UNCERTAINTY ANALYSIS OF THE SIMULATIONS OF EFFECTS OF DISCHARGING TREATED WASTEWATER TO THE RED RIVER OF THE NORTH AT FARGO, NORTH DAKOTA, AND MOORHEAD, MINNESOTA

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By Edwin A. Wesolowski

ABSTRACT

Two separate studies to simulate the effects of discharging treated wastewater to the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota, have been completed. In the first study, the Red River at Fargo Water-Quality Model was calibrated and verified for ice-free conditions. In the second study, the Red River at Fargo Ice-Cover Water-Quality Model was verified for ice-cover conditions.

To better understand and apply the Red River at Fargo Water-Quality Model and the Red River at Fargo Ice-Cover Water-Quality Model, the uncertainty associated with simulated constituent concentrations and property values was analyzed and quantified using the Enhanced Stream Water Quality Model-Uncertainty Analysis. The Monte Carlo simulation and first-order error analysis methods were used to analyze the uncertainty in simulated values for six constituents and properties at sites 5, 10, and 14 (upstream to downstream order). The constituents and properties analyzed for uncertainty are specific conductance, total organic nitrogen (reported as nitrogen), total ammonia (reported as nitrogen), total nitrite plus nitrate (reported as nitrogen), 5-day carbonaceous biochemical oxygen demand for ice-cover conditions and ultimate carbonaceous biochemical oxygen demand for ice-free conditions, and dissolved oxygen. Results are given in detail for both the ice-cover and ice-free conditions for specific conductance, total ammonia, and dissolved oxygen.

The sensitivity and uncertainty of the simulated constituent concentrations and property values to input variables differ substantially between ice-cover and ice-free conditions. During ice-cover conditions, simulated specific-conductance values are most sensitive to the headwater-source specific-conductance values upstream of site 10 and the point-source specific-conductance values downstream of site 10. These headwater-source and point-source specific-conductance values also are the key sources of uncertainty. Simulated total ammonia concentrations are most sensitive to the point-source total ammonia concentrations at all three sites. Other input variables that contribute substantially to the variability of simulated total ammonia concentrations are the headwater-source total ammonia and the instream reaction coefficient for biological decay of total ammonia to total nitrite. Simulated dissolved-oxygen concentrations at all three sites are most sensitive to headwater-source dissolved-oxygen concentration. This input variable is the key source of variability for simulated dissolved-oxygen concentrations at sites 5 and 10. Headwater-source and point-source dissolved-oxygen concentrations are the key sources of variability for simulated dissolved-oxygen concentrations at site 14.

During ice-free conditions, simulated specific-conductance values at all three sites are most sensitive to the headwater-source specific-conductance values. Headwater-source specific-conductance values also are the key source of uncertainty. The input variables to which total ammonia and dissolved oxygen are most sensitive vary from site to site and may or may not correspond to the input variables that contribute the most to the variability. The input variables that contribute the most to the variability of simulated total ammonia concentrations are point-source total ammonia, instream reaction coefficient for biological decay of total ammonia to total nitrite, and Manning's roughness coefficient. The input variables that contribute the most to the variability of simulated dissolved-oxygen concentrations are reaeration rate, sediment oxygen demand rate, and headwater-source algae as chlorophyll a.

INTRODUCTION

Two separate studies to simulate the effects of discharging treated wastewater to the Red River of the North (hereinafter referred to as the Red River) at Fargo, N. Dak., and Moorhead, Minn., have been completed by the U.S. Geological Survey in cooperation with the North Dakota Department of Health and the Minnesota Pollution Control Agency. In the first study, the Enhanced Stream Water Quality Model (QUAL2E) computer program written by Brown and Barnwell (1987) was calibrated and verified for ice-free conditions (Wesolowski, 1994). In that study, the model is referred to as the Red River at Fargo Water-Quality (RRatFGO QW) Model. In the second study, the RRatFGO QW Model was verified for ice-cover conditions (Wesolowski, 1996) and is referred to as the Red River at Fargo Ice-Cover Water-Quality (RRatFGOIC QW) Model.

Separate data sets were collected from the same subreach of the Red River during a 1-day sampling period in order to verify the calibrated RRatFGO QW Model for ice-free conditions (Wesolowski, 1994) and the RRatFGOIC QW Model for ice-cover conditions (Wesolowski, 1996). The RRatFGO QW Model had been calibrated for ice-free conditions using a data set collected during 1989 and 1990 (Wesolowski, 1994). The calibrated model was considered verified for each condition when the simulated constituent concentrations and property values were within one standard deviation of the measured constituent concentrations and property values at most sites in the subreach. Verification of the calibrated model indicates that the model accurately estimates expected (average) constituent concentrations and property values for conditions present during the 1-day sampling period. However, random variations in loads and biological and chemical processes that can occur on days that have hydraulic conditions similar to those during the 1-day sampling period are not considered. These variations can result in constituent concentrations and property values that are different from those measured during the sampling period. To better understand and apply the RRatFGO QW Model and the RRatFGOIC QW Model, the uncertainty associated with simulated constituent concentrations and property values was analyzed and quantified.

The purpose of this report is to describe the results of the uncertainty analysis of water-quality simulations for ice-cover and ice-free conditions. Data collected during ice-cover conditions (February 23-24, 1995) were used for model verification and data collected during ice-free conditions (August 29-30, 1989, and August 28, August 30-31, and September 5-7, 1990) were used for model calibration. The study subreach begins just downstream of Dam A (locally referred to as North Dam; Wesolowski, 1994, p. 9), which is about 0.1 mile downstream of the 12th Avenue North bridge in Fargo, N. Dak., and extends 30.8 miles downstream to a site 0.8 mile upstream of the confluence of the Buffalo and Red Rivers (fig. 1). The locations of the data-collection sites used in this study are shown in figure 1, and a description of the sites is given in table 1.

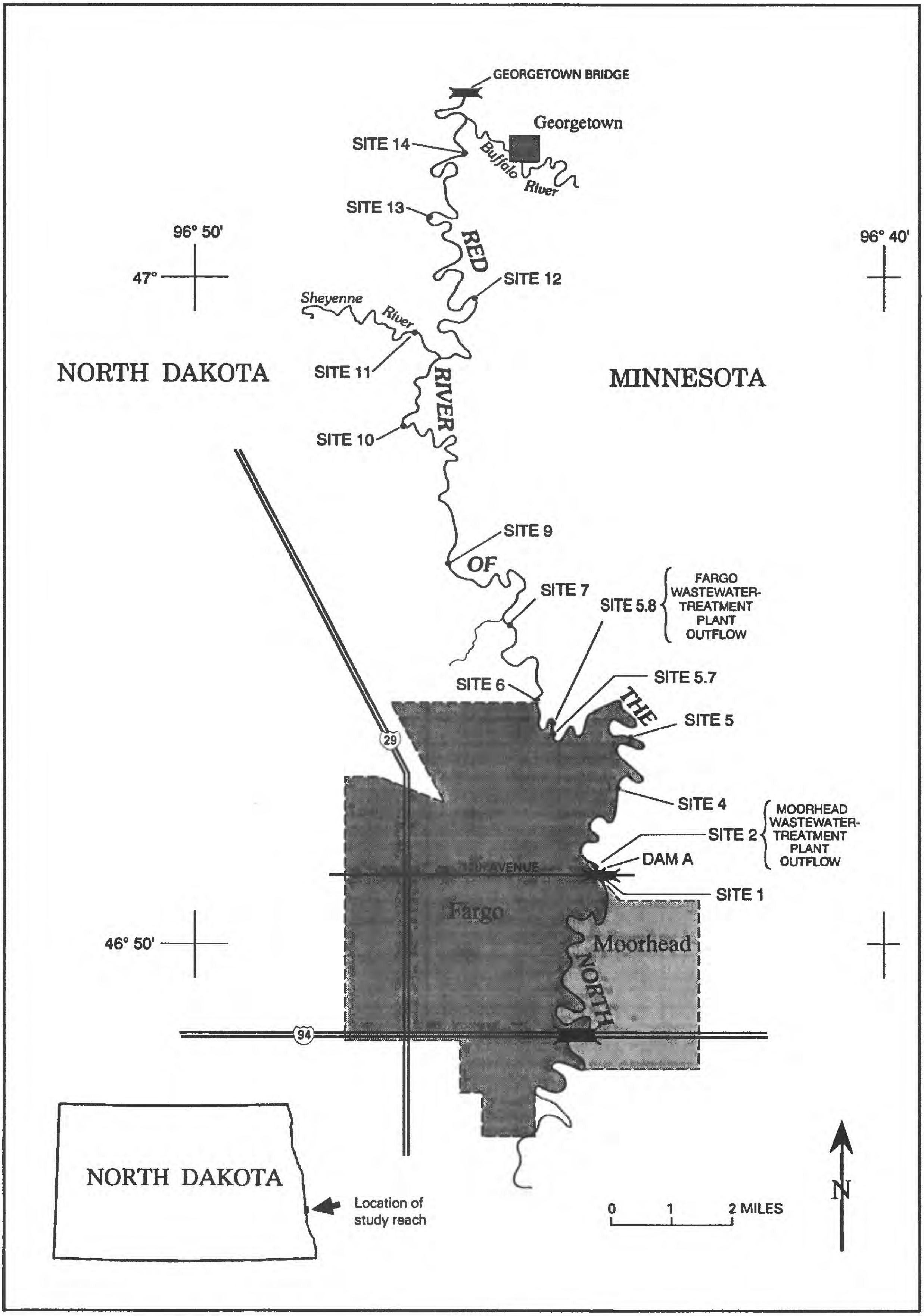

Figure 1. Location of study subreach on the Red River of the North and data-collection sites from Fargo, North Dakota, to Georgetown, Minnesota.

