

Application and Evaluation of the HEC-RAS-Nutrient Simulation Module (NSM I)

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PURPOSE: The purpose of this Ecosystem Management and Restoration Research Program (EMRRP) technical note is to document the application and evaluation study of the Hydrologic Engineering Center-River Analysis System-Nutrient Simulation Module I (HEC-RAS-NSM I) model for the Lower Minnesota River. HEC-RAS is a one-dimensional (1D) riverine hydraulic model that can be used to analyze flows and sediment transport (HEC 2010a, 2010b). A new nutrient water quality module — NSM I — was developed for the HEC-RAS model. The NSM I was designed to simulate aquatic dissolved oxygen, carbonaceous biological oxygen demand, nitrogen and phosphorus cycles, and algae biomass with simplified processes and minimum state variables. The processes and formulations in NSM I is adapted, in part, from the Enhanced Stream Water Quality Model (QUAL2E) (Brown and Barnwell 1987), its improvements (Chapra et al., 2008), and the one-dimensional (cross sectionally averaged) hydrodynamic and water quality model (CE-QUAL-RIV1) (EL 1995). The HEC-RAS-NSM I model could be utilized for US Army Corps of Engineer’s (USACE’s) water resources management and ecosystem restoration.

BACKGROUND: Eutrophication is currently the most widespread water quality problem in the nation and accounts for about 60% of the impaired conditions of rivers in the U.S. (Carpenter et al. 1998; USEPA 2007). The effect of eutrophication is high production of plankton algae (“algal blooms”) and excessive growth of weeds and macroalgae, leading to decreased dissolved oxygen, which, in turn, may prevent water bodies from meeting water quality standards for their designed use. The prevailing opinion is that the eutrophication problem is caused by high nitrogen and phosphorus loads from human activities. The relationship between cause and effect are often complex. To evaluate the relationship, water quality models have been shown to be powerful tools. Decision makers and stakeholders benefit from the ability to run scenario simulations to assess future water quality situations across a broad range of conditions. In contrast to standing waters, the effects of eutrophication on running water ecosystems have not been given much attention. Many studies have focused on nutrient transport by rivers to other ecosystems, such as lakes and estuaries, because nutrients are accumulating there. However, there are also effects of eutrophication in streams and rivers themselves, including direct effects and indirect effects of eutrophication on physical characteristics, chemistry, and on the biota that are living in the stream or river. A public-domain, fully integrated riverine hydraulic, sediment and water quality model that encompasses diagnostic, predictive, and operational applications in conjunction with monitoring data is needed for USACE’s water resources management and ecosystem restoration. HEC-RAS is in the public domain, it has been widely used to analyze flows and sediment transport in the United States and around the world. A new water quality module, NSM I, has been developed for the HEC-RAS model. The NSM I is a nutrient simulation module developed as a

dynamic link library (DLL). Various kinetic processes and equations in NSM I, and its integration with HEC-RAS, have been critically tested and verified previously, and the focus in this technical note is on the real world application. The HEC-RAS-NSM I was applied to the Lower Minnesota River (LMNR) for the assessment of riverine water quality. A six-year period (2001 – 2006) was simulated to verify the performance of the HEC-RAS-NSM I model against field data. The LMNR HEC-RAS-NSM I model captured the spatial and temporal trends in all modeled water quality constituents, including temperature, total dissolved solids, inorganic suspended solids, algae, organic phosphorus and nitrogen, phosphate, ammonia, nitrate, biological oxygen demand, and dissolved oxygen. With rare exceptions, the statistical measures of model performance were excellent. The HEC-RAS-NSM I model should be considered as a useful riverine hydraulic and water quality tool.

HEC-RAS-NSM I MODEL DESCRIPTION: The HEC-RAS is a one-dimensional (1D) steady and unsteady flow hydraulics program capable of simulating a full network of open channels and hydraulic structures, such as bridges, culverts, and weirs, with variable spatial discretization. A key component of HEC-RAS is its graphical user interface (GUI), which standardizes many aspect of data entry and facilitates an efficient display of model results and communication between model sub-components (HEC 2010a, 2010b). This section briefly discusses NSM I and its integration with HEC-RAS.

Physical Transport of Water Quality Constituents. The basis of the water quality model is the principle of mass conservation. The model includes transport and reactions that affect water quality variables that are either dissolved or in particulate form in the water column. HEC-RAS solves a 1D advection-dispersion transport module for each water quality constituent as follows:

$$\frac{\partial}{\partial t}(VC) = -\frac{\partial}{\partial x}(QC)\Delta x + \frac{\partial}{\partial x}\left(AD_x \frac{\partial C}{\partial x}\right)\Delta x + S_L + S_B + S_K \quad (1)$$

where Q = inflow, A = cross-sectional flow area, x = distance along channel, t = time, V = volume of the water quality cell (m^3), C = concentration of a constituent (g/m^3), D_x = dispersion coefficient (m^2/s), S_L = source/sink term representing direct and diffuse loading rate ($g\ m^{-3}\ s^{-1}$), S_B = source/sink term representing boundary loading rate, including upstream, downstream, and benthic interaction ($g\ m^{-3}\ s^{-1}$), S_K = source/sink term representing biogeochemical reaction rate ($g\ m^{-3}\ s^{-1}$).

HEC-RAS solves Equation 1 for each water quality cell and for each state variable. The equation requires that if there is a source of mass at a location, the mass being introduced must be accounted for. The QUICKEST-ULTIMATE explicit numerical scheme is used to solve this equation in HEC-RAS. The resultant finite-difference solution to Equation 1 is

$$V^{n+1}C^{n+1} = V^n C^n + \Delta t \left(Q_{up} C_{up}^* - Q_{dn} C_{dn}^* + D_{dn} A_{dn} \frac{\partial C^*}{\partial x_{dn}} - D_{up} A_{up} \frac{\partial C^*}{\partial x_{up}} \right) + \Delta t SS \quad (2)$$

where C^{n+1} = concentration of a constituent at present time step (g/m^3), C^n = concentration of a constituent at previous time step (g/m^3), C_{up}^* = QUICKEST concentration of a constituent at

upstream (g/m^3), C_{up}^* = QUICKEST derivative of a constituent at upstream (g/m^4), D_{up} = upstream face dispersion coefficient (m^2/s), V^{n+1} = volume of the water quality cell at present time step (m^3), V^n = volume of the water quality cell at previous time step (m^3), Q_{up} = upstream face flow (m^3/s), A_{up} = upstream face cross section area (m^2), SS = total source and sink terms of a constituent ($\text{g}/\text{m}^3/\text{s}$).

Water Temperature. Water temperature is an important factor for controlling water quality in rivers. Many water quality kinetic coefficients are temperature dependent. Water temperature simulation has been implemented using a full energy budget approach. The source and sink term for temperature; i.e., the change in water temperature with respect to time due to heat exchange at the water surface, is computed as follows:

$$SS_{Heat} = \frac{q_{net}}{\rho_w C_{pw}} \frac{A_s}{V} \quad (3)$$

where SS_{Heat} = heat source or sink term ($^{\circ}\text{C}/\text{s}$), q_{net} = net heat flux at the air water interface (W/m^2), ρ_w = density of water (kg/m^3), C_{pw} = specific heat of water ($\text{J kg}^{-1} \text{ } ^{\circ}\text{C}^{-1}$), A_s = area of the water quality cell (m^2).

The net heat flux (q_{net}) is calculated from a heat budget of the following terms:

$$q_{net} = q_{sw} + q_{aim} - q_b + q_h - q_l \quad (4)$$

where q_{sw} = solar radiation (W/m^2), q_{aim} = atmospheric (downwelling) longwave radiation (W/m^2), q_b = back (upwelling) longwave radiation (W/m^2), q_h = sensible heat (W/m^2), and q_l = latent heat (W/m^2).

Nutrient Simulation Module: NSM I. Kinetic processes and corresponding time rates of change of the concentration due to biochemical reactions are determined separately from NSM I. Figure 1 shows the schematic of water quality state variables and kinetic processes included in NSM I. The NSM I includes processes that deposit or transfer material onto the sediment bed, but they do not model the fate of those constituents once they are in the bed. This framework is a direct descendant of previous water quality models including QUAL2E (Brown and Barnwell 1987), QUAL2K (Chapra et al. 2008), CE-QUAL-RIV1 (EL 1995). Each of the arrows in Figure 1 represents a kinetic process that proceeds at a rate which is controlled by the users through their input of kinetic data.

The NSM I is designed to conduct aquatic water quality simulation with simplified processes and minimum state variables. It simulates carbonaceous biological oxygen demand (CBOD), dissolved oxygen (DO), simplified nitrogen and phosphorus cycles, which resulted in organic nitrogen, ammonia, nitrate-nitrite, organic phosphorus, and total inorganic phosphorus, and algae and benthic algae biomass as additional state variables. Table 1 lists the water quality state variables included in NSM I. A discussion of each of the kinetic equations can be found in Zhang and Johnson (in preparation).

