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Edmund G. Brown Jr.
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MEMORANDUM

Date: March 14, 2012

To: File: Laguna de Santa Rosa; TMDL Development and Planning

From: Steve Butkus

Subject: Laguna de Santa Rosa TMDL Linkage Analysis through the Application of Water Quality Models

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The development of the Laguna de Santa Rosa (Laguna) Total Maximum Daily Load (TMDL) for impairment of beneficial uses due to low dissolved oxygen and high nutrients requires a “linkage analysis” (CSWRCB 2005). A linkage analysis describes the method used to establish the relationship between pollutant loading and instream water quality response. The basic goal is to describe the process for establishing a linkage between nutrient loads and the instream dissolved oxygen (DO) conditions. Linkage analyses can vary widely across TMDLs. This memorandum serves to document the DO response model results for specific model simulations.

1. MODEL SELECTION

Two QUAL2Kw water quality models were developed and evaluated for use in the TMDL linkage analysis (Butkus 2011a) to represent the lentic and lotic surface water types found in the Laguna watershed. The models were based on the River and Stream Water Quality Model (QUAL2K) receiving waters quality response model that is supported by the U.S. Environmental Protection Agency (Chapra et al. 2006). The QUAL2K model was written as open source code for model improvements. One such model upgrade is the QUALKw model version (Pelletier et al. 2006; Pelletier and Chapra 2008). The QUAL2Kw framework was used for the model due to improvements over the QUAL2K model, including addition of capability to simulate attached bottom algae.

Lower Santa Rosa Creek downstream of the Piner Creek confluence to the confluence with the mainstem Laguna de Santa Rosa was selected to represent lotic reaches in the lower Laguna watershed. The mainstem Laguna de Santa Rosa at Lake Jonive (Cummings 2004), the open water area south of Occidental Road near Sebastopol, was selected to represent lentic areas of the Laguna. The models were used to simulate various load reductions and stream flows to advise the TMDL allocation process and implementation decisions. Additional information on the model selection, development, and evaluations can be found in Butkus (2011a).

2. MODEL CONSTRUCTION

2.1. Stream Flow

The developed water quality models were applied to simulations representing low flow critical conditions. A range of flows were simulated to represent various impacts of critical low flow. The most commonly-reported statistic for analyses of low flows is based on percentiles (Helsel and Hirsch 2002). TMDL load capacities are often derived based on the "7-day 10-year low flow". This low flow statistic is referred to as the “7Q10”. The 7Q10 is the 10th percentile of the distribution of annual values of Y, where Y is the lowest average of mean daily flows over any consecutive 7-day period for a given year. Several different flow duration periods have been identified to describe the impacts to aquatic life over the entire low flow regime (Pryce 2004).

Mean daily flows for each model were compiled from stream flow gages operating on Lower Santa Rosa Creek at Willowside Road (USGS Gage #1146320) and Lake Jonive at Occidental Road (USGS Gage #11465750). Daily stream flow values have only been collected at the two stream flow gages since 1999. Calculation of flow statistics beyond this period (i.e., 7Q20) would require unacceptable data extrapolation (Searcy 1959).

Estimates of critical flow statistics can be calculated at a gage further downstream that does have an adequate data record. Stream flow values have been measured for over 70 years on the nearby, downstream gage on the Russian River at Hacienda Bridge (USGS Gage #11467000). Two statistically significant regression models were developed using daily mean flows from the downstream Russian River to allow the calculation of low flow statistics for the gages on the modeled Laguna reaches (Butkus, 2011a). Table 1 presents critical low flow statistics for the two Laguna stream flow gages used for the model simulations.

Although flow-duration and low-flow frequency statistics commonly are computed on an annual basis, they also can be computed on a seasonal or monthly basis. For example, the low flow statistics for the summer dry period could be calculated using just daily mean flows from those dates in the period of record. The annual low flow statistic for the 7Q10 has an equivalent annual risk of a 7Q20 for a semiannual seasonal period like the summer dry period (USEPA 1984).

2.2. Stream Flow Rating Curves

The model requires a depth-flow rating curve for each modeled reach. Depth-flow rating curves were derived from the stream flow gages operating on Lower Santa Rosa Creek (USGS Gage #1466320) and Lake Jonive (USGS Gage #11465750). The USGS rating tables (containing flow and elevation) published for these gages were fitted using nonlinear regression to a power function (i.e, depth = αQ^{β}) for representation in the model (Table 5).