Table 1. Site number, description, and location of data-collection sites

[Unless otherwise indicated, data were collected at each site in 1989 and in 1995]

Site number	Description	Miles downstream from site 1	Location
1	Synoptic sampling[1] and streamflow measurement.	0	Beginning of study reach. Immediately downstream from Dam A (locally referred to as North Dam), which is about 0.1 mile below 12th Avenue North bridge.
2	Synoptic sampling[1].	.1	Moorhead, Minn., wastewater-treatment plant outflow (buried pipe).
4	Synoptic sampling[1] and streamflow measurement.	2.3	Near intersection with 25th Avenue North.
5	Synoptic sampling[1].	5.2	Near intersection with 35th Avenue North east of Cardinal Muench Seminary.
5.7	Synoptic sampling[1] and streamflow measurement, 1995.	8.0	Near west parking lot entrance to Trollwood Park.
5.8	Synoptic sampling[1], 1995.	8.4	Fargo, N. Dak., wastewater-treatment plant outflow (buried pipe).
6	Synoptic sampling[1], 1989, and streamflow measurement, 1995.	9.4	At bridge on Cass County, N. Dak., Road No. 20.
7	Synoptic sampling[1] and streamflow measurement.	11.8	Immediately upstream from previous Fargo, N. Dak., wastewater-treatment plant outflow.
9	Synoptic sampling[1] and streamflow measurement.	15.0	East of Cass County, N. Dak., Road No. 31 and 2.5 miles north of Cass County, N. Dak., Road No. 20.
10	Synoptic sampling[1] and streamflow measurement.	19.2	East of Cass County, N. Dak., Road No. 31 and about 5 miles north of Cass County, N. Dak., Road No. 20.
11	Synoptic sampling[1] and streamflow measurement.	20.8	At bridge over Sheyenne River on Cass County, N. Dak., Road No. 31.
12	Synoptic sampling[1] and streamflow measurement.	23.0	Near intersection with Clay County, Minn., ditch no. 28, 3.5 miles south of Georgetown, Minn.
13	Synoptic sampling[1], 1989.	27.5	East of Cass County, N. Dak., Road No. 31 and about 9 miles north of Cass County, N. Dak., Road No. 20.
14	Synoptic sampling[1] and streamflow measurement.	30.7	Near end of study reach. About 1 mile west of Georgetown, Minn., and 1.5 miles upstream from Georgetown bridge.

[1]Several water-quality samples were collected during a 24-hour period.

The author wishes to thank Charles S. Melching, Hydraulic Engineer, U.S. Geological Survey, Illinois District, for his comprehensive, professional review of the report and for the time he spent consulting with the author on various technical aspects of the report.

UNCERTAINTY-ANALYSIS METHODS

A total of three uncertainty-analysis methods--the sensitivity analysis (SA) method, the Monte Carlo simulation (MCS) method, and the first-order error analysis (FOEA) method--are available in the Enhanced Stream Water Quality Model-Uncertainty Analysis (QUAL2E-UNCAS) documentation (Brown and Barnwell, 1987). The sensitivity of dissolved-oxygen concentrations at sites 5, 10, and 14 to a selected group of 20 input variables, including windspeed, hydraulic parameters, reaction coefficients, and headwater-source and point-source streamflows and loads, was assessed by Wesolowski (1994). In that study, the SA method was used to accomplish a one-variable-at-a-time approach, and the sensitivity was determined relative to the dissolved-oxygen concentration for each site. The dissolved-oxygen concentration for each site was computed by the calibrated model using the calibration data set as input. The sensitivity was determined by increasing the calibrated value of one input variable by 50 percent and keeping the values of the other input variables constant. For the next sensitivity sequence, the changed input variable was returned to the original value and the next input variable was increased by 50 percent, and so on. The sensitivity in this analysis was not normalized.

A more appropriate method for assessing variable-interaction effects on the simulated output concentrations is to analyze the normalized sensitivity of the model output for several constituent concentrations or property values to variations of more than one input variable at a time. In QUAL2E-UNCAS, normalized sensitivity is calculated as part of the FOEA method. The combined effects of input-variable sensitivity and uncertainty in the determination of key input variables affecting model-output reliability may be evaluated with the MCS and FOEA methods (Melching and Yoon, in press). A detailed explanation of both methods, as used in this study, is given in Brown and Barnwell (1987).

In this study, the MCS and FOEA methods are used to analyze the uncertainty in simulated values for six constituents and properties at sites 5, 10, and 14. Sites 5, 10, and 14 were used because these sites also were used in the sensitivity analysis conducted by Wesolowski (1994). The six constituents and properties evaluated in this study are specific conductance, total organic nitrogen (reported as nitrogen), total ammonia (reported as nitrogen), total nitrite plus nitrate (reported as nitrogen), 5-day carbonaceous biochemical oxygen demand for ice-cover conditions and ultimate carbonaceous biochemical oxygen demand for ice-free conditions, and dissolved oxygen. Detailed results are given herein for both the ice-cover and ice-free conditions for specific conductance, total ammonia, and dissolved oxygen.

Model input variables, which are specified in terms of flow, water-quality characteristics (including reaction coefficients), and local climatology, drive the system being modeled and are specified by the user. The most important aspect of applying uncertainty-analysis methods, such as the MCS and the FOEA, is the quantification of the uncertainty in model input variables (Melching and Yoon, in press). In this study, the quantified uncertainty in the model input variables is expressed as a coefficient of variation (the standard deviation divided by the mean). All of the input variables associated with simulating constituent concentrations and property values for ice-cover and ice-free conditions using the RRatFGO QW Model were considered uncertain and are included in the MCS and the FOEA. The coefficients of variation for the input variables are given in table 2.

For many of the input variables, data were not available to calculate the coefficient of variation specific to the Red River between Fargo, N. Dak., and Georgetown, Minn. Therefore, the coefficient of

Table 2. Coefficients of variation for input variables for the Red River at Fargo Water-Quality Model for ice-cover and ice-free conditions

[Total organic nitrogen, total ammonia, total nitrite, and total nitrate are reported as nitrogen; total organic phosphorus and total phosphorus are reported as phosphorus; --, input variable not applied to given conditions; X, input variable applied to given conditions]

Input variable	Coefficient of variation for input variable	Ice-cover conditions	Ice-free conditions	Source
Evaporation coefficient-ae	0.10	--	X	Brown and Barnwell, 1987
Evaporation coefficient-be	.10	--	X	Brown and Barnwell, 1987
Unit of dissolved-oxygen uptake per unit of total ammonia oxidized to total nitrite	.06	X	X	Melching and Yoon, in press
Unit of dissolved-oxygen uptake per unit of total nitrite oxidized to total nitrate	.03	X	X	Melching and Yoon, in press
Unit of dissolved oxygen produced per unit of algal growth	.10	X	X	Brown and Barnwell, 1987
Unit of dissolved-oxygen uptake per unit of algal respired	.10	X	X	Brown and Barnwell, 1987
Fraction of algal biomass that is nitrogen	.10	X	X	Brown and Barnwell, 1987
Fraction of algal biomass that is phosphorus	.10	X	X	Brown and Barnwell, 1987
Maximum specific algal growth rate	.20	--	X	Brown and Barnwell, 1987
Algal respiration rate	.20	--	X	Brown and Barnwell, 1987
Nitrogen half-saturation coefficient	.10	--	X	Brown and Barnwell, 1987
Phosphorus half-saturation coefficient	.10	--	X	Brown and Barnwell, 1987
Linear algal selfshading coefficient	.10	--	X	Brown and Barnwell, 1987
Nonlinear algal selfshading coefficient	.10	--	X	Brown and Barnwell, 1987
Light-saturation coefficient	.10	--	X	Brown and Barnwell, 1987
Light-averaging factor	.02	--	X	Brown and Barnwell, 1987
Number of daylight hours	.02	--	X	Brown and Barnwell, 1987
Total daily solar radiation	.10	--	X	Brown and Barnwell, 1987
Algal preference factor for ammonia	.20	--	X	Brown and Barnwell, 1987
5-day to ultimate carbonaceous biochemical oxygen demand conversion coefficient	.10	X	--	Brown and Barnwell, 1987
Temperature correction for ultimate carbonaceous biochemical oxygen demand decay rate	.03	X	X	Brown and Barnwell, 1987
Temperature correction for rate of loss of ultimate carbonaceous biochemical oxygen demand by settling	.03	X	X	Brown and Barnwell, 1987
Temperature correction for reaeration rate	.03	X	X	Brown and Barnwell, 1987

