SIMULATION OF WASTEWATER EFFECTS ON DISSOLVED OXYGEN DURING LOW STREAMFLOW IN THE RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA, AND MOORHEAD, MINNESOTA

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

Introduction

Pursuant to Section 303(d) of the Clean Water Act, both North Dakota and Minnesota identified part of the Red River of the North (Red River) as water-quality limited. The states are required to determine the total maximum daily load (TMDL) that can be discharged to a water-quality limited reach from various pollution sources without contravening water-quality standards (U.S. Environmental Protection Agency, 1991). A work group consisting of local, State, and Federal agency representatives that was organized in June 1994 decided that a TMDL should be developed in phases for a subreach of the Red River at Fargo, N. Dak., and Moorhead, Minn. (fig. 1). In the first phase, which is the basis for this report, the focus is on attainment of the instream dissolved-oxygen (DO) standard during low streamflows, and only Fargo and Moorhead wastewater-treatment-plant discharges and Sheyenne River inflow are considered.

The study reach begins about 0.1 mile (mi) downstream (north) of the 12th Avenue North bridge in Fargo and extends 30.8 mi downstream to a site 0.8 mi upstream of the confluence of the Buffalo and Red Rivers (fig. 1). Nitrification of total ammonia (ammonia) from Fargo and Moorhead wastewater consumes most of the DO in the study reach (Wesolowski, 1994). Because the new (1995) Fargo plant already is nitrifying its wastewater, the work group needed to determine the maximum ammonia concentration for wastewater from the nonnitrifying Moorhead plant. To accomplish this task, the Red River at Fargo Water-Quality (RRatFGO QW) model (Wesolowski, 1994, 1996b) was used to simulate the effects of various wastewater-management alternatives during low streamflow. This report presents the results of those simulations to determine the usefulness of the model for management decisions. The simulations and report were completed in cooperation with the North Dakota Department of Health.

Boundary Conditions

The hypothetical boundary conditions used in the simulations to determine if existing (1996) and future (2006) wastewater would contravene North Dakota and Minnesota DO standards for the Red River during low streamflows are shown in table 1. Streamflows listed for the Red River and the Sheyenne River represent low streamflows during June through September (summer) and December through March (winter). Low streamflows were calculated as the 7-day, 10-year low streamflows (the minimum 7-consecutive-day average streamflows expected to be exceeded in all but 1 year in 10) based on data for 1953-88. Streamflows used to simulate summer water-quality conditions are substantially lower than streamflows used in calibration of the model (Wesolowski, 1994), which probably increases the uncertainty of the transport and water-quality components of the model. The uncertainty of the simulations from the calibrated model was documented by Wesolowski (1996a). The work group estimated that, during low streamflow, the headwater-source DO concentration was 80 percent of saturation. Treatment-plant dry-weather discharge, ammonia concentrations, and 5-day carbonaceous biochemical oxygen demand were estimated by work group members from Fargo and Moorhead. The remaining summer boundary conditions were obtained from the August 29-30, 1989, data set (Wesolowski, 1994), and the remaining