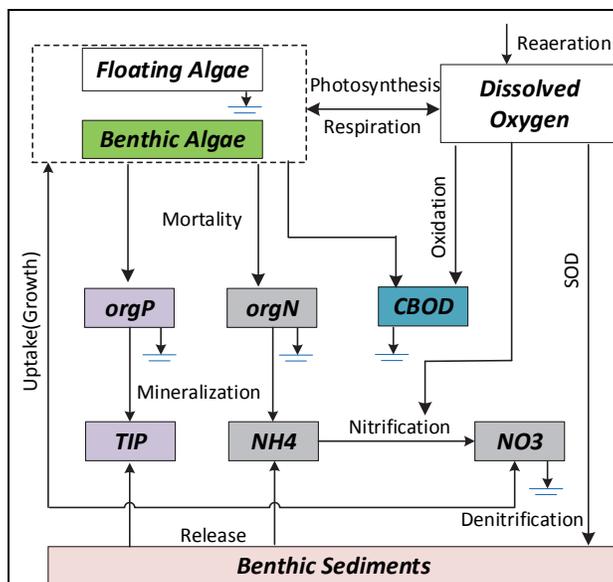


Figure 1. Water quality processes and kinetic interactions of the variables in NSM I.

Table 1. List of the water quality state variables in NSM I.		
Variable Name	Symbol	Unit
General Constituent	C_i	mg/L
Algae	A_p	mg-A/L
Benthic Algae	A_b	g-A/m ²
Organic Nitrogen	$orgN$	mg-N/L
Ammonia Nitrogen	NH_4	mg-N/L
Nitrate-Nitrite Nitrogen	NO_3	mg-N/L
Organic Phosphorus	$orgP$	mg-P/L
Total Inorganic Phosphorus	TIP	mg-P/L
Carbonaceous BOD Group	$CBOD$	mg-O/L
Dissolved Oxygen	DO	mg-O/L

APPLICATION OF HEC-RAS-NSM I MODEL TO THE LOWER MINNESOTA RIVER:

The Minnesota River runs 330 miles from its origin in Big Stone Lake on the South Dakota border to its confluence with the Mississippi River near the Twin Cities of Minneapolis and St. Paul, Minnesota. The Minnesota River contributes the highest sediment and nutrient loads to the Mississippi River upstream of Lake Pepin, a natural impoundment in Navigation Pool 4 (MCES 2002 and 2004). A number of other studies provided further evidence of poor water quality in the LMNR) (Larson 2002, Kloiber 2004). This reach of the river has been listed as impaired due to low levels of dissolved oxygen and high levels of turbidity, bacteria, mercury, and PCBs (MPCA 2008). Concerns over high algal biomass and dissolved oxygen depletion during low discharge periods, deposition of nutrient-rich sediment, and excessive loads of nitrogen and phosphorus to the system have led to an assessment of water quality and the development of a CE-QUAL-W2

(Cole and Wells 2010) model for use in establishing goals for load reduction of point and nonpoint sources and evaluation of management scenarios to improve current water quality conditions in the system (Smith et al. 2010).

HEC-RAS-NSM I has been verified using analytical solutions for the transport of non-conservative substances in open channel flow. In this study, it was applied to a real-life problem to evaluate its capability to simulate the concentrations of algae, DO, CBOD, and nutrients in the LMNR. The model was tested to determine how well results from the model match actual measurements from the river using six water years (2001 – 2006) of data representing a wide range of conditions. The model domain encompasses the lower forty miles of the Minnesota River, which lie within the seven-county Twin Cities Metropolitan Area. Figure 2 is a detailed map of the LMNR study area, including all major tributaries, wastewater treatment plants, power plant, and airport outfalls.

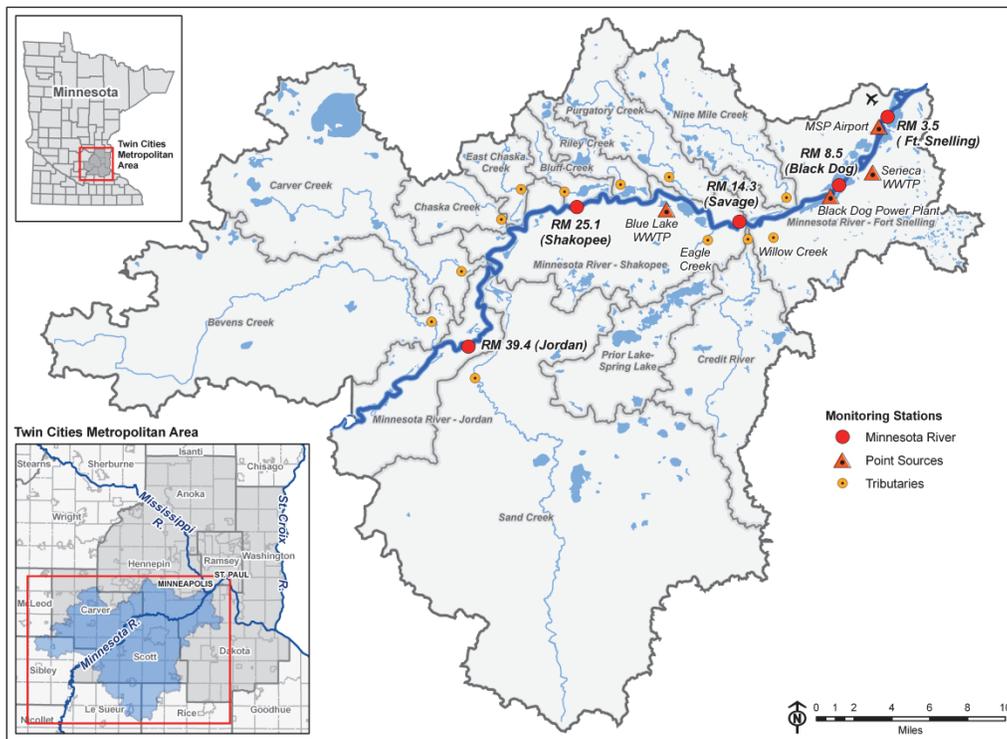


Figure 2. Lower Minnesota River study area (Craig Skone, MCES).

The LMNR was modeled with 90 longitudinal segments, varying in length from 134.0 to 2321.4 m (Figure 3). Figure 3 shows a schematic of the HEC-RAS modeled segments. The upstream-downstream boundary of the LMNR was located between river miles (RM) 39.4 and 3.5, where the MCES has maintained long-term sampling stations for more than 40 years (Figure 2). The HEC-RAS channel geometry for the LMNR was originally developed by the USACE, St. Paul District. Four major tributaries were identified for their contribution to the LMNR model for water years 2001-2006: Sand Creek, Carver Creek, Credit River, and Nine Mile Creek. Sufficient data existed for the period 2004-2006 to define seven additional tributaries in the model: Chaska Creek, East Chaska Creek #EC1 (upstream outlet), East Chaska Creek #EC3 (downstream outlet), Bluff Creek,

Riley Creek, Purgatory Creek, Eagle Creek, and Willow Creek. Daily inflows and water temperatures and concentrations of dissolved organic carbon, total organic carbon, total inorganic carbon, pH, total dissolved solids, total suspended solids, total iron, dissolved iron, ammonia-nitrogen, nitrate-nitrogen, ortho-phosphorus, total phosphorus, and other constituents measured were available from gage stations located on these tributaries (Figure 2). There are numerous point source discharges from industrial facilities and small wastewater treatment plants (WWTP). Two larger WWTPs represent the third and fourth largest plants in the state of Minnesota. The LMNR receives permitted discharges from several other facilities, notably stormwater discharges from an international airport and cooling-water discharges from a power-generating plant. A total of six point sources were identified for use in the model (Smith et al. 2010). Five-day carbonaceous biochemical oxygen demand concentrations were used to define $CBOD_U$ inputs for the point sources because they are measured more frequently. Also, the discharge permits are defined in terms of $CBOD_5$. Meteorological input data included short- and long-wave radiation, air temperature, vapor pressure, wind speed, and precipitation. Hourly average meteorological data included in US Environmental Protection Agency (USEPA) BASINS (<http://www.epa.gov/waterscience/basins>) was used in this study. The data was collected from the weather station at the Minneapolis-St. Paul Airport. Initial conditions must be specified for each water quality constituent. Initial conditions were obtained from field data.

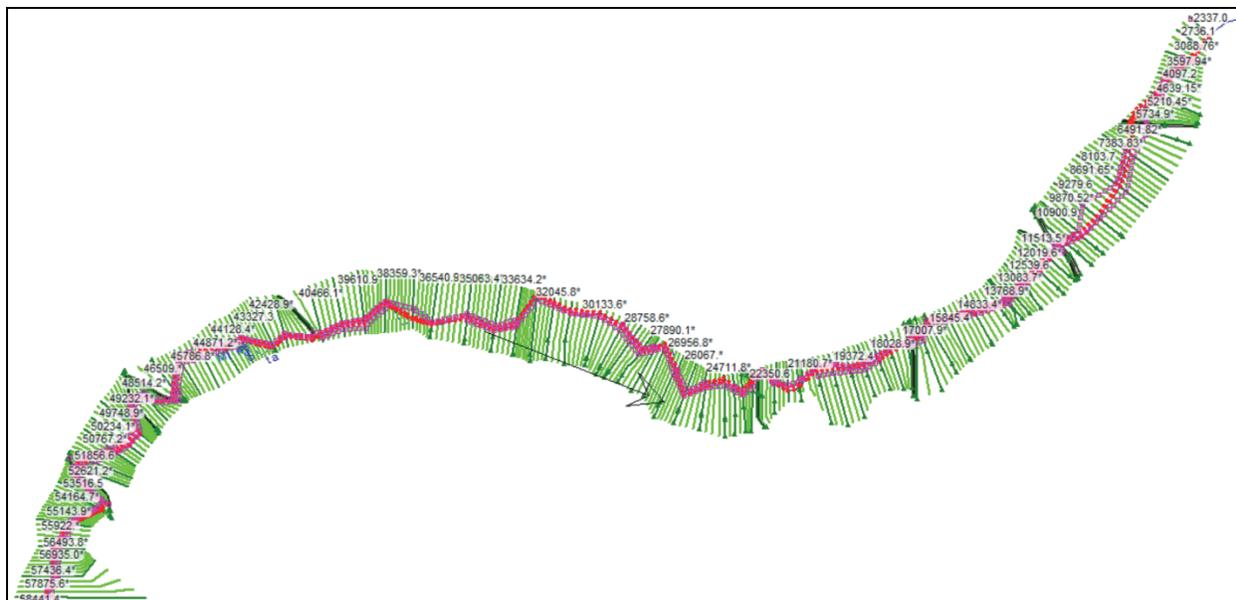


Figure 3. Schematic of the LMNR HEC-RAS model with cross section configurations.