2.3. Initial and Upstream Concentrations

The model requires specifying initial and upstream concentrations for each variable in each segment. Initial and upstream concentrations for model simulations of current conditions were derived from recent measurements. Diel data of dissolved oxygen, water temperature, and pH collected in 2011 were used as initial and upstream conditions (NCRWQCB 2011). The median value for each hour was derived from diel data collected over 6 days in the headwaters of Copeland Creek. These hourly median values were used for the initial and upstream conditions for the lentic model. Diel data were also collected over 12 days in the headwaters of Santa Rosa Creek. The median value for each hour was derived and used for the initial and upstream conditions for the lotic model. Other required input concentrations variables were estimated by the methods described in Butkus (2011). Citations to the derivation method for each constituent are presented in Table 3.

Concentrations initial and upstream concentrations for model simulations of current conditions were based on Regional Water Board staff sampling of pollutant concentrations. Upstream concentrations were derived by area-weighting concentrations sampled from different land covers (NCRWQCB 2010). Samples were collected during both wet and dry periods, but only the median dry period concentration data were used for model simulations of critical summer periods (Butkus 2011). Tables 4 and 5 present the areas-weighted concentrations used for the initial and upstream variable concentrations of each model.

2.4. Source Loads

The model allows specifying both nonpoint source and point source loads and flows to any model segment. For model development, nonpoint source loads were evenly distributed among each of the model segments, and were represented by the inflow concentrations and flows from the local drainage area to the modeled reaches. Local drainage inflow concentrations were derived by area-weighting the land covers based on the NCRWQCB 2010 (Tables 4 and 5).

Flows from local drainage were estimated by area-weighting. The local drainage area for the modeled segments of Santa Rosa Creek is 3.73% of the drainage area of the stream flow gage operating on Lower Santa Rosa Creek at Willowside Road (USGS Gage #1146320). The local drainage area for the modeled segments of Lake Jonive is 1.84% of the drainage area of stream flow gage operating on Lake Jonive at Occidental Road (USGS Gage #11465750). Local inflow volumes were set at these percentages of the flow measured at these gages.

The City of Santa Rosa treats municipal wastewater from Santa Rosa, Rohnert Park, Cotati, and Sebastopol at the Subregional Water Reclamation System (SWRS) utilizing advanced wastewater treatment. The SWRS is permitted to discharge wastewater only during the non-critical period of October 1 to May 14. In addition, the discharge volume of wastewater is limited based on receiving water flow volume. These permit limitations assure that wastewater is not discharged during critical periods. Therefore, no point source loads were included in this model application since point source discharges are not allowed during critical low flow periods.

2.5. Other Model Constants

The models required information on several other state variables. The values used for model development of these variables are specifically described in Butkus (2011a). User manual recommendations for sediment and light characteristics were selected.

The model uses meteorological data that affect specific mechanistic processes. Wind speed affects oxygen reaeration rates, and temperature conduction and convection. Wind speed was assumed to be zero to model the minimum oxygen reaeration rate with the atmosphere. This assumption models a worst-case condition that serves as an inherent margin of safety for the TMDL. Cloud cover affects photosynthesis rates. Cloud cover was assumed to be zero to model the maximum photosynthetic rate. This assumption also models a worst-case condition that also serves as an inherent margin of safety for the TMDL. Air and dew point temperatures are used only for the temperature model component of QUAL2kw which was not applied in these model simulations.

Solar radiation is estimated from input data based on the time of year, latitude and longitude, cloud cover, and shade. Simulations were run at the summer solstice (i.e., June 21) to model the maximum light available for increased photosynthetic rate. This assumption also models a worst-case condition that also serves as an inherent margin of safety for the TMDL.

The model requires a percent shade value to represent the percent of solar radiation that is blocked because of riparian or topographic shade. Shade was assumed to be zero for each model. This assumption models a worst-case condition that serves as an inherent margin of safety for the TMDL.

3. MODEL SIMULATIONS

The model results of daily minimum DO concentration were used to assess support of aquatic life uses (i.e., SPWN, WARM, COLD). The model results of the diel range of DO concentration were used to assess impairment from biostimulatory substances, since higher ranges of diel DO concentrations are directly related to algal productivity. The results of the model simulations are presented in Figures 1-18 and discussed below.