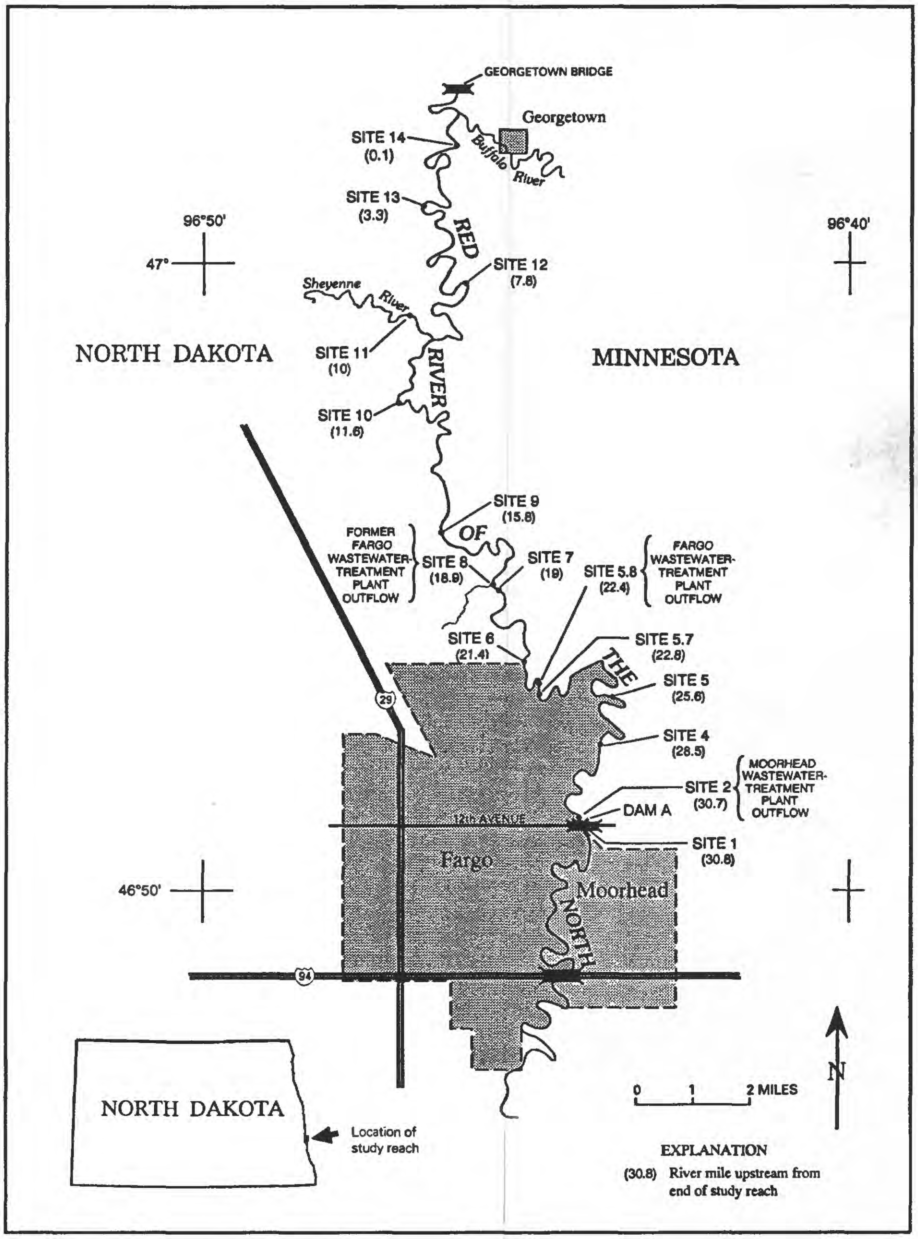

Figure 1. Location of study reach on the Red River.

Table 1. Hypothetical boundary conditions used to simulate ammonia and DO concentrations during summer and winter low streamflows

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; $CBOD_5$, 5-day carbonaceous biochemical oxygen demand; DO, dissolved oxygen; °F, degrees Fahrenheit; L, low; M, middle; H, high; Mgal/d, million gallons per day]

	Summer 1996			Summer 2006			Winter 1996			Winter 2006		
	1	2	3	4	5	6	7	8	9	10	11	12
Red River headwater source												
Streamflow (ft^3/s)	16	16	16	16	16	16	55	55	55	55	55	55
Ammonia (mg/L as N)	.15	.15	.15	.15	.15	.15	.15	.15	.15	.15	.15	.15
$CBOD_5$ (mg/L)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
DO (mg/L)	[1]7.4	[1]7.4	[1]7.4	[1]7.4	[1]7.4	[1]7.4	13.4	13.4	13.4	13.4	13.4	13.4
Water temperature (°F)	70.3	70.3	70.3	70.3	70.3	70.3	32.5	32.5	32.5	32.5	32.5	32.5
Reaeration coefficient[2]	L = 1.7	M = 3.0	H = 4.3	L = 1.7	M = 3.0	H = 4.3	L = 0	[3]M	[4]H	L = 0	[3]M	[4]H
Moorhead treated wastewater point source												
Discharge (Mgal/d)[5]	4.04	4.04	4.04	4.42	4.42	4.42	4.04	4.04	4.04	4.42	4.42	4.42
Ammonia (mg/L as N)	12.5	12.5	12.5	[6]12.5	[6]12.5	[6]12.5	17.9	17.9	17.9	17.9	17.9	17.9
$CBOD_5$ (mg/L)	5.7	5.7	5.7	5.7	5.7	5.7	3.2	3.2	3.2	3.2	3.2	3.2
DO (mg/L)	6.8	6.8	6.8	6.8	6.8	6.8	10.5	10.5	10.5	10.5	10.5	10.5
Fargo treated wastewater point source												
Discharge (Mgal/d)[5]	9.00	9.00	9.00	10.7	10.7	10.7	9.00	9.00	9.00	10.7	10.7	10.7
Ammonia (mg/L as N)	.30	.30	.30	.30	.30	.30	.04	.04	.04	.04	.04	.04
$CBOD_5$ (mg/L)	1.5	1.5	1.5	1.5	1.5	1.5	2.7	2.7	2.7	2.7	2.7	2.7
DO (mg/L)	7.0	7.0	7.0	7.0	7.0	7.0	10.2	10.2	10.2	10.2	10.2	10.2
Sheyenne River point source												
Streamflow (ft^3/s)	13	13	13	13	13	13	19	19	19	19	19	19
Ammonia (mg/L as N)	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10
$CBOD_5$ (mg/L)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
DO (mg/L)	8.6	8.6	8.6	8.6	8.6	8.6	12.7	12.7	12.7	12.7	12.7	12.7