Model Calibration and Verification. During model calibration and verification, agreement between modeled results and observed data was evaluated visually and quantitatively. A variety of quantifiable measures of model fit are described in Moriasi et al. (2007). The authors choose the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and Percent error (PBIAS) as evaluators of HEC-RAS-NSM I model performance.

$$R^2 = \frac{\left(\sum_i (OV_i - \overline{OV})(MV_i - \overline{MV}) \right)^2}{\sum_i (OV_i - \overline{OV})^2 \sum_i (MV_i - \overline{MV})^2} \quad (5)$$

$$NSE = 1.0 - \frac{\sum_i (OV_i - MV_i)^2}{\sum_i (OV_i - \overline{OV})^2} \quad (6)$$

$$PBIAS = \frac{\sum_i (OV_i - MV_i)}{\sum_i OV_i} * 100 \quad (7)$$

where n = number of observations during the simulation period, OV_i = observed value at the i time step, \overline{OV} = mean observed value for the time period, MV_i = modeled value at the i time step, \overline{MV} = mean modeled value for the time period.

Calibration was done in several phases. First, adjustable parameters in the hydraulic model were set to maximize the fit to observed values for water elevations and flow discharge. The next phase of the calibration focused on adjustable parameters in the NSM I. Most water quality parameters were derived from existing LMNR CE-QUAL-W2 (Smith et al. 2010). If parameters were not available, a series of model runs were performed to calibrate the simulation results against field data, maintaining parameter values within the bounds of literature values. Final calibrated NSM I coefficients are summarized in Table 2.

Model Results and Comparisons with Observed Data. The HEC-RAS model was run for a six-year simulation period from 2001 through 2006. River flows were available at three USGS gaging stations. Riverine water quality measurements were available from five locations for evaluating model performance. River locations with monitoring data are shown in Figure 2. The river locations are RM 39.4 (Jordan), 25.1 (Shakopee), 14.3 (Savage), 8.5 (Black Dog), and 3.5 (Fort Snelling). Their corresponding cross sections in HEC-RAS are labeled as XS 58441, XS 40346, XS 23004, XS 13579, and XS 5601. The section labeled RM 39.4 near Jordan represents the inflow boundary condition, and RM 3.5 near Fort Snelling contains the most complete calibration data set. RM 3.5 was used as the primary calibration site because it is near the Minnesota River mouth, below all major point sources, and in the reach with the most significant water quality problems. Output from the HEC-RAS-NSM model includes results of intermediate calculations such as computation of individual process terms, as well as computed water quality. Results from the NSM may be combined with output from the hydrodynamic model to facilitate graphical output such as combined time series and profile plots of simulated discharge and water quality. The plotted model results are hourly averages of model output for each constituent and for each station, whereas the observed data were collected at various times throughout the day for each station and date collected.

Table 2. Water quality coefficients used in HEC-RAS.			
Coefficient		Unit	Value
Ratio of chlorophyll-a to algal biomass	α_0	$\mu\text{g-Chl/mg-A}$	14.815
Fraction of algal biomass that is N	α_1	mg-N/mg-A	0.08
Fraction of algal biomass that is P	α_2	mg-P/mg-A	0.005
Maximum algal growth rate	μ_{mxp}	day^{-1}	1.9
Algal respiration rate	k_r	day^{-1}	0.2
Algal settling velocity	σ_1	m/d	0.3
Half-saturation constant for light	K_L	W/m^2	18
Half-saturation constant for N	K_N	mg-N/L	0.05
Half-saturation constant for P	K_P	mg-P/L	0.001
Non-algal light extinction coefficient	λ_0	m^{-1}	0.581
Linear algal self-shading coefficient	λ_1	$\text{m}^{-1} (\mu\text{g-Chl/L})^{-1}$	0.03
Nonlinear algal self-shading coefficient	λ_2	$\text{m}^{-1} (\mu\text{g-Chl/L})^{-2/3}$	0.05
Algal preference factor for ammonia	P_N	-	0.5
O ₂ production per unit of algal growth	α_3	$\text{mg-O}_2/\text{mg-A}$	1.4
O ₂ uptake per unit of algae respired	α_4	$\text{mg-O}_2/\text{mg-A}$	1.1
O ₂ uptake per unit of NH ₃ oxidation	α_5	$\text{mg-O}_2/\text{mg-N}$	3.43
O ₂ reaeration rate	k_2	day^{-1}	1.0
CBOD decay rate	k_1	day^{-1}	0.04
CBOD settling rate	k_3	day^{-1}	0.3
Biological oxidation rate of NH ₃	β_1	day^{-1}	0.3
Hydrolysis rate of organic N	β_3	day^{-1}	0.0128
Organic N settling rate	σ_4	day^{-1}	0.01
Benthos source rate for ammonia N	σ_3	$\text{g-N m}^{-2} \text{d}^{-1}$	0.001
Nitrification oxygen inhibition factor	K_{NR}	$\text{mg-O}_2/\text{L}$	0.65
Hydrolysis rate of organic P	β_4	day^{-1}	0.0128
Benthos source rate for dissolved P	σ_2	$\text{g-P m}^{-2} \text{d}^{-1}$	0.01
Organic P settling rate	σ_5	day^{-1}	0.01

To assess the model performance with regard to sediment and nutrient predictions, acceptable simulation of river hydraulics is important. Model hydraulic outputs along with observed data at RM 3.5 are shown in Figure 4. Note that the gaging station at RM 3.5 was not installed until January 2004. The model tends to predict flow and water elevation levels very well. The R², NSE, and PBIAS statistic values for flow and water elevation are 0.98, 0.98, -1.5% and 0.98, 0.97, 0, respectively. In fact, all of these indices are excellent. The HEC-RAS did quite a good job modeling riverine flow and the water surface in the LMNR.

The MCES operates a long-term monitoring program for water quality in metroarea rivers with five stations on the LMNR (Figure 2). For three years, 2004-2006, the monitoring programs were enhanced to fulfill model data requirements. More intensive monitoring was conducted at low river flows during summer to capture water quality under critical conditions for oxygen. Special

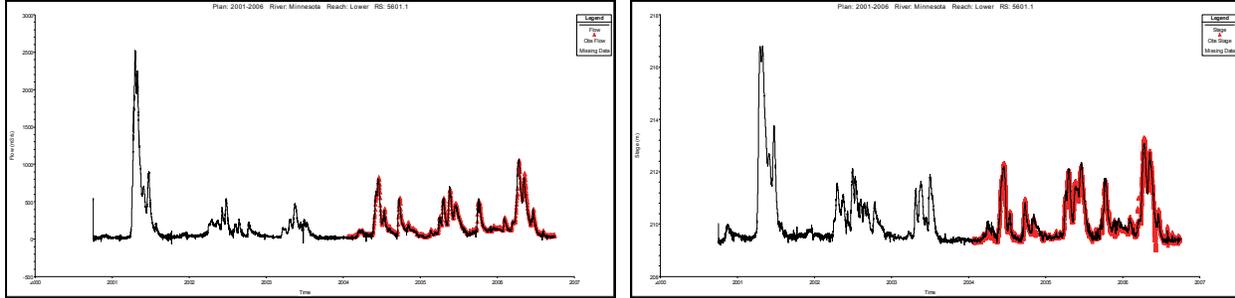


Figure 4. Time series plots of simulated and observed flow discharges (a) and water elevations (b) at RM 3.5.

studies were designed to answer specific questions, such as whether groundwater inputs are significant to the river, and to support key model inputs, such as the rates of oxygen production and respiration by algae. Calibration and evaluation of biological/chemical constituents followed calibration of the physical components of the HEC-RAS-NSM system. The stations chosen for comparison of simulated and observed data are locations at RM 25.1, 14.3, 8.5, and 3.5. Comparisons of field and model data were made for six major model state variables: (1) temperature, (2) total dissolved solids (TDS), (3) inorganic suspended sediments (ISS), (4) organic nitrogen (orgN), (5) ammonium (NH₄), (6) nitrate-nitrite, (7) organic phosphorous (orgP), (8) dissolved inorganic phosphorous, (9) algal biomass, (10) DO, and (11) CBOD. Organic nitrogen and organic phosphorous refer to the sum of phytoplankton and detrital particulate nitrogen and phosphorous, respectively. Time series plots of simulated and observed data are shown in Figure 5 to Figure 15. The computed performance statistics for selected constituents over the model simulations are provided in Table 3.

