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Technical Memorandum

Prepared for: Western Virginia Water Authority

Project Title: Roanoke River Water Quality Evaluation

Project No.: 158864

Technical Memorandum

Subject: Screening Level Modeling of Nutrient Dynamics in the Roanoke River

Date: August 28, 2023

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Executive Summary

This technical memorandum describes the methods and results of a screening level modeling investigation of water quality in the Roanoke River in and downstream of Roanoke, Virginia. The evaluation was performed to determine if nutrients (and especially nitrogen) were likely to be a contributing factor to local benthic macroinvertebrate impairments via eutrophication-related response variables such as dissolved oxygen (DO), pH, or bottom algae biomass. The modeling team applied a screening-level process and tool developed by the Water Research Foundation. The model domain consists of 15 segments over 12.3 kilometers (km) extending from United States Geological Survey (USGS) gage 02055000 (Roanoke River near Roanoke, VA) to just downstream of the Virginia Department of Environmental Quality (DEQ) monitoring station 4AROA198.08.

The model was calibrated to available hydraulic and water quality monitoring to represent low-flow, warm-season conditions. The model calibration scenario showed that most nutrient-related response variables are at levels that support aquatic life uses. The screening-level model and water quality monitoring data together indicate that DO within the study reaches does not typically fall below the water quality criterion of 5 mg/L. And although pH is often above 8 standard units (s.u.), the relatively high alkalinity and buffer capacity of the river prevents pH from exceeding 9 s.u. Ammonia and nitrate nitrogen were not predicted to exceed toxic criteria or thresholds.

Both the model and available data show that bottom algae biomass can accrue to relatively high levels (>25 g ash free dry mass/m^2) in the study reaches. The model demonstrated that the warm season bottom algae growth rate was limited by light and phosphorus, but not by nitrogen, carbon, or temperature. Despite low phosphorus inputs from the Western Virginia Water Authority (WVWA) wastewater treatment facility and other sources, bottom algae were predicted to maintain moderate algal growth rates by a combination of luxury uptake and in-stream recycling of the available phosphorus. Bottom algae accrual is favored during periods of stable streamflows, low death/grazing rates, and possibly by scour-resistant algal mat structures.

Both the model and monitoring data indicated that median bottom algal biomass was similar upstream and downstream of the WVWA outfall, suggesting that the WVWA is not a principal causative factor of bottom algae accruals. Model scenarios demonstrated that due to lack of significant nitrogen limitation, even 90 percent reductions in nitrogen inputs from all sources (including WVWA) would not cause significant reductions in algal biomass. Algal growth was predicted to remain limited by light and phosphorus rather than nitrogen. Bottom algal biomass was predicted to be moderately sensitive to phosphorus reduction. However, considering that orthophosphate phosphorus is already below detection limits in most of the study reaches, it is unclear if significant additional phosphorus reductions are practicable.

Section 1: Introduction

This technical memorandum presents the methods and results of a screening level modeling investigation of water quality in the Roanoke River near Roanoke, Virginia. The WVWA performed this investigation in support of ongoing efforts by WVWA and the Virginia DEQ to evaluate potential causes of benthic macroinvertebrate impairments in the Roanoke River (stations 4AROA202.02and 4AROA198.08; Figure 1). DEQ had previously identified nitrogen as a potential stressor for station 4AROA198.08. This possibility was based on regional correlations between nitrogen and stream condition index scores (SCI) (Virginia DEQ, 2017), and periodic exceedances of an empirical nitrogen threshold at station 4AROA198.08 (Virginia DEQ, 2020). Since 2020, WVWA and DEQ have performed additional monitoring and data analysis to refine the stressor analysis and investigate the role of nitrogen, among other stressors. This screening level model analysis is one of these study components.

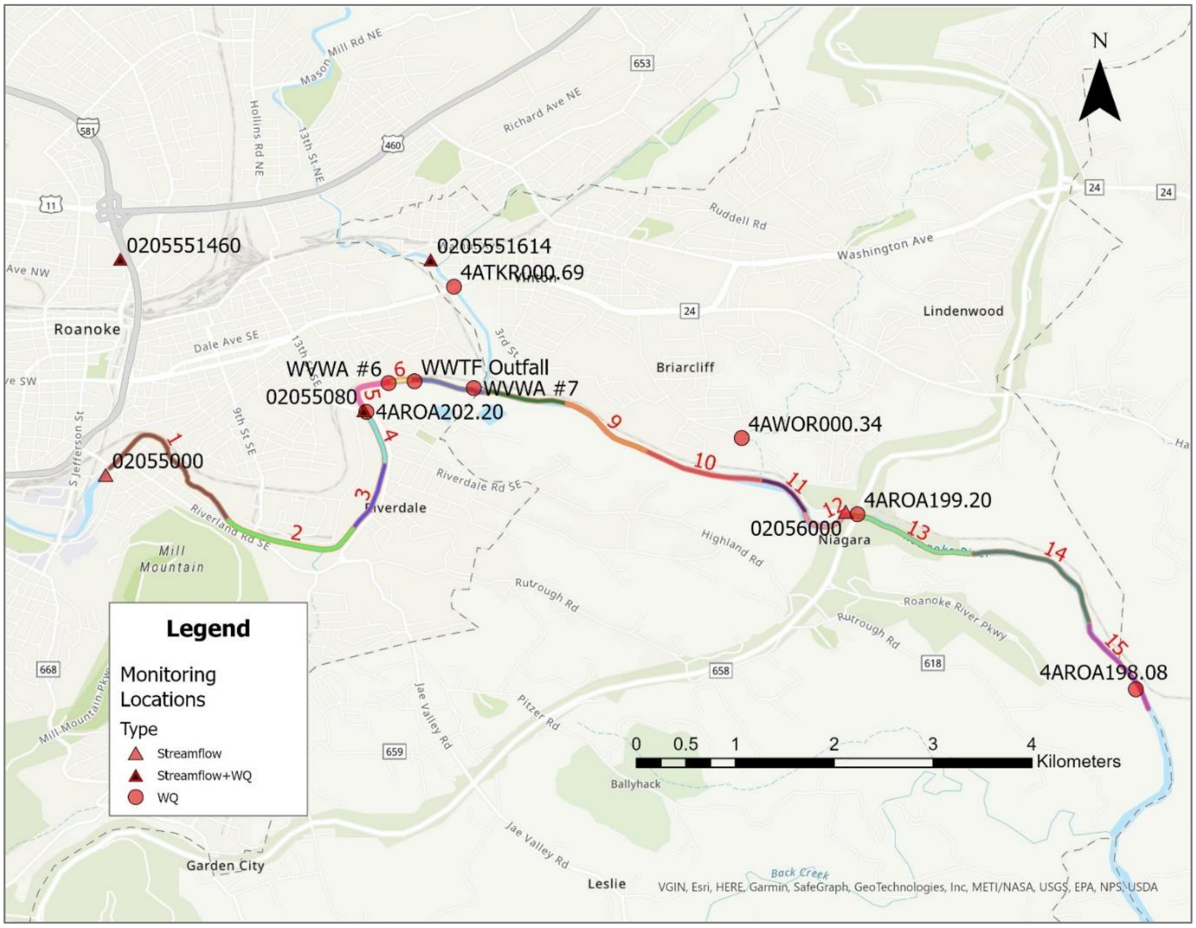

Figure 1 – Map showing study area and xQUAL2Kw model segments (labelled in red) and monitoring stations.

The model-based evaluation described in this memo is intended to complement other empirical/statistical stressor analyses being performed by the project partners. Empirical/statistical analyses are important tools for stressor analysis. However, the complexity of water quality and biological dynamics can confound statistical data interpretation. This is especially true with a constituent such as nitrogen, which is typically elevated in agricultural runoff, stormwater runoff, and wastewater effluent, and so serves as a general measure of anthropogenic watershed impacts. The cross-correlation of nitrogen with many other potential stressors confounds the ability to identify nitrogen as the specific cause of impairments based simply on nitrogen concentrations alone. In such circumstances, mechanistic-based methods can provide insights into whether nitrogen species actually cause rather than simply correlate with use impacts.

Screening-level water quality models can be useful tools for exploring the relationship between nutrient in-stream responses and in-stream response variables such as dissolved oxygen, pH, and algal biomass. As used in this document, the term “screening level model” refers to a water quality model calibrated sufficiently to explore the relationship between nutrient loads/concentrations and response variables such as dissolved oxygen (DO), pH, and algal biomass. Although screening-level models have various potential uses (Bier-man and others, 2013; Bell and DeBoer, 2019), the primary objective of this effort was to gain insights into the sensitivity of the Roanoke River trophic responses to nutrients, and especially nitrogen inputs.

Section 2 of this technical memorandum describes how the water quality model was set up and calibrated. Section 3 describes the model scenarios and sensitivity analyses that were performed to explore the sensitivity of response variables to nitrogen and other parameters. Section 4 summarizes the major conclusions from this modeling exercise.

Section 2: Methods

The modeling team utilized a process developed by the Water Research Foundation (WRF) project entitled *LINK4T17*: *Screening-Level Modeling of Site-Specific Nutrient Responses* (Bell and DeBoer, 2019). In addition to providing guidance on the screening model process, WRF also developed a tool (SCREEN-NUT) to facilitate model development and application. This section describes the SCREEN-NUT tool, the underlying xQUAL2Kw model, and how the model was applied to the Roanoke River.

2.1 Overview of SCREEN-NUT

SCREEN-NUT is a Microsoft Excel-based workbook to aid users in executing screening-level evaluations of stream responses to changes in nutrient inputs. SCREEN-NUT is a pre- and post-processor to facilitate the use of QUAL2Kw version 6.0. QUAL2Kw was developed by the Washington Department of Ecology for simulating water quality in one-dimensional stream systems. SCREEN-NUT assists the user in creating up to four parallel scenarios in xQUAL2Kw, which is a version of QUAL2Kw in which up to four scenarios can be executed simultaneously. xQUAL2Kw simulates major eutrophic processes in streams, DO sags, and pH dynamics. Major model inputs include flows and constituent concentrations associated with headwaters, point sources, and diffuse (nonpoint source) inputs. SCREEN-NUT has several features intended to reduce the time required for xQUAL2Kw scenario creation and sensitivity/uncertainty analysis. These include pre-defined model parameter groups, a simplified mechanism to vary model parameters by user-specific percentages, and an option to apply a Monte Carlo analysis of uncertainty/sensitivity to model parameters.