[1]80 percent of saturation to more accurately define conditions during low streamflow.
[2]Per day, base e, 68°F.
[3]Varies by model subreach as follows: 0.46, 0.11, 0.11, 0.46, 0.11, 0.11, 0.11, 0.11, 0.11, 0.11, 0.11.
[4]Varies by model subreach as follows: 0.46, 0.46, 0.11, 0.46, 0.46, 0.11, 0.11, 0.11, 0.11, 0.11, 0.11.
[5]Dry-weather discharge resulting from lower inflow to plants because of less-than-normal precipitation, infiltration, and seepage into the sewage collection system.
[6]Maximum concentration is 0.3 mg/L for condition 4a, 4.2 mg/L for condition 5a, and 6.9 mg/L for condition 6a to prevent the instream instantaneous minimum DO concentration from being less than 5.0 mg/L at site 5.

winter conditions were obtained from the February 23-24, 1995, data set (Wesolowski, 1996b).

The hypothetical boundary conditions given in table 1 are in sets of three that are identical except for the reaeration coefficients, which represent low, middle, and high reaeration rates during summer and winter low streamflows and provide a range of possible DO concentrations. The low reaeration coefficient for the summer was estimated using Smoot's equation (1987), which uses stream velocity, depth, and slope. Using streamflows and point-source discharges given in table 1, velocities and depths used in Smoot's equation were simulated by the model. Because simulated velocities are suspected to be faster than measured velocities and simulated depths are suspected to be shallower than measured depths, the reaeration coefficient obtained from Smoot's equation probably is high and will result in higher simulated DO concentrations than if greater depths and lower velocities are used. The high reaeration coefficient for the summer was estimated using streamflow of 16 cubic feet per second (ft^3/s) and a streamflow/reaeration coefficient relation developed by Wesolowski (1994). The middle reaeration coefficient is the average of the low and high coefficients.

The low reaeration coefficient for the winter, assuming complete ice cover and little or no algae activity, was assumed to be zero. The middle reaeration coefficient was derived by the method used by Wesolowski (1996b). In that method, each of the two model subreaches that receive point-source discharge was assumed to be 20-percent ice free, and a reaeration coefficient of 2.3 per day for ice-free conditions was estimated using streamflow of 55 ft^3/s and the streamflow/reaeration coefficient relation mentioned earlier. The estimated coefficient for those two subreaches was 0.46 per day (20 percent of 2.3 per day), and the estimated coefficient for the remaining subreaches, assuming complete ice cover, was 0.11 per day (5 percent of 2.3 per day). The high reaeration coefficient was estimated assuming higher-than-normal air temperatures that would increase the size of the ice-free areas normally associated with lower temperatures. Each of the two subreaches immediately downstream from the subreaches that receive point-source discharge also was assumed to be 20-percent ice free. The estimated coefficient for those four subreaches was 0.46 per day, and the estimated coefficient for the remaining subreaches, assuming complete ice cover, was 0.11 per day.

Simulations for Summer and Winter Conditions

Preliminary simulations indicated that ammonia concentrations unexpectedly increased at river mile 19.0, the approximate location of the former Fargo plant (Wesolowski, 1996b) and peaked downstream at river mile 13.8. The organic-nitrogen hydrolysis rate for model subreaches that coincide with river miles 19.0 to 14.0 was estimated during model calibration to be 0.19 per day (Wesolowski, 1994). This rate was suitable for the calibrated model but no longer is appropriate because the discharge location of the Fargo treated wastewater point source has been moved upstream from river mile 18.9 to river mile 22.4. Therefore, before final simulations, the hydrolysis rates for model subreaches that coincide with river miles 23.4 to 19.2 were changed from 0.02 to 0.09 per day and the rates for model subreaches that coincide with river miles 19.0 to 14.0 were changed from 0.19 to 0.09 per day.

