 500 mL of water, and 4.0 for 250 mL of water.

Table 6. Statistical summaries for selected field property values and constituent concentrations for the Red River of the North, September 24 through 27, 2003.

[Site names and locations are given in table 1. Number in parentheses is parameter code. µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; BOD, biochemical oxygen demand; µg/L, micrograms per liter; <, less than; --, not calculated; WWTP, wastewater-treatment plant; E, estimated]

	Specific conductance (µS/cm at 25°C) (00095)	pH (standard units) (00400)	Temperature, water (°C) (00010)	Dissolved oxygen (mg/L) (00300)	BOD, 5-day (mg/L) (00319)	BOD ultimate[1,2] mg/L	Nitrogenous BOD, 5-day (mg/L) (00321)	Nitrogenous BOD, ultimate[1,2] (mg/L)
Site 1; Red River 0.1 mile below 12th Ave N., Fargo, N. Dak. (RM448.90)								
Number of values	9	9	9	9	9	2	9	2
Minimum	688	8.0	13.7	8.6	1.19	7.13	0.18	1.83
Mean	724	8.2	14.4	9.0	1.45	--	.22	--
Median	725	8.2	14.6	8.8	1.49	--	.20	--
Maximum	750	8.3	14.8	9.8	1.65	7.32	.38	1.91
Site 2; Red River at WWTP outflow at Moorhead, Minn.								
Number of values	9	9	9	9	9	2	9	2
Minimum	1,160	7.0	14.5	7.3	6.44	62.2	7.22	49.4
Mean	1,166	7.0	15.3	7.5	7.29	--	9.62	--
Median	1,170	7.0	15.3	7.5	7.26	--	8.82	--
Maximum	1,170	7.0	16.3	7.7	7.89	62.4	13.2	52.8
Site 4; Red River 2.3 mile below 12th Ave. at Fargo, N. Dak. (RM446.60)								
Number of values	9	9	9	9	9	2	9	2
Minimum	732	8.1	13.5	8.1	2.25	11.6	1.51	5.94
Mean	754	8.1	14.1	8.6	2.66	--	1.95	--
Median	758	8.1	14.0	8.6	2.71	--	2.01	--
Maximum	769	8.2	15.0	9.3	2.94	11.7	2.29	6.03
Site 5; Red River 2 mile above N. Broadway St. Bridge at Fargo, N. Dak.								
Number of values	8	8	8	8	8	2	8	2
Minimum	751	8.1	11.7	8.2	2.24	9.76	1.37	4.8
Mean	767	8.2	12.4	9.0	2.54	--	1.62	--
Median	770	8.2	12.4	9	2.56	--	1.60	--
Maximum	776	8.2	13.2	9.5	2.74	10.6	2.01	5.58
Site 5.7; Red River 0.6 mile above N. Broadway St. Bridge at Fargo, N. Dak.								
Number of values	9	9	9	9	9	2	9	2
Minimum	750	8.1	11.3	8.8	2.16	9.05	1.23	3.66
Mean	769	8.2	11.9	9.1	2.44	--	1.53	--
Median	771	8.2	12.1	9.1	2.43	--	1.60	--
Maximum	781	8.2	12.2	9.4	2.64	10.1	1.69	4.71
Site 5.8; Red River at WWTP outflow at Fargo, N. Dak.								
Number of values	1	1	1	1	9	2	9	2
Minimum	1,180	7.4	19.7	8.8	1.31	12.5	1.83	.46
Mean	--	--	--	--	1.72	--	--	--
Median	--	--	--	--	1.66	--	--	--
Maximum	1,180	7.4	19.7	8.8	2.19	13.2	5.94	13.7

Table 6. Statistical summaries for selected field property values and constituent concentrations for the Red River of the North, September 24 through 27, 2003.—Continued

[Site names and locations are given in table 1. Number in parentheses is parameter code. µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; BOD, biochemical oxygen demand; µg/L, micrograms per liter; <, less than; --, not calculated; WWTP, wastewater-treatment plant; E, estimated]

Carbonaceous BOD, 5-day (mg/L) (00320)	Carbonaceous BOD, ultimate[1,2] (mg/L)	Nitrite plus nitrate, unfiltered (mg/L) (00630)	Ammonia, unfiltered (mg/L) (00610)	Ammonia plus organic nitrogen, water, unfiltered (mg/L) (00625)	Nitrogen, total, unfiltered (mg/L) (00600)	Phosphorus, unfiltered (mg/L) (00665)	Chlorophyll *a* (µg/L) (70951)	Chlorophyll *b* (µg/L) (70952)
Site 1; Red River 0.1 mile below 12th Ave N., Fargo, N. Dak. (RM448.90)								
9	2	9	9	9	9	9	2	2
.95	5.22	.02	<.01	.47	.49	.18	15.3	1.99
1.23	--	.03	--	.53	.56	.24	--	--
1.23	--	.03	--	.54	.56	.24	--	--
1.46	5.49	.05	<.01	.58	.61	.31	16.8	3.56
Site 2; Red River at WWTP outflow at Moorhead, Minn.								
9	2	9	9	9	9	9	2	2
--	9.4	9.82	9.89	10.7	21.1	3.74	<6.00	<2.00
--	--	10.1	10.6	11.5	21.6	3.86	--	--
--	--	10.1	10.5	11.3	21.4	3.85	--	--
--	13	10.4	11.4	12.2	22.2	4.02	E6.67	E2.22
Site 4; Red River 2.3 mile below 12th Ave. at Fargo, N. Dak. (RM446.60)								
9	2	9	9	9	9	9	2	2
.36	5.57	.68	.20	.87	1.68	.41	13.1	2.19
.71	--	.78	.4	1.11	1.89	.47	--	--
.70	--	.77	.35	1.12	1.89	.45	--	--
1.01	6.86	.89	.54	1.29	2.18	.62	13.4	2.22
Site 5; Red River 2 mile above N. Broadway St. Bridge at Fargo, N. Dak.								
8	2	8	8	8	8	8	2	2
.53	4.96	.75	.17	.86	1.61	.43	3.80	2.08
.92	--	.88	.21	1.00	1.88	.4	--	--
1.01	--	.90	.20	1.02	1.95	.44	--	--
1.20	5.02	.96	.34	1.13	1.99	.46	16.0	5.05
Site 5.7; Red River 0.6 mile above N. Broadway St. Bridge at Fargo, N. Dak.								
9	2	9	9	9	9	9	2	2
.55	5.39	.78	.08	.77	1.55	.40	12.5	3.14
.91	--	.92	.13	.90	1.82	.42	--	--
.90	--	.93	.14	.92	1.87	.43	--	--
1.14	5.39	1.01	.17	.97	1.92	.44	16.0	4.14
Site 5.8; Red River at WWTP outflow at Fargo, N. Dak.								
9	1	9	9	8	9	9	0	0
1.34	12.7	19.6	<.01	.50	21.3	4.76	--	--
1.75	--	23.1	--	1.11	24.1	4.84	--	--
1.71	--	23.6	--	.80	24.8	4.84	--	--
2.19	--	25.4	<.01	2.10	25.3	4.94	--	--

Table 6. Statistical summaries for selected field property values and constituent concentrations for the Red River of the North, September 24 through 27, 2003.—Continued

[Site names and locations are given in table 1. Number in parentheses is parameter code. µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; BOD, biochemical oxygen demand; µg/L, micrograms per liter; <, less than; --, not calculated; WWTP, wastewater-treatment plant; E, estimated]

Table 6. Statistical summaries for selected field property values and constituent concentrations for the Red River of the North, September 24 through 27, 2003.—Continued

[Site names and locations are given in table 1. Number in parentheses is parameter code. µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; BOD, biochemical oxygen demand; µg/L, micrograms per liter; <, less than; --, not calculated; WWTP, wastewater-treatment plant; E, estimated]

	Specific conductance (µS/cm at 25°C) (00095)	pH (standard units) (00400)	Temperature, water (°C) (00010)	Dissolved oxygen (mg/L) (00300)	BOD, 5-day (mg/L) (00319)	BOD ultimate[1,2] mg/L	Nitrogenous BOD, 5-day (mg/L) (00321)	Nitrogenous BOD, ultimate[1,2] (mg/L)	Carbonaceous BOD, 5-day (mg/L) (00320)	Carbonaceous BOD, ultimate[1,2] (mg/L)	Nitrite plus nitrate, unfiltered (mg/L) (00630)	Ammonia, unfiltered (mg/L) (00610)	Ammonia plus organic nitrogen, water, unfiltered (mg/L) (00625)	Nitrogen, total, unfiltered (mg/L) (00600)	Phosphorus, unfiltered (mg/L) (00665)	Chlorophyll *a* (µg/L) (70951)	Chlorophyll *b* (µg/L) (70952)
Site 6; Red River at Cass Co. 20 Bridge at Fargo, N. Dak. (RM439.15)																	
Number of values	9	9	9	9	9	2	8	2	9	2	9	9	9	9	9	2	2
Minimum	810	8.0	12.9	8.8	1.76	9.85	.18	4.52	.54	5.33	3.39	.06	.76	4.52	.95	9.90	2.17
Mean	848	8.1	13.2	9.2	2.01	--	.96	--	1.15	--	4.67	.10	.86	5.53	1.18	--	--
Median	860	8.1	13.0	9.2	2.06	--	1.12	--	.88	--	4.75	.10	.82	5.60	1.21	--	--
Maximum	867	8.1	14.1	9.9	2.15	10.4	1.33	4.62	1.96	5.78	5.57	.14	1.13	6.37	1.29	E10.0	E3.33
Site 7; Red River 1.5 mile below Cass Co. 20 at Fargo, N. Dak. (RM437.6)																	
Number of values	9	9	9	9	9	2	8	2	8	2	9	8	9	9	9	2	2
Minimum	815	8.0	12.3	8.5	1.79	10.1	.05	2.01	.65	6.26	3.34	.03	.51	4.09	.81	E10.0	E3.33
Mean	853	8.1	12.7	9.2	1.93	--	1.47	--	1.32	--	4.47	.08	.94	5.40	1.08	--	--
Median	856	8.1	12.5	9.4	1.94	--	.80	--	1.36	--	4.72	.08	.87	5.63	1.15	--	--
Maximum	871	8.2	13.4	9.8	2.13	10.3	7.08	3.84	2.13	8.26	5.22	.14	1.56	6.46	1.22	13.8	3.68
Site 9.5; Red River at Cass Co. 22 Bridge below Fargo, N. Dak.																	
Number of values	9	9	9	9	9	2	7	2	9	2	9	9	9	9	9	2	2
Minimum	837	8.1	11.5	8.9	1.57	9.22	.18	3.47	.50	5.75	3.86	<.01	.46	4.45	.85	9.90	1.04
Mean	866	8.1	12.2	9.2	1.80	--	.86	--	1.14	--	4.41	.09	.82	5.22	1.06	--	--
Median	871	8.1	12.4	9.2	1.78	--	.87	--	.88	--	4.52	.08	.83	5.53	1.11	--	--
Maximum	881	8.2	12.8	9.6	2.11	9.93	1.23	4.07	2.11	5.86	4.79	.15	1.12	5.77	1.17	14.2	4.87
Site 10; Red River 3.7 mile above Cass Co. 22 Bridge below Fargo, N. Dak.																	
Number of values	9	9	9	9	9	2	9	2	9	2	9	8	9	9	9	2	2
Minimum	866	8.1	11.4	9.3	1.50	8.57	.14	3.75	.72	4.46	3.34	<.01	.92	4.26	.87	E9.68	E3.22
Mean	880	8.1	11.9	9.7	1.74	--	.45	--	1.28	--	4.30	.05	1.03	5.34	1.05	--	--
Median	884	8.1	11.8	9.5	1.69	--	.27	--	1.35	--	4.38	.04	1.02	5.41	1.09	--	--
Maximum	889	8.2	12.5	10.1	2.11	9.23	.96	4.11	1.97	5.48	4.96	.19	1.27	5.93	1.16	<12.0	<4.00