Because screening-level evaluations emphasize the differences between scenarios (rather than absolute responses), the post-processing sheets within SCREEN-NUT are designed to aid the user in comparing scenario results both graphically and with tables. The model output summarized in SCREEN-NUT include nutrient concentrations, DO, pH, chlorophyll-a (phytoplankton), and chlorophyll-a (bottom algae). Output for DO and pH include both daily averages and diel variability.

Because SCREEN-NUT uses xQUAL2Kw, it is subject to the limitations of that model. For example, xQUAL2Kw is suitable for modeling stream systems which are well-mixed laterally and vertically and would not be suitable for some large river systems or impoundments for which a 2-D or 3-D representation would be required. The Roanoke River is relatively well-mixed vertically and laterally in most locations, so this was not considered a limitation of the present application. xQUAL2Kw is typically used to simulate a single mainstem stream or river, in which tributaries are represented as point sources rather than explicitly modeled. As implemented in SCREEN-NUT, the model simulates steady-state streamflow conditions.

2.2 Model Set-Up

Subsections below describe various aspects of the model set-up and adjustment for the Roanoke River.

2.2.1 Extent and Segmentation

The QUAL2Kw model domain consists of 15 segments over 12.3 km extending from USGS gage 02055000 (Roanoke River near Roanoke, VA) to just downstream of DEQ monitoring station 4AROA198.08 (Figure 1, Table 1). The WVWA outfall is represented as a point source, entering the mainstem at model river km 6.855. Tinker Creek and Wolf Creek are also represented as point sources.

2.2.2 Hydraulics and Water Balance

Within the model, hydraulics were simulated by Manning's formula for all segments. Some exploratory attempts were made to apply xQUAL2Ks's weir option to simulate hydraulics in segment 11 which ends at Niagara Dam. However, the stream velocity and depths were ultimately more reasonable using the Manning's formula for this segment as well. Segment elevations and slopes were calculated based on USGS digital elevation models as accessed through the USGS National Map. Average segment widths were also determined from USGS topographic maps. Manning's n coefficients were initially set to represent river channels with weeds and stones (0.045), and then adjusted during calibration as discussed further in section 2.2.5.1.

The modeling team chose to simulate the Roanoke River under August median streamflow conditions. This represents a streamflow that is lower than average, but not exceedingly rare, and is close to the 20th percentile streamflow of the river. The August median streamflow is appropriate for exploring typical trophic responses under warm season, low-flow considerations, and for calibrating the model to water quality data collected under a limited range of streamflow conditions during the warm weather months.

Table 1. Segments of the Roanoke River xQUAL2k Model

Segment	From	To	Length (km)	Average Width (m)	Starting Elevation (m)	Ending Elevation (m)
1	USGS 02055000	Nr 800 River Ave	1.60	33	275.7	273.2
2	Near 800 River Ave	Unnamed trib.	1.21	34	273.2	271.7
3	Unnamed trib.	Unnamed trib.	0.66	35	271.7	270.3
4	Unnamed trib.	USGS 02055080	0.59	33	270.3	269.7
5	USGS 02055080	WVWA #6	0.47	30	269.7	269.6
6	WVWA #6	Outfall	0.21	31	269.6	269.6
7	Outfall	Tinker Creek	0.62	31	269.6	269.6
8	Tinker Creek	Unnamed location	0.67	40	269.6	269.5
9	Unnamed location	Unnamed trib.	0.83	42	269.5	269.4
10	Unnamed trib	Wolf Creek	0.95	45	269.4	269.3
11	Wolf Creek	Niagara Dam	0.59	52	269.3	269.1
12	Niagara Dam	USGS 02056000	0.52	50	255.5	249.8
13	USGS 02056000	Unnamed trib.	1.05	57	249.8	246.2
14	Unnamed trib.	Unnamed trib.	1.38	56	246.2	240.8
15	Unnamed trib.	Downstream boundary	0.99	35	240.8	240.8
		TOTAL	**12.33**		275.7	240.8

Headwater streamflow was set to the 2005-2022 August median streamflow at USGS gage 02055000 (Roanoke River near Roanoke, VA). The WVWA effluent flow was set to 45.2 cubic feet per second (cfs) (~29.2 million gallons per day [MGD]), which is the median effluent flow rate for 2018-2022 August conditions according to WVWA effluent monitoring data. Tinker Creek streamflow was based on 2019 - 2023 August median conditions at USGS gage 0205551614 (Tinker Creek above Glade Creek), multiplied by a factor (1.44) to account for the drainage area of Glade Creek. The streamflow of Wolf Creek was calculated as a proportion (~6%) of the Tinker Creek streamflow based on their respective drainage areas.

QUAL2Kw accepts user-specified diffuse inflows to account for ungaged inputs to the mainstem. The diffuse inflow for model segments 1 through 12 was calculated as the 2005-2022 August median streamflow at USGS gage 2056000 (Roanoke River at Niagara) minus the headwater, WVWA, Tinker Creek, and Wolf Creek flows. The same longitudinal inflow rate was applied to model segments 13 through15. Table 2 summarizes the inflows to the model domain by source.

Table 2. Summary of Inflows

Flow	Flow Rate (cfs)	Flow Rate (MGD)
Headwater	120.5	77.8
WVWA	45.2	29.2
Tinker Creek	37.5	24.2
Wolf Creek	1.5	1.0
Diffuse flows	24.0	15.5
TOTAL	228.7	147.7

2.2.3 Model Options

The QUAL2Kw model was run with an 11.2 minute time step and a simulation period of 45 days, long enough for water quality and algal variables to reach a steady-state condition. Sediment diagenesis was not explicitly simulated. Rather, low to moderate sediment fluxes were specified for ammonia nitrogen (2 mg/m^2/d), and inorganic phosphorus (0.5 mg P/m^2/d). The sediment oxygen demand was set to 1.5 g/m^2/day for segments in the backwater water of the Niagara Dam (7 through 11), and 0.5 g/m^2/day in other segments. The bottom SOD and bottom algae coverage were set to 100%. In this manner, the predicted benthic algae measurements represent the average for the entire stream bottom, which is typically a lower value than measured by scraping stream substrate in shallow areas. Bottom algae were simulated with a zero order growth model.

Air temperatures were set to vary from 21.5 to 25.0 degrees C, and relatively humidity was set to vary between 50 and 75 percent. Dewpoints were calculated from relative humidity and temperature within SCREEN-NUT. Shading was calculated based on SCREEN-NUT's option based on wide channels with tall dense riparian vegetation. Other meteorological options were based on SCREEN-NUT defaults. The internal reaeration option was chosen, by which the specific reaeration algorithm is based on the predicted stream velocity and depth conditions.

2.2.4 Water Quality Inputs

The water quality model requires water quality inputs for all inflows to the model, including the headwater, WVWA, Tinker Creek, Wolf Creek, and diffuse flows. These include values for field parameters (temperature DO, pH, specific conductance), CBOD, and major nutrient species such as nitrate, ammonia, organic nitrogen, inorganic phosphorus, and organic phosphorus. Temperature and DO of inputs vary over the course of the day. The daily range in inflow water temperature was set to 21.5 – 25 degrees, consistent with typical August conditions. The general approach taken for other parameters was to set these values to the median growing season (May – October) observations from the available monitoring data collected during 2008-2022. Table 3 summarizes the water quality assumptions of the major inputs.

Headwater water quality was informed by available data collected upstream of the WVWA outfall, including field parameters from USGS station 02055080 (Roanoke River at 13th St) and grab samples from DEQ station 4A ROA202.20. Tinker Creek water quality was informed by DEQ monitoring results from 4ATKR000.69, and Wolf Creek by station 4AWOR000.34. Diffuse flow water quality was set equal to the headwater water quality. The f-ratio (i.e., ratio of ultimate to 5-day DO demand) for fast CBOD5 was set to 2.5 for fast CBOD (from WVWA) and 4.0 for slow CBOD (other watershed inputs).

Inputs from WVWA were informed by 2018-2022 Discharge Monitoring Report (DMR) monitoring data and also by examining differences in water quality between WVWA stations #6 (upstream of the outfall) and #7 (downstream of the outfall). For parameters with a censored median value, the value was initially set to half of the detection limit, although some of those values were adjusted slightly during calibration. The WVWA effluent was modeled with a nitrate-nitrogen concentration of 16 mg/L and a total phosphorus concentration of 0.060 mg/L, all of which was assumed to be inorganic phosphorus.

Table 3. Summary of Water Quality Input Assumptions

Flow	Avg. Temp. (deg. C)	Sp. Cond. (uS/cm)	Avg. DO (mg/L)	pH (s.u.)	CBODu[1] (mg/L)	Org. N (mg/L)	NH4-N (mg/L)	NO3-N (mg/L)	Org. P (mg/L)	Inorg. P (mg/L)	Alkalinity (mg/L as $CaCO_3$)
Headwater	23.2	376	8.5	8.2	1.0	0.18	0.02	0.56	0.01	0.01	166
WVWA	21.9	687	7.8	7.1	4.4	0.85	0.05	16.0	0.00	0.06	100
Tinker Cr.	20.0	490	9.8	8.1	2.0	0.18	0.02	1.3	0.00	0.01	205
Wolf Cr.	17.4	231	9.5	8.2	2.0	0.15	0.01	0.96	0.00	0.04	100
Diffuse	23.2	376	8.5	8.2	1.0	0.18	0.02	0.56	0.01	0.10	166

[1]CBODu is the CBOD-ultimate, calculated as the CBOD5 multiplied by the assumed f-ratio described in this section.