A 0.09 per day hydrolysis rate for model subreaches that coincide with river miles 23.4 to 14.0 is consistent with those used for other model subreaches, and the change causes only a small decrease (0.08 to 0.07 per day) in the overall hydrolysis rate of the study reach.

The maximum simulated ammonia concentration was 3.5 milligrams per liter (mg/L) for summer 1996 (fig. 2) and increased to 3.7 mg/L for summer 2006 (fig. 3) because of the increase in discharge from the Moorhead plant. Inflows from the Fargo plant and the Sheyenne River, which have lower ammonia concentrations, decreased these concentrations by dilution.

The DO standard for the Red River is 5.0 mg/L (Wesolowski, 1994, p. 6). The North Dakota Department of Health and the Minnesota Pollution Control Agency have interpreted this standard as a daily-minimum concentration. Therefore, because the measured DO concentration varies throughout the day and the model simulates only daily-average concentrations, the daily-minimum concentration was obtained as follows. The measured DO concentrations in the August 29-30, 1989, data set for river mile 25.6 (site 5) ranged from 7.1 to 10.3 mg/L. Site 5 represents the approximate location of the lowest DO concentration in a profile of concentrations throughout the study reach. The amplitude in the DO concentrations at site 5 for the August 29-30, 1989, data set was equal to one-half of the range, or 1.6 mg/L. The minimum allowable daily-average concentration was determined by adding 1.6 mg/L to 5.0 mg/L. Thus, in this study, the minimum daily-average concentration allowable for the summer at site 5 is considered to be 6.6 mg/L. The simulated DO concentrations (figs. 2 and 3) at site 5 are less than the minimum allowable average. Thus, the North Dakota and Minnesota DO standards are contravened at site 5 for hypothetical boundary conditions 1 through 6 (table 1).

To determine the hypothetical boundary conditions that maximize the ammonia concentration for Moorhead wastewater without contravening North Dakota and Minnesota DO standards at site 5, ammonia concentrations used for conditions 4, 5, and 6 were changed by iterative simulations. The modified hypothetical boundary conditions (4a, 5a, and 6a) for ammonia were determined to be 0.3 mg/L for condition 4a, 4.2 mg/L for condition 5a, and 6.9 mg/L for condition 6a (table 1). Simulations obtained using the modified conditions are shown in figure 4. Thus, nitrification of Moorhead wastewater or another wastewater-management change is required to achieve the ammonia concentration for conditions 4a, 5a, and 6a.

The maximum simulated ammonia concentration was about 2.0 mg/L for winter 1996 (fig. 5) and increased to 2.1 mg/L for winter 2006 (fig. 6) because of the increase in discharge from the Moorhead plant. Inflows from the Fargo plant and the Sheyenne River, which have lower ammonia concentrations, decreased these concentrations by dilution.

Because of the low reaeration coefficients, DO concentrations generally decrease during the winter throughout the study reach (figs. 5 and 6). Inflow from the Fargo plant has little effect on the concentrations, but inflow from the Sheyenne River appreciably increases the concentrations. The North Dakota and Minnesota DO standards are not contravened in the study reach during the winter. The usefulness of the model for wastewater-management decisions was demonstrated by simulating the effects of wastewater-management alternatives on the DO standards. Furthermore, iterative simulations demonstrated the extent of the change required in a targeted boundary condition to maintain the DO standard.