Table 3. Model performance statistics at four stations for selected water quality constituents.													
	H	Q	ISS	TDS	TEMP	orgN	NH ₄	NOx	orgP	PO ₄	Algae	DO	CBOD
	m	m ³ /s	mg/L	mg/L	°C	mg-N/L	mg-N/L	mg-N/L	mg-P/L	mg-P/L	mg-A/L	mg-O ₂ /L	mg-O ₂ /L
Station at RM 25.1													
R ²	-	-	0.75	0.97	0.97	0.84	0.89	0.98	0.80	0.97	0.89	0.88	0.73
NSE	-	-	0.57	0.97	0.96	0.83	0.89	0.98	0.78	0.97	0.89	0.88	0.68
PBIAS(%)	-	-	34	0.1	-2.6	-1.1	0.0	0.9	1.2	1.8	-2.4	1.2	-11.5
Station at RM 14.3													
R ²	-	-	0.70	0.93	0.98	0.67	0.92	0.98	0.50	0.81	0.71	0.77	0.43
NSE	-	-	0.64	0.92	0.97	0.58	0.92	0.98	0.46	0.71	0.70	0.76	0.29
PBIAS(%)	-	-	26	1.3	-3.8	-5.4	-0.9	4.5	-3.6	23.0	0.1	2.4	-16.1
Station at RM 8.5													
R ²	-	-	-	0.94	0.98	0.70	0.76	0.87	0.73	0.82	0.68	0.85	0.48
NSE	-	-	-	0.92	0.98	0.65	0.74	0.86	0.72	0.75	0.66	0.83	0.33
PBIAS(%)	-	-	-	2.1	-4.1	-4.7	-14	6.3	-3.9	18.6	1.16	3.2	15.4
Station at RM 3.5													
R ²	0.98	0.98	0.54	0.92	0.98	0.47	0.76	0.92	0.47	0.71	0.61	0.76	0.04
NSE	0.97	0.98	0.39	0.89	0.98	0.29	0.66	0.91	0.45	0.54	0.58	0.76	-4.3
PBIAS(%)	0	-1.5	48	3.0	-2.7	-9.0	-6.1	8.6	-9.4	27.5	1.18	1.9	37.4

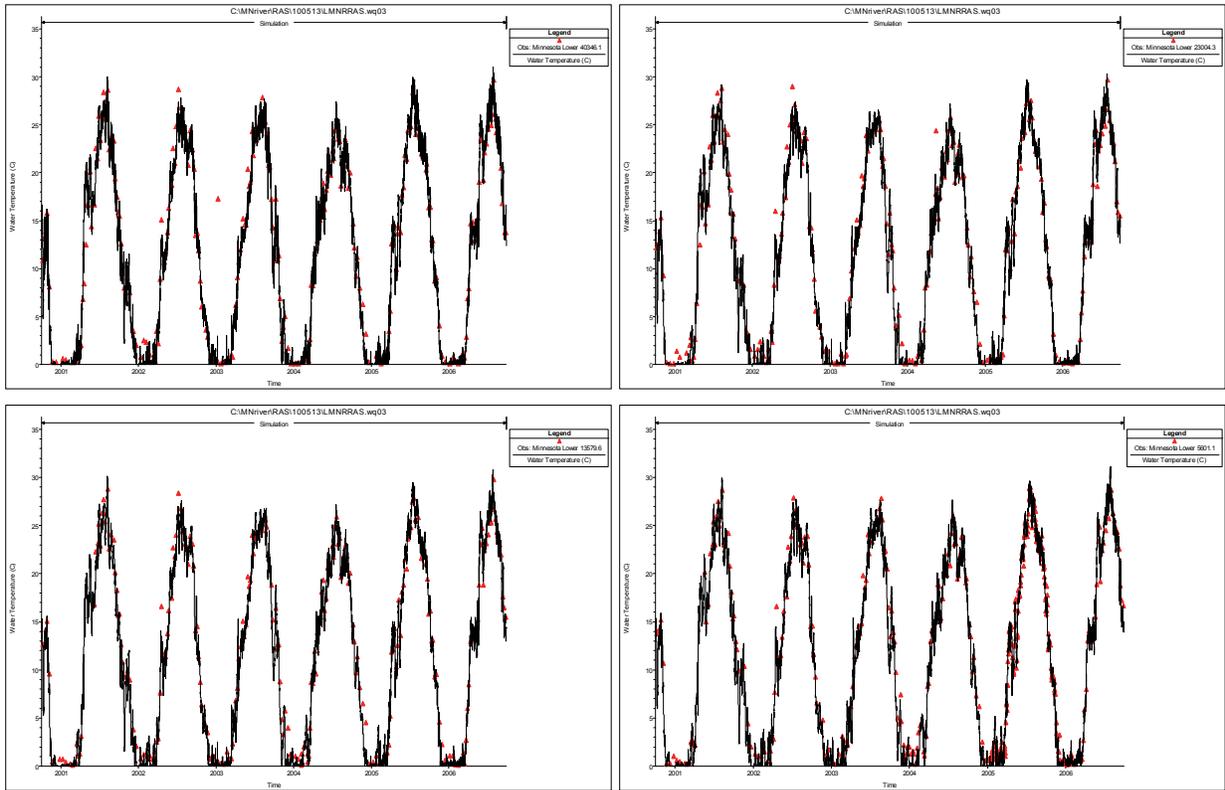


Figure 5. Time series plots of simulated and observed water temperatures for four stations.

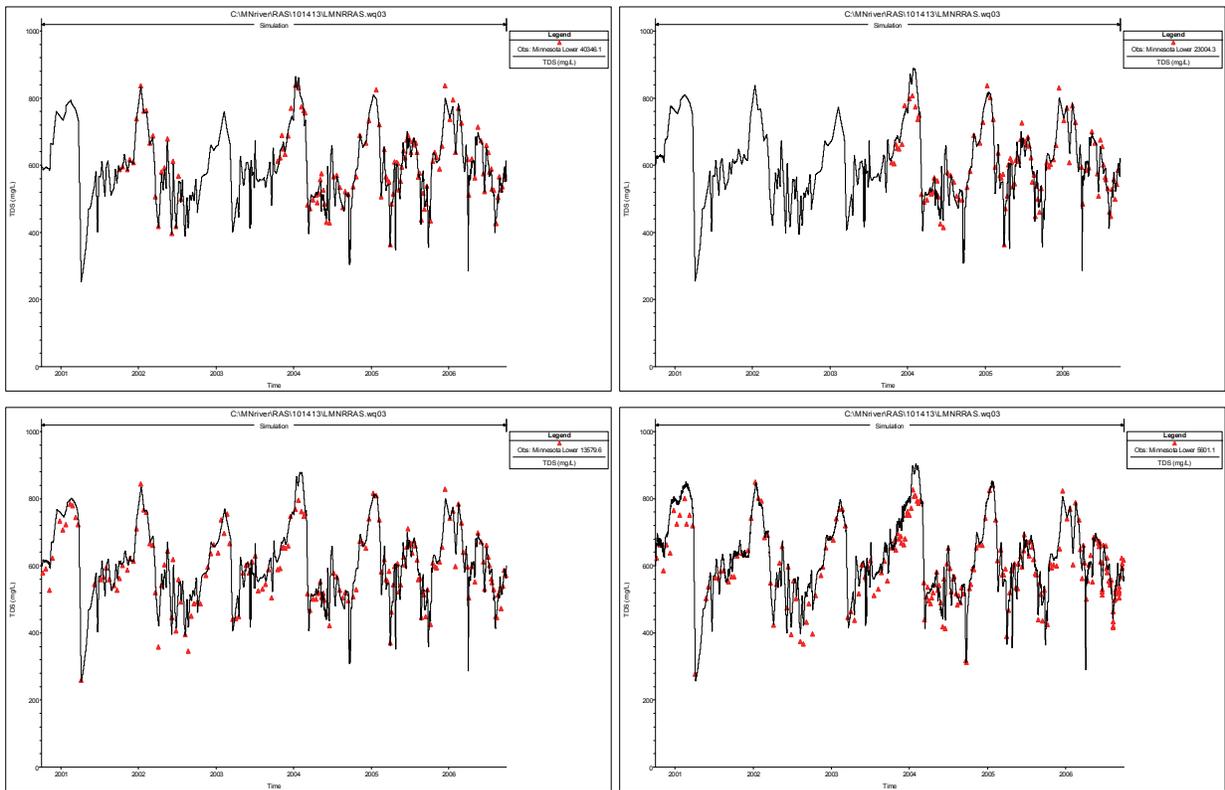


Figure 6. Time series plots of simulated and observed total dissolved solids for four stations.