2.2.5 Model Calibration

Subsections below describe the approach taken to calibrate the screening model for hydraulics and water quality.

2.2.5.1 Hydraulics

The simulated streamflow was consistent with the August median streamflows (Figure 2), which verified that that prescribed water balance was entered into the model correctly. The primary hydraulic adjustment during model the calibration phase was to decrease the Manning's n roughness coefficients for the segments (7-11) most affected by backwater from Niagara Dam, and increase the Manning's n roughness coefficients for other segments. This served to create a reasonable longitudinal variation in the depth-velocity profile. The free-flowing segments were simulated with velocities mostly in the 0.25-0.40 meters per second (m/s) range, and the backwater-affected segments had simulated velocities in the 0.1 – 0.2 m/s range (Figure 3). Free-flowing segments were simulated with average depths of 0.3 – 0.4 m, and the backwater-affected segments were simulated with depths of 0.8 – 1.6 m under this low streamflow condition (Figure 4).

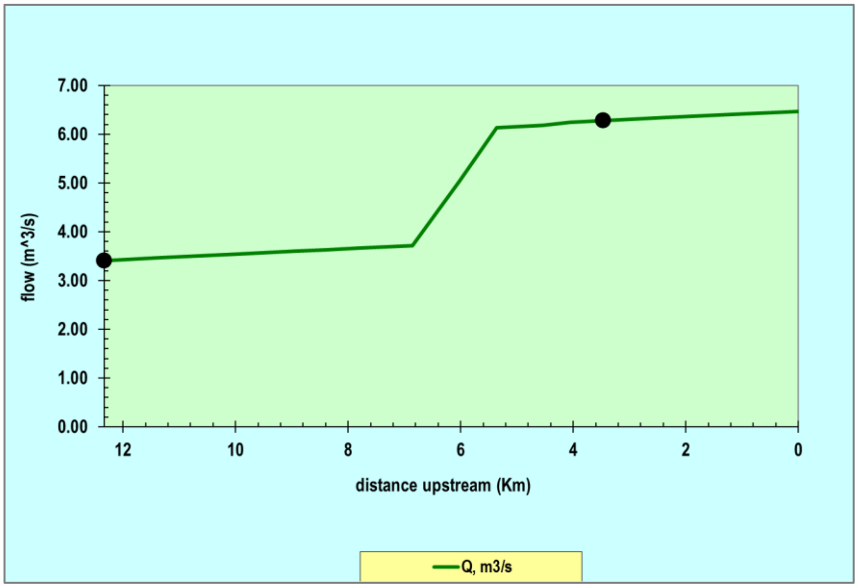

Figure 2 – Streamflow profile. The black circles represent the prescribed August median streamflows.

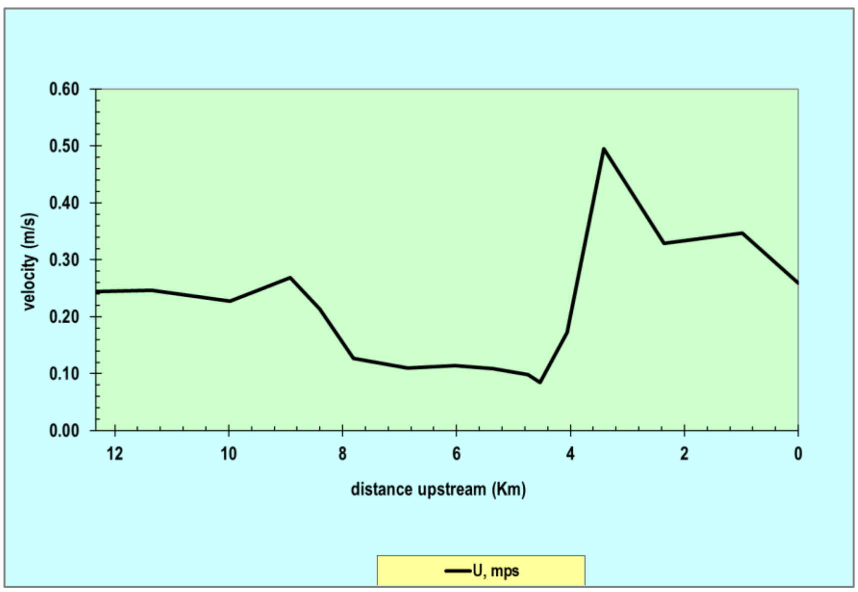

Figure 3 – Water velocity profile.

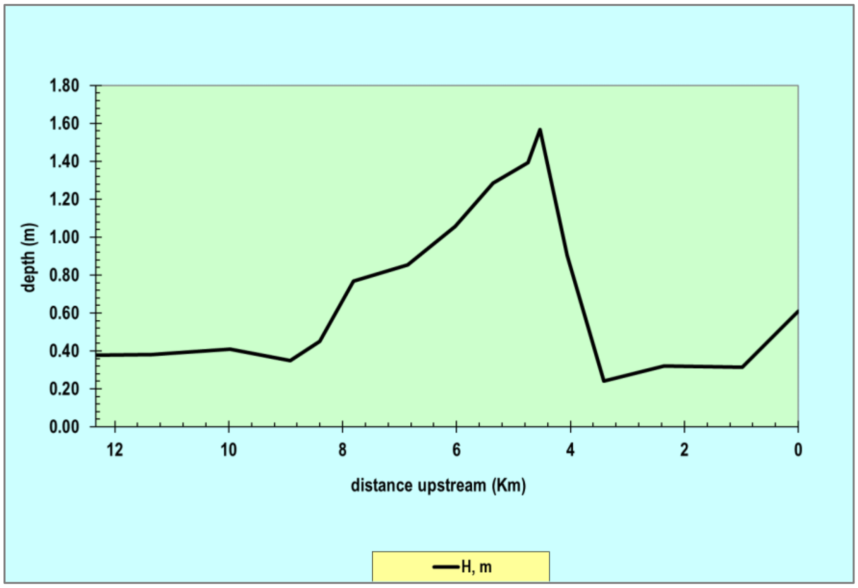

Figure 4 – Simulated average water depth profile.

2.2.5.2 Water Quality

For water quality, the model was calibrated against data collected at monitoring stations 4AROA202.2, WVWA #6, WVWA #7, 4AROA199.20, and 4A198.09. The observed in-stream water quality at these stations were processed to calculate the median and interquartile range (IQR) for the 2008-2022 period, or whatever subset of that monitoring period was available at a given station. The observed median and IQR were used as guides for graphical calibration. For this screening-level application, the goal of the calibration was to re-produce the major warm-season longitudinal profiles in temperature, DO, pH, nutrient, and algal-related pa-rameters.

QUAL2Kw was initially executed with the SCREEN-NUT's median calibrated values parameter set, which rep-resents the median values used in a survey of many QUAL2Kw applications, as compiled by the United States Environmental Protection Agency (USEPA) (Cope and others, 2020). During calibration, the primary adjustments were as follows:

- Increase of the maximum bottom algae growth rate and decrease of the respiration and death rates. These adjustments were made primarily to increase the predicted bottom algal biomass closer to the median observed values (22 – 35 mg ash free dry mass (AFDM)/m^2), and to match the typical daily observed variability in DO (2-3 mg/L).
- Decrease of the default nitrification rate, increase in denitrification, increase in the maximum bottom algal uptake rate for nitrogen, and slight reduction of the bottom algae ammonia reference. These adjustments were made to improve the model fit to the observed longitudinal profiles of ammonia and nitrate nitrogen.
- Decrease of the inorganic phosphorus settling rate and the bottom algal phosphorus uptake rate. Thes adjustments were made to maintain a base level of inorganic phosphorus (0.005 – 0.020 mg/L) throughout the longitudinal profile.

The final set of calibration parameters is provided in Attachment A.

Because the model was set up to simulate typical August temperatures, the water temperatures were simulated as slightly higher than the May-October medians (Figure 5). The specific conductivity profile was reasonably well simulated (Figure 6), with the main pattern being a modest increase in specific conductance downstream of the WVWA outfall.

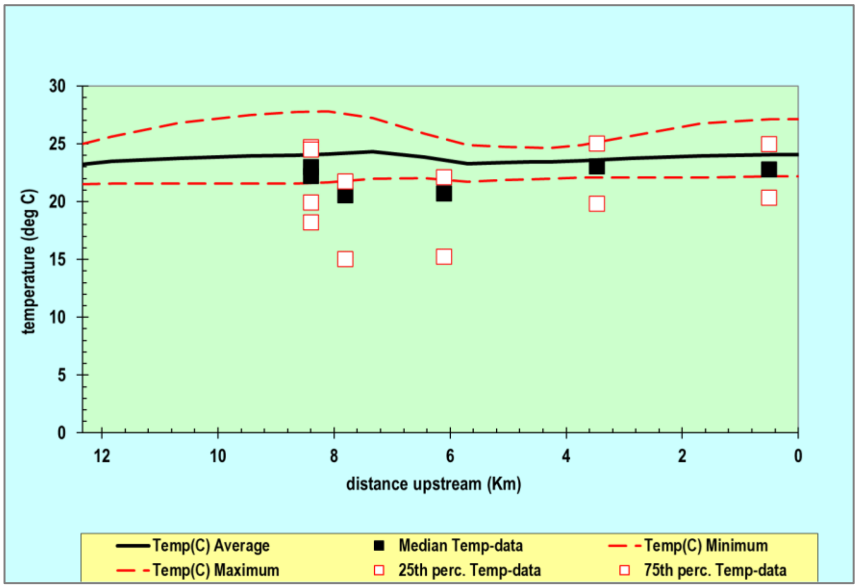

Figure 5 – Simulated and observed water temperature. The simulated water temperature was set to typical August values, and so are in the upper IQR of observed May – October values.