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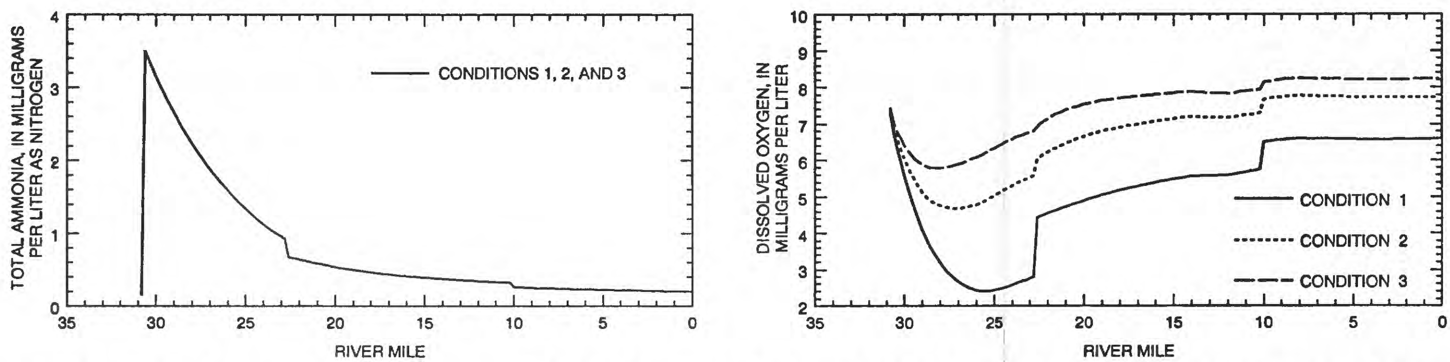

Figure 2. Simulated concentrations for conditions 1, 2, and 3 (summer 1996) for the Red River at Fargo, N. Dak., and Moorhead, Minn.

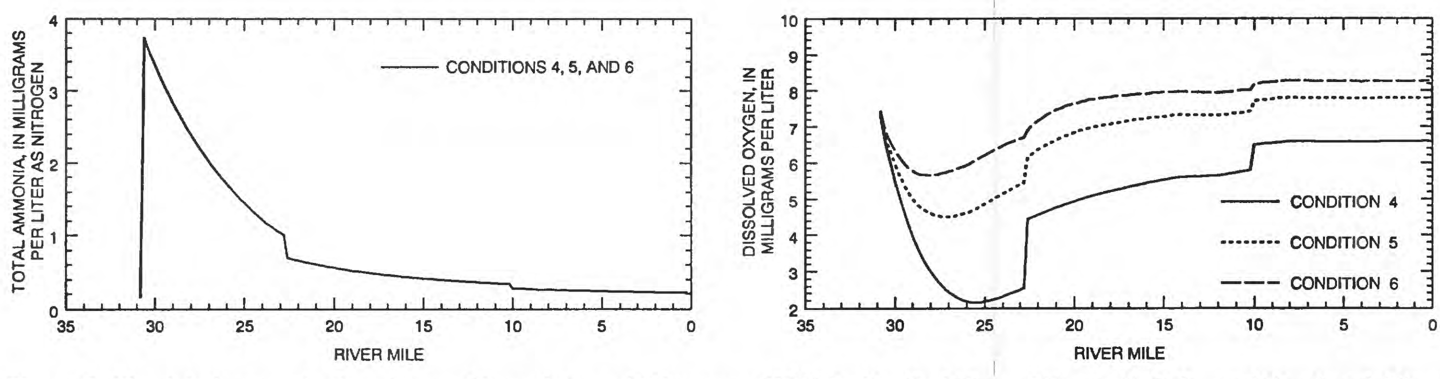

Figure 3. Simulated concentrations for conditions 4, 5, and 6 (summer 2006) for the Red River at Fargo, N. Dak., and Moorhead, Minn.

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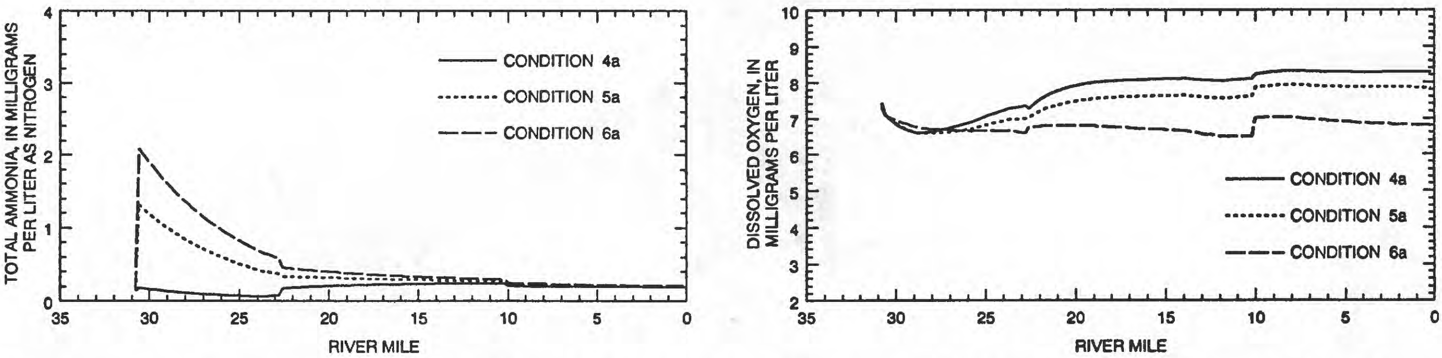