Table 2. Coefficients of variation for input variables for the Red River at Fargo Water-Quality Model for ice-cover and ice-free conditions—Continued

[Total organic nitrogen, total ammonia, total nitrite, and total nitrate are reported as nitrogen; total organic phosphorus and total phosphorus are reported as phosphorus; --, input variable not applied to given conditions; X, input variable applied to given conditions]

Input variable	Coefficient of variation for input variable	Ice-cover conditions	Ice-free conditions	Source
Temperature correction for sediment oxygen demand rate	0.03	X	X	Brown and Barnwell, 1987
Temperature correction for instream reaction coefficient for hydrolysis of total organic nitrogen to total ammonia	.03	X	X	Brown and Barnwell, 1987
Temperature correction for total organic nitrogen settling rate	.03	X	X	Brown and Barnwell, 1987
Temperature correction for instream reaction coefficient for biological decay of total ammonia to total nitrite	.03	X	X	Brown and Barnwell, 1987
Temperature correction for benthos source rate for total ammonia	.03	X	X	Brown and Barnwell, 1987
Temperature correction for instream reaction coefficient for biological decay of total nitrite to total nitrate	.03	X	X	Brown and Barnwell, 1987
Temperature correction for instream reaction coefficient for biological decay of total organic phosphorus to total phosphorus	.03	X	X	Brown and Barnwell, 1987
Temperature correction for total organic phosphorus settling rate	.03	X	X	Brown and Barnwell, 1987
Temperature correction for benthos source rate for total phosphorus	.03	X	X	Brown and Barnwell, 1987
Temperature correction for algal growth rate	.03	--	X	Brown and Barnwell, 1987
Temperature correction for algal respiration rate	.03	--	X	Brown and Barnwell, 1987
Temperature correction for algal settling rate	.03	--	X	Brown and Barnwell, 1987
Dispersion correction constant	.20	X	X	Brown and Barnwell, 1987
Manning's roughness coefficient	.25	X	X	Singh and Melching, 1993
Trapezoidal-channel side slope 1	.05	X	X	Brown and Barnwell, 1987
Trapezoidal-channel side slope 2	.05	X	X	Brown and Barnwell, 1987
Trapezoidal-channel bottom width	.05	X	X	Brown and Barnwell, 1987
Slope of channel	.05	X	X	Brown and Barnwell, 1987
Mean elevation of reach	.05	--	X	Brown and Barnwell, 1987
Dust-attenuation coefficient	.10	--	X	Brown and Barnwell, 1987
Fraction of cloudiness	.05	--	X	Brown and Barnwell, 1987

Table 2. Coefficients of variation for input variables for the Red River at Fargo Water-Quality Model for ice-cover and ice-free conditions—Continued

[Total organic nitrogen, total ammonia, total nitrite, and total nitrate are reported as nitrogen; total organic phosphorus and total phosphorus are reported as phosphorus; --, input variable not applied to given conditions; X, input variable applied to given conditions]

Input variable	Coefficient of variation for input variable	Ice-cover conditions	Ice-free conditions	Source
Dry bulb air temperature	0.05	--	X	Brown and Barnwell, 1987
Wet bulb air temperature	.05	--	X	Brown and Barnwell, 1987
Atmospheric pressure	.002	X	X	Calculated[2]
Wind velocity	.10	--	X	Brown and Barnwell, 1987
Ultimate carbonaceous biochemical oxygen demand decay rate	.20	X	X	Calculated[2]
Rate of loss of ultimate carbonaceous biochemical oxygen demand by settling	.25	X	X	Brown and Barnwell, 1987
Sediment oxygen demand rate	.36	X	X	Calculated[1]
Reaeration rate	.50	X	X	Melching and Yoon, in press
Instream reaction coefficient for hydrolysis of total organic nitrogen to total ammonia	.20	X	X	Brown and Barnwell, 1987
Organic nitrogen settling rate	.20	X	X	Brown and Barnwell, 1987
Instream reaction coefficient for biological decay of total ammonia to total nitrite	.20	X	X	Calculated[2]
Instream reaction coefficient for biological decay of total nitrite to total nitrate	.20	X	X	Calculated[2]
Instream reaction coefficient for biological decay of total organic phosphorus to total phosphorus	.25	X	X	Calculated[2]
Ratio of chlorophyll a to algal biomass	.10	--	X	Brown and Barnwell, 1987
Algal settling rate	.20	--	X	Brown and Barnwell, 1987
Light-extinction coefficient	.10	--	X	Brown and Barnwell, 1987
Initial temperature for all model subreaches	.03	X	--	Calculated[2]
Headwater-source streamflow	.03	X	X	Calculated[2]
Headwater-source temperature	.03	--	X	Calculated[2]
Headwater-source dissolved oxygen	.07	X	X	Calculated[2]
Headwater-source ultimate carbonaceous biochemical oxygen demand	.28	X	X	Calculated[2]
Headwater-source specific conductance	.07	X	X	Calculated[2]
Headwater-source algae as chlorophyll a	.50	--	X	Calculated[2]

Table 2. Coefficients of variation for input variables for the Red River at Fargo Water-Quality Model for ice-cover and ice-free conditions—Continued

[Total organic nitrogen, total ammonia, total nitrite, and total nitrate are reported as nitrogen; total organic phosphorus and total phosphorus are reported as phosphorus; --, input variable not applied to given conditions; X, input variable applied to given conditions]

Input variable	Coefficient of variation for input variable	Ice-cover conditions	Ice-free conditions	Source
Headwater-source total organic nitrogen	0.18	X	X	Calculated[2]
Headwater-source total ammonia	.20	X	X	Calculated[2]
Headwater-source total nitrite	.14	X	X	Calculated[2]
Headwater-source total nitrate	.14	X	X	Calculated[2]
Headwater-source total organic phosphorus	.15	X	X	Brown and Barnwell, 1987
Headwater-source total phosphorus	.33	X	X	Calculated[2]
Point-source streamflow	.03	X	X	Calculated[2]
Point-source temperature	.03	--	X	Calculated[2]
Point-source dissolved oxygen	.10	X	X	Calculated[2]
Point-source ultimate carbonaceous biochemical oxygen demand	.16	X	X	Calculated[2]
Point-source specific conductance	.07	X	X	Calculated[2]
Point-source algae as chlorophyll a	.50	--	X	Calculated[2]
Point-source total organic nitrogen	.37	X	X	Calculated[2]
Point-source total ammonia	.16	X	X	Calculated[2]
Point-source total nitrite	.15	X	X	Calculated[2]
Point-source total nitrate	.12	X	X	Calculated[2]
Point-source total organic phosphorus	.05	X	X	Brown and Barnwell, 1987
Point-source total phosphorus	.06	X	X	Brown and Barnwell, 1987

[1]Calculated using data collected August 28, 1990, August 30-31, 1990, and September 5-7, 1990.
[2]Calculated using data collected August 29-30, 1989.

variation for each of these input variables was estimated from Brown and Barnwell (1987, p. 86) or other literature. When data were available, the coefficient of variation was calculated from data collected during August 29-30, 1989, and August 28, August 30-31, and September 5-7, 1990 (Wesolowski, 1994), rather than from data collected during February 23-24, 1995. The coefficient of variation for measured input variables was determined for ice-free conditions and applied to ice-cover conditions because the coefficient was expected to be larger for ice-free conditions, and use of the larger coefficient would result in a more conservative uncertainty analysis (greater uncertainty of simulated concentrations) for ice-cover conditions.

Monte Carlo Simulation

In addition to specifying the coefficient of variation for each of the input variables, a probability distribution function must be specified for each of the input variables considered uncertain in the MCS. In QUAL2E-UNCAS (Brown and Barnwell, 1987), the probability distribution function of the input variables can be designated as normal or lognormal. For this study, input variables were assumed to have a normal probability distribution. Burges and Lettenmaier (1975, p. 122) stated that the use of any other distribution implies more information about the input variables than is specified. During a MCS, the number of simulations must be large enough to avoid large errors in the estimated values of standard deviation yet small enough to avoid long computation times. Brown and Barnwell (1987, p. 85) indicated that "about 2,000 simulations are required to achieve estimates of output standard deviations with 95-percent confidence intervals of 5 percent." Thus, 2,000 simulations were used in this study. In QUAL2E-UNCAS, the assumption is made that all input variables act independently. Thus, each input is randomized independently from the others.