The lotic model was run for 20 cycles to achieve steady state conditions. The lentic model was run for 1000 cycles to achieve steady state conditions. The long model run time was required for the lentic model as a result of high water residence time during critical low flow conditions.

Figure 1 shows the lentic model results for daily minimum DO concentrations along the channel thalweg at different critical low stream flows. The results show that the upstream daily minimum DO concentration of 9.44 mg/L was reduced within the first model segment based on lake mechanistic processes and then remained stable along the channel thalweg, indicating steady state conditions. Critical low flows at 7Q20 and higher result in daily minimum DO concentrations above 6 mg/L. Lower flows result in lower daily minimum DO concentrations.

Figure 2 shows the lentic model results for the diel DO concentration range. The diel DO concentration range is directly related to the phytoplankton productivity. Diel DO concentration ranges are relatively high, near 3 mg/L. Lower flows result in higher diel DO concentration ranges; indicating higher productivity.

Figure 3 shows the lotic model results for daily minimum DO concentrations along the thalweg at different critical low stream flows. The results show that the upstream daily minimum DO concentration of 9.28 mg/L was reduced within the first river mile and then remained relatively stable to the outflow, indicating steady state conditions. Critical low flows result in daily minimum DO concentrations above 6 mg/L. Lower flows result in lower daily minimum DO concentrations.

Figure 4 shows the lotic model results for the diel DO concentration range. The diel DO concentration range is directly related to the stream benthic algal productivity. Diel DO concentration ranges are relatively low near 0.5 mg/L. Higher flows result in a lower diel DO concentration ranges; indicating lower productivity.

Figure 5 shows the change in DO concentrations from the model headwaters to the model outflow at different critical low stream flows for the lentic model. The difference between the headwaters and the outflow DO concentration represents the effect of the model processes on the headwaters concentrations. The results show that the lentic model reduces the daily minimum DO concentration between 2 and 4 mg/L during critical low flows. The diel range of DO concentration increases between 1 and 3 mg/L due to increased productivity.

Figure 6 shows the change in DO concentrations from the model headwaters to the model outflow at different critical low stream flows for the lotic model. The results show that the lotic model reduces the daily minimum DO concentration between 2 and 3 mg/L during critical low flows. The diel range of DO concentration decreases slightly indicating limited benthic algal productivity.

Figure 7 shows the effect of nutrient reduction on the resulting daily minimum DO concentrations predicted by the lentic model. External and internal nutrient loads were reduced (10%-90%) and increased (120%) from the current load. Results show that only reductions in total carbon loading result in a positive improvement in minimum daily DO concentrations. These results are likely due to the relatively high sediment oxygen demand (SOD) represented in the lentic model. The calibrated SOD value of 10 $gO_2/m^2/L$ is at the top range of recommended values (Chapra 1997) and represents sediment highly enriched with organic material. SOD exerts a much greater effect on daily minimum DO concentration than direct algal productivity. However, increased algal productivity generates particulate organic matter that is transported to benthic sediments during senescence and increases the SOD indirectly.

Figure 8 shows the effect of nutrient reduction on the resulting diel range of DO concentrations predicted by the lentic model. Results indicate that only reduction in total phosphorus loads were shown to lower the diel range of DO concentration. The diel range increases as nitrogen is reduced due to the shift from the stoichiometry specified in the model. The calibrated model specified the total nitrogen to total phosphorus stoichiometric ratio at 7.2 to 1. These results indicate that phosphorus is the limiting nutrient for planktonic algal productivity in the lentic model. Algal biomass production is limited by phosphorus in most fresh waters. Lake restoration and management is most often directed at controlling the loading of phosphorus to prevent accelerated eutrophication (Cooke et al. 1986).

Figure 9 shows the effect of nutrient reduction on the resulting daily minimum DO concentrations predicted by the lotic model. Results show that only reductions in total carbon loading have a positive improvement in minimum daily DO concentrations. These results are likely due to the sediment oxygen demand (SOD) represented in the Santa Rosa Creek model. The calibrated SOD value of 2.6 $gO_2/m^2/L$ is represents sediment enriched with organic material (Chapra 1997). SOD exerts a much greater effect on daily minimum DO concentration than direct benthic algal productivity.