[1]Results reported after 96 days were referred to as ultimate oxygen demand.

[2]Parameter code not available.

Table 7. Comparison of wastewater-treatment plant effluent water-quality data at different sampling locations for Fargo, North Dakota and Moorhead, Minnesota.

[mg/L, milligrams per liter; °C, degrees Celsius; BOD, biochemical oxygen demand; WWTP, wastewater-treatment plant; --, not calculated; <, less than]

	pH (standard units) (00400)	Temperature, water (°C) (00010)	Dissolved oxygen (mg/L) (00300)	BOD, 5-day (mg/L) (00319)	Carbonaceous BOD, 5-day (mg/L) (00320)	Ammonia, unfiltered (mg/L) (00610)	Phosphorus, unfiltered (mg/L) (00665)
Red River of the North at WWTP outflow at Moorhead, Minn. (site 2)[1]							
Number of values	9	9	9	9	9	9	9
Minimum	7.0	14.5	7.3	6.44	--	9.89	3.74
Mean	7.0	15.3	7.5	7.29	--	10.6	3.86
Median	7.0	15.3	7.5	7.26	--	10.5	3.85
Maximum	7.0	16.3	7.7	7.89	--	11.4	4.02
Last sampling point inside Moorhead, Minn., WWTP[2]							
Number of values	5	5	5	--	3	3	1
Minimum	7.0	14.0	6.9	--	3.6	8.70	4.18
Mean	7.4	15.6	7.6	--	4.8	8.90	--
Median	7.7	16.0	7.6	--	4.9	8.80	--
Maximum	7.7	17.0	8.2	--	5.8	9.20	4.18
Red River of the North at WWTP outflow at Fargo, N. Dak. (site 5.8)[1]							
Number of values	1	1	1	9	9	9	9
Minimum	7.4	19.7	8.8	1.31	1.34	<.01	4.76
Mean	--	--	--	1.72	1.75	--	4.84
Median	--	--	--	1.66	1.71	--	4.84
Maximum	7.4	19.7	8.8	2.19	2.19	<.01	4.94
Last sampling point inside Fargo, N. Dak., WWTP[2]							
Number of values	5	5	2	3	--	2	--
Minimum	7.5	19.7	8.6	3.10	--	<.10	--
Mean	7.5	20.4	--	3.50	--	--	--
Median	7.5	20.8	--	3.30	--	--	--
Maximum	7.6	20.9	8.6	4.10	--	.13	--

[1]Based on data for samples collected during 2003 study, September 24 through 27, 2003. Samples were collected by the U.S. Geological Survey and analyzed by the North Dakota Department of Health, Bismarck, North Dakota.

[2]Based on data for daily samples collected September 22 through 27, 2003. Samples were collected and analyzed by staff at the wastewater-treatment plant.

Figure 9. Moorhead, Minnesota, wastewater-treatment plant outfall during September 24 through 27, 2003, streamflows.

Model Implementation

The Fargo WASP water-quality model was developed using the USEPA WASP model, Version 7.3 (Ambrose and others, 1988; Wool and others, 2003; U.S. Environmental Protection Agency, 2005). WASP 7.3 is an enhanced Windows version of the WASP model and has features that include a preprocessor, a rapid data processor, and a graphical postprocessor that facilitate application of the model. The basic equation solved by the WASP 7.3 model is the one-dimensional, advection-dispersion, mass-transport equation, which is numerically integrated in space and time for each water-quality constituent. For the purposes of this study, the WASP model was used in a steady-state mode.

Computational Grid

The physical domain of the Fargo WASP water-quality model includes the Red River main stem from just downstream from Dam A (site 1) to about 2 mi upstream from the confluence of the Sheyenne and Red Rivers (site 10, fig. 10). The model includes one main-branch and two point-source sites representing discharges from the Moorhead WWTP outfall (site 2) and the Fargo WWTP outfall (site 5.8). The 19.2-mi reach of the Red River is represented by 306 one-dimensional segments. Model segments were proportionally distributed among the sites so each segment was about 330 ft in length.

Streamflow and Water-Quality Boundary Conditions

Streamflow and water-quality boundary conditions were specified for September 17 through September 27, 2003. The first 7 days were used as an initialization period. That number of days represents about twice the traveltime through the study reach. Thus, simulated results subsequent to the 7-day initialization period should be unaffected by initial conditions.

Streamflow boundary conditions were specified for the most upstream (main-branch) site (site 1) and for each of the two point-source sites (sites 2 and 5.8; the WWTP outfalls). A single streamflow value was specified for each of the boundary conditions and held constant because streamflow was assumed to be steady. An upstream streamflow boundary condition of 73 ft^3/s was determined by taking an average of the instantaneous streamflow measured at site 4 on September 24, 2003 (table 2), with the daily mean streamflow at the Red River of the North at Fargo gaging station (05054000; fig. 3) on September 24, 2003. Daily mean discharges from the Moorhead and Fargo WWTPs were obtained from the respective facilities. Discharge from the WWTP outfalls was added as a point inflow in the model segment that represented the actual location of the WWTP outfall. The mean discharge for September 24 through 27, 2003, at the Moorhead WWTP outfall (site 2) was 5.6 ft^3/s and at the Fargo WWTP outfall (site 5.8) was 16.3 ft^3/s.

As with streamflow boundary conditions, water-quality boundary conditions were specified for the most upstream site (site 1) and for each of the two point-source sites (sites 2 and 5.8). Water-quality boundary conditions were specified for DO, $CBOD_u$, nitrate, ammonia, organic nitrogen, and chlorophyll *a* (a surrogate for phytoplankton). An average of the measured time series of concentrations was used to define the water-quality boundary conditions.

The following assumptions were made before specifying water-quality boundary conditions in the model:

- Nitrite plus nitrate concentrations were used to represent nitrate concentrations because samples were not analyzed for nitrite concentrations. Hereinafter, nitrite plus nitrate will be referred to as nitrate.
- If measured concentrations for selected constituents were less than the detection limit, half the detection limit was used as the water-quality boundary condition.
- Because of safety issues associated with measuring field properties at the Fargo WWTP outfall (site 5.8), the average DO concentration of 8.7 mg/L for samples collected at the last sampling location inside the Fargo WWTP (table 7) was used as the water-quality boundary condition for the Fargo WWTP outfall, and the average chlorophyll *a* concentration for samples collected at the Moorhead WWTP outfall (site 2) was used as the boundary condition for the Fargo WWTP outfall.
- Organic nitrogen concentrations were calculated by subtracting ammonia concentrations from Kjeldahl nitrogen concentrations (table 5).

Model Calibration and Testing

The Fargo WASP water-quality model was calibrated for streamflow, transport, DO, and ammonia using data collected from September 24 through 27, 2003. Model testing was performed using available data from the 1989 and 1990 data sets collected during the Wesolowski (1994) study.

Streamflow and Transport

The Fargo WASP water-quality model was calibrated for streamflow and transport during steady-state conditions throughout the study reach. In the USEPA WASP model, streamflow can be simulated using a kinematic wave formulation (Wool and others, 2003). The kinematic wave formulation, which is based on Manning's equation, assumes one-dimensional flow and uses channel slope, width, initial depth, flow, and roughness to calculate water movement (Wool and