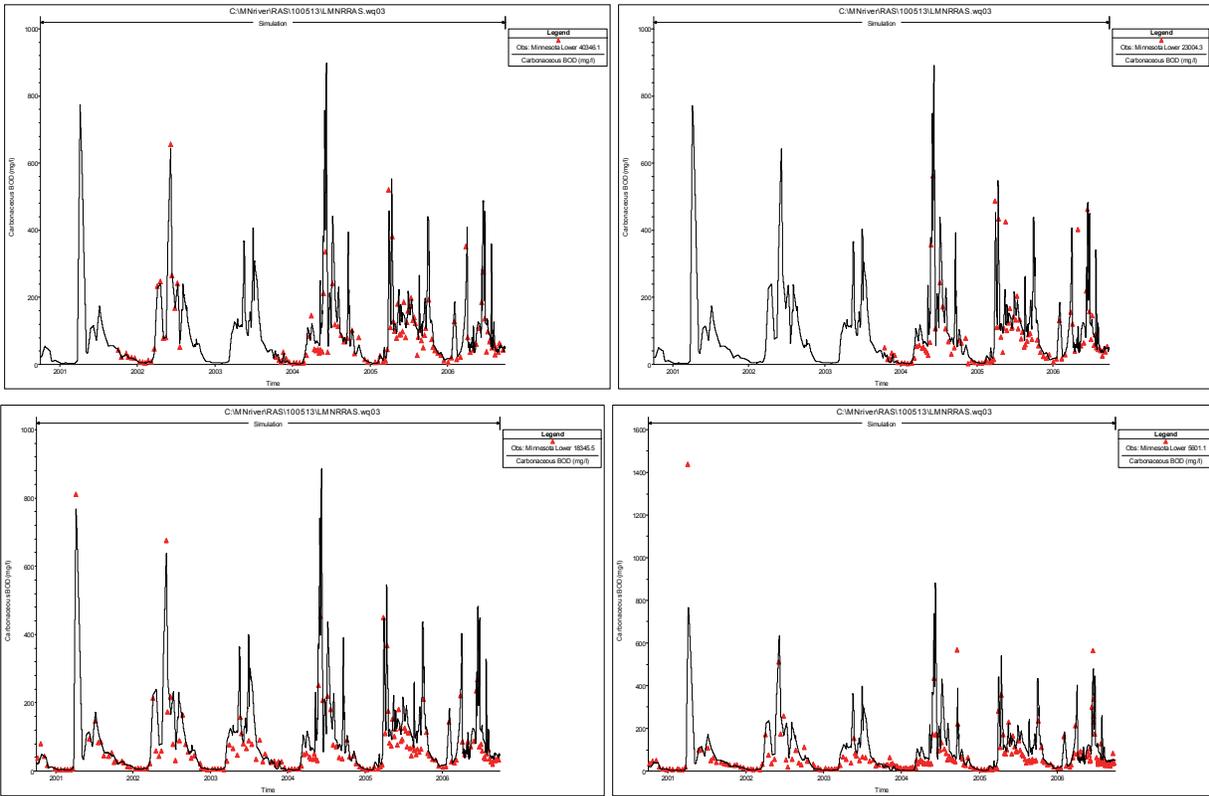


Figure 7. Time series plots of simulated and observed inorganic suspended sediments for four stations.

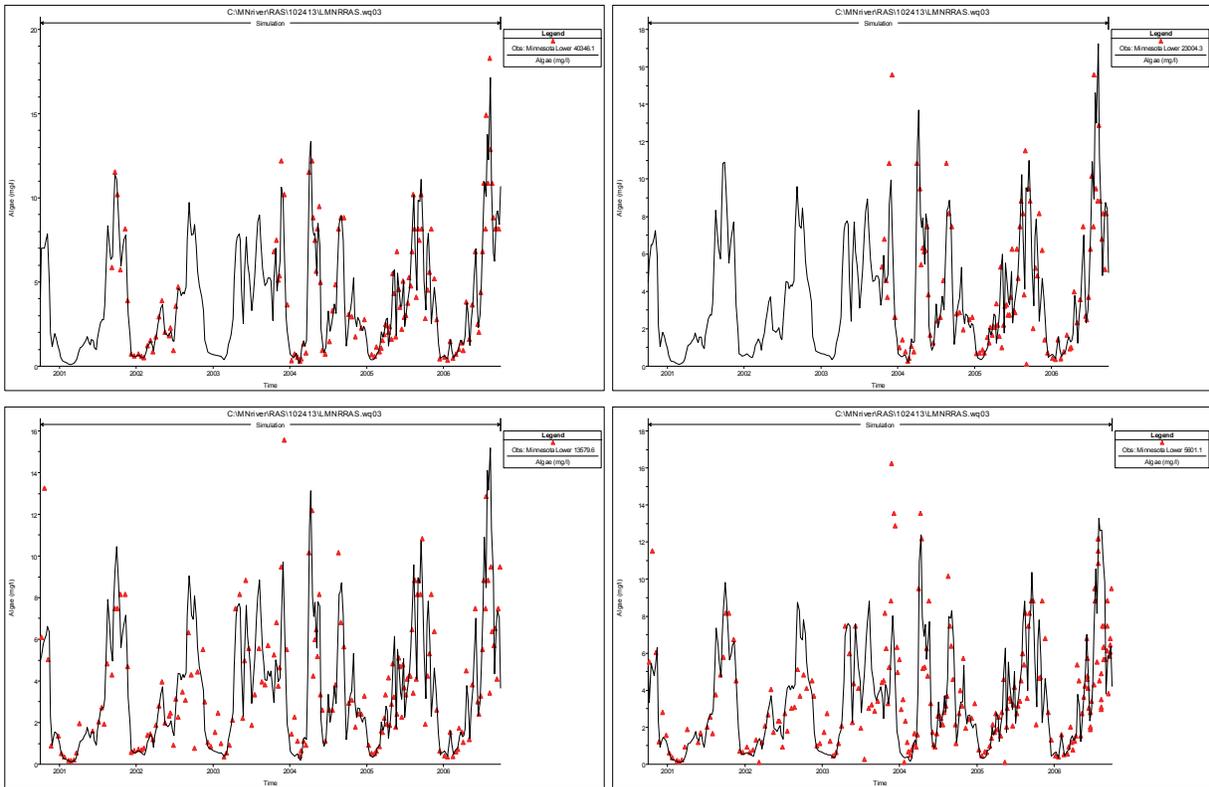


Figure 8. Time series plots of simulated and observed algal concentration for four stations.

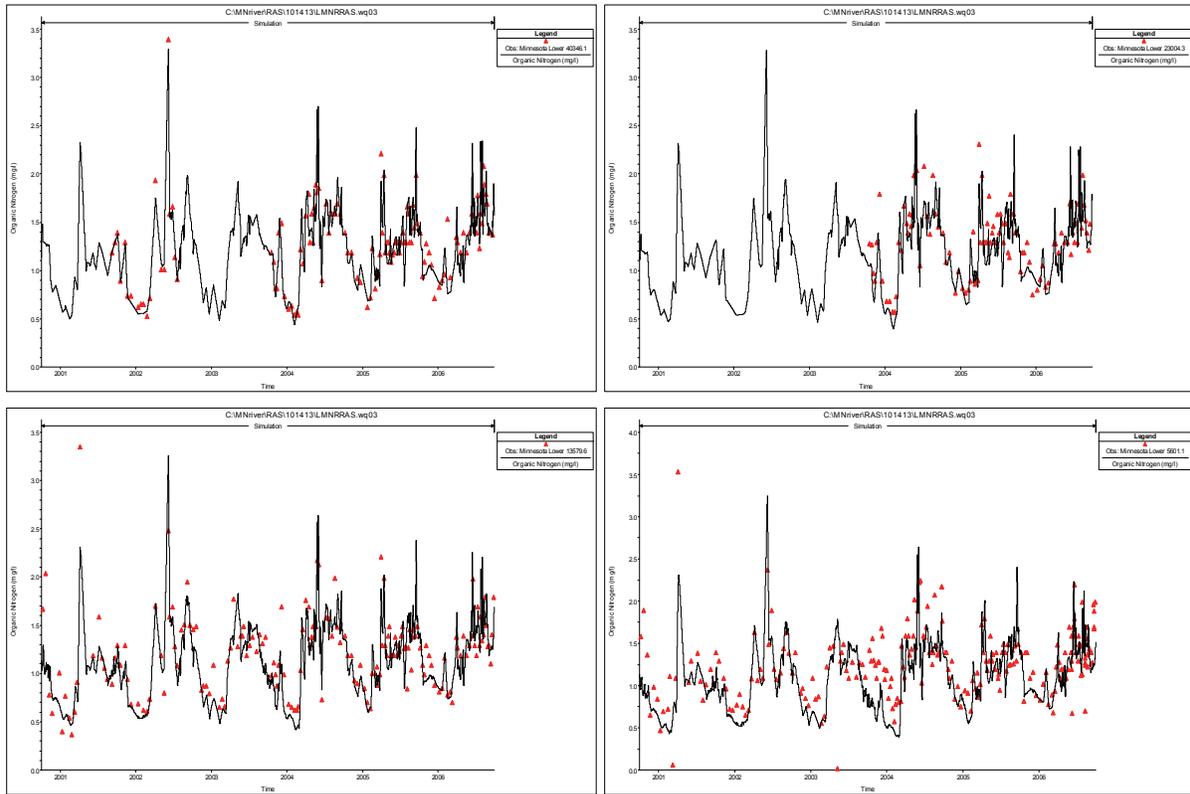


Figure 9. Time series plots of simulated and observed organic nitrogen for four stations.