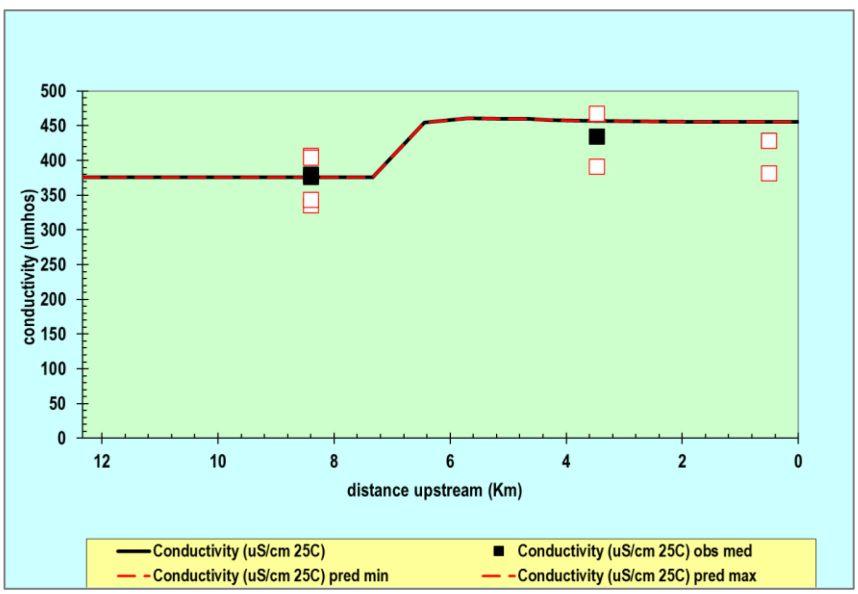

Figure 6 - Observed and simulated specific conductance.

The model simulated a relatively flat DO profile with median DO concentrations in the in the 8-10 mg/L range and diel variability of up to 2-3 mg/L in most locations (Figure 7). This is consistent with the observed data, although the observed data show some locally higher DO concentrations (e.g., station 4AROA198.09) that might be due to site-specific aeration or algal conditions. The predicted and observed pH profile was also relatively flat (Figure 8), probably due to the relatively high alkalinity (150 -180 mg/L as $CaCO_3$) and buffering capacity of the Roanoke River. The predicted pH values were slightly higher than the May-October IQR, which may be due to the simulation of a relatively high bottom algal biomass under August streamflows and temperatures.

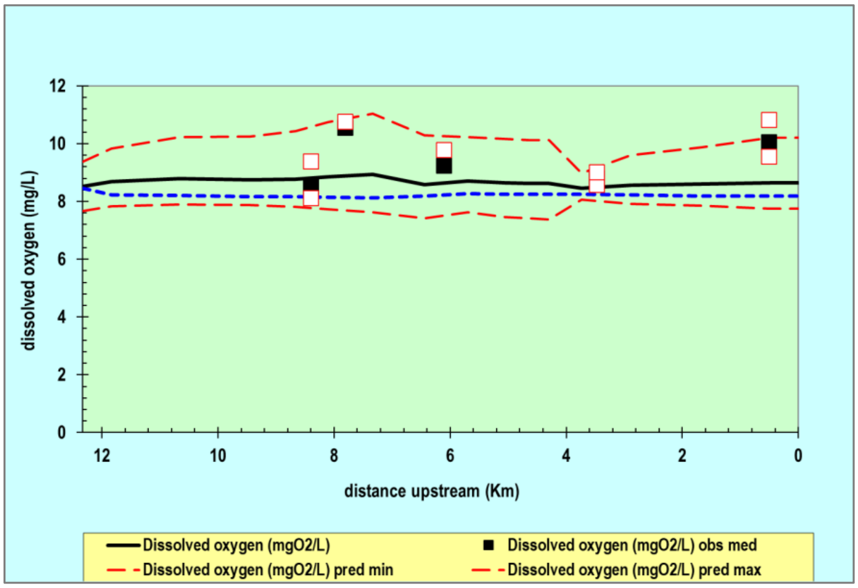

Figure 7 – Observed and simulated dissolved oxygen.

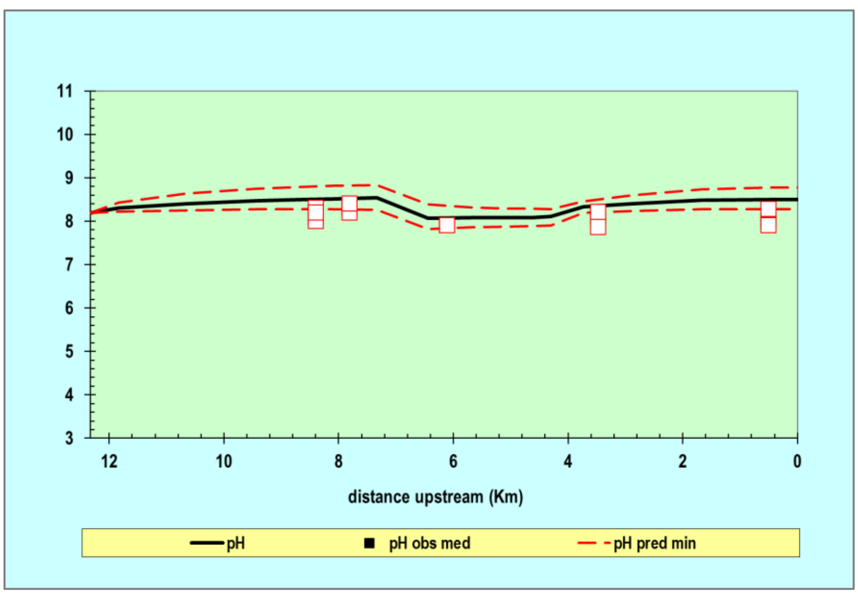

Figure 8 – Observed and simulated pH.

The model and data both show a modest downstream increase in ammonia nitrogen concentrations (Figure 9). The ammonia profile is relatively well simulated apart from anomalously higher ammonia concentrations at a station just downstream of Niagara Dam. The conclusion of higher ammonia concentrations at that location is based on six samples at station 4AROA199.20. It is unclear if these data are representative, or if there is an unaccounted-for local ammonia source in that vicinity. The model correctly simulates the marked increase in nitrate nitrogen and total nitrogen below the WVWA outfall, followed by downstream attenuation of these parameters due to dilution and algal update (Figure 10). The total nitrogen profile (Figure 11) is very similar to the nitrate nitrogen profile.

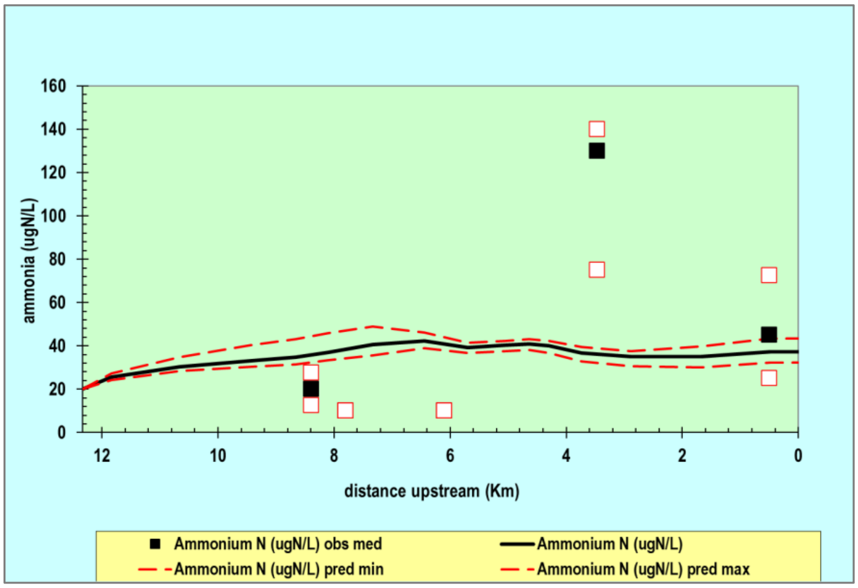

Figure 9 – Observed and simulated ammonia nitrogen.

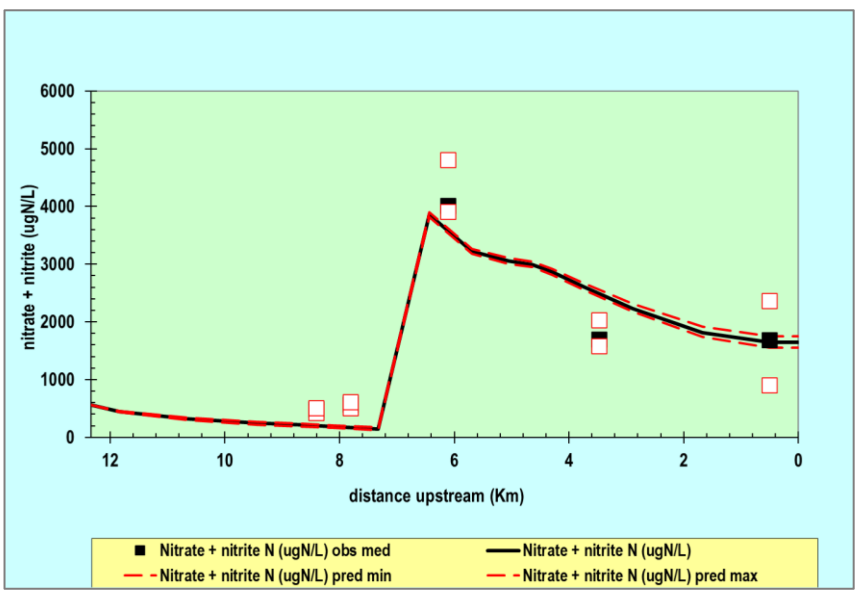

Figure 10 – Observed and simulated nitrate nitrogen.