During the MCS, each input variable is sampled at random from the corresponding normal probability distribution. The normal probability distribution for the variable is defined by a mean value that is equal to the best estimate obtained from measurement or calibration (Wesolowski, 1994, p. 132-136) and by a coefficient of variation (table 2). Once a random value has been obtained for each input variable, the RRatFGO QW Model or the RRatFGOIC QW Model is run for these input variables. Each run results in one MCS of the constituent concentrations and property values. The constituent concentrations and property values computed in the MCS are stored, and the process is repeated until 2,000 simulations are completed. The entire distribution of the constituent concentrations and property values computed in the 2,000 simulations then is analyzed to determine the minimum, maximum, mean, range, variance (standard deviation and coefficient of variation), and skewness coefficient (the degree to which a frequency distribution departs from symmetry). The validity of this method is not affected by nonlinearity in the water-quality model (Brown and Barnwell, 1987, p. 84).

The 95-percent confidence interval (CI) calculated using the standard deviation and mean obtained from the MCS of a given constituent concentration or property value represents the variability of that constituent or property. The variability results from uncertainties in the knowledge of the hydraulic, biological, and chemical processes that affect the constituent concentrations or property values for all days with similar loads, flows, and forcing functions (user-specified inputs that drive the system being modeled). In contrast, the 95-percent CI obtained from measured concentrations or values for the same constituent or property represents the variability of the measured constituent or property in the stream only during the sampling period (C. S. Melching, U.S. Geological Survey, written commun., 1995). Ideally, the MCS CI would include the measured CI.

First-Order Error Analysis

FOEA provides insight on model performance in terms of key input variables that require detailed study and the overall model-simulation reliability. FOEA is used to determine which input variables substantially affect the uncertainty of various water-quality constituents or properties. Once these input variables are determined, carefully designed sampling programs can be applied to reduce the variance (uncertainty) in these input variables and in the computed water-quality constituent concentrations or property values.

In the FOEA, if the input variables are not correlated, the variance of a given output variable may be estimated as

$$Var(Y) = \sigma_Y^2 \approx \sum_{i=1}^{p} \left[\left(\frac{\partial Y}{\partial X_i} \right)_{Xm} \sigma_i \right]^2, \quad (1)$$

where

Y is an output variable;

σ_Y^2 is the variance of output variable Y;

p is the number of input variables considered to be uncertain;

X is an input variable;

Xm indicates that the derivative is taken at the mean values of the input variables; and

σ_i is the standard deviation of input variable X_i, which is equal to the product of the mean value and the coefficient of variation of input variable X_i.

The component of variance resulting from an input variable is the product of the derivative squared and the standard deviation squared for that input variable divided by the total variance for the output variable. The component of variance is expressed as a percent. The derivatives required in FOEA are determined numerically by increasing the input-variable values, one at a time, by 5 percent, determining the change in the constituent concentration or property value of interest, and dividing that change by the increase in the input-variable value (Melching and Yoon, in press). The use of a 5-percent increment in the calibrated input-variable values was recommended by Brown and Barnwell (1987, p. 84). In this study, all of the input variables were perturbed so that the contributions from all input variables to the simulated variance are computed.

FOEA uses a first-order approximation to the Taylor-series relation to compute variances in multivariate situations. The model for which FOEA is applied is assumed to be linear, and in QUAL2E-UNCAS the input variables are assumed to act independently (Brown and Barnwell, 1987). A linear approximation of the model simulation output process is used to compute an estimate of the output variance. If the model simulation of the water-quality constituents and properties is approximately linear, the difference between the coefficient of variation determined using the MCS and the coefficient of variation determined using the FOEA is small and the FOEA results are reliable. However, Brown and Barnwell (1987, p. 81) noted that, although FOEA provides a direct estimate of model sensitivity, the variability computed with FOEA could be more indicative of the variance of model components than of the dynamics of the model structure and should be taken into consideration when interpreting FOEA results.

UNCERTAINTY ANALYSIS OF THE SIMULATIONS OF EFFECTS OF DISCHARGING TREATED WASTEWATER DURING ICE-COVER CONDITIONS

Very good agreement (less than 0.5-percent difference) was obtained between the base mean (the mean simulated with the RRatFGOIC QW Model) and the MCS mean for all six constituents and properties included in the uncertainty analysis. This close agreement indicates that the means of the RRatFGOIC QW Model computations of the constituent concentrations and property values are the same as the means that would be obtained using the assumption that the model is approximately linear. Selected statistics for specific-conductance values are given in table 3, statistics for total ammonia concentrations are given in table 4, and statistics for dissolved-oxygen concentrations are given in table 5. Except for

Table 3. Selected statistics for specific-conductance values simulated with the Red River at Fargo Ice-Cover Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-cover conditions, February 23-24, 1995, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[μS/cm, microsiemens per centimeter at 25 degrees Celsius]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Ice-Cover Water-Quality Model			
Base mean, μS/cm	615	639	871
Monte Carlo simulation			
Minimum, μS/cm	467	496	701
Maximum, μS/cm	754	777	1,030
Mean, μS/cm	616	640	872
Range, μS/cm	287	281	329
Standard deviation, μS/cm	42	41	44
Coefficient of variation	.07	.06	.05
Skewness coefficient	.03	.03	.03
95-percent confidence interval, μS/cm	534 to 698	560 to 720	786 to 985
First-order error analysis			
Standard deviation, μS/cm	42	41	44
Coefficient of variation	.07	.06	.05
Measured			
Mean, μS/cm	621	639	865
Standard deviation, μS/cm	6	24	7
Coefficient of variation	.01	.04	.01
95-percent confidence interval, μS/cm	606 to 633	584 to 694	847 to 883

dissolved-oxygen concentrations at site 14, the measured 95-percent CI at all three sites for specific-conductance values, total ammonia concentrations, and dissolved-oxygen concentrations is within the MCS 95-percent CI. This result is reasonable because the measured values represent variances for only 1 day, whereas the MCS values represent variances for all days with similar loads, flows, and forcing functions. At site 14, the measured upper 95-percent CI limit for dissolved oxygen exceeds the MCS upper 95-percent CI limit. Although the measured values appear to be outliers, given available information, they could not be discounted because of sampling error nor could they be attributed to some known process in the river (Wesolowski, 1996).

Specific Conductance

The standard deviation and coefficient of variation for specific-conductance values obtained with the MCS and the FOEA are identical for each site (table 3). Very little skewness is shown in the MCS results. As indicated by the coefficients of variation, the variability of the measured specific-conductance values, although less, fluctuates more between sites than the variability of the MCS specific-conductance values. The MCS coefficients of variation uniformly decrease in the downstream direction.

Table 4. Selected statistics for total ammonia concentrations simulated with the Red River at Fargo Ice-Cover Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-cover conditions, February 23-24, 1995, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[Total ammonia is reported as nitrogen; mg/L, milligrams per liter]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Ice-Cover Water-Quality Model			
Base mean, mg/L	0.29	0.28	0.17
Monte Carlo simulation			
Minimum, mg/L	0.18	0.18	0.11
Maximum, mg/L	.40	.40	.26
Mean, mg/L	.29	.28	.17
Range, mg/L	.22	.22	.15
Standard deviation, mg/L	.04	.04	.02
Coefficient of variation	.14	.14	.12
Skewness coefficient	.01	.12	.17
95-percent confidence interval, mg/L	0.21 to 0.37	0.20 to 0.36	0.13 to 0.21
First-order error analysis			
Standard deviation, mg/L	0.04	0.04	0.02
Coefficient of variation	.14	.14	.12
Measured			
Mean, mg/L	0.27	0.28	0.16
Standard deviation, mg/L	.004	.011	.006
Coefficient of variation	.01	.04	.04
95-percent confidence interval, mg/L	0.26 to 0.28	0.26 to 0.30	0.15 to 0.17

Simulated specific-conductance values at sites 5 and 10 are most sensitive to the headwater-source specific-conductance values as indicated by the ranking of the normalized sensitivity coefficients (results for February 23-24, 1995; table 6). Thus, specific-conductance values in two-thirds of the study reach are most sensitive to the headwater-source specific-conductance values for ice-cover conditions. This sensitivity is changed in the lower part of the study reach because of the magnitude of inflow from the Sheyenne River. The change in sensitivity is demonstrated at site 14 where the specific-conductance value is most sensitive to the point-source specific-conductance value followed by the headwater-source specific-conductance value. Thus, specific-conductance values in the study reach are governed by either the headwater-source specific-conductance values (sites 5 and 10) or the point-source specific-conductance values (site 14).