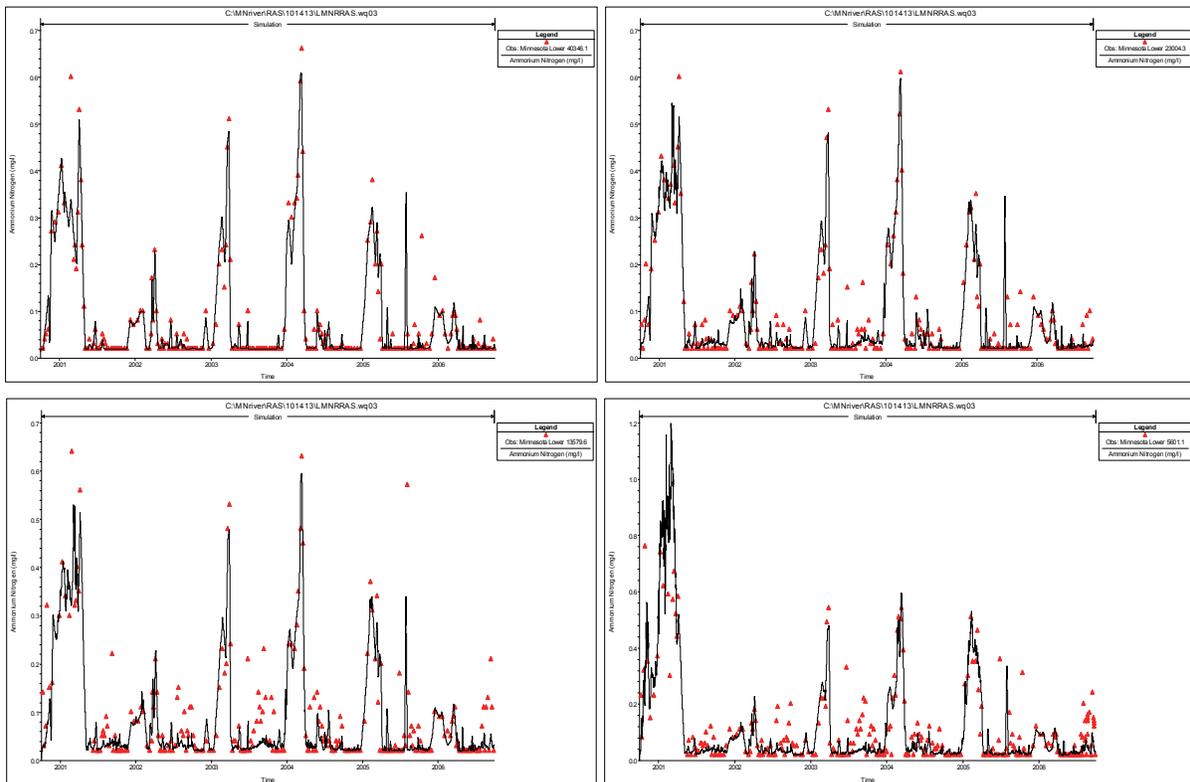


Figure 10. Time series plots of simulated and observed ammonium nitrogen for four stations.

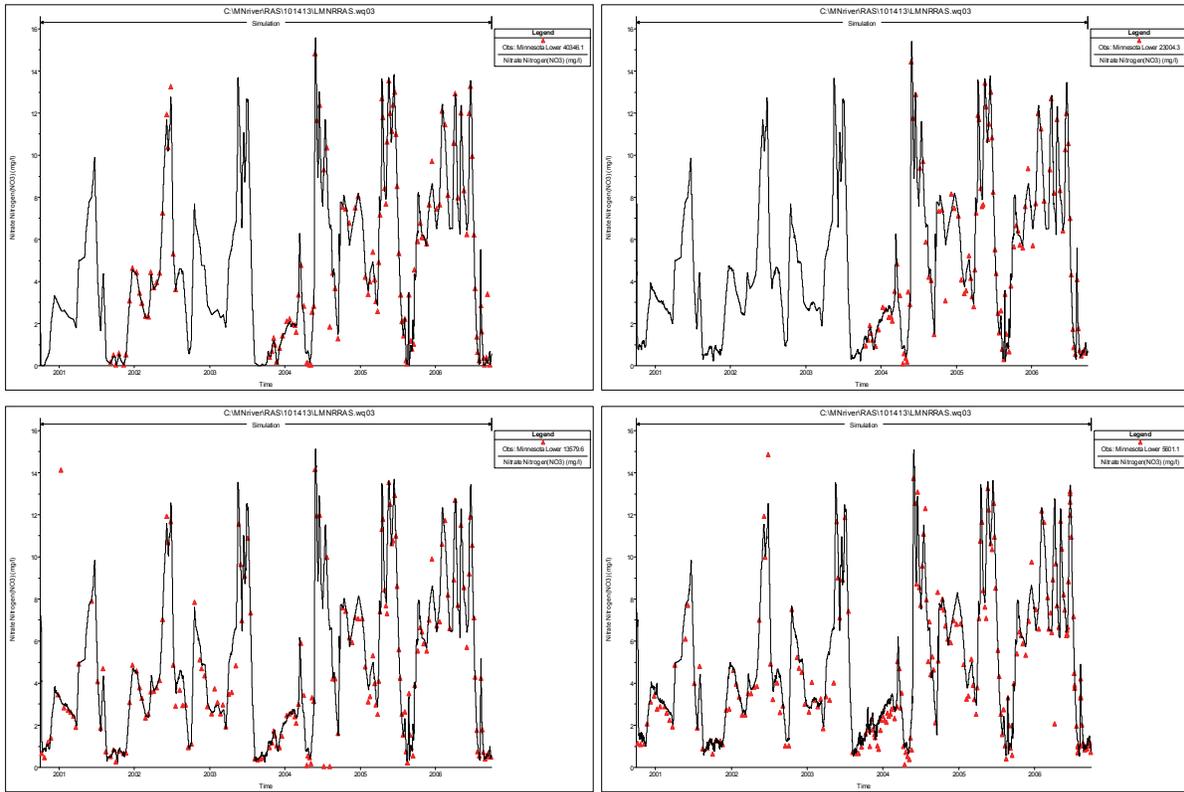


Figure 11. Time series plots of simulated and observed nitrate-nitrite nitrogen for four stations.

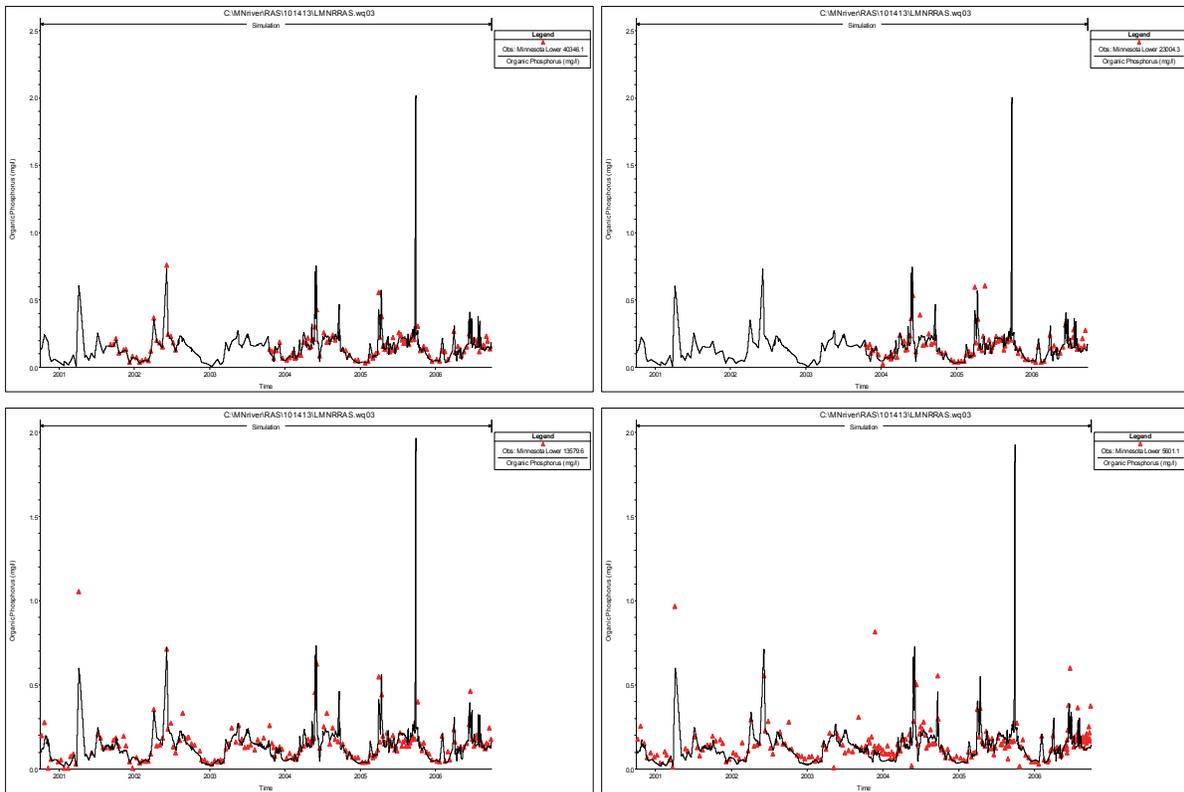


Figure 12. Time series plots of simulated and observed organic phosphorus for four stations.