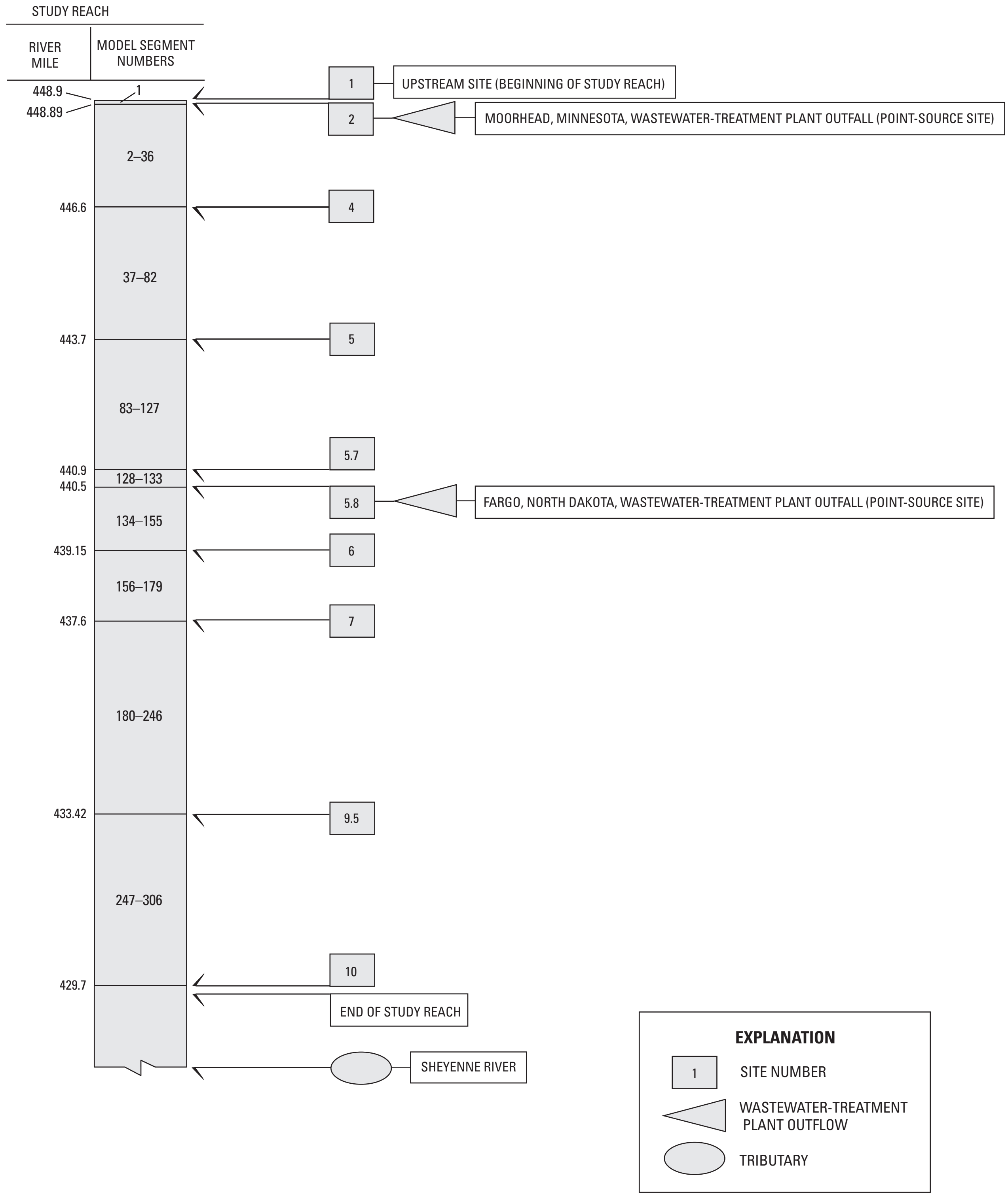


Figure 10. Schematic of the Fargo Water-Quality Analysis Simulation Program model.

others, 2003). In the kinematic wave formulation, the default is a rectangular channel shape unless the hydraulic coefficients for velocity and depth are specified. Initially, the kinematic wave formulation was used to simulate streamflow in the Fargo WASP water-quality model, but the assumption of a rectangular channel shape resulted in simulated velocities and depths that were not in close agreement with measured velocities and depths. Therefore, to better simulate velocities and depths with the Fargo WASP water-quality model, hydraulic coefficients were specified. Accurate velocities are important in calibration of the model for transport because of the effects of velocity on traveltime. Accurate depths are important in calibration of the model for DO because of the effects of depth on reaeration.

In the USEPA WASP model, power functions are used, after hydraulic coefficients are specified, to relate velocity, depth, and channel width to streamflow. The power functions are described by

$$V = aQ^b, \quad (1)$$

$$D = cQ^d, \quad (2)$$

$$B = eQ^f, \quad (3)$$

where

V is the average velocity, in feet per second;
Q is streamflow, in cubic feet per second;
D is the average depth, in feet;
B is the average width, in feet; and
a, b, c, d, e, and f are empirical hydraulic coefficients.

When the power functions are used to simulate streamflow, the USEPA WASP model only requires specification of the hydraulic coefficients for velocity (eq. 1) and depth (eq. 2) because the coefficients for width (eq. 3) are implicitly determined by continuity (Wool and others, 2003). Brown and Barnwell (1987) indicated exponents *b* and *d* should be estimated and then multipliers *a* and *c* should be calibrated to measured streamflow, velocity, and depth. For this study, average literature values of 0.43 and 0.45 were used for exponents *b* and *d*, respectively (Wool and others, 2003). Multipliers *a* and *c* then were calculated from 2003 measured streamflow, velocity, and depth for each site (table 8).

After the power functions were specified for the Fargo WASP water-quality model, the model was calibrated for transport. Because of uncertainty associated with the traveltime and velocity determined from the dye study for site 4, calibration for transport was started at site 5. Thus, all sites downstream from site 5 were used in the calibration. Calibration was achieved by fitting simulated time-concentration dye curves to measured time-concentration dye curves through the adjustment of velocity and longitudinal dispersion coefficients. Velocity was adjusted by varying the segments to which the power functions were applied until the best fit between measured and simulated traveltimes was achieved. Initially, the power function for a given site was applied midway between the sites immediately upstream and downstream from the given site. The segments to which a given power function was applied then were adjusted to achieve the best fit between the measured and simulated traveltimes (table 9). The longitudinal dispersion coefficients computed by Wesolowski (1994) for the same reach of the Red River as used in this study were between 10 and 100 ft^2/s. For the Fargo WASP water-quality model, longitudinal dispersion coefficients were determined from calibration and were within the typical range of those computed by Wesolowski (1994). Longitudinal dispersion coefficients for the Fargo WASP water-quality model were determined to be 10 ft^2/s for segments 1–59 (sites 1 to 4), 22 ft^2/s for segments 60–157 (sites 5 to 6), and 55 ft^2/s for segments 158–306 (sites 7 to 10).

After the Fargo WASP water-quality model was calibrated for transport, goodness-of-fit statistics were computed for selected features of the time-concentration dye curves. Goodness-of-fit statistics were computed only for sites where a SCUFA was used to measure dye concentration (namely, sites 5.7, 7, and 10, table 10). The simulated time-concentration dye curves for the SCUFA sites were in reasonable agreement with the measured time-concentration dye curves (fig. 11). The simulated peak concentrations for sites 5.7, 7, and 10 were within 10 percent of the measured concentrations (fig. 11 and table 10). Dye concentrations measured with the SCUFA and Turner Designs model 10 fluorometers generally are accurate to within 5 percent of the calibration standard (Thomas Brumett, Turner Designs, Inc., written commun., 2007). The peak concentrations for sites 5.7, 7, and 10 were closest to a calibration standard of 10 µg/L, so measured dye concentrations should be accurate to within plus or minus 0.5 µg/L. On the basis of the accuracy of the SCUFA, differences between the measured and simulated peak concentrations for sites 5.7, 7, and 10 were within the measurement error of the fluorometer. The simulated traveltimes of the dye cloud centroids for sites 5.7, 7, and 10 were within 7 percent of the measured traveltimes (table 10). The variances of the simulated dye concentrations were similar to the variances of the measured dye concentrations (table 10), indicating dispersion was reproduced reasonably well. For sites 5, 6, and 9.5, the overall timing of the simulated dye cloud was reasonable as compared with that of the measured dye clouds (fig. 12). Also, for sites 5, 6, and 9.5, the peak concentrations were all within 0.5 µg/L, or the measurement error of the fluorometer.

Table 8. Estimated hydraulic coefficients for power functions used in Fargo Water-Quality Analysis Simulation Program model.

[*a* and *b*, velocity multiplier and exponent used in the power function, $V = aQ^b$; *c* and *d*, depth multiplier and exponent used in the power function, $D = cQ^d$]

Site number (fig. 2)	*Q*[1] (cubic feet per second)	*V*[2] (feet per second)	*a*[4]	*b*[3]	*D*[5] (feet)	*c*[7]	*d*[6]
4	84.3	0.61	0.0906	0.43	2.19	0.2976	0.45
5	82.9	.40	.0599	.43	2.19	.2997	.45
5.7	83.3	.37	.0552	.43	2.26	.3093	.45
6	95.4	.63	.0887	.43	2.14	.2751	.45
7	100.8	.39	.0537	.43	2.48	.3115	.45
9.5	99.8	.47	.0649	.43	2.72	.3429	.45
10	85.9	.65	.0958	.43	2.49	.3363	.45

[1]Measured streamflow on September 24, 25, or 26, 2003.

[2]Average measured velocity between September 24 and 26, 2003.

[3]An average literature value (Brown and Barnwell, 1987).

[4]Given *Q*, *V*, and *b*, the power function was used to solve for *a*.

[5]Average measured depth on September 24, 25, or 26, 2003.

[6]An average literature value (Brown and Barnwell, 1987).

[7]Given *Q*, *V*, and *d*, the power function was used to solve for *c*.

Table 9. Calibrated hydraulic coefficients for power functions used in Fargo Water-Quality Analysis Simulation Program model.

[*a* and *b*, velocity multiplier and exponent used in the power function, $V = aQ^b$; *c* and *d*, depth multiplier and exponent used in the power function, $D = cQ^d$]

Segments where power function was applied	*a*	*b*	*c*	*d*
1–59	0.0906	0.43	0.2976	0.45
60–83	.0599	.43	.2997	.45
84–133	.0552	.43	.3093	.45
134–213	.0537	.43	.3115	.45
214–247	.0649	.43	.3429	.45
248–306	.0958	.43	.3363	.45

Table 10. Goodness-of-fit statistics for calibration of transport.