The components of variance for specific-conductance values (table 6) at the three sites show a ranking pattern similar to that of the normalized sensitivity coefficients. Thus, at corresponding sites, the same input variables are the key sources of sensitivity and uncertainty in the specific-conductance values. Nearly all of the variance in specific-conductance values in the river as far downstream as site 10 (99.92 percent at site 5 and 98.72 percent at site 10) results from headwater-source specific-conductance values. The contribution of the headwater-source specific-conductance value to the total variance in specific-conductance values decreases markedly to 32.69 percent at site 14. The contribution of the point-

Table 5. Selected statistics for dissolved-oxygen concentrations simulated with the Red River at Fargo Ice-Cover Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-cover conditions, February 23-24, 1995, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[mg/L, milligrams per liter]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Ice-Cover Water-Quality Model			
Base mean, mg/L	13.1	12.5	12.3
Monte Carlo simulation			
Minimum, mg/L	10.5	10.0	10.0
Maximum, mg/L	15.9	15.2	14.6
Mean, mg/L	13.2	12.5	12.3
Range, mg/L	5.4	5.2	4.6
Standard deviation, mg/L	.90	.86	.74
Coefficient of variation	.07	.07	.06
Skewness coefficient	-.03	-.02	-.07
95-percent confidence interval, mg/L	11.3 to 14.8	10.8 to 14.2	10.8 to 14.0
First-order error analysis			
Standard deviation, mg/L	0.90	0.86	0.74
Coefficient of variation	.07	.07	.06
Measured			
Mean, mg/L	12.7	12.7	14.1
Standard deviation, mg/L	.42	.20	.16
Coefficient of variation	.03	.02	.01
95-percent confidence interval, mg/L	11.9 to 13.5	12.3 to 13.1	13.8 to 14.4

source specific-conductance value to the total variance is 65.18 percent at site 14. The total variability of simulated specific-conductance values, expressed as a standard deviation, ranges from 41 to 44 microsiemens per centimeter at 25 degrees Celsius (table 3). The estimation uncertainty for specific-conductance values, expressed as a coefficient of variation, is about 6 percent (table 3) and is comparable to the magnitude of uncertainty (7 percent) for the input variables (table 6).

Total Ammonia

The standard deviation and coefficient of variation for total ammonia concentrations obtained with the MCS and the FOEA are identical for each site (table 4). Some positive skewness is shown in the MCS results for sites 10 and 14; however, the skewness does not substantially affect the estimated mean and standard deviation as indicated by the agreement between the base mean and the MCS mean and between the MCS standard deviation and the FOEA standard deviation. As indicated by the coefficients of variation, the model simulation of total ammonia concentrations shows a slight decrease in variability at downstream sites, whereas the measured values show a slight increase in variability at downstream sites.

In terms of the components of variance, the uncertainty for total ammonia concentrations is caused by a larger number of input variables than is the uncertainty for either specific-conductance values or

Table 6. Results of first-order error analysis of specific-conductance values simulated with the Red River at Fargo Ice-Cover Water-Quality Model for data collected February 23-24, 1995, and the Red River at Fargo Water-Quality Model for data collected August 29-30, 1989

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; number in parentheses represents a ranking of the sensitivity and variance of the property value to the input variable with 1 being the most sensitive normalized sensitivity coefficient or the highest component of variance]

Input variable[1]	Coefficient of variation for input variable	Normalized sensitivity coefficient[2]			Component of variance[3] (percent)		
		Site 5	Site 10	Site 14	Site 5	Site 10	Site 14
February 23-24, 1995							
Headwater-source specific conductance	0.07	0.97 (1)	0.90 (1)	0.42 (2)	99.92 (1)	98.72 (1)	32.69 (2)
Point-source specific conductance	.07	.03 (2)	.10 (2)	.58 (1)	.08 (2)	1.19 (2)	65.18 (1)
August 29-30, 1989							
Headwater-source specific conductance	0.07	0.92 (1)	0.74 (1)	0.54 (1)	99.27 (1)	88.49 (1)	57.84 (1)
Point-source specific conductance	.07	.08 (2)	.26 (2)	.46 (2)	.68 (2)	11.38 (2)	41.94 (2)

[1]Input variables are not shown if the ranking of the normalized sensitivity coefficient was greater than five and the component of variance was less than 2 percent at all three sites.
[2]Represents a percentage change in the simulated property value resulting from a 5-percent change in each input variable (equation VI-1 in Brown and Barnwell, 1987, p. 83).
[3]Represents the percentage of the total variance in the simulated property value resulting from the perturbation of the corresponding input variable.

dissolved-oxygen concentrations. Many input variables have substantial normalized sensitivity coefficients and components of variance (results for February 23-24, 1995; table 7). Simulated total ammonia concentrations are most sensitive to the point-source total ammonia concentrations at all three sites. The sensitivity to the point-source total ammonia concentrations at sites 5 and 10 is followed by sensitivity to the point-source streamflows, the headwater-source streamflows, and the headwater-source total ammonia concentrations. The sensitivity to the point-source total ammonia concentration at site 14 is followed by sensitivity to the temperature correction for instream reaction coefficient for biological decay of total ammonia to total nitrite, the initial temperature for all model subreaches, and the instream reaction rate for biological decay of total ammonia to total nitrite.

Although at site 14 the temperature correction for instream reaction coefficient for biological decay of total ammonia to total nitrite ranks second among the normalized sensitivity coefficients, the contribution of this input variable to the total variance in total ammonia concentrations is only 1.07 percent. This is because the temperature correction for instream reaction coefficient for biological decay of total ammonia to total nitrite is known with low uncertainty as reflected in the coefficient of variation value of 0.03. In contrast, the instream reaction coefficient for biological decay of total ammonia to total nitrite has a relatively low normalized sensitivity coefficient rank of 4, but the contribution of this input variable to the total variance is about 25 percent. This input variable also has a much greater uncertainty as indicated by the coefficient of variation value of 0.20.

The components of variance for total ammonia concentrations (table 7) at all three sites do not follow the same ranking pattern as that of the normalized sensitivity coefficients. Thus, at corresponding sites, the same input variables are not the key sources of sensitivity and uncertainty in the total ammonia concentrations. At site 5, the contribution of the headwater-source and point-source total ammonia concentrations to the total variance is about 95 percent. At site 10, the contribution from those two variables plus the instream reaction coefficient for biological decay of total ammonia to total nitrite is about 90 percent. At site 14, the contribution from the same three variables is about 84 percent. Manning's roughness coefficient and the instream reaction coefficient for hydrolysis of total organic nitrogen to total ammonia contribute an additional 10 percent to the total variance at that site. Thus, the uncertainty that results from the headwater-source and point-source input variables generally decreases in the downstream direction, and the uncertainty that results from Manning's roughness coefficient and the instream reaction coefficients increases in the downstream direction. Furthermore, with increased traveltime (or increased distance from the source), reaction coefficients become more important than boundary conditions in affecting the uncertainty of total ammonia concentration.

Dissolved Oxygen

The standard deviation and coefficient of variation for dissolved-oxygen concentrations obtained with the MCS and the FOEA are identical for each site (table 5). Although more than twice as much negative skewness is shown in the MCS results for site 14 than in the results for sites 5 and 10, the skewness does not substantially affect the estimated mean and standard deviation as indicated by the agreement between the base mean and the MCS mean and between the MCS standard deviation and the FOEA standard deviation. As indicated by the coefficients of variation, the variability of both the MCS and the measured dissolved-oxygen concentrations decreases in the downstream direction.

The normalized sensitivity coefficients and components of variance for dissolved-oxygen concentrations (results for February 23-24, 1995; table 8) are very similar to those for specific conductance except for the sediment oxygen demand rate. Dissolved-oxygen concentrations are not sensitive to the

Table 7. Results of first-order error analysis of total ammonia concentrations simulated with the Red River at Fargo Ice-Cover Water-Quality Model for data collected February 23-24, 1995, and the Red River at Fargo Water-Quality Model for data collected August 29-30, 1989

[Total organic nitrogen, total ammonia, and total nitrite are reported as nitrogen; number in parentheses represents a ranking of the sensitivity and variance of the constituent concentration to the input variable with 1 being the most sensitive normalized sensitivity coefficient or the highest component of variance; mg/L, milligrams per liter]

Input variable[1]	Coefficient of variation for input variable	Normalized sensitivity coefficient[2]			Component of variance[3] (percent)		
		Site 5	Site 10	Site 14	Site 5	Site 10	Site 14
			February 23-24, 1995				
Temperature correction for instream reaction coefficient for biological decay of total ammonia to total nitrite	0.03	0.10 (6)	0.34 (6)	0.47 (2)	0.06	0.61	1.07
Manning's roughness coefficient	.25	-.05 (8)	-.11 (8)	-.13 (8)	.84	4.59	5.80 (4)
Instream reaction coefficient for hydrolysis of total organic nitrogen to total ammonia	.20	.01 (9)	.08 (9)	.15 (7)	.01	1.56	4.62 (5)
Instream reaction coefficient for biological decay of total ammonia to total nitrite	.20	-.08 (7)	-.25 (7)	-.34 (4)	1.40	14.19 (3)	24.82 (2)
Initial temperature for all model subreaches	.03	-.12 (5)	-.32 (5)	-.42 (3)	<1.00	<1.00	<1.00
Headwater-source streamflow	.03	-.49 (3)	-.44 (3)	-.11 (10)	1.31	1.02	.06
Headwater-source total ammonia	.20	.44 (4)	.36 (4)	.32 (5)	47.47 (1)	29.04 (2)	20.84 (3)
Point-source streamflow	.03	.54 (2)	.52 (2)	.18 (6)	1.57	1.38	.15
Point-source total ammonia	.16	.55 (1)	.56 (1)	.54 (1)	47.25 (2)	45.90 (1)	38.22 (1)
			August 29-30, 1989				
Manning's roughness coefficient	0.25	-0.35 (6)	-0.43 (17)	-0.77 (5)	15.77 (3)	19.52 (3)	26.14 (2)
Wet bulb air temperature	.05	-.015 (9)	-.53 (6)	-1.07 (2)	.11	1.20	2.00
Instream reaction coefficient for biological decay of total ammonia to total nitrite	.20	-.47 (5)	-.69 (4)	-1.25 (1)	18.23 (2)	32.99 (2)	43.94 (1)
Headwater-source streamflow	.03	-.78 (4)	-.60 (5)	-.36 (10)	1.12	.56	.08
Headwater-source temperature	.03	-1.30 (1)	-.80 (2)	-.98 (3)	3.11 (4)	.98 (5)	.61
Point-source streamflow	.03	1.00 (3)	.80 (3)	.65 (17)	1.81	.98 (6)	.27
Point-source total ammonia	.16	1.03 (2)	.92 (1)	.80 (4)	54.93 (1)	36.75 (1)	11.59