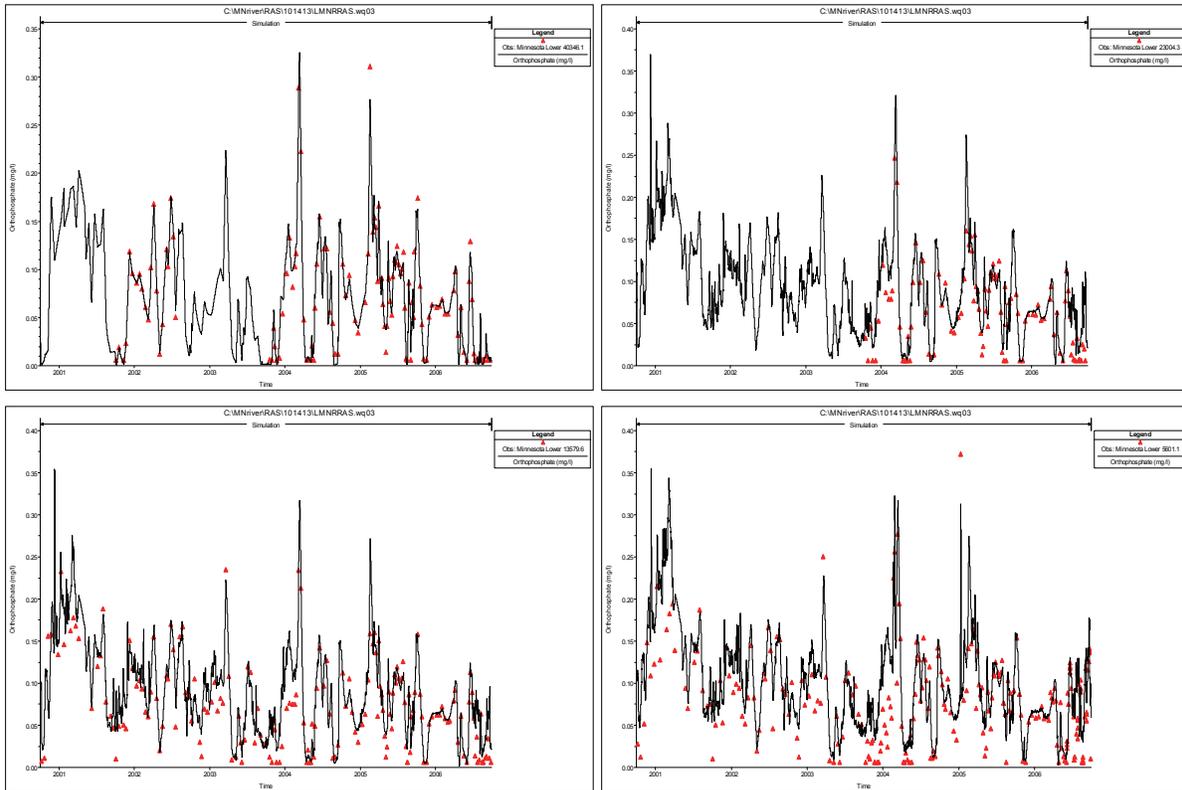


Figure 13. Time series plots of simulated and observed dissolved inorganic phosphorus for four stations.

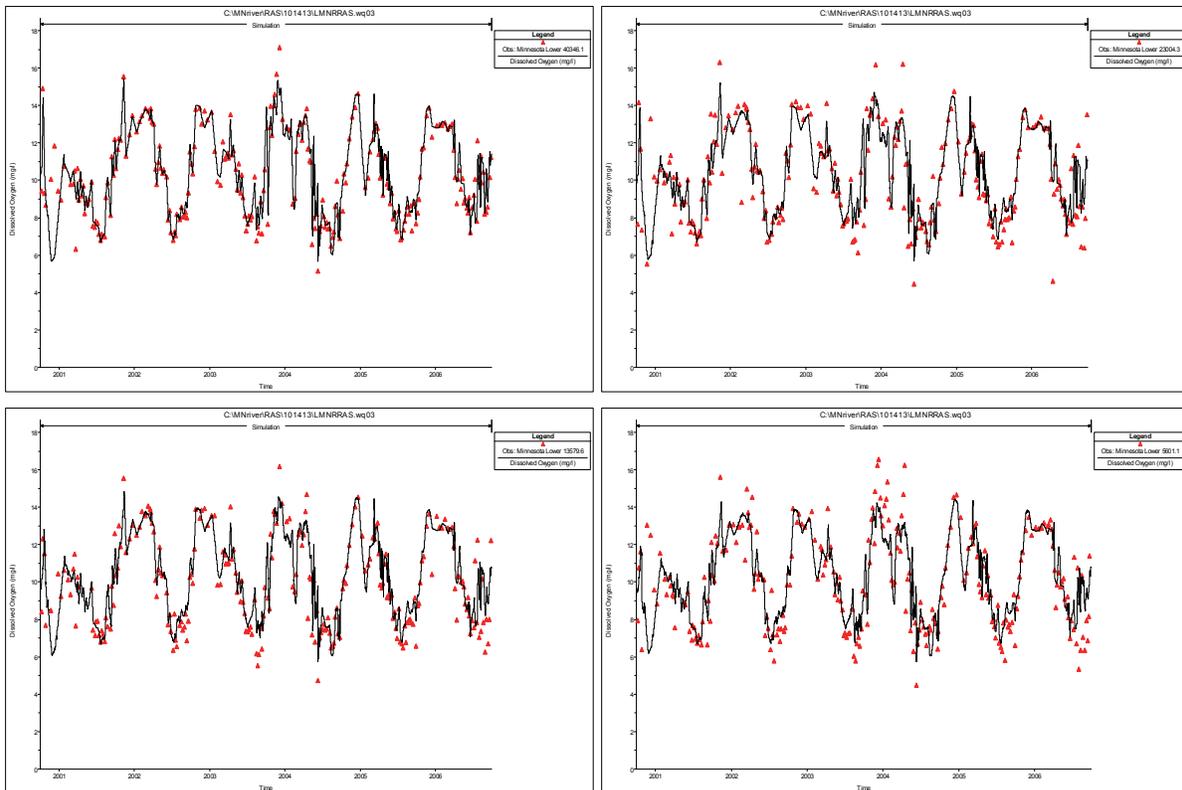


Figure 14. Time series plots of simulated and observed dissolved oxygen for four stations.

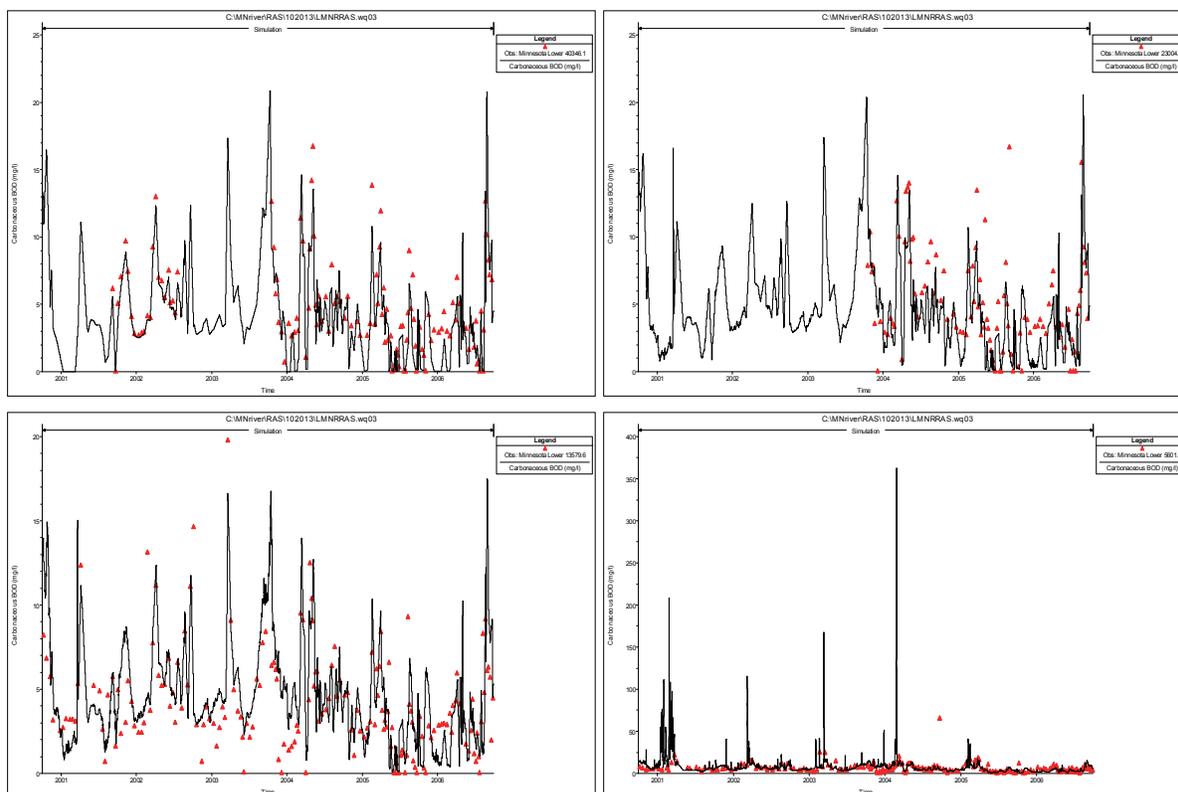


Figure 15. Time series plots of simulated and observed CBOD for four stations.

Time series plots for comparison of simulated and observed water temperatures at each station are presented in Figure 5. For six years, temperature was monitored continuously at four stations. As shown in Figure 5 and Table 3, the HEC-RAS-NSM I model did a very good job of predicting water temperature. Water temperature model simulations in LMNR consistently and accurately predicted water temperatures observed at each station. The PBIAS for modeled temperatures at four stations during the six-year simulation period is less than 5% of the measured temperatures. Figure 6 shows the final calibration results for simulated and observed total dissolved solids at four stations for the six years. The model tends to predict the TDS very well. Figure 7 shows the final calibration results for simulated and observed total inorganic suspended solids at four stations for the six years. Peak values predicted by the model were not observed. Certainly, the model represents the central tendency of the observations, although one-to-one agreement between model and instantaneous observations is not always present. The model tends to predict the overall trends well, capturing temporal and spatial trends. There were decreases in the R^2 , ENS, and PBIAS values for the simulation period relative to temperature and TDS. These decreases occurred because the HEC-RAS-NSM I only simulates the transport and net settling processes of suspended sediments. The NSM I includes no resuspension mechanism. Once a particle is deposited on the bottom, it remains there. The employment of net settling is a primary distinction between NSM I and a true sediment transport module included in HEC-RAS. Namely, a true sedimentation algorithm is required for the model to reproduce the full range of observed suspended sediment concentrations in the LMNR.