Figure 10 shows the effect of nutrient reduction on the resulting diel range of DO concentrations predicted by the lotic model. Results show that only reduction in total phosphorus loads were shown to lower the diel range of DO concentration. Reduction in total nitrogen increase the diel range of DO concentration until about a 30% reduction where the range declines. These results indicate that phosphorus is the limiting nutrient for benthic algal productivity in the lotic model. However, this benthic algal productivity is low as compared to the phytoplankton algal productivity shown in the lentic model. The diel range of DO concentration from the lentic model is approximately 3 mg/L, as compared to a 0.5 mg/L diel range simulated with the lotic model (Figures 8 and 10).

4. MODELED LINKAGES

Figures 11 and 12 show the oxygen demanding substances in the benthic sediment are the primary mechanism of DO depletion in both lentic and lotic surface water quality models. SOD was estimated for the water quality models through mass balance model calibration. SOD has been measured in many locations by a number of different methods. Measured SOD rates range from 0.05 gO_2/m^2/day for sediment caused by high mineral soil erosion (Chapra 1997) to 33 gO_2/m^2/day measured downstream of a paper mill discharge (USEPA 1995).

SOD values for sandy, benthic sediments range from 0.2 – 1.0 gO_2/m^2/day. SOD values that range from 1 - 10 gO_2/m^2/day are indicative of enriched sediment (Chapra 1997). Calibrated SOD values for the lotic and lentic water quality models were 2.6 gO_2/m^2/day and 10.0 gO_2/m^2/day, respectively. The lentic water quality model SOD was estimated at the highest value considered acceptable to the model parameter values (Pelletier and Chapra 2008).

SOD is caused by the oxidation of organic matter in benthic sediments. These sediments originate from many sources. Particulate matter from wastewater discharges can result in sediments with a high organic content. Allochthonous material (e.g., leaf litter) and watershed soils can also contribute to benthic SOD. Highly productive eutrophic conditions generate algal and macrophytic biomass that can become deposited in the sediment as organic material upon senescence (i.e., autothonous material). Regardless of the source, the oxidation of deposited benthic organic matter will exert a SOD on the water body (Chapra 1997).

Chapra (1997) applied the “Streeter-Phelps” model to demonstrate the linear relationship between SOD and the downward flux of organic carbon. The model results showed that the steady-state SOD equals about 130% of the downward flux of organic carbon. The downward flux of organic carbon is also linearly related to the water column concentration of ultimate carbonaceous biochemical oxygen demand ($CBOD_u$) and the particle settling rate. $CBOD_u$ is a measure of the total organic carbon concentration and provides an estimate of the total amount of oxygen that carbon will consume. Therefore, a reduction in water column $CBOD_u$ would provide a proportionate reduction in the SOD of newly deposited sediment assuming a mean settling velocity.

Figures 13 and 14 show the modeled linkage between total phosphorus concentration and $CBOD_u$. Total phosphorus concentrations are shown to limit both phytoplankton and benthic algal biomass. Algal biomass contributes to $CBOD_u$ upon senescence, which then contributes to the SOD by settling. Reductions in total phosphorus concentrations would be expected to reduce algal biomass, $CBOD_u$ and SOD. However, large reductions in total phosphorus concentrations would be needed to remove relatively small amounts of $CBOD_u$. Therefore, reductions in allochthonous $CBOD_u$ loading would be needed to help reduce SOD values.

Figures 15 and 16 show the modeled linkage between total phosphorus and the diel range of DO concentration. The diel DO concentration range is directly related to algal productivity. Diel DO concentration ranges are large in highly productive aquatic ecosystems due to plant photosynthesis and respiration. Lower flows were shown to result in higher diel DO concentration ranges; indicating higher productivity (Figures 2 and 4). The lentic model results show a much higher diel range of DO concentration than the lotic model. Both models show the linkage between diel DO concentration and total phosphorus. However, large reductions in total phosphorus concentration would be needed to achieve relatively small changes in diel DO concentration. Therefore, the diel range of DO concentration was not a good variable to assess the Basin Plan narrative criteria for biostimulatory substances (i.e., total phosphorus concentration).