[µg/L, micrograms per liter. Percent difference is simulated minus measured divided by measured]

Site number (fig. 2)	Peak concentration (µg/L)			Traveltime of dye cloud centrorid (hours)			Variance of dye cloud concentration ($µg^2/L^2$)	
	Measured	Simulated	Percent difference	Measured	Simulated	Percent difference	Measured	Simulated
5.7	5.32	4.82	–9.4	24.33	23.63	–2.9	2.67	3.23
7	3.23	3.20	–.9	36.02	33.50	–7.0	.60	.77
10	2.20	2.14	–2.7	58.47	59.70	2.1	.51	.45

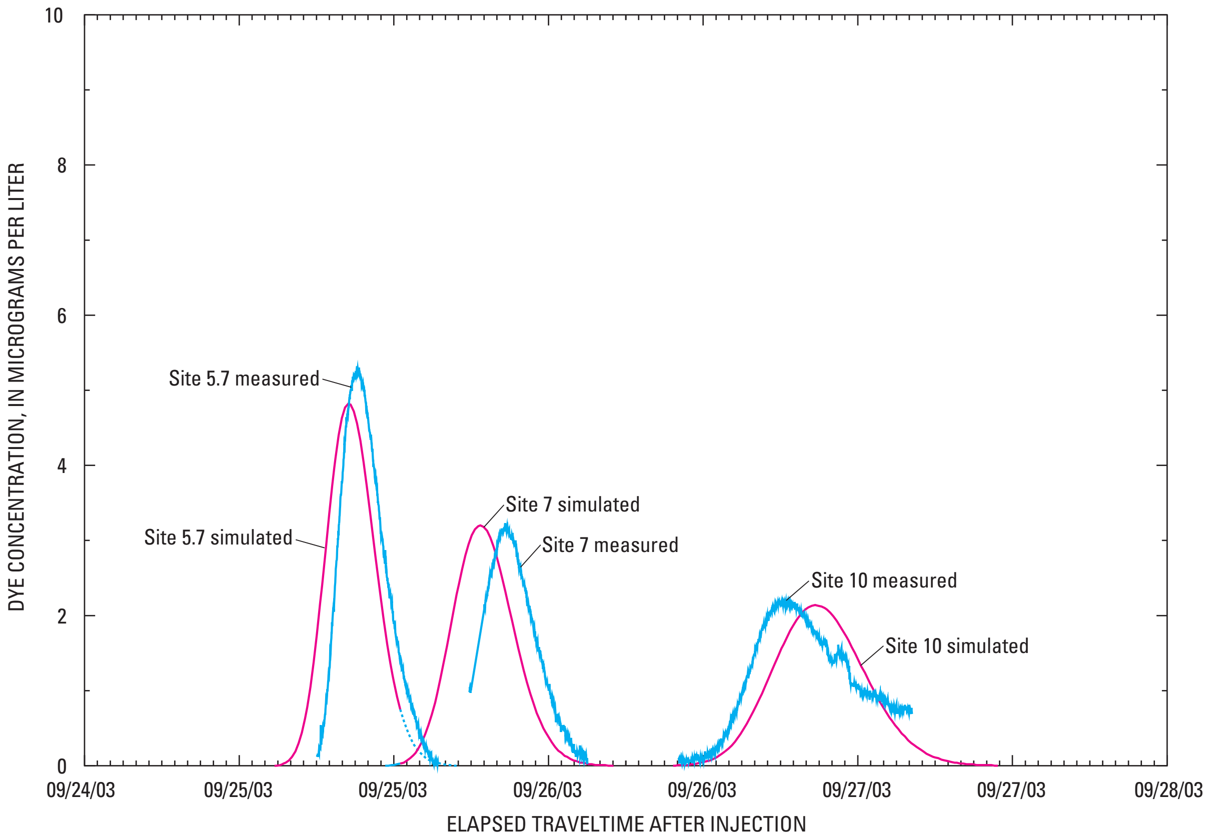


Figure 11. Measured and simulated dye concentrations for Fargo Water-Quality Analysis Simulation Program model calibration sites 5.7, 7, and 10 for September 24 through 27, 2003. At these sites, the dye concentration of the water was measured continuously using a Self-Contained Underwater Fluorescence Apparatus (SCUFA) submersible fluorometer.

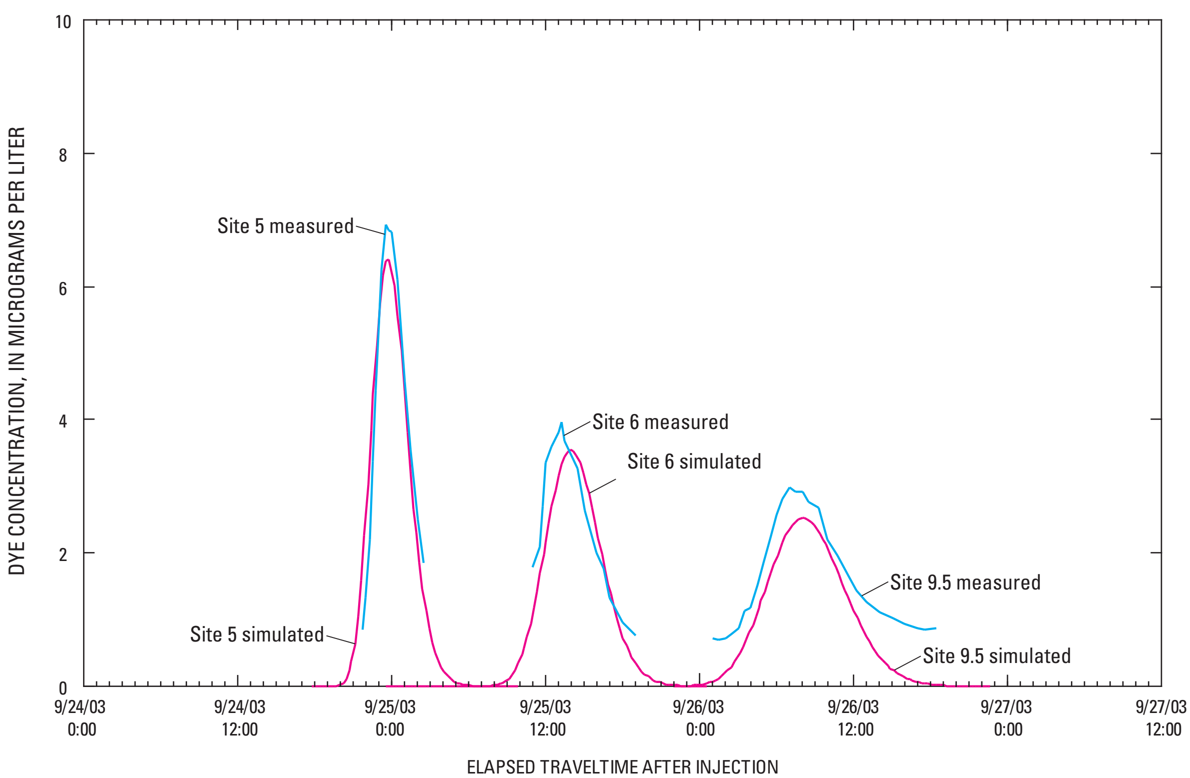


Figure 12. Measured and simulated dye concentrations for Fargo Water-Quality Analysis Simulation Program model calibration sites 5, 6, and 9.5 for September 24 through 27, 2003. At these sites, the dye concentration of the water was measured discretely using a Turner Designs model 10 fluorometer.

Water Quality

Several state variables and kinetic interactions are used in the USEPA WASP model to simulate DO and nutrient cycles (fig. 13). Although the phosphorus cycle can be simulated, only DO and the nitrogen cycle were simulated for the Fargo WASP water-quality model. State variables are defined here as those variables for which concentrations were simulated over time. State variables used in the Fargo WASP water-quality model included DO, CBOD, nitrate, ammonia, and organic nitrogen. Ultimate CBOD was used to represent CBOD in the Fargo WASP water-quality model. Several kinetic interactions affecting the state variables and model parameters describing the kinetic interactions were included in the Fargo WASP water-quality model (table 11). The Fargo WASP water-quality model was calibrated for DO and ammonia by specifying model parameters and adjusting selected model parameters to achieve the best fit between measured and simulated concentrations at sites 4, 5, 5.7, 6, 7, 9.5 and 10.

A combination of measured values, literature values, and calibrated values was used for the model parameters (table 11). The reaeration-rate coefficient and sediment oxygen demand describe kinetic interactions involving reaeration by atmospheric oxygen and DO consumption (fig. 13 and table 11). The calculated average reaeration-rate coefficient of 1.4 per day was used in the Fargo WASP water-quality model (table 4). For sediment oxygen demand, an average value was used from the Wesolowski (1994) study because sediment oxygen demand was not measured during the 2003 study (table 11). The BOD decay-rate constant describes the kinetic interaction between $CBOD_u$ and DO, and was determined through calibration (table 11). Biochemical oxygen demand decay-rate constants can be determined graphically, but the graphical method did not work for this study because too few data were available. Instead, the BOD decay rate was determined through calibration and was varied spatially to account for different decay rates downstream from the two different WWTPs. A BOD decay-rate constant of 0.09 per day was used downstream from the Moorhead WWTP, and a decay-rate constant of 0.25 per day was used downstream from the Fargo WWTP. Settling of $CBOD_u$ is a kinetic interaction that can be simulated (fig. 13), but it was not simulated in the Fargo WASP water-quality model because measured CBOD settling rates were not available. Ultimate CBOD settling is most likely negligible because $CBOD_5$ and total suspended solids concentrations are typically low from both of the WWTPs (table 7; Bob Zimmerman, Moorhead Wastewater Treatment Facility, written commun., 2007; Peter Bilstad, Fargo Wastewater Treatment Plant, written commun., 2007). Nitrification is the kinetic interaction between ammonia and dissolved oxygen whereby ammonia, in the presence of oxygen and nitrifying bacteria, is converted through a two-step process to nitrate. During the nitrification process, oxygen is consumed at a rate that is described by the nitrification rate constant (table 11). The nitrification rate constant can be determined graphically, but too few data were available in this study. Organic nitrogen is converted into ammonia through the process of mineralization (bacterial decomposition). Mineralization was simulated in the Fargo WASP water-quality model and is described by the dissolved organic nitrogen mineralization rate constant (table 11). An average value of 0.02 per day from Wesolowski (1994) was used in the model. Phytoplankton was not simulated as a state variable; however, model parameters relating to phytoplankton were specified in order to simulate photosynthetic production of oxygen and respiratory consumption of oxygen by phytoplankton (table 11). A combination of literature and calibrated values was used for model parameters related to phytoplankton. Many of the model parameters have a temperature coefficient associated with them (table 11), which is used to calculate the effect of temperature on the model parameter. Temperature can be simulated as a state variable in the USEPA WASP model, but for the Fargo WASP water-quality model, a mean water temperature was computed for each site on the main stem of the river and held constant. The mean water temperature for a given site (table 6) then was applied to the segment of the study reach that contained the given site and to segments midway between the site immediately upstream from the given site and the site immediately downstream from the given site.

After the model parameters were specified and calibrated, mean measured concentrations were compared with mean simulated concentrations. Simulated results for DO, ammonia, $CBOD_u$, nitrate, and organic nitrogen for sites 4, 5, 5.7, 6, 7, 9.5, and 10 are presented, along with measured concentrations for site 1 for reference (figs. 14, 15, and 16). The effect of the WWTPs on constituent concentrations is visible in the longitudinal profile of measured and simulated concentrations. Changes in measured constituent concentrations generally occurs downstream from the WWTPs, which can result in a corresponding change in model parameters. In the USEPA WASP model, selected model parameters can be varied spatially. As a result, prediction of constituent concentrations tended to be grouped into two reaches—one downstream from the Moorhead WWTP (site 2) and another downstream from the Fargo WWTP (site 5.8).