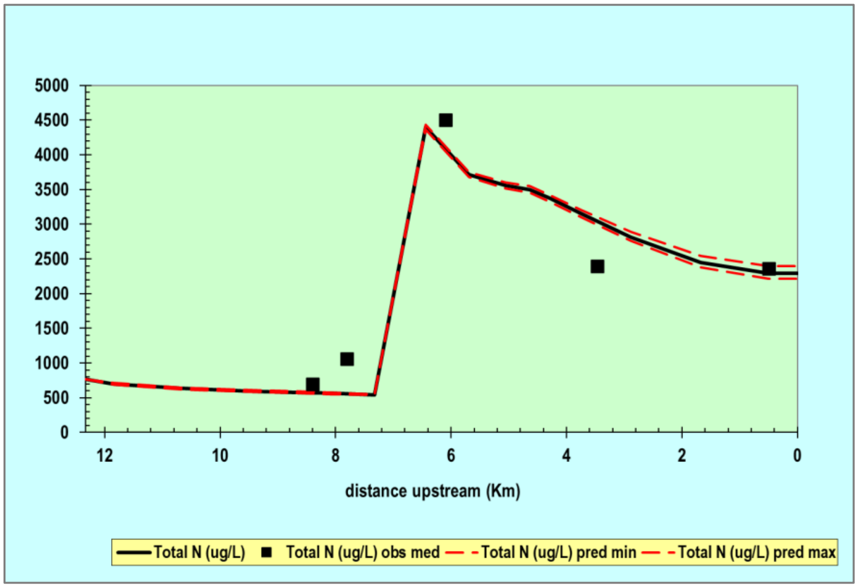

Figure 11 – Observed and predicted total nitrogen.

Figure 12 presents the predicted inorganic phosphorus profile. The majority of the WVWA and DEQ orthophosphate-P samples were reported as below the method detection limits (MDLs), which were generally 0.050 mg/L for the WVWA stations and 0.024 mg/L for the DEQ stations. Hence, the markers on Figure 12 represent the MDLs rather than quantified values for orthophosphate-P. Analyses for total dissolved phosphorus confirmed that the majority of values were in the 0.005 – 0.020 mg/L range in these reaches. The model simulates a reasonable profile for total phosphorus (Figure 13).

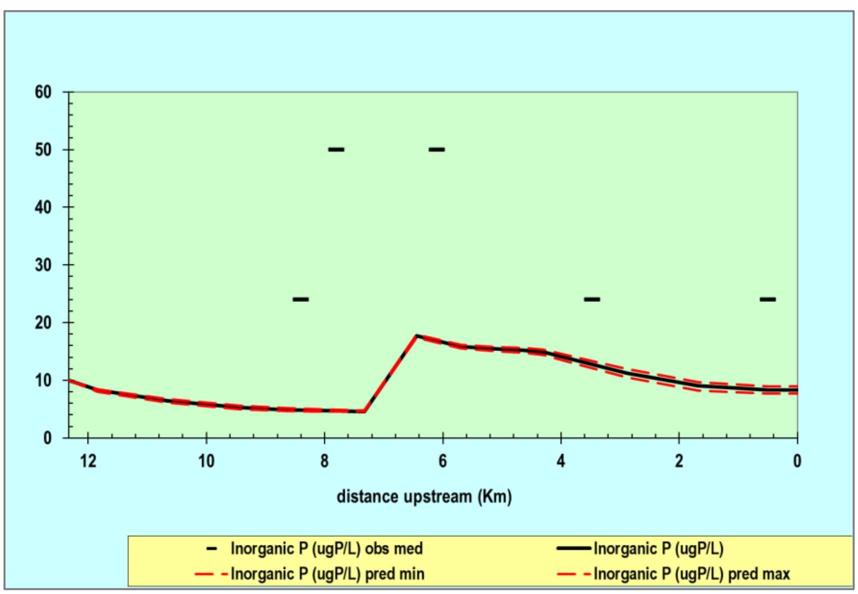

Figure 12 – Simulated inorganic phosphorus. The markers represent method detection limits for orthophosphate-P.

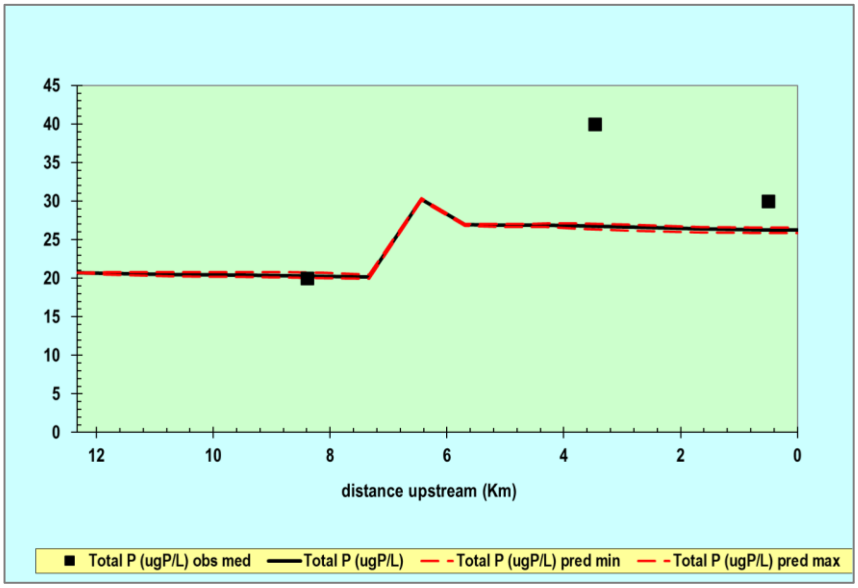

Figure 13 – Observed and simulated total phosphorus.

The model predicts the typical bottom algal biomass, showing similar median values in reaches upstream and downstream of the WVWA outfall (Figure 14). Note that due to the availability of relatively few bottom algae measurements, this graphic also displays the minimum and maximum bottom algae values, rather than the median and IQR. The predicted bottom algal biomass is sensitive to the assumed maximum growth rate. But maximum growth rates higher than the calibrated value (50 g AFDM/m^2/d) tend to cause overestimation of DO and pH, which was a major factor in the final calibration.

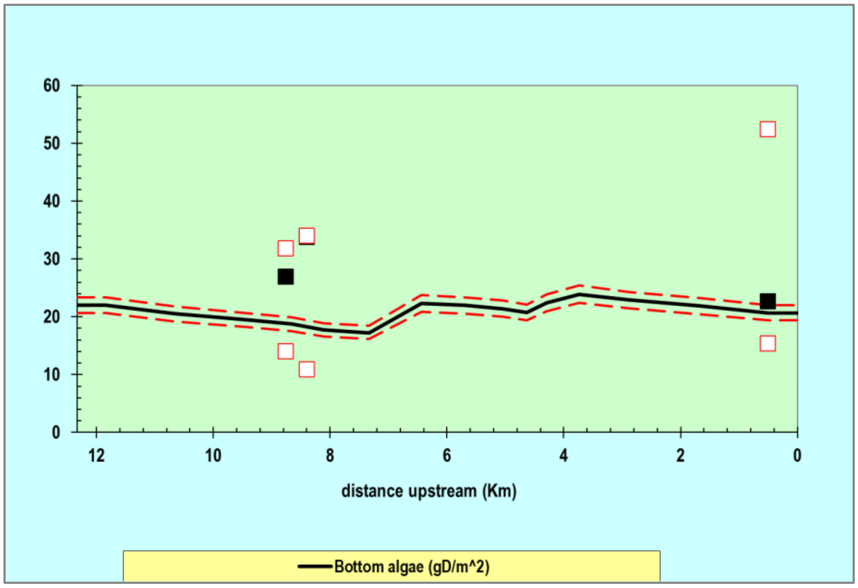

Figure 14 – Observed and predicted bottom algae biomass, expressed in units of ash free dry mass per m^2. The black squares are the median observed values and the white squares are the minimum and maximum values observed.

Overall, the modeling team concluded that the model's ability to predict the longitudinal profile of water quality was sufficient for screening-level purposes, which focused on evaluating the relative responses between scenarios. Full calibration for more precise quantitative predictions would benefit from additional information on the depth and stream velocity profile, time of travel, shading, and additional water quality observations between the existing monitoring stations.

Section 3: Model Application

This section describes how the model was applied to provide insights into nutrient and algal dynamics in the study area. The first step was to examine model scenario 1 (i.e., the calibration condition described in Section 2) for general insights on nutrient concentrations, DO/pH concentrations, algal biomass, and limitations on algal growth. Several model scenarios were also performed to evaluate how response variables (DO, pH and algal biomass) might change in response to changes to nitrogen and phosphorus inputs.

3.1 Insights from the Calibration Scenario

Following are major observations from model scenario 1 (the calibration scenario), considering both the available monitoring data and calibrated model results:

- The model confirms that the Roanoke River is unlikely to experience DO impairments (<5 mg/L), even considering diel variability caused by bottom algae photosynthesis/respiration and temperature variations. Overall, the river is well aerated and tends to stay close to DO saturation levels.
- The model confirms that the Roanoke River has relatively high pH (>8 s.u.), and pH can occasionally even exceed 8.5. However, exceedances of the water quality criterion of 9.0 are not observed in the data nor predicted by the model. Diel variability in pH is relatively low due to high alkalinity (~150-180 mg/L as CaCO3) and associated buffer capacity.

- Overall, bottom algal gross primary productivity was moderate to high, predicted to range from 7 to 16 $gO_2/m^2/d$) in the study area. The combination of moderate to high bottom algae productivity and low removal rates can lead to high algal biomass accrual (>25 g AFDM/m^2) under stable low stream-flows.
- Bottom algae was predicted to be limited by light and phosphorus availability. The light limitation factor varied from 0% (i.e., preventing essentially all growth) at night to ~90% (i.e., supporting growth at 90% of the maximum rate) at midday (Figure 15). The phosphorus limitation factor was about 70%, indicating a moderate phosphorus limitation. The combined effect was a limitation of bottom algae to about 65% of its maximum growth rate. Although phosphorus loads to the river are relatively low, luxury phosphorus uptake and internal phosphorus recycling are sufficient to support moderate bottom algal growth rates.