Figures 17 and 18 show the modeled linkage between total phosphorus and algal biomass as measured by chlorophyll-*a* content. Chlorophyll-a in the phytoplankton was used to assess the linkage for the lentic model. Measured 2008 mean summer concentrations from Lake Jonive and the USEPA Ecoregional nutrient criteria for lakes (USEPA 2001) are shown with the linkage from the lentic model results (Figure 17). The results show that large reductions in total phosphorus are needed to meet the USEPA Ecoregional nutrient criteria. The linkage from the lotic model results is shown with the California nutrient numeric endpoint criteria for benthic algal biomass. The results show that a reduction in total phosphorus concentration to below 50 µg/L would be needed to meet the criterion of presumptively unimpaired beneficial uses (Figure 18).

5. FINDINGS

- Both the lentic and the lotic model results show that lower flows result in a lower daily minimum DO concentration and a higher range of diel DO concentrations. Higher flows show improved daily minimum DO concentration and lower productivity as indicated by the lower diel range of DO concentrations.

- Both the lentic and lotic model results show that only reductions in total carbon loading have a positive improvement in minimum daily DO concentrations. These results are due to the relatively high sediment oxygen demand (SOD) represented in the models. SOD was estimated for the water quality models through mass balance model calibration. The calibrated values of SOD rates used in the models both represent levels of sediment highly enriched with organic carbon.

- Published modeling results have shown that the steady-state SOD equals about 130% of the downward flux of organic carbon (Chapra 1997). The downward flux of organic carbon is also linearly related to the water column concentration of ultimate carbonaceous biochemical oxygen demand ($CBOD_u$) and the particle settling rate. Therefore, a reduction in water column $CBOD_u$ would provide a proportionate reduction in the SOD of newly deposited sediment assuming a mean settling velocity.

- The linkage is shown between total phosphorus concentration and $CBOD_u$. Algal biomass contributes to $CBOD_u$ upon senescence, which then contributes to the SOD by settling. The modeled results show that a large reduction in total phosphorus concentrations would be needed to remove relatively small amounts of $CBOD_u$. Therefore, reductions in allochthonous $CBOD_u$ loading would be needed to help reduce SOD values.

- Both the lentic and lotic model results show that only reductions in total phosphorus loads are shown to lower the diel range of DO concentration, indicating lower algal productivity. These results indicate that phosphorus was the limiting nutrient for algal productivity in both models. However, the benthic algal productivity in the lotic model was much lower than the phytoplankton algal productivity shown in the lentic model. The diel range of DO concentration from the lentic model is approximately 3 mg/L, as compared to a 0.5 mg/L diel range simulated with the lotic model.

- The linkage was shown between total phosphorus and the diel range of DO concentration. The diel DO concentration range is directly related to algal productivity. The modeled results show that a large reduction in total phosphorus concentration would be needed to achieve relatively small changes in diel DO concentration. Therefore, the diel range of DO concentration is not a good variable to assess the Basin Plan narrative criteria for biostimulatory substances (i.e., total phosphorus concentration).

- The linkage was shown between total phosphorus and algal biomass as measured by chlorophyll-*a* content. The modeled results from the lentic model show that large reductions in total phosphorus are needed to meet the USEPA Ecoregional nutrient criteria for lakes. The linkage from the lotic model results was compared to the California nutrient numeric endpoint criteria for benthic algal biomass. The modeled results from the lotic model showed that a large reduction in total phosphorus concentration would be needed to meet the criterion of presumptively unimpaired beneficial uses.

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TABLES

Table 1. Stream Flow Statistics from Gages on Modeled Reaches

Flow Statistic	**Santa Rosa Creek at Willowside Road**		**Lake Jonive at Occidental Road**	
	flow (cfs)	flow (cms)	flow (cfs)	flow (cms)
7Q1	7.68	0.2174	1.90	0.0539
7Q2	3.85	0.1091	0.68	0.0191
7Q5	2.74	0.0775	0.40	0.0114
7Q10	2.22	0.0629	0.30	0.0084
7Q20	1.96	0.0554	0.24	0.0069
7Q50	1.66	0.0471	0.19	0.0054
7Q100	1.08	0.0306	0.10	0.0028