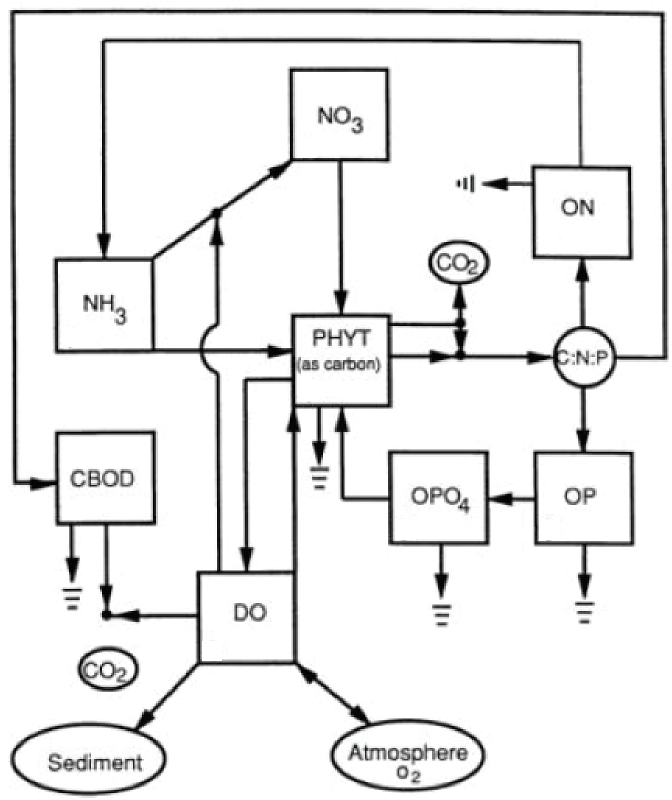
For sites downstream from the Moorhead WWTP, DO concentrations were slightly underpredicted; for sites downstream from the Fargo WWTP, DO concentrations were slightly overpredicted (fig. 14). The difference between average simulated DO concentrations and average measured concentrations for sites 5.7 and 6 were less than 2 percent. Overall, the average simulated concentrations for all calibration sites were within 6 percent of the average measured concentrations.

Accurate simulation of DO is dependent upon many kinetic interactions. Concurrent with calibration, model parameters that describe the major kinetic interactions affecting DO were increased by 50 percent to determine the sensitivity of DO to these model parameters. The prediction of DO appears to be most sensitive to the reaeration-rate coefficient (table 12). For all model parameters, with the exception of the nitrification rate constant, a 50-percent increase resulted in a consistent change in DO for all sites. With a 50-percent increase in the nitrification rate constant, DO decreased at site 5, but increased slightly at sites 7 and 10 (table 12). This is likely related to the disparate contributions of ammonia from the WWTPs. During the 2003 study, the average ammonia load (streamflow multiplied by concentration and an appropriate conversion factor) from the Moorhead WWTP was 323 pounds per day and the average ammonia load from the Fargo WWTP was 0.45 pound per day. This large difference in loads results in an increase in ammonia concentrations just downstream from the Moorhead WWTP, but further downstream concentrations steadily decrease. Concentrations continue to decrease downstream from the Fargo WWTP because the ammonia load from Fargo is small. With a 50-percent increase in the nitrification rate constant, more ammonia is nitrified downstream from the Moorhead WWTP, which results in lower concentrations of ammonia downstream from the Fargo WWTP. Thus, at the end of the reach, less ammonia is available for nitrification which results in less oxygen being consumed. The disparate contributions of ammonia from the WWTPs also affect the prediction of the DO concentrations. The nitrification rate constant cannot be varied spatially (or temporally) in the USEPA WASP model (Wool and others, 2003). The nitrification rate constant of 2.5 per day is generally accurate for sites downstream from the Moorhead WWTP, but is too high for sites downstream from the Fargo WWTP. The high nitrification rate downstream from the Fargo WWTP causes too much ammonia to be oxidized at sites 6 and 7, which causes very low concentrations of ammonia at sites 9.5 and 10. Therefore, with low ammonia concentrations at sites 9.5 and 10 and a high nitrification rate, little nitrification occurs, which causes less oxygen to be consumed and DO to be overpredicted at the end of the study reach.

Ammonia concentrations were slightly overpredicted for sites downstream from the Moorhead WWTP, whereas, for sites downstream from the Fargo WWTP, ammonia concentrations were increasingly underpredicted (fig. 14). The pattern of overprediction at the beginning of the study reach and underprediction at the downstream end of the reach resulted from using a single nitrification rate constant of 2.5 per day for the entire stream reach throughout the simulation. Because the nitrification rate constant cannot be varied spatially or temporally in the USEPA WASP model, a nitrification rate constant that resulted in some overprediction and some underprediction of concentrations was unavoidable. Overall, the average simulated ammonia concentrations are within the range of measured concentrations (fig. 14).

For all sites, simulated $CBOD_u$ concentrations were within 15 percent of the measured concentrations or the amount of laboratory error associated with the BOD test (American Public Health Association, American Water Works Association, and Water Environment Federation, 1995; fig. 15). The average measured $CBOD_u$ concentration increases between sites 6 and 7; however, the Fargo WASP water-quality model does not simulate this increase. There is no known point source between sites 6 and site 7 (Andy Bradshaw, Moorhead Wastewater Treatment Facility, oral commun., 2007).

Nitrate concentrations were overpredicted by an average of 20 percent for all calibration sites (fig. 16). Several factors may have contributed to the overprediction of nitrates: nitrite plus nitrate concentrations were used for boundary conditions instead of nitrate concentrations; nitrification was overpredicted for the end of the reach; denitrification was not simulated; and the interaction between phytoplankton and nitrate was not simulated. There is some error associated with the laboratory test for nitrates, but it is not large enough to account for the overprediction of nitrates. Organic nitrogen concentrations were



EXPLANATION

NO_3 = nitrate nitrogen
NH_3 = ammonia nitrogen
ON = organic nitrogen
PHYT = phytoplankton
CBOD = carbonaceous biological oxygen demand, ultimate
OPO_4 = orthophosphate
OP = organic phosphorus
DO = dissolved oxygen
CO_2 = carbon dioxide
O_2 = oxygen

Figure 13. State variable interactions for nutrient cycles and dissolved oxygen in U.S. Environmental Protection Agency's Water Quality Simulation Program (WASP; from Wool and others, 2003).

consistently underpredicted (fig. 16). The concentrations were underpredicted by an average of 21 percent for all calibration sites. Organic nitrogen concentrations may have been underpredicted because the interaction between phytoplankton and organic nitrogen was not simulated.

Table 11. Model parameters used for Fargo Water-Quality Analysis Simulation Program model.

[mv, measured value; lv, literature value; --, comparable value not available; cv, calibrated value]

Model parameter	Type	Value used in Fargo Water-Quality Analysis Simulation Program model	Calibrated value used in Wesolowski (1994) study
Parameters related to dissolved oxygen			
Reaeration-rate coefficient at 20 degrees Celsius (per day)	mv	1.4	1.7, 1.4
Reaeration rate-temperature coefficient (dimensionless)	lv	1.03 (default[1])	1.024
Oxygen to carbon stoichiometric ratio (dimensionless)	lv	2.67 (default[1])	--
Sediment oxygen demand (grams of oxygen per square foot per day)	lv	0.1	0.1
Sediment oxygen demand temperature coefficient (dimensionless)	lv	1.06	1.06
Parameters related to carbonaceous biochemical oxygen demand			
Biochemical oxygen demand decay rate constant at 20 degrees Celsius (per day)	cv	0.09, 0.25	0.05
Biochemical oxygen demand decay rate temperature coefficient (dimensionless)	lv	1.047	1.047
Parameters related to ammonia			
Nitrification rate constant at 20 degrees Celsius (per day)	cv	2.5	--
Nitrification rate temperature coefficient	lv	1.047	--
Half saturation constant for nitrification oxygen limit (milligrams of oxygen per liter)	cv	1	--
Parameters related to organic nitrogen			
Dissolved organic nitrogen mineralization rate constant at 20 degrees Celsius (per day)	lv	0.02	Varied by reach
Dissolved organic nitrogen mineralization temperature coefficient (dimensionless)	lv	1.047	1.047
Parameters related to phytoplankton			
Phytoplankton maximum growth rate constant at 20 degrees Celsius (per day)	cv	1	1.6
Phytoplankton growth rate temperature coefficient (dimensionless)	lv	1.047	1.047
Phytoplankton carbon to chlorophyll ratio (dimensionless)	cv	15	--
Phytoplankton endogenous respiration rate constant (per day)	lv	0.06	0.06
Phytoplankton respiration rate temperature coefficient (dimensionless)	lv	1.047	1.047

[1]From U.S. Environmental Protection Agency Water-Quality Analysis Simulation Program model documentation (Wool and others, 2003).