[1]Input variables are not shown if the ranking of the normalized sensitivity coefficient was greater than five and the component of variance was less than 2 percent at all three sites.
[2]Represents a percentage change in the simulated constituent concentration resulting from a 5-percent change in each input variable (equation VI-1 in Brown and Barnwell, 1987, p. 83).
[3]Represents the percentage of the total variance in the simulated constituent concentration resulting from the perturbation of the corresponding input variable.

sediment oxygen demand rate during ice-cover conditions. However, the sediment oxygen demand rate becomes a source of uncertainty as water travels downstream.

Simulated dissolved-oxygen concentrations are most sensitive to the headwater-source and point-source dissolved-oxygen concentrations. For ice-cover conditions, dissolved-oxygen concentrations are affected more by dilution than by consumption during biological processes because, at low temperatures, biological activity is negligible and the corresponding reaction coefficients and their standard deviations are small. The estimation uncertainty for dissolved-oxygen concentrations, expressed as a coefficient of variation, is about 7 percent (table 5) and is comparable to the magnitude of uncertainty (about 7 to 10 percent) for the headwater-source and point-source input variables (table 8).

UNCERTAINTY ANALYSIS OF THE SIMULATIONS OF EFFECTS OF DISCHARGING TREATED WASTEWATER DURING ICE-FREE CONDITIONS

Very good agreement (less than or equal to 2-percent difference) was obtained between the base mean (the mean simulated with the RRatFGO QW Model) and the MCS mean for all six constituents and properties included in the uncertainty analysis. However, substantial skewness existed in the distribution of the MCS of total ammonia and dissolved oxygen, indicating nonlinearity in the model.

Selected statistics for specific-conductance values are given in table 9, statistics for total ammonia concentrations are given in table 10, and statistics for dissolved-oxygen concentrations are given in table 11. Except for dissolved-oxygen concentrations at site 5, the measured 95-percent CI at all three sites for specific-conductance values, total ammonia concentrations, and dissolved-oxygen concentrations is within the MCS 95-percent CI. This result is reasonable because the measured values represent variances for only 1 day, whereas the MCS values represent variances for all days with similar loads, flows, and forcing functions. At site 5, the measured upper 95-percent CI limit for dissolved-oxygen concentrations exceeds the MCS upper 95-percent CI limit because of large unsimulated diurnal variations in dissolved-oxygen concentrations resulting from substantial photosynthesis and respiration caused by an algal bloom upstream of the study reach (Wesolowski, 1994, p. 50).

Specific Conductance

The standard deviation and coefficient of variation for specific-conductance values obtained with the MCS and the FOEA are almost identical for each site (table 9). As indicated by the coefficients of variation, the variability of the measured specific-conductance values is less than the variability of the MCS and FOEA specific-conductance values. The measured coefficients of variation and the MCS and FOEA coefficients of variation have opposite trends in the downstream direction--the measured coefficients increase slightly in the downstream direction and the MCS and FOEA-estimated coefficients decrease slightly in the downstream direction. In other words, the model simulations of specific-conductance values show greater variability at upstream sites, whereas the measured values show greater variability at downstream sites.

Simulated specific-conductance values at all three sites are most sensitive to the headwater-source specific-conductance values as indicated by the normalized sensitivity coefficients (results for August 29-30, 1989; table 6). The sensitivity steadily decreases in the downstream direction. In contrast, sensitivity to the point-source specific-conductance values steadily increases in the downstream direction because the point-source loads are small relative to the headwater-source load. This condition differs from during ice-

Table 8. Results of first-order error analysis of dissolved-oxygen concentrations simulated with the Red River at Fargo Ice-Cover Water-Quality Model for data collected February 23-24, 1995, and the Red River at Fargo Water-Quality Model for data collected August 29-30, 1989

[Total ammonia and total nitrite are reported as nitrogen; number in parentheses represents a ranking of the sensitivity and variance of the constituent concentration to the input variable with 1 being the most sensitive normalized sensitivity coefficient or the highest component of variance; mg/L, milligrams per liter]

Input variable[1]	Coefficient of variation for input variable	Normalized sensitivity coefficient[2]			Component of variance[3] (percent)		
		Site 5	Site 10	Site 14	Site 5	Site 10	Site 14
			February 23-24, 1995				
Sediment oxygen demand rate	0.36	<0.10	<0.10	<0.10	0.25 (2)	3.10 (2)	4.26 (3)
Headwater-source dissolved oxygen	.07	.98 (1)	.96 (1)	.60 (1)	99.55 (1)	94.42 (1)	48.04 (1)
Point-source dissolved oxygen	.10	.01 (2)	.04 (2)	.40 (2)	.03 (3)	.38 (3)	45.25 (2)
			August 29-30, 1989				
Maximum specific algal growth rate	0.20	0.08 (5)	0.16 (7)	0.16 (5)	7.06 (4)	6.71 (4)	7.19 (4)
Manning's roughness coefficient	.25	-.004 (17)	.08 (17)	.14 (8)	.02	2.42 (6)	7.69 (3)
Wet bulb air temperature	.05	-.06 (11)	-.33 (3)	-.28 (2)	.26	1.70 (8)	1.31 (7)
Atmospheric pressure	.002	.58 (1)	1.15 (1)	1.11 (1)	<1.00	<1.00	<1.00
Sediment oxygen demand rate	.36	-.07 (6)	-.12 (13)	-.10 (13)	14.74 (3)	11.52 (2)	9.58 (2)
Reaeration rate	.50	.03 (13)	.18 (6)	.19 (4)	5.58 (6)	53.55 (1)	60.89 (1)
Instream reaction coefficient for biological decay of total ammonia to total nitrite	.20	<.10	<.10	<.10	3.35 (8)	2.29 (7)	.12
Headwater-source streamflow	.03	.12 (4)	.23 (4)	.12 (9)	<1.00	<1.00	<1.00
Headwater-source temperature	.03	-.52 (3)	-.37 (2)	-.12 (10)	6.18 (5)	.79	.09
Headwater-source dissolved oxygen	0.07	.52 (2)	.08 (16)	.02 (17)	34.40 (1)	.19	.01
Headwater-source algae as chlorophyll a	.50	<0.10	<0.10	<0.10	20.14 (2)	9.79 (3)	5.01 (5)
Point-source temperature	.03	-.02 (15)	-.15 (9)	-.21 (3)	<1.00	<1.00	<1.00
Point-source total ammonia as nitrogen	.16	-.08 (10)	-.19 (5)	-.12 (11)	3.82 (7)	5.67 (5)	2.27 (6)

[1]Input variables are not shown if the ranking of the normalized sensitivity coefficient was greater than five and the component of variance was less than 2 percent at all three sites.
[2]Represents a percentage change in the simulated constituent concentration resulting from a 5-percent change in each input variable (equation VI-1 in Brown and Barnwell, 1987, p. 83).
[3]Represents the percentage of the total variance in the simulated constituent concentration resulting from the perturbation of the corresponding input variable.

Table 9. Selected statistics for specific-conductance values simulated with the Red River at Fargo Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-free conditions, August 29-30, 1989, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[μS/cm, microsiemens per centimeter at 25 degrees Celsius]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Water-Quality Model			
Base mean, μS/cm	662	678	704
Monte Carlo simulation			
Minimum, μS/cm	527	564	585
Maximum, μS/cm	793	787	810
Mean, μS/cm	663	679	705
Range, μS/cm	266	223	225
Standard deviation, μS/cm	43	37	35
Coefficient of variation	.06	.05	.05
Skewness coefficient	-.03	-.06	-.09
95-percent confidence interval, μS/cm	580 to 748	606 to 751	636 to 774
First-order error analysis			
Standard deviation, μS/cm	43	37	35
Coefficient of variation	.06	.05	.05
Measured			
Mean, μS/cm	664	677	[1]695
Standard deviation, μS/cm	12	22	21
Coefficient of variation	.02	.03	.03
95-percent confidence interval, μS/cm	640 to 688	634 to 720	654 to 736

[1]Data are from site 13.

cover conditions when the shift in sensitivity from upstream to downstream is more abrupt (table 6) because of the relatively large point-source load (site 11) in comparison to the headwater-source load.