Table 2. Channel Characteristics of Water Quality Models

Reach	**Depth Rating Curve**		**Velocity Rating Curve**	
	Coefficient (α)	**Exponent (ß)**	**Coefficient (α)**	**Exponent (ß)**
Santa Rosa Creek	0.2422	0.1522	0.0322	0.2354
Lake Jonive	1.6258	0.1680	0.0006	0.4910

Table 3. Source of Initial and Upstream Concentration Data Used in Model Applications

Constituent	Method	Citation
Temperature	Diel data measured in 2011	NCRWQCB, 2011
Dissolved Oxygen	Diel data measured in 2011	NCRWQCB, 2011
pH	Diel data measured in 2011	NCRWQCB, 2011
Conductivity	Median value of measured diel data that was used for model calibration	NCRWQCB, 2008; Butkus, 2011
Alkalinity	Median measured in Russian River	Brown & Sayers-Fay, 2007
	Mean measured in the Laguna	AES, 2004
$CBOD_u$ slow & fast	Derived from total organic carbon (TOC) and particulate matter (PM) concentrations	1) NCRWQCB, 2010: [TOC] and [PM] from LCLM 2) Emery et al 1971: [BOD_5] derived from [TOC] 3) Pelletier & Chapra, 2008: [$CBOD_u$] derived from [BOD_5] 4) Bowie, 1985: $CBOD_u$ slow from [BOD_5] and [PM]
Organic-N	Derived from total-N minus ammonium-N minus nitrate-N	Standard Methods 4500-N
Ammonium-N	Concentration estimated by LCLM	NCRWQCB, 2010
Nitrate-N	Concentration estimated by LCLM	NCRWQCB, 2010
Organic-P	Derived from measured ratio of inorganic-P & total-P	NCRWQCB, 2010
Inorganic-P	Concentration estimated by LCLM	NCRWQCB, 2010
Phytoplankton	Derived biomass from chlorophyll *a*	Standard Method 100200(I)(1)
Particulate Organic Matter	Derived from total organic carbon concentration estimated by LCLM. Assumed same particulate fraction of carbon as measured for phosphorus.	NCRWQCB, 2010
Inorganic Solids	Derived from median value of measured conductivity data that was used for model calibration	1) Butkus, 2011: [Inorg Solids] = [TDS] – [DOC] 2) Chapra, 1997: TDS = 0.64 * Conductivity 3) NCRWQCB, 2008: Mean Measured Conductivity

Table 4. State Variable Data Used in the Lake Jonive Model

Constituent	Units	Upstream Concentration	Local Drainage Concentration
Temperature	ºC	15.3 - 18.3	15.1
Dissolved Oxygen	mg/L	9.2 - 9.9	9.7
pH	standard units	8.0 - 8.2	8.3
Conductivity	µmhos	621	621
Alkalinity	mg $CaCO_3$/L	202	202
$CBOD_u$ slow	mgO_2/L	0.34	0.37
$CBOD_u$ fast	mgO_2/L	1.14	1.21
Organic-N	µgN/L	167	174
Ammonium-N	µgN/L	108	114
Nitrate-N	µgN/L	433	478
Organic-P	µgP/L	114	132
Inorganic-P	µgP/L	262	298
Phytoplankton	µg/L	26.9	26.9
Particulate Organic Matter	mg/L	1.84	2.06
Inorganic Solids	mg/L	393.8	394.1

Table 5. State Variable Data Used in the Santa Rosa Creek Model

Constituent	Units	Upstream Concentration	Local Drainage Concentration
Temperature	ºC	13.9 - 16.3	15.1
Dissolved Oxygen	mg/L	9.4 - 10.0	9.7
pH	standard units	8.3 - 8.4	8.3
Conductivity	µmhos	650	650
Alkalinity	mg $CaCO_3$/L	150	150
$CBOD_u$ slow	mgO_2/L	0.26	0.42
$CBOD_u$ fast	mgO_2/L	0.90	1.21
Organic-N	µgN/L	150	145
Ammonium-N	µgN/L	77	145
Nitrate-N	µgN/L	516	367
Organic-P	µgP/L	52	177
Inorganic-P	µgP/L	127	337
Phytoplankton	µg/L	0.5	0.5
Particulate Organic Matter	mg/L	1.19	2.30
Inorganic Solids	mg/L	413.1	411.6

FIGURES