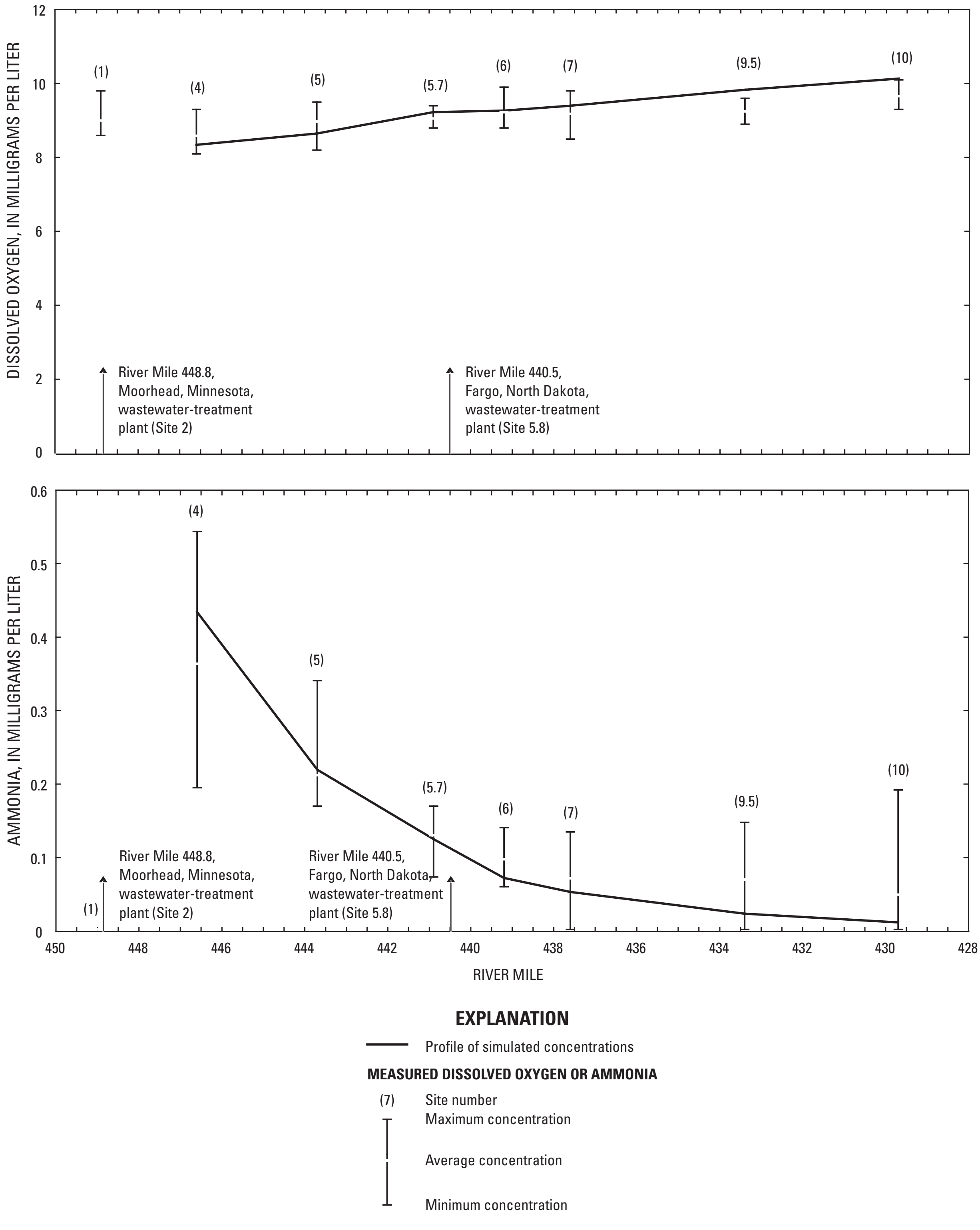


Figure 14. Maximum, mean, and minimum measured dissolved-oxygen and ammonia concentrations for calibration (September 24 through 27, 2003) data set and average simulated concentrations for Fargo Water-Quality Analysis Simulation Program model calibration sites.

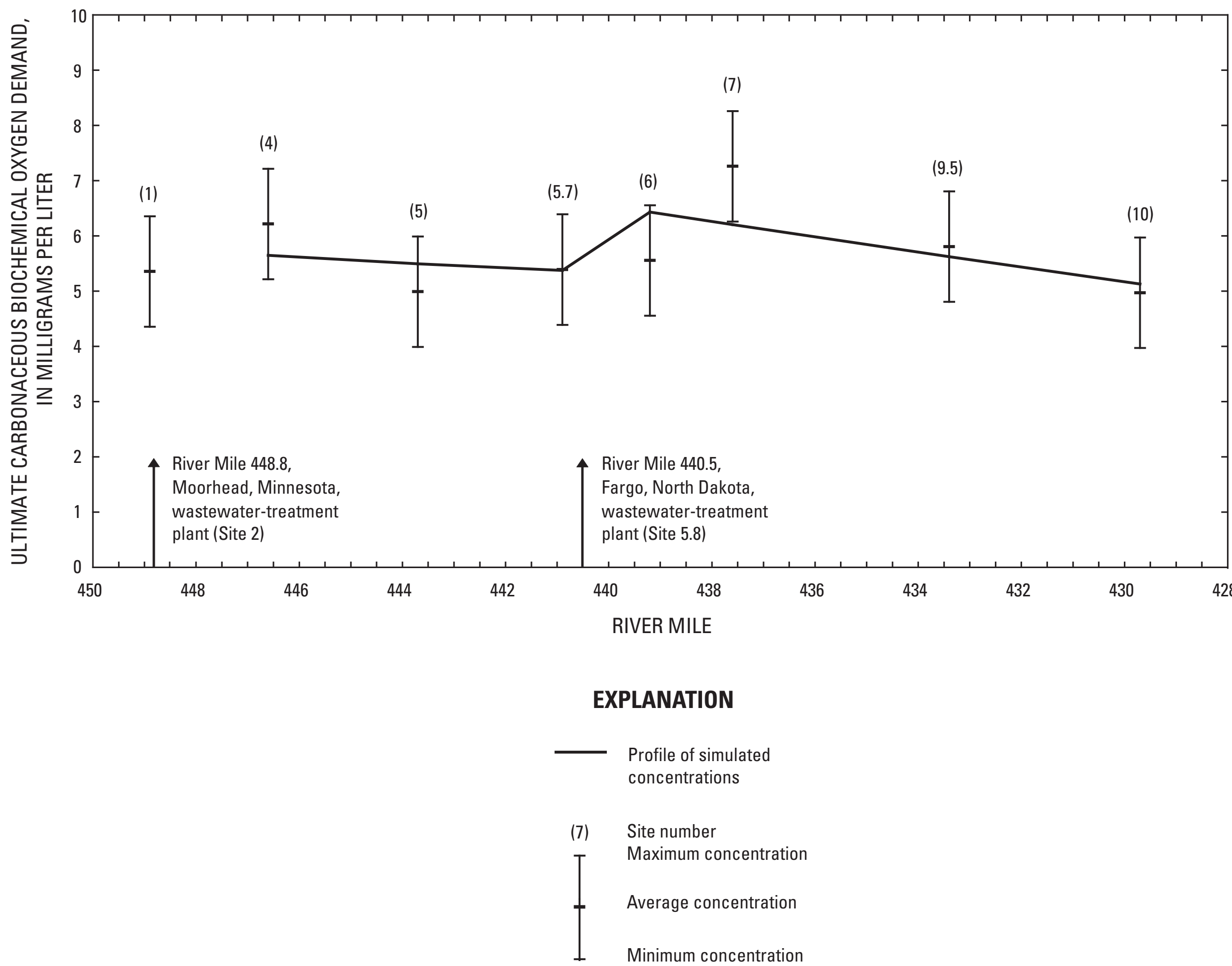


Figure 15. Maximum, mean, and minimum measured ultimate carbonaceous biochemical oxygen demand concentrations for calibration (September 24 through 27, 2003) data set and average simulated concentrations for Fargo Water-Quality Analysis Simulation Program model calibration sites.

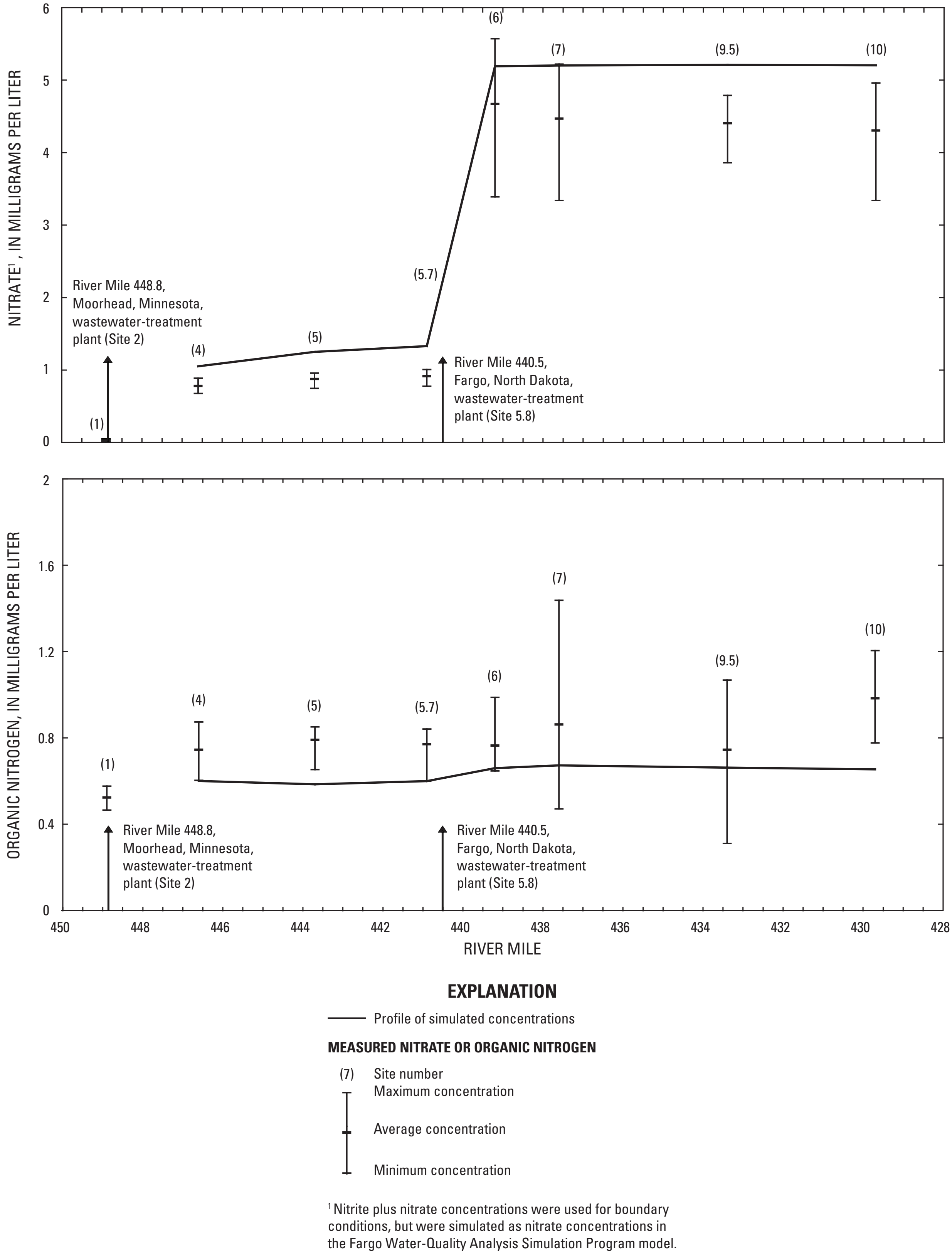


Figure 16. Maximum, mean, and minimum measured nitrate and organic nitrogen concentrations for calibration (September 24 through 27, 2003) data set and average simulated concentrations for Fargo Water-Quality Analysis Simulation Program model calibration sites.