The components of variance for specific-conductance values (table 6) at all three sites follow the same ranking pattern as that of the normalized sensitivity coefficients. Thus, at corresponding sites, the same input variables are the key sources of sensitivity and uncertainty in the specific-conductance values. At site 5, the contribution of the headwater-source specific-conductance value to the total variance in specific-conductance values is 99.27 percent. This decreases to 88.49 percent at site 10 and 57.84 percent at site 14. In contrast, the contribution of the point-source specific-conductance value to the total variance in specific-conductance values increases from 0.68 percent at site 5 to 41.94 percent at site 14. The total variability of simulated specific-conductance values, expressed as a standard deviation, ranges from 35 to 43 microsiemens per centimeter at 25 degrees Celsius (table 9). This estimation uncertainty for specific-conductance values, expressed as a coefficient of variation, is about 6 percent (table 9) and is comparable to the magnitude of uncertainty (7 percent) for the input variables (table 6). In comparison, the coefficient of variation for the measured values ranges from 2 to 3 percent (table 9).

Table 10. Selected statistics for total ammonia concentrations simulated with the Red River at Fargo Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-free conditions, August 29-30, 1989, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[Total ammonia is reported as nitrogen; mg/L, milligrams per liter]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Water-Quality Model			
Base mean, mg/L	0.37	0.57	0.23
Monte Carlo simulation			
Minimum, mg/L	0.10	0.12	0
Maximum, mg/L	.77	1.4	.90
Mean, mg/L	.38	.59	.25
Range, mg/L	.67	1.3	.90
Standard deviation, mg/L	.08	.15	.10
Coefficient of variation	.21	.25	.40
Skewness coefficient	.35	.64	1.0
95-percent confidence interval, mg/L	0.22 to 0.54	0.30 to 0.88	0.05 to 0.45
First-order error analysis			
Standard deviation, mg/L	0.08	0.14	0.09
Coefficient of variation	.22	.25	.39
Measured			
Mean, mg/L	0.30	0.48	[1]0.18
Standard deviation, mg/L	.12	.05	.02
Coefficient of variation	.40	.10	.11
95-percent confidence interval, mg/L	0.24 to 0.36	0.46 to 0.50	0.17 to 0.19

[1]Data are from site 13.

Total Ammonia

The standard deviation and coefficient of variation for total ammonia concentrations obtained with the MCS and the FOEA are in close agreement for each site (table 10). Some positive skewness is shown in the MCS results for all three sites; however, the skewness does not substantially affect the estimated mean and standard deviation because the estimated mean and standard deviation are in close agreement with the base mean and FOEA standard deviation. In contrast to specific-conductance values, the model simulations of total ammonia concentrations show greater variability at downstream sites, whereas the measured values show greater variability at upstream sites.

Simulated total ammonia concentrations are sensitive to and are affected by variances from a large number of input variables (table 7). At site 5, the concentrations are most sensitive to the headwater-source and point-source variables. Headwater-source temperature ranks highest among the normalized sensitivity coefficients, but the contribution of this input variable to the total variance is only 3.11 percent. Point-source total ammonia concentration ranks second among the normalized sensitivity coefficients, and the contribution of this input variable to the total variance is 54.93 percent. The instream reaction coefficient for biological decay of total ammonia to total nitrite and Manning's roughness coefficient,

Table 11. Selected statistics for dissolved-oxygen concentrations simulated with the Red River at Fargo Water-Quality Model and with the Monte Carlo simulation method, calculated with the first-order error analysis method, and measured during ice-free conditions, August 29-30, 1989, on the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota

[mg/L, milligrams per liter]

Statistic	Location		
	Site 5	Site 10	Site 14
Red River at Fargo Water-Quality Model			
Base mean, mg/L	8.4	7.2	7.7
Monte Carlo simulation			
Minimum, mg/L	5.9	0	0
Maximum, mg/L	10.4	12.3	14.2
Mean, mg/L	8.4	7.1	7.4
Range, mg/L	4.5	12.3	14.2
Standard deviation, mg/L	.55	1.2	1.4
Coefficient of variation	.07	.17	.19
Skewness coefficient	-.36	-1.39	-1.68
95-percent confidence interval, mg/L	7.2 to 9.6	4.7 to 9.4	4.7 to 9.8
First-order error analysis			
Standard deviation, mg/L	0.52	0.91	0.94
Coefficient of variation	.06	.13	.12
Measured			
Mean, mg/L	8.5	7.0	[1]7.2
Standard deviation, mg/L	1.0	.6	.4
Coefficient of variation	.12	.09	.06
95-percent confidence interval, mg/L	6.5 to 10.5	5.8 to 8.2	6.4 to 8.0

[1]Data are from site 13.

which rank fifth and sixth among the normalized sensitivity coefficients, contribute an additional 34 percent to the total variance at site 5.

At site 10, the concentrations still are most sensitive to the headwater-source and point-source variables. However, the reaction coefficients begin dominating in terms of percentage of the total variance contribution. At site 10, the contribution of the point-source total ammonia concentration, the headwater-source temperature, and the point-source streamflow, which rank first, second, and third among the normalized sensitivity coefficients, is 38.71 percent of the total variance. The instream reaction coefficient for biological decay of total ammonia to total nitrite and Manning's roughness coefficient, which rank fourth and seventeenth among the normalized sensitivity coefficients, contribute an additional 52.51 percent to the total variance at site 10.

At site 14, the concentrations are most sensitive to the reaction coefficients. The contribution of the instream reaction coefficient for biological decay of total ammonia to total nitrite, which ranks highest among the normalized sensitivity coefficients, is 43.94 percent of the total variance. The contribution of Manning's roughness coefficient, which ranks fifth among the normalized sensitivity coefficients, is 26.14 percent of the total variance.

The total variability of the FOEA total ammonia concentrations, expressed as a standard deviation, ranges from 0.08 to 0.14 milligram per liter (table 10). This estimation uncertainty for total ammonia concentrations, expressed as a coefficient of variation, increases from 22 to 39 percent in the downstream direction. In comparison, the coefficient of variation for the measured values decreases from 40 percent at site 5 to 10 percent at site 10 and then increases to 11 percent at site 14 (table 10). The greater measured coefficient of variation at site 5 (0.40) may be caused partly by sampling or analytical error. The uncertainty in defining the instream reaction coefficient for biological decay of total ammonia to total nitrite and Manning's roughness coefficient results in a large variance in total ammonia concentrations as water travels downstream. A reduction in the uncertainty of these input variables would reduce the corresponding coefficient of variation because the uncertainty accumulates in the downstream direction.

Dissolved Oxygen

The standard deviation and coefficient of variation for dissolved-oxygen concentrations obtained with the MCS and the FOEA are in close agreement at site 5 but begin to show substantial differences in the downstream direction (table 11). These differences indicate that substantial nonlinearities are present in the dissolved-oxygen concentrations simulated with the RRatFGO QW Model. The effects of the nonlinearities increase in the downstream direction and cannot be estimated adequately with the linear approximation applied in the FOEA. The MCS of dissolved-oxygen concentrations have a greater skewness at all three sites than the MCS of either specific-conductance values or total ammonia concentrations. The negative skewness more substantially affects the simulations of concentrations as water travels downstream. As for total ammonia concentrations, the MCS of dissolved-oxygen concentrations show greater variability at downstream sites, whereas the measured concentrations show greater variability at upstream sites.

The components of variance for dissolved-oxygen concentrations at all three sites do not follow the same ranking pattern as that of the normalized sensitivity coefficients. The ranking patterns of the normalized sensitivity coefficients and the components of variance are changing as water travels downstream (table 8). Also, for some input variables, large changes occur in the components of variance between site 5 and site 10.

At all three sites, atmospheric pressure ranks highest among the normalized sensitivity coefficients. However, the contribution of atmospheric pressure to the total variance in dissolved-oxygen concentrations is less than 1.00 percent because of the very low coefficient of variation for this input variable (0.002). At site 5, the headwater-source dissolved-oxygen concentration ranks second among the normalized sensitivity coefficients. The contribution of this input variable to the total variance rapidly decreases in the downstream direction from 34.40 percent at site 5 to 0.19 percent at site 10. At site 5, the uncertainty in dissolved-oxygen concentrations is caused mostly by the headwater-source dissolved-oxygen and algae as chlorophyll a concentrations. The contribution of these two input variables to the total variance is 54.54 percent. The contribution of the reaeration rate to the total variance is 5.58 percent at site 5 and 53.55 percent at site 10. The contribution of the sediment oxygen demand rate is substantial but gradually decreases in the downstream direction from 14.74 percent at site 5 to 9.58 percent at site 14. The contribution of the headwater-source algae as chlorophyll a concentration also gradually decreases in the downstream direction from 20.14 percent at site 5 to 5.01 percent at site 14. The reaeration rate is the highest source of uncertainty (60.89 percent) in the dissolved-oxygen concentration at site 14. The uncertainty in defining the sediment oxygen demand rate, the reaeration rate, and the headwater-source algae as chlorophyll a concentration (table 8) results in a large variance in dissolved-oxygen concentrations as water travels downstream. A reduction in the uncertainty of these three input variables would reduce the corresponding component of variation because the uncertainty accumulates in the downstream direction.