The NSM I only allows one algae group to be defined and simulated (Zhang and Johnson in preparation). Observed algal biomass was converted from chlorophyll *a* measurements, whereas the observed algal data are in units of *Chl a* concentration ($\mu\text{g/L}$). Figure 8 shows the final calibration results for simulated and observed algal concentrations at four stations for six years. Both time series plots and statistic indices of algal biomass indicate that the model performs well overall for each station. Simulated concentrations are quite small during the winter time of the year until the temperature and light conditions are suitable for algal growth. Peak concentrations of algal biomass simulated for the summer (July-August) range from 5.0 mg/L to 7.5 mg/L.

Three forms of nitrogen are simulated: organic nitrogen, ammonium and nitrate-nitrite. Figure 9 to Figure 11 show the final calibration results for simulated and observed concentrations at four stations for six years. The model tends to do very well with nitrogen species predictions. In fact, R^2 , NSE, and PBIAS statistic values are all “satisfactory,” except organic nitrogen at RM 3.5. Even at Fort Snelling, the PBIAS is less than 10%. Organic nitrogen inputs from inflowing streams are very high relative to internal fluxes, where the main sources are from algal mortality. Then the organic nitrogen concentration begins to decrease, owing to the formation of ammonium. Simulated and observed organic nitrogen concentrations average 1.3 mg-N/L, which represents a substantial quantity of nitrogen. Ammonium nitrogen concentrations are quite low in the LMNR, averaging less than 0.1 mg-N/L. The seasonal ammonium pattern of low winter concentrations and high summer values is reproduced by the model. The model simulated reduced ammonium concentrations, corresponding to increased algal biomass. Comparisons between simulated and observed concentrations are quite satisfactory. As can be seen in Figure 11, nitrate nitrogen concentrations are relatively high, averaging 5 mg-N/L. Again the comparison is quite satisfactory.

Figure 12 and Figure 13 show the final calibration results for simulated and observed organic phosphorus and orthophosphate (PO_4 or SRP) at four stations for six years. The model tends to do very well with phosphorus species predictions. Their PBIAS are less than 10% of the observed data at four stations. However, the isolated high spikes in organic phosphorous concentrations predicted by the model in the summer of 2005 throughout the entire reach of the river were not observed in the field data. The average concentration of organic phosphorus is approximately 0.2 mg-P/L. Its seasonal variation is approximately comparable to the organic nitrogen, showing an increase during the summer months due to the increase in algae-associated organic phosphorus.

Inorganic phosphorus concentrations average 0.08 mg-P/L. A seasonal depletion is observed. As nitrogen concentrations are always high, phosphorous limits primary production in the LMNR. The model captured temporal and spatial trends of PO_4 . However, the model tends to overestimate PO_4 at the three downstream stations (RM 14.3, RM 8.5, and RM 3.5). Phosphorus enters surface water primarily as particulate matter. Consequently, in surface water quality studies, the focus is often on the sediment-associated forms of phosphorus, as these tend to dominate the total phosphorus. Important processes related to the phosphorus cycle in a water body include, among others, detachment and deposition of sediment particles, adsorption and desorption of soluble phosphorus to/from sediment particles, both in suspension and in the bed sediment. NSM I does not simulate phosphate sorption on suspended sediments; this limitation may be part of the reason for overestimation.

Figure 14 shows the final calibration results for simulated and observed DO concentrations at four stations for six years. Low dissolved-oxygen concentrations occur most often in late summer at lower flows in the LMNR. The model accurately simulated DO concentrations; however, the six-year mean error for DO indicates that the model slightly underestimated DO. This is especially prevalent during the summer periods in most water years. Although the model underestimates DO levels, the model is well within the standard accepted level of tolerance for DO, 1.00 mg/L. The PBIAS is less than 10% of the observed data at four stations. For all but CBOD in NSM I, there exists a relatively straightforward relationship between the model state variables and standard water-quality measurements. The CBOD is a lumped variable and made up of both algal and nonalgal biomass. In NSM I, CBOD and algae are separate state variables; thus, it is necessary to either subtract algal effects from measured CBOD or add algal effects to modeled CBOD. Therefore, observed CBOD₅ data were converted into CBOD_u, then algal biomass consumption of oxygen subtracted for model comparison. Time series plots for comparisons of simulated and observed CBOD_u for four stations are shown in Figure 15. The comparison is quite good except for RM 3.5; peak CBOD values predicted by the model were not observed at RM 3.5. This is thought to be related to two point source inputs before this station from the Blue Lake and Seneca WWTPs. Additionally, CBOD is not the best representative constituent in water quality modeling; it was simulated in NSM I using a lumped first order decay. This leads us to apply HEC-RAS-NSM II to the LMNR in the future. The NSM II was derived from the limitations of NSM I. The NSM II has the ability to simulate aquatic carbon cycle and multiple algal groups. Overall, the statistic indices for each station, for all constituents, are fairly good and similar to the accuracy reported for other water quality model studies (Arhonditsis and Brett 2004).

CONCLUSIONS: A new nutrient water quality module, NSM I, was developed for the HEC-RAS model. The NSM I simulates BOD, DO, simplified nitrogen and phosphorus cycles, and algae biomass in riverine systems. The HEC-RAS hydraulic simulation produces hydraulic outputs at each specified time scale for use as input to the NSM I. This integrated HEC-RAS-NSM I model was applied to the LMNR in the northern US. The model is able to predict observed water quality concentration along the LMNR. Moreover, the model reproduces temporal and spatial distributions of nitrogen, phosphorus, algae, CBOD, and DO against results created from CE-QUAL-W2. The HEC-RAS-NSM I model allows realistic predictions based on the combined effects of hydraulic, biological, and chemical processes on longitudinal variations in water quality. A greater degree of spatial resolution of water quality was obtained than would otherwise have been possible, due to the relatively complex hydraulics of HEC-RAS. This shows that the HEC-RAS-NSM I model can provide a real predictive capability and aid in assessing riverine water quality. The NSM I is a simplified eutrophication model. A major advantage of NSM I is that it demands less input data and computational effort, which makes it suitable for quick studies or for projects where there is limited data available. Because of its widespread use in flood analysis and other hydraulic studies, most large river systems, as well as many smaller rivers and streams in the US, have already been modeled with HEC-RAS. An existing riverine hydraulic HEC-RAS model can quickly be adapted to model water quality. Thus, the overall cost to stakeholders interested in water quality modeling is dramatically reduced.

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REFERENCES

- Arhonditsis, G.B., and M.T. Brett. 2004. Evaluation of the current state of mechanistic aquatic biogeochemical modeling. *Mar. Ecol. Prog. Ser.* (271): 13-26.
- Brown, L.C., and T.O. Barnwell, 1987. *The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS*. EPA/600/3-87-007, Athens, GA: U.S. Environmental Protection Agency.
- Carpenter, S., N. Caraco, D. Correll, R. Howarth, A. Sharply, and V. Smith. 1998. Nonpoint source pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8(3): 559-68.
- Chapra, S.C., G.J. Pelletier, and H. Tao. 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.11: *Documentation and Users Manual*.
- Cole, T.M., and S.A. Wells. 2010. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71. Portland, OR: Department of Civil and Environmental Engineering, Portland State University.
- Environmental Laboratory (EL). 1995. *CE-QUAL-RIV1: A dynamic, one-dimensional (longitudinal) water quality model for streams, user's manual*. Instruction Report EL-95-2, Vicksburg, MS: US Army Engineer Waterways Experiment Station.
- Hydrologic Engineering Center (HEC). 2010a. *HEC-RAS: River analysis system user's reference manual version 4.1*. Davis, California: Hydrologic Engineering Center. US Corps of Engineers.
- Hydrologic Engineering Center (HEC). 2010b. *HEC-RAS: River analysis system hydraulic reference manual version 4.1*. Davis, California: Hydrologic Engineering Center, US Corps of Engineers..
- Kloiber, S. M. 2004. *Regional progress in water quality*. St. Paul, MN: Metropolitan Council.
- Larson, C. E., D.K. Johnson, R.J. Flood, M.L. Meyer, T.J. O'Dea, S.M. Schellhaass. 2002. *Lake Pepin phosphorus study, 1994-1998*. St. Paul, MN: Metropolitan Council Environmental Services.
- Metropolitan Council (MCES). 2002. *Lake Pepin phosphorus study, 1994-1998*. St. Paul, Minnesota.
- Metropolitan Council (MCES). 2004. *Regional progress in water quality*. St. Paul, Minnesota.
- Minnesota Pollution Control Agency (MPCA). 2008. Clean Water Act Section 303(d) Total Maximum Daily Load List. St. Paul, Minnesota.
- Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Binger, R.D. Hermel, and T. Veith. 2007. Model evaluating guidelines for systematic quantification of accuracy in water simulations. *Transactions of ASABE* 50(3), 885-900.
- Smith, D.L., T.L. Threadgill, and C.E. Larson, 2010. *Modeling the hydrodynamics and water quality of the Lower Minnesota River using CE-QUAL-W2*. Vicksburg, MS: US Army Engineer Research and Development Center.

U.S. Environmental Protection Agency (USEPA). 2007. National Section 303(d) List Fact Sheet. US Environmental Protection Agency, Retrieved June 13, 2007, from http://iaspub.epa.gov/waters/national_rept.control.

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