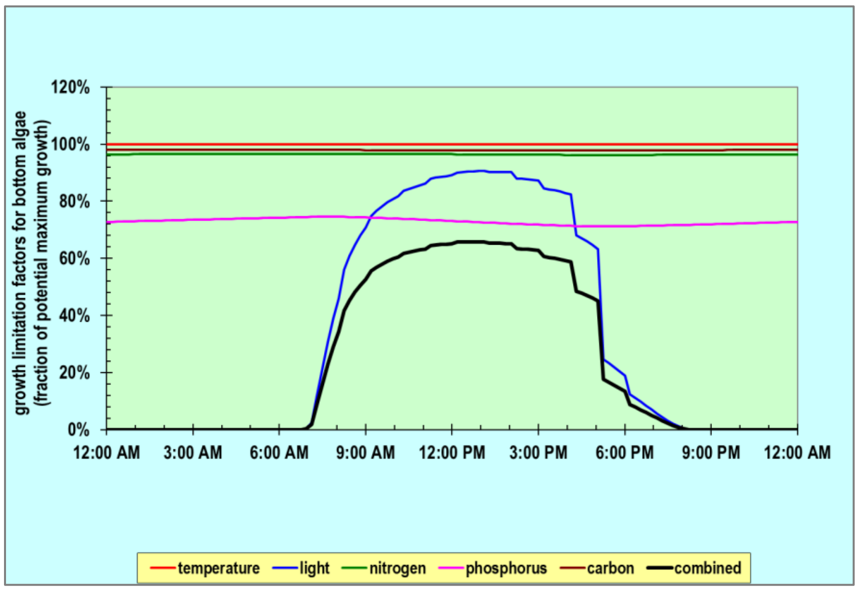

Figure 15 – Predicted limitation factors for bottom algae near station 4AROA198.09 under scenario 1 (calibration conditions). A limitation factor of 100% indicates no growth limitation, and a limitation factor of 0% indicates complete growth limitation.

- Factors such as temperature, nitrogen, and carbon did not significantly limit bottom algal growth rates in the lower study reaches. Summer temperatures are favorable for bottom algal growth, and nitrogen and carbon were in excess of concentrations that would limit bottom algae growth rates.
- The calibrated death rate for bottom algae was relatively low (0.1/day). The use of a low death rate was needed during model calibration to increase predicted bottom algae biomass to observed levels without over-predicting algal effects on DO and pH. This value suggests that algal removal rates by death, grazing, sloughing, etc. are relatively low when streamflows are low and stable.
- In both the observed data and the calibrated model predictions, the median bottom algae biomass was similar upstream and downstream of the WVWA outfall and the Niagara Dam. The Niagara Dam might dampen stream velocities after small precipitation events, and thus reduce algal biomass scour below the dam under those conditions. A more detailed hydraulic model would be required to confirm or refute that possibility.

- Ammonia concentrations were not predicted to reach levels expected to cause aquatic life toxicity, even considering the relatively high pH values greater than 8 s.u. However, the higher ammonia concentrations below Niagara Dam could merit additional investigation.
- Although the WVWA outfall causes a measurable increase in nitrate nitrogen, concentrations of this constituent do not reach levels associated with chronic or acute toxicity to benthic macroinvertebrates. Median nitrate nitrogen concentrations are in the 1.0 to 3.0 mg/L range in most of the model domain, and about 2.4 mg/L at station 4AROA198.09. Virginia DEQ has not promulgated a nitrate criterion for aquatic life protection. But for comparison, the Minnesota Pollution Control Agency (2022) applied USEPA criteria development methods and derived cool/warmwater nitrate nitrogen criteria of 8 mg/L (chronic) and 60 mg/L (acute).

  As another basis of comparison, the Canadian water quality guidelines for nitrate nitrogen are 3.0 mg/L (long-term exposure) and 124 mg/L (short-term exposure) (Canadian Environmental Quality Guidelines, 2012). However, the conservatively low value for log-term (indefinite) exposure was "derived with mostly no- and some low-effect data", and was controlled by sensitive salmonid species rather than macroinvertebrates, for which the cited thresholds were 11.3 mg/L or higher. Similarly, Van Dam and others (2022) concluded that a long-term nitrate nitrogen threshold of 15 mg/L was protective of 95% of species, and a threshold as low 7.6 mg/L was protective of 99% of species. Some researchers have found that nitrate toxicity decreases with hardness (Baker and others, 2017), and so the relatively high hardness (>50 mg/L as $CaCO_3$) of the Roanoke River may further reduces the likelihood of direct toxic impacts.

3.2 Exploratory Scenarios

Based on the calibrated model, the primary nutrient-related response variable of interest is bottom algal biomass. This is because DO and pH conditions are generally favorable under existing conditions, and neither the data nor model indicate toxicity by nutrient-related constituents. Additional model scenarios were performed to explore the predicted sensitivity of bottom algal biomass to reductions in nitrogen and phosphorus inputs. The scenarios that were performed were as follows:

- **Scenario 1**: Calibrated model; no reduction to nutrient inputs.
- Scenario group 2: Nitrogen reduction (all nitrogen species reduced equally)
  - **Scenario 2A**: Nitrogen reduced by 35 percent in all model inputs (headwater, tributaries, diffuse flow, and WVWA effluent).
  - **Scenario 2B**: Nitrogen reduced by 70 percent in all model inputs.
  - **Scenario 2C**: Nitrogen reduced by 90 percent in all model inputs.
- Scenario group 3: Phosphorus reduction (all phosphorus species reduced equally)
  - **Scenario 3A**: Phosphorus reduced by 35 percent in all model inputs.
  - **Scenario 3B**: Phosphorus reduced by 70 percent in all model inputs.
  - **Scenario 3C**: Phosphorus reduced by 90 percent in all model inputs.
- Scenario group 4: Dual nutrient reduction (all nutrient species reduced equally)
  - **Scenario 4A**: Nitrogen and phosphorus reduced by 35 percent in all model inputs.
  - **Scenario 4B**: Nitrogen and phosphorus reduced by 70 percent in all model inputs.
  - **Scenario 4C**: Nitrogen and phosphorus reduced by 90 percent in all model inputs.

All the scenarios described above should be considered sensitivity analysis scenarios for testing model responses, rather than feasible or recommended management scenarios. Considering that phosphorus is currently below detection limits throughout much of the study reach, significant reductions in this parameter might not be practical. However, the sensitivity analysis scenarios can still provide insights into the factors that control bottom algal biomass in the study reach.

3.2.1 Scenario Group 2 - Nitrogen Reduction

None of the group 2 (nitrogen reduction) scenarios were predicted to significantly reduce bottom algae biomass in the Roanoke River (Figure 16). The growth limitation charts for these scenarios (e.g., Figure 17) indicate that bottom algae would remain limited by light and phosphorus at station 4AROA198.09 even with 90 percent reduction in total nitrogen inputs. As result, algal biomass was predicted to be relatively insensitive to changes in nitrogen concentrations.

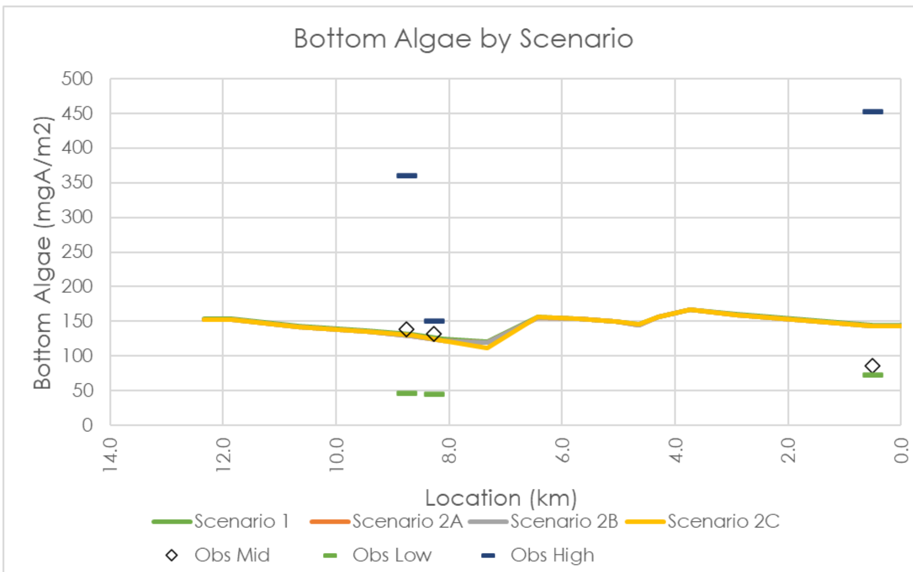

Figure 16 – Predicted bottom algal biomass for scenario 1 and scenarios 2A (35% TN reduction), 2B (70% TN reduction), and 2C (90% TN reduction). Bottom algal biomass is shown in units of mg/m² chlorophyll-a.