Table 12. Percent change in dissolved-oxygen concentration as a result of a 50-percent increase in selected model parameters.

Model parameter	Percent change in dissolved-oxygen concentration		
	Site 5	Site 7	Site 10
Reaeration-rate coefficient at 20 degrees Celsius (dimensionless)	6.2	4.7	3.0
Nitrification rate constant at 20 degrees Celsius (per day)	–2.0	.8	.7
Ultimate biochemical oxygen demand decay rate constant at 20 degrees Celsius (per day)	–.9	–2.0	–2.2
Phytoplankton maximum growth rate constant at 20 degrees Celsius (per day)	1.7	1.9	2.1
Phytoplankton endogenous respiration rate at 20 degrees Celsius (per day)	–.1	–.1	–.1
Sediment oxygen demand (grams of oxygen per square foot per day)	–.3	–.3	–.3

Model Testing

The performance of the Fargo WASP water-quality model was tested by using August 1989 and August 1990 streamflows and water-quality data from the Wesolowski (1994) study for boundary conditions and comparing simulated results to the measured data. During the time of data collection by Wesolowski, the Fargo WWTP outfall was located at site 8 (fig. 2 from Wesolowski, 1994). In 1995, the Fargo WWTP outfall was relocated further upstream to site 5.8 (fig. 2). Therefore, testing could be performed using the August 1989 and August 1990 data sets for the study reach up to and including site 7 as long as boundary conditions were not specified for the relocated Fargo WWTP outfall site (site 5.8).

Traveltimes were tested using streamflows that ranged from 60 to 407 ft^3/s. Comparisons were made between the measured traveltime of the dye cloud centroid for site 7 and the simulated traveltime of the dye cloud centroid. Streamflows for the upstream boundary (site 1) and Moorhead WWTP outfall (site 2) were specified. Results for the August 1989 and August 1990 data sets were good; differences between the measured and simulated traveltimes were less than 7 percent (table 13). Dispersion coefficients were unchanged during model testing.

Model performance for the simulation of DO and ammonia was tested by specifying measured water-quality boundary conditions from August 1989 and August 1990 for the upstream boundary (site 1) and the Moorhead WWTP outfall (site 2). Other than reaeration rates, the 2003 calibrated model parameters (tables 9 and 10) were unchanged. Reaeration rates for the 1989 and 1990 data sets were determined using the equation given in figure 8. Reaeration rates for a streamflow of 140 ft^3/s in 1989 and a streamflow of 200 ft^3/s in 1990 were determined to be 1.07 and 0.91 per day, respectively. Results for DO and ammonia for sites 4, 5, 6, and 7 are shown in figures 17 and 18. Measured DO concentrations were underpredicted by less than 15 percent for both data sets (fig. 17). The simulated DO concentrations were within or close to the range of measured DO concentrations for the August 1989 period, but were considerably less than the measured DO concentrations for the August 1990 period. Results for ammonia were poor; measured ammonia concentrations were underpredicted by as much as 70 percent for both data sets (fig. 18).

Overall, application of the Fargo WASP water-quality model to the August 1989 and August 1990 data sets resulted in poor agreement between the measured and simulated concentrations. This likely is a result of changes in the composition of the waste load for the Moorhead WWTP. Both Fargo and Moorhead made improvements to their WWTPs after 1990. The Moorhead WWTP added a tertiary treatment process in the spring of 2003 that uses a Biofilm Carrier System to convert ammonia to nitrate (Andy Bradshaw, Moorhead Wastewater Treatment Facility, written commun., 2007). In 1995, the Fargo WWTP started to continuously discharge wastewater and added a tertiary treatment process that uses trickling filters to convert ammonia to nitrate (Peter Bilstad, Fargo Wastewater Treatment Plant, written commun., 2007). For the Moorhead WWTP, the average ammonia concentration for the 2003 study was about 30 to 40 percent less than the average concentration for the 1989 and 1990 data sets, and the average $CBOD_u$ concentration was about 46 to 70 percent less than the averages for the August 1989 and August 1990 data sets (table 14). For the Fargo WWTP, average ammonia concentrations have been reduced to less than the detection limit of 0.01 mg/L, and the average $CBOD_u$ concentration for the 2003 study was about 60 to 70 percent less than the averages for 1989 and 1990 (table 14). The change in waste-load composition for the two WWTPs resulted in two main differences between the Wesolowski (1994) study and the 2003 study. These differences are (1) rate constants have changed and (2) DO is no longer being substantially depressed downstream from the Moorhead and Fargo WWTPs (fig. 14). The Fargo WASP water-quality model is valid for current (after 2003) treatment processes at the Fargo and Moorhead WWTPs.

Table 13. Measured and simulated traveltimes for streamflows from the Wesolowski (1994) study and the 2003 study.

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

Site number (fig. 2)	Date of dye injection	Streamflow[1] (ft^3/s)	Traveltime of dye cloud centroid (hours)		Percent difference between measured and simulated traveltimes
			Measured	Simulated	
7	8/8/1989	195	22.6	21.8	–3.5
7	8/17/1989	60	38.9	36.4	–6.4
7	4/25/1990	407	16.1	16.1	0
7	10/19/1990	160	25.3	23.9	–5.6
7	9/24/2003	73	36.0	33.6	–6.7

[1]A flow of 6 cubic feet per second was used for the Minnesota wastewater-treatment plant outfall for both the 1989 and 1990 data sets.

[2]From Fargo Water-Quality Analysis Simulation Program model.

Summary

In 2003, the U.S. Geological Survey, in cooperation with the North Dakota Department of Health, the Minnesota Pollution Control Agency, and the cities of Fargo, North Dakota, and Moorhead, Minnesota, conducted a time-of-travel and reaeration-rate study to provide information to calibrate a water-quality model for low-flow conditions (streamflows of less than 150 cubic feet per second). Data collected from September 24 through 27, 2003, were used to develop and calibrate the U.S. Environmental Protection Agency Water Quality Analysis Simulation Program model (hereinafter referred to as the Fargo WASP water-quality model) for a 19.2-mile reach of the Red River of the North (hereinafter referred to as the Red River).

The data-collection network consisted of 10 sites, including the Fargo and Moorhead wastewater-treatment plant outfall sites. Streamflow measurements provided channel-geometry data for the model, and dye and propane gas tracers were used to determine traveltime and to calculate reaeration-rate coefficients. The calculated reaeration-rate coefficients ranged from 1.18 to 1.58 per day. The calculated reaeration-rate coefficient for an average streamflow of 85.1 cubic feet per second from site 4 to site 10 was 1.4 per day. On the basis of residence time, the calculated reaeration-rate coefficient from site 4 to site 10 is the most accurate estimate of the reaeration-rate coefficient for the study reach.

In the Fargo WASP water-quality model, the 19.2-mile reach of the Red River is represented by 306 one-dimensional, 330-ft segments. The Moorhead and Fargo wastewater-treatment plants are represented as point sources. Streamflow and water-quality boundary conditions were specified for September 17 through September 27, 2003. The first 7 days were used as an initialization period. Streamflow and water-quality boundary conditions were specified for the most upstream site and for each of the two point-source wastewater-treatment plant outfalls. A single streamflow value was specified for each of the boundary conditions and held constant because streamflow was assumed to be steady. Water-quality boundary conditions were specified for dissolved oxygen, ultimate carbonaceous biochemical oxygen demand, nitrate, ammonia, nitrogen, and chlorophyll *a* (phytoplankton). An average of the measured time series of concentrations was used to define water-quality boundary conditions.

Power functions, which relate velocity, depth, and channel width to streamflow, were used to simulate streamflow in the Fargo WASP water-quality model. For each site, two power functions were defined: one for velocity and one for depth. A combination of literature values and measured values was used for the hydraulic coefficients in the power equations.

The Fargo WASP water-quality model was calibrated for the transport of dye by fitting simulated time-concentration dye curves to measured time-concentration dye curves through the adjustment of velocity and longitudinal dispersion coefficients. Velocity was adjusted by varying the segments to which the power functions were applied until the best fit between measured and simulated traveltimes was achieved. Longitudinal dispersion coefficients were determined from calibration and ranged from 10 to 55 feet squared per second. Simulated time-concentration dye curves were in reasonable agreement with measured time-concentration dye curves. Simulated peak concentrations for sites 5.7, 7, and 10 were within 10 percent of the measured concentrations. Simulated traveltimes of the dye cloud centroid for sites 5.7, 7, and 10 were within 7 percent of the measured traveltimes. The variances of the simulated dye concentrations were similar to the variances of the measured dye concentrations, indicating dispersion was reproduced reasonably well.

The Fargo WASP water-quality model was calibrated for dissolved oxygen and ammonia by specifying model parameters and adjusting selected model parameters to achieve the best fit between measured and simulated concentrations. A combination of measured values, literature values, and calibrated values was used for model parameters.