SUMMARY AND CONCLUSIONS

Two separate studies to simulate the effects of discharging treated wastewater to the Red River of the North at Fargo, North Dakota, and Moorhead, Minnesota, have been completed. In the first study, the Enhanced Stream Water Quality Model (QUAL2E) was calibrated and verified for ice-free conditions. In that study, the model is referred to as the Red River at Fargo Water-Quality (RRatFGO QW) Model. In the second study, the RRatFGO QW Model was verified for ice-cover conditions and is referred to as the Red River at Fargo Ice-Cover Water-Quality (RRatFGOIC QW) Model.

Separate data sets were collected from the same subreach of the Red River of the North to verify the calibrated RRatFGO QW Model for ice-free conditions and the RRatFGOIC QW Model for ice-cover conditions. The calibrated model was considered verified for each condition when the simulated constituent concentrations and property values were within one standard deviation of the measured constituent concentrations and property values at most sites in the subreach.

Verification of the calibrated model indicates that the model accurately estimates expected (average) constituent concentrations and property values for conditions present during a 1-day sampling period. However, random variations in loads and biological and chemical processes that can occur on days that have hydraulic conditions similar to those during the 1-day sampling period are not considered. To better understand and apply the RRatFGO QW Model and the RRatFGOIC QW Model, the uncertainty associated with simulated constituent concentrations and property values was analyzed and quantified using the Enhanced Stream Water Quality Model-Uncertainty Analysis (QUAL2E-UNCAS). The Monte Carlo simulation (MCS) and first-order error analysis (FOEA) methods were used to analyze the uncertainty in simulated values for six constituents and properties at sites 5, 10, and 14 (upstream to downstream order). The constituents and properties used are specific conductance, total organic nitrogen (reported as nitrogen), total ammonia (reported as nitrogen), total nitrite plus nitrate (reported as nitrogen), 5-day carbonaceous biochemical oxygen demand for ice-cover conditions and ultimate carbonaceous biochemical oxygen demand for ice-free conditions, and dissolved oxygen. Detailed results are given in this report for both the ice-cover and ice-free conditions for specific conductance, total ammonia, and dissolved oxygen.

The uncertainty of the model input variables, which are specified in terms of flow, water-quality characteristics (including reaction coefficients), and local climatology, was quantified. For many of the input variables, data were not available to calculate coefficients of variation. Therefore, the coefficient of variation for each of these input variables was estimated from literature. When data were available, the coefficient of variation was calculated from data collected during August 29-30, 1989, and August 28, August 30-31, and September 5-7, 1990. Input variables were assumed to have a normal probability distribution.

During the MCS, each input variable is sampled at random from the corresponding normal probability distribution. Each input is randomized independently from the others. The distribution of constituent concentrations and property values computed in 2,000 simulations was analyzed statistically to determine the minimum, maximum, mean, range, variance (standard deviation and coefficient of variation), and skewness coefficient. The validity of this method is not affected by nonlinearity in the water-quality model.

FOEA is used to determine which input variables substantially affect the uncertainty of various water-quality constituents or properties. FOEA output consists of a tabulation of normalized sensitivity coefficients and a listing of the components of variance. The normalized sensitivity coefficient represents a percentage change in the simulated constituent concentrations or property values resulting from a 5-percent change in each input variable. The component of variance represents the percentage of the total variance in the simulated constituent concentration or property value resulting from the perturbation of the corresponding input variable.

The model for which FOEA is applied is assumed to be linear and the input variables are assumed to act independently. If the model simulation of the water-quality constituents and properties is approximately linear, the difference between the coefficient of variation determined using the MCS and the coefficient of variation determined using the FOEA is small and the FOEA results are reliable.

For ice-cover conditions, very good agreement was obtained between the base mean and the MCS mean for all six constituents and properties included in the uncertainty analysis. This close agreement indicates that the means of the RRatFGOIC QW Model computations of the constituent concentrations and property values are the same as the means that would be obtained using the assumption that the model is approximately linear.

The standard deviation and coefficient of variation for specific-conductance values, total ammonia concentrations, and dissolved-oxygen concentrations obtained with the MCS and the FOEA are either identical or in close agreement for each site. Although the MCS results for specific conductance, total ammonia, and dissolved oxygen show some skewness at all three sites, the estimated mean and standard deviation are not substantially affected as indicated by the agreement between the base mean and the MCS mean and by the MCS standard deviation being either identical or in close agreement to the FOEA standard deviation. Thus, the accuracy of the key sources of uncertainty identified in the FOEA is confirmed.

Simulated specific-conductance values are most sensitive to the headwater sources upstream of site 10 and the point sources downstream of site 10. These headwater and point sources also are the key sources of uncertainty. The headwater-source load and the point-source load from site 11 (Sheyenne River) dominate the system in comparison to the point-source loads from sites 2 and 5.8.

Simulated total ammonia concentrations are most sensitive to point-source total ammonia concentrations at all three sites. Generally, as the total ammonia concentration travels downstream, more of the variance is caused by instream reaction coefficients and less is caused by headwater-source and point-source input variables. However, point-source total ammonia still contributes the most to the variability of simulated total ammonia concentrations at site 14. A reduction in the uncertainty of these three input variables would reduce the corresponding components of variance.

Headwater-source dissolved-oxygen concentrations rank highest among the normalized sensitivity coefficients and are the key source of variability for simulated dissolved-oxygen concentrations at sites 5 and 10. Headwater-source and point-source dissolved-oxygen concentrations are the key sources of variability for simulated dissolved-oxygen concentrations at site 14. For ice-cover conditions, dissolved-oxygen concentrations are affected more by dilution than by consumption during biological processes because, at low temperatures, biological activity is negligible and the corresponding reaction coefficients and their standard deviations are small.

For ice-free conditions, very good agreement was obtained between the base mean and the MCS mean for all six constituents and properties included in the uncertainty analysis. However, substantial skewness existed in the distribution of the MCS of total ammonia and dissolved oxygen, indicating nonlinearity in the model.

The standard deviation and coefficient of variation for specific-conductance values, total ammonia concentrations, and dissolved-oxygen concentrations obtained with the MCS and the FOEA are either identical or in close agreement for each site except for dissolved-oxygen concentrations at sites 10 and 14. Although the MCS results for specific conductance and total ammonia show some skewness at all three sites, the skewness does not substantially affect the estimated mean and standard deviation because the estimated mean and standard deviation are in close agreement with the base mean and FOEA estimated standard deviation. Thus, the accuracy of the key sources of uncertainty identified in the FOEA is confirmed.

The MCS of dissolved-oxygen concentrations indicate a greater skewness than the MCS of either specific-conductance values or total ammonia concentrations. The skewness more substantially affects the simulations of concentrations as water travels downstream. These differences indicate that substantial nonlinearities are present in the dissolved-oxygen concentrations simulated with the RRatFGO QW Model. This nonlinearity caused standard deviations obtained from the FOEA to differ from standard deviations obtained from the MCS. Thus, the accuracy of the FOEA results is somewhat reduced in quantitative terms but is accurate in relative terms.

Simulated specific-conductance values are most sensitive to the headwater-source specific conductance at sites 5, 10, and 14. The headwater-source specific conductance also is the key source of uncertainty. The headwater-source load dominates the system because the point-source loads from sites 2, 5.8, and 11 are relatively small.

The input variables that contribute the most to the variability of simulated total ammonia concentrations are point-source total ammonia, instream reaction coefficient for biological decay of total ammonia to total nitrite, and Manning's roughness coefficient. The contribution of the point-source total ammonia concentration to the total variance decreases in the downstream direction. The contribution of the instream reaction coefficient for biological decay of total ammonia to total nitrite and Manning's roughness coefficient to the total variance increases in the downstream direction. Thus, between sites 5 and 10, reaction coefficient input variables become the largest contributors to the total variance of total ammonia concentrations.

The input variables that contribute the most to the variability of simulated dissolved-oxygen concentrations are reaeration rate, sediment oxygen demand rate, and headwater-source algae as chlorophyll a. The contribution of the headwater-source algae as chlorophyll a and the sediment oxygen demand rate to the total variance decreases in the downstream direction, but the contribution of the reaeration rate to the total variance increases in the downstream direction. A reduction in the uncertainty of these three input variables would reduce the corresponding component of variance.

A reduction in the coefficient of variation for the key input variables identified by the FOEA method for the constituents and properties used in this study for both the ice-cover and the ice-free conditions would reduce the corresponding component of variance. Rather than using the coefficients of variation from literature, a carefully designed sampling program in which the necessary data to quantify key input variable coefficients of variation were collected could be used to reduce the uncertainty of the key input variables. Uncertainty of the key input variables also could be reduced by collecting data during climatic and hydraulic conditions that differ from those that existed when data used to calculate the coefficients of variation were collected.

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