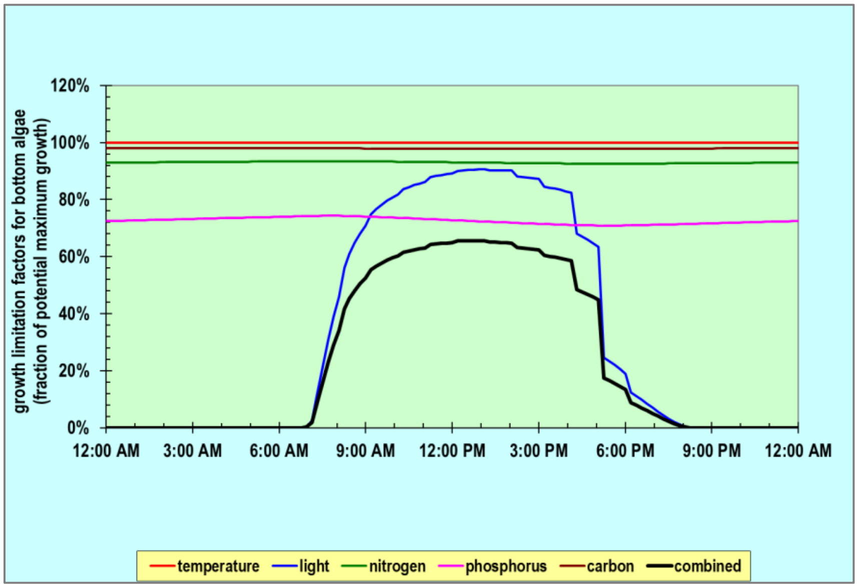

Figure 17 – Predicted growth limitation factors for bottom algae near station 4AROA198.08 under scenario 2C (90% TN reduction).

3.2.2 Scenario Group 3 - Phosphorus Reduction

A 35 percent reduction of phosphorus (Scenario 3A) was predicted to reduce bottom algal biomass by 5-18 percent depending on location in the study reach, including about 14 percent at 4AROA198.08 (Figure 18). A 70 percent reduction of phosphorus (Scenario 3B) was predicted to reduce bottom algal biomass by 46-50 percent, including about 42 percent at 4AROA198.09. And a 90 percent reduction of phosphorus (Scenario 3B) was predicted to reduce bottom algal biomass by 46-85 percent, including about 74 percent at 4AROA198.08. The growth limitation charts for these scenarios (e.g., Figure 19) indicate that the phosphorus limitation factors would be reduced to about 63, 43, and 20 percent under scenarios 3A, 3B, and 3C respectively, compared to about 70 percent under scenario 1 (calibrated conditions).

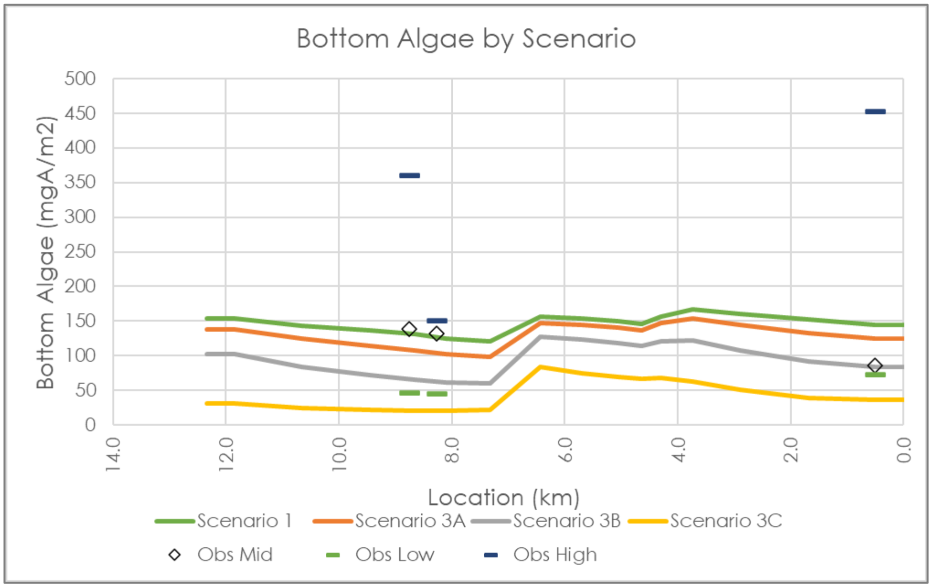

Figure 18 - Predicted bottom algal biomass for scenario 1 and scenarios 3A (35% TP reduction), 3B (70% TP reduction), and 3C (90% TP reduction). Bottom algal biomass is shown in units of mg/m² chlorophyll-a.

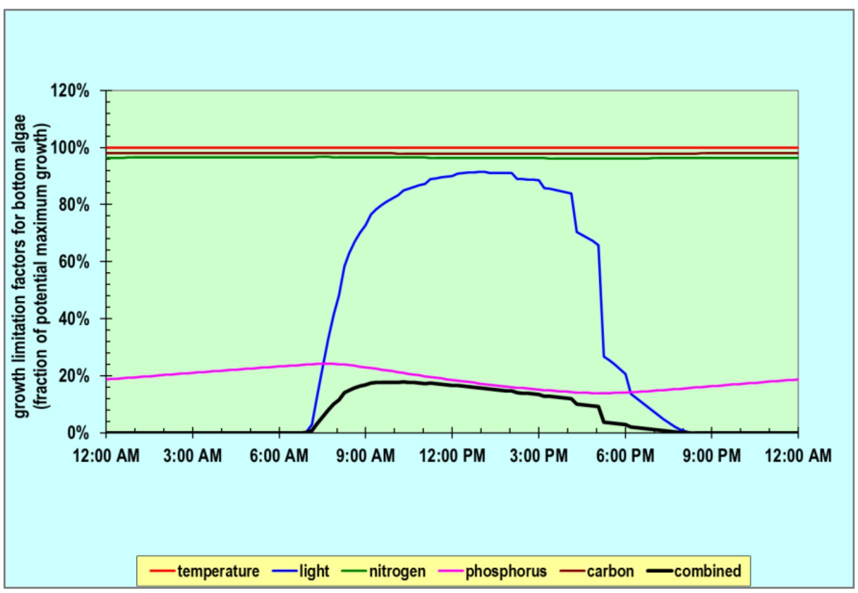

Figure 19 - Predicted growth limitation factors for bottom algae near station 4AROA198.08 under scenario 3C (90% TP reduction).

3.2.3 Scenario Group 4 – Dual Nutrient Reduction

Under the dual nutrient reduction scenarios (4A, 4B, and 4C), bottom algae levels and growth limitation factors were predicted to be essentially identical to those under the equivalent phosphorus reduction scenarios (3A, 3B, and 3C). The same percent reductions in bottom algae were predicted between the group 3 (phosphorus reduction) rand corresponding group 4 (dual nutrient control) scenarios. Similarly, the nutrient limitation factors (e.g., Figure 21) demonstrated a 20-63 percent phosphorus limitation under the group 4 scenarios, similar to group 3 scenarios. This demonstrates that the predicted reductions in bottom algal biomass under scenario group 4 were almost entirely due to phosphorus reduction.

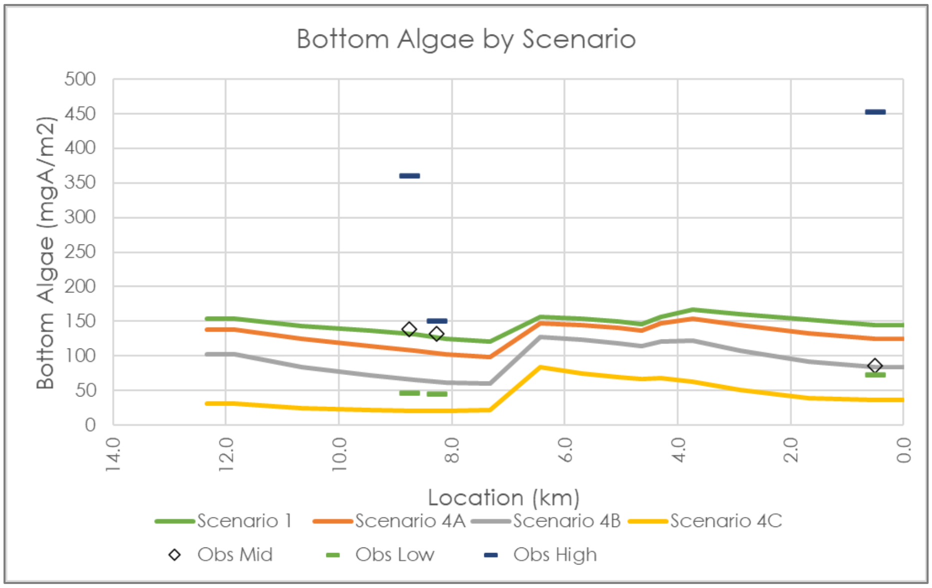

Figure 20 - Predicted bottom algal biomass for scenario 1 and scenarios 4A (35% TP reduction), 4B (70% TP reduction), and 4C (90% TP reduction). Bottom algal biomass is shown in units of mg/m² chlorophyll-a.

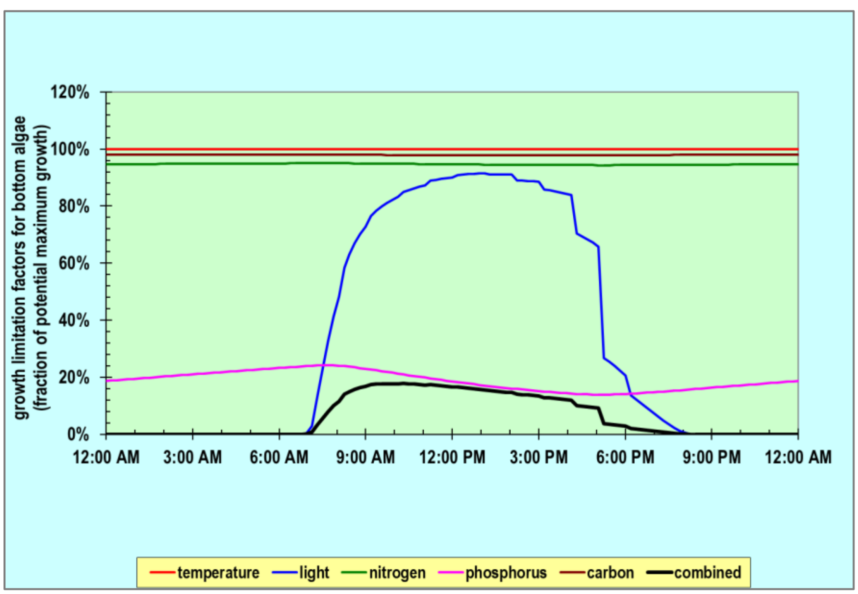

Figure 21 - Predicted growth limitation factors for bottom algae near station 4AROA198.08 under scenario 4C (90% TN and TP reduction).