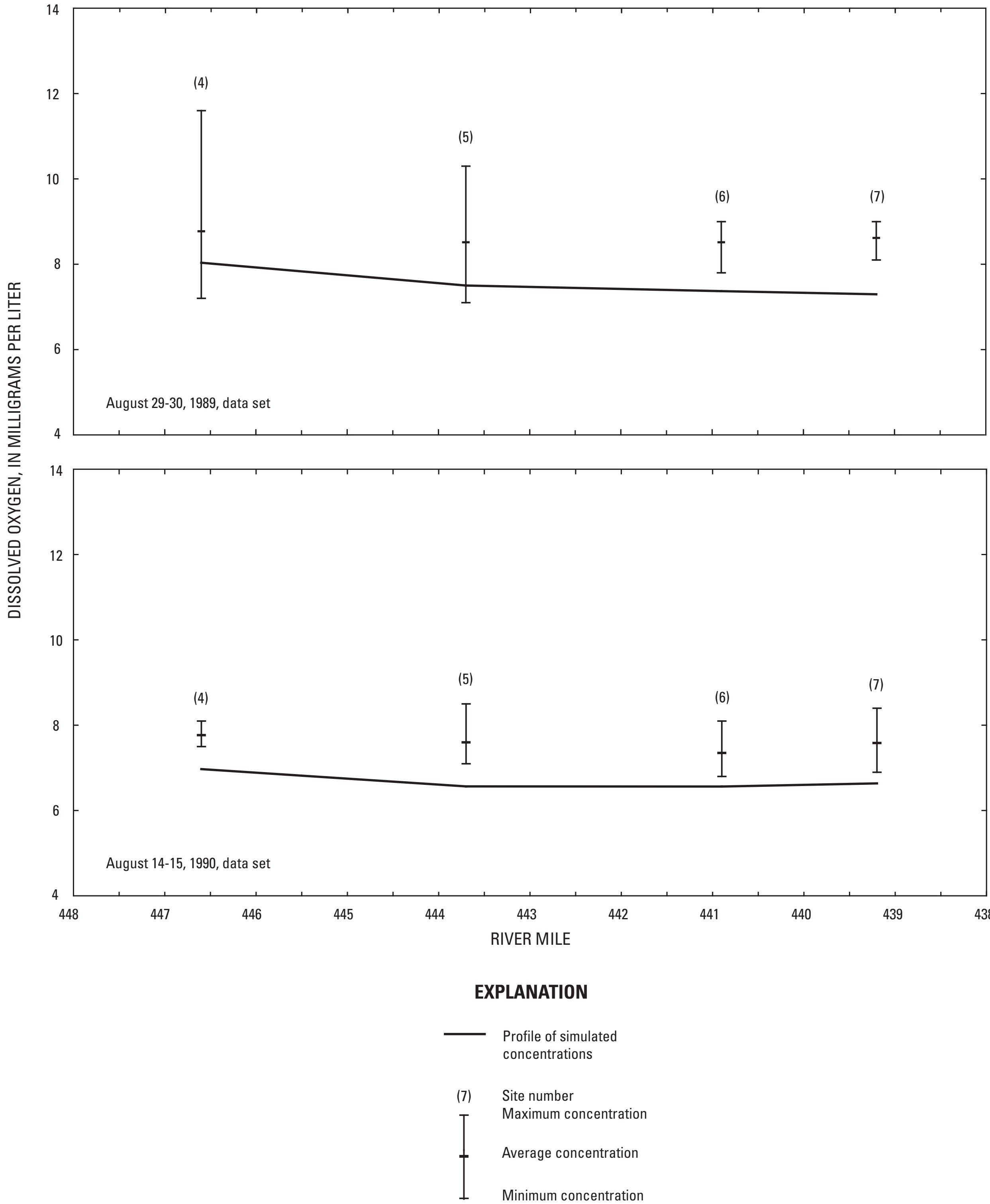


Figure 17. Maximum, mean, and minimum measured dissolved-oxygen concentrations for August 29–30, 1989, and August 14–15, 1990, data sets and average simulated concentrations for Fargo Water-Quality Analysis Simulation Program model data set for sites 4, 5, 6, and 7.

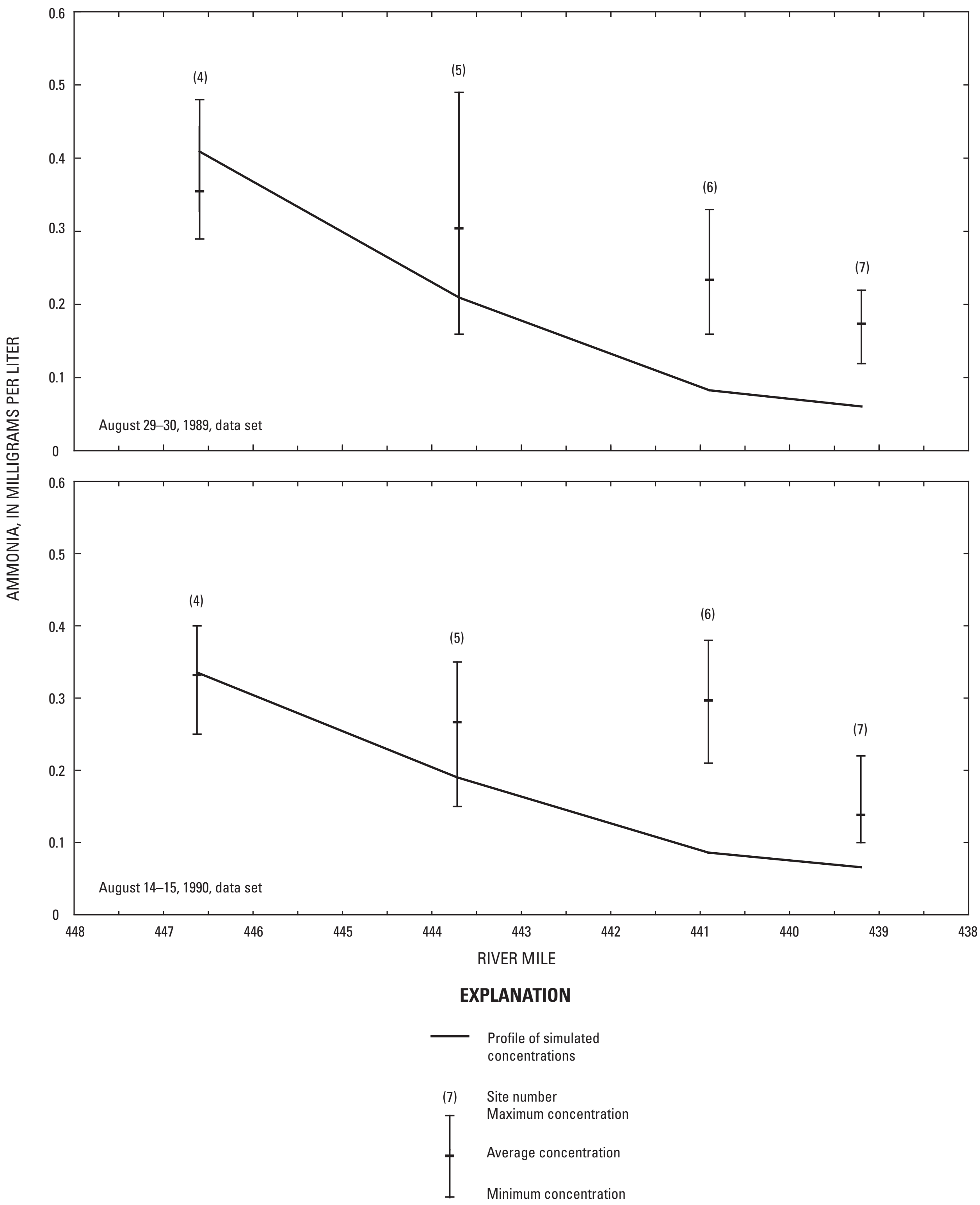


Figure 18. Maximum, mean, and minimum measured ammonia concentrations for August 29–30, 1989, and August 14–15, 1990, data sets, and average simulated concentrations for Fargo Water-Quality Analysis Simulation Program model data set for sites 4, 5, 6, and 7.

Table 14. Selected water-quality constituent concentrations in effluent from the Moorhead and Fargo wastewater-treatment plants before and after addition of tertiary treatment to convert ammonia to nitrate (as measured during USGS studies).

[BOD, biochemical oxygen demand; mg/L, milligrams per liter; WWTP, wastewater-treatment plant]

Month and year in which data were collected	Ultimate carbonaceous BOD (mg/L)	Ammonia, unfiltered (mg/L)	Nitrite plus nitrate, unfiltered (mg/L)	Ammonia plus organic nitrogen, unfiltered (mg/L)
Moorhead WWTP[1]				
August 1989	21	15.8	0.60	22
August 1990	36.5	17.7	1.03	20
September 2003	11.2	10.6	10.1	11.5
Fargo WWTP[2]				
August 1989	29	9.81	0.23	14.9
August 1990	48	4.45	1.13	11.7
September 2003	12.7	<.01	23.1	1.1

[1]Moorhead WWTP added tertiary treatment in 2003.

[2]Fargo WWTP added tertiary treamtent in 1995.

Measured constituent concentrations and model parameters were affected by discharge from the wastewater-treatment plants. As a result, prediction of constituent concentrations tended to be grouped into two reaches—one downstream from the Moorhead wastewater-treatment plant and another downstream from the Fargo wastewater-treatment plant.

Dissolved oxygen concentrations were slightly underpredicted for sites downstream from the Moorhead wastewater-treatment plant and slightly overpredicted for sites downstream from the Fargo wastewater-treatment plant. Average simulated dissolved oxygen concentrations for all calibration sites were within 6 percent or less of the average measured concentrations. The combination of low ammonia concentrations and a high nitrification rate caused dissolved oxygen to be overpredicted at the downstream end of the study reach.

Ammonia concentrations were slightly overpredicted for sites downstream from the Moorhead WWTP, whereas for sites downstream from the Fargo WWTP, ammonia concentrations were increasingly underpredicted. The pattern of overprediction at the beginning of the study reach and underprediction at the downstream end of the reach resulted from using a single nitrification rate constant for the entire stream reach throughout the simulation. The average simulated ammonia concentrations are within the range of measured concentrations.

Simulated ultimate carbonaceous biochemical oxygen demand concentrations were within 15 percent of the measured concentrations, or the amount of laboratory error associated with the biochemical oxygen demand test. Nitrate concentrations were overpredicted by an average of 20 percent and may have been caused by several different factors. Organic nitrogen concentrations were consistently underpredicted, possibly because the interaction between phytoplankton and organic nitrogen was not simulated.

Data sets from August 1989 and August 1990 were used to test the performance of the Fargo WASP water-quality model. For streamflows that ranged from 60 to 407 cubic feet per second, differences between the measured and simulated traveltimes were less than 7 percent. Measured dissolved-oxygen concentrations were underpredicted by less than 15 percent for both data sets. Measured ammonia concentrations were underpredicted by as much as 70 percent for both data sets.

Overall, application of the Fargo WASP water-quality model to the August 1989 and August 1990 data sets resulted in poor agreement between the measured and simulated concentrations. This likely is a result of changes in the composition of the waste load for the Moorhead wastewater-treatment plant. Tertiary treatment at both wastewater-treatment plants has substantially reduced ammonia concentrations in the plants' effluent. The change in waste-load composition for the two wastewater-treatment plants probably resulted in two main differences between the 1994 study and the 2003 study. These differences are (1) rate constants have changed and (2) dissolved oxygen is no longer being substantially depressed downstream from the wastewater-treatment plants. The Fargo WASP water-quality model is valid for current (after 2003) treatment processes at the Fargo and Moorhead wastewater-treatment plants.

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