Figure 4. Simulated concentrations for modified conditions 4a, 5a, and 6a (summer 1996) for the Red River at Fargo, N. Dak., and Moorhead, Minn.

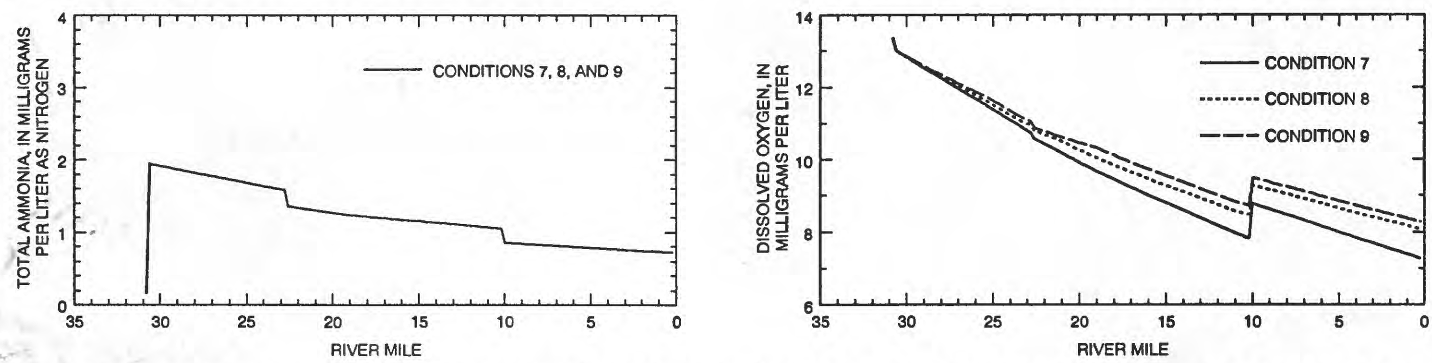

Figure 5. Simulated concentrations for conditions 7, 8, and 9 (winter 1996) for the Red River at Fargo, N. Dak., and Moorhead, Minn.

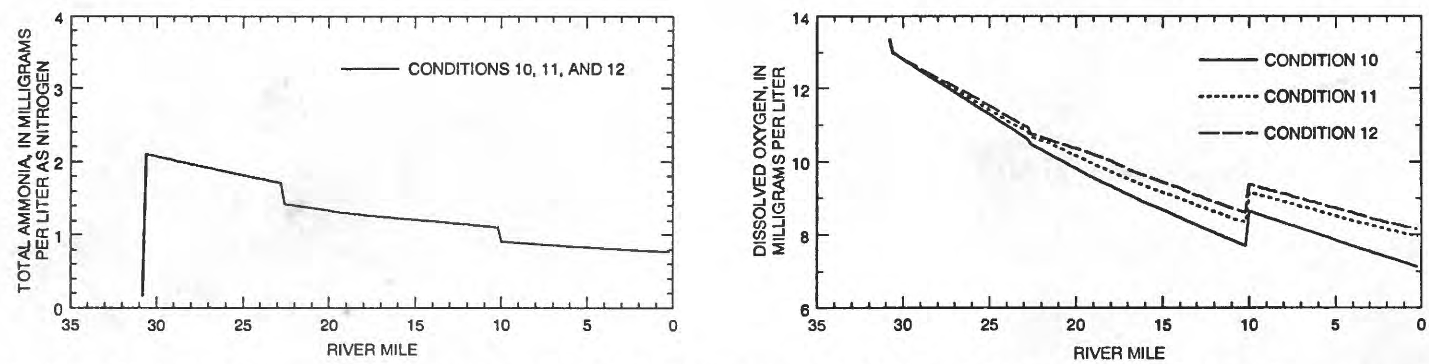

Figure 6. Simulated concentrations for conditions 10, 11, and 12 (winter 2006) for the Red River at Fargo, N. Dak., and Moorhead, Minn.

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