Section 4: Conclusions

Following are the major conclusions of this screening-level modeling analysis of nutrient dynamics in the Roanoke River:

1. *Most nutrient-related response variables are at levels that support aquatic life uses*. The screening-level model and water quality monitoring data together indicate that DO does not typically fall below the water quality criterion of 5 mg/L. Despite the moderate to high primary productivity of the river, DO exchange with the atmosphere is relatively high such that the diel variability in DO does not typically exceed 2-3 mg/L. And although pH is often above 8 s.u., the relatively high alkalinity and buffer capacity of the river prevents pH from exceeding 9 s.u. Ammonia and nitrate nitrogen were not predicted to exceed toxic criteria or thresholds.

2. *Bottom algae biomass can accrue to relatively high levels despite a moderate phosphorus limitation*. DEQ monitoring data demonstrate that bottom algal biomass can accrue to relatively high levels in the Roanoke River. This modeling study cannot conclude whether the bottom algae biomass is a contributing factor to benthic macroinvertebrate impairments. Although the bottom algae does not appear to cause low DO concentrations or excessive pH, it is possible that the algae alters the physical benthic habitat enough to affect the SCI scores. The water quality model confirmed moderate to high primary productivity and provides several insights into factors controlling the bottom algae growth rate and biomass accrual potential. These include:

    a. Light: Light availability during midday was high enough to support bottom algal growth rates at about 90% of the maximum calibrated rate. However, during the morning and afternoon, topographic and tree shading were predicted to exert a growth rate limitation.

    b. Phosphorus: Bottom algae were predicted to experience a moderate phosphorus limitation under existing conditions. The combination of light and phosphorus limitation was predicted to limit bottom algal growth rates to about 65% of maximum calibrated growth rates at midday, and to lower growth rates at other times. The phosphorus limit is caused by low phosphorus concentrations 0.050 – 0.020 mg/L) in the study reaches, which itself is driven by low phosphorus inputs and bottom algae uptake. Phosphorus was below detection limits (<0.050 mg/L or <0.024 mg/L) in a high proportion of the available sample results, leading to uncertainty in the prevailing concentrations and exact degree of phosphorus limitation. The model predicted that, despite the low phosphorus concentrations, bottom algae could maintain moderate algal growth rates by a combination of luxury uptake and in-stream recycling of the available phosphorus.

    c. Low death/removal rate: Model calibration required a relatively low algal death rate (0.1/day). The model simulates steady-hydraulics under a low streamflow condition, and so it does not explicitly predict the frequency of algal scour by high stream velocities. However, the use of a low death rate implicitly simulates conditions during which removal rates by scour, sloughing, grazing, and cell death are relatively low. The high algal biomass accruals are therefore probably favored by low removal rates during period of stable streamflow, and possibly also by the presence of scour-resistant algal mats. Bottom algae characteristics that increase resistance to scour include a low vertical profile, strong adhesion, an interwoven matrix of strong filaments, and mats with relatively uniform surfaces (Peterson, 1996). If algal mats are resistant to scour, it would not require extremely high growth rates for algae to accrue and persist over time.

3. <u>*Point source nitrogen controls would not be expected to reduce bottom algae or affect other nutrient-related response variables*</u>. Both the model and monitoring data indicated that median bottom algal biomass was similar upstream and downstream of the WVWA outfall, suggesting that the WVWA discharge is not a principal causative factor of bottom algae accruals. Model scenarios demonstrated that due to lack of significant nitrogen limitation, even 90 reductions in nitrogen inputs from all sources (including WVWA) would not cause significant reductions in algal biomass. The system was predicted to remain limited by light and phosphorus rather than nitrogen.

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Attachment A: Calibrated Rates and Parameters

Roanoke River xQUAL2Kw Model

Parameter	*Value*	*Units*
Stoichiometry:		
Carbon	**40**	**gC**
Nitrogen	**7.2**	**gN**
Phosphorus	**1**	**gP**
Dry weight	**100**	**gD**
Chlorophyll	**0.7**	**gA**
Inorganic suspended solids:		
Settling velocity	**0.61**	**m/d**
Oxygen:		
Reaeration model	**Internal**	
Reaeration user model parameter A	**3.93**	
Reaeration user model parameter B	**0.5**	
Reaeration user model parameter C	**-1.5**	
Temp correction	**1.024**	
Reaeration wind effect	**None**	
O2 for carbon oxidation	**2.67**	**gO_2/gC**
O2 for NH4 nitrification	**4.57**	**gO_2/gN**
Oxygen inhib model CBOD oxidation	**Exponential**	
Oxygen inhib parameter CBOD oxidation	**0.60**	**L/mgO2**
Oxygen inhib model nitrification	**Exponential**	
Oxygen inhib parameter nitrification	**0.60**	**L/mgO2**
Oxygen enhance model denitrification	**Exponential**	
Oxygen enhance parameter denitrification	**0.60**	**L/mgO2**
Oxygen inhib model phyto resp	**Exponential**	
Oxygen inhib parameter phyto resp	**0.60**	**L/mgO2**
Oxygen enhance model bot alg resp	**Exponential**	
Oxygen enhance parameter bot alg resp	**0.60**	**L/mgO2**
Slow CBOD:		
Hydrolysis rate	**0.2**	**/d**
Temp correction	**1.047**	
Oxidation rate	**0.05**	**/d**
Temp correction	**1.047**	
Fast CBOD:		
Oxidation rate	**2.5**	**/d**
Temp correction	**1.047**	
Organic N:		
Hydrolysis	**0.2**	**/d**
Temp correction	**1.07**	
Settling velocity	**0.11**	**m/d**
Ammonium:		

Nitrification	1	/d
Temp correction	1.07	
Nitrate:		
Denitrification	2	/d
Temp correction	1.07	
Sed denitrification transfer coeff	1	m/d
Temp correction	1.07	
Organic P:		
Hydrolysis	0.43	/d
Temp correction	1.07	
Settling velocity	0.1	m/d
Inorganic P:		
Settling velocity	0	m/d
Sed P oxygen attenuation half sat constant	0.45254	mgO_2/L
Phytoplankton:		
Max Growth rate	2.5	/d
Temp correction	1.07	
Respiration rate	0.1	/d
Temp correction	1.07	
Death rate	0.05	/d
Temp correction	1.07	
Nutrient limitation model for N and P	Minimum	
Nitrogen half sat constant	15	ugN/L
Phosphorus half sat constant	2	ugP/L
Inorganic carbon half sat constant	1.30E-05	moles/L
Phytoplankton use HCO3- as substrate	Yes	
Light model	Half saturation	
Light constant	58	langleys/d
Ammonia preference	25	ugN/L
Settling velocity	0.15	m/d
Include transport of phytoplankton	Yes	
Nitrogen uptake water column fraction	1	
Phosphorus uptake water column fraction	1	
Bottom Algae:		
Growth model	Zero-order	
Max Growth rate	50	$gD/m^2/d$ or /d
Temp correction	1	
First-order model carrying capacity	200	gD/m^2
Basal respiration rate	0.1	/d
Photo-respiration rate parameter	0.6	unitless

Temp correction	**1.04**	
Excretion rate	**0.1**	**/d**
Temp correction	**1.04**	
Death rate	**0.1**	**/d**
Temp correction	**1.04**	
Scour function	**Flow**	
Coefficient of scour function	**0**	**/d/cms or /d/mps**
Exponent of scour function	**0**	
Minimal biomass after scour event	**0**	**gD/m^2**
Catastrophic scour rate during flood event	**0**	**/d**
Critical flow or vel for catastrophic scour	**0**	**cms or m/s**
External nitrogen half sat constant	**206**	**ugN/L**
External phosphorus half sat constant	**74**	**ugP/L**
Inorganic carbon half sat constant	**6.61E-05**	**moles/L**
Bottom algae use HCO3- as substrate	**Yes**	
Light model	**Half saturation**	
Light constant	**59**	**langleys/d**
Ammonia preference	**25**	**ugN/L**
Nutrient limitation model for N and P	**Minimum**	
Subsistence quota for nitrogen	**7.4**	**mgN/gD**
Subsistence quota for phosphorus	**2**	**mgP/gD**
Maximum uptake rate for nitrogen	**720**	**mgN/gD/d**
Maximum uptake rate for phosphorus	**50**	**mgP/gD/d**
Internal nitrogen half sat ratio	**2.2**	
Internal phosphorus half sat ratio	**1.4**	
Nitrogen uptake water column fraction	**1**	
Phosphorus uptake water column fraction	**1**	
Detritus (POM):		
Dissolution rate	**0.63**	**/d**
Temp correction	**1.07**	
Settling velocity	**0.5**	**m/d**
pH:		
Partial pressure of carbon dioxide	**375**	**ppm**
Hyporheic metabolism		
Model for biofilm oxidation of fast CBOD	**Zero-order**	
Max biofilm growth rate	**5**	**gO2/m^2/d or /d**
Temp correction	**1.047**	
Fast CBOD half-saturation	**0.5**	**mgO2/L**
Oxygen inhib model	**Exponential**	
Oxygen inhib parameter	**0.60**	**L/mgO2**
Respiration rate	**0.2**	**/d**

Temp correction	**1.07**	
Death rate	**0.05**	**/d**
Temp correction	**1.07**	
External nitrogen half sat constant	**15**	**ugN/L**
External phosphorus half sat constant	**2**	**ugP/L**
Ammonia preference	**25**	**ugN/L**
First-order model carrying capacity	**100**	**gD/m^2**
Photosynthetic quotient and respiratory quotient for phytoplankton and bottom algae		
Photosynthetic quotient for NO3 vs NH4 use	**1.30**	**/d**
Respiratory quotient	**1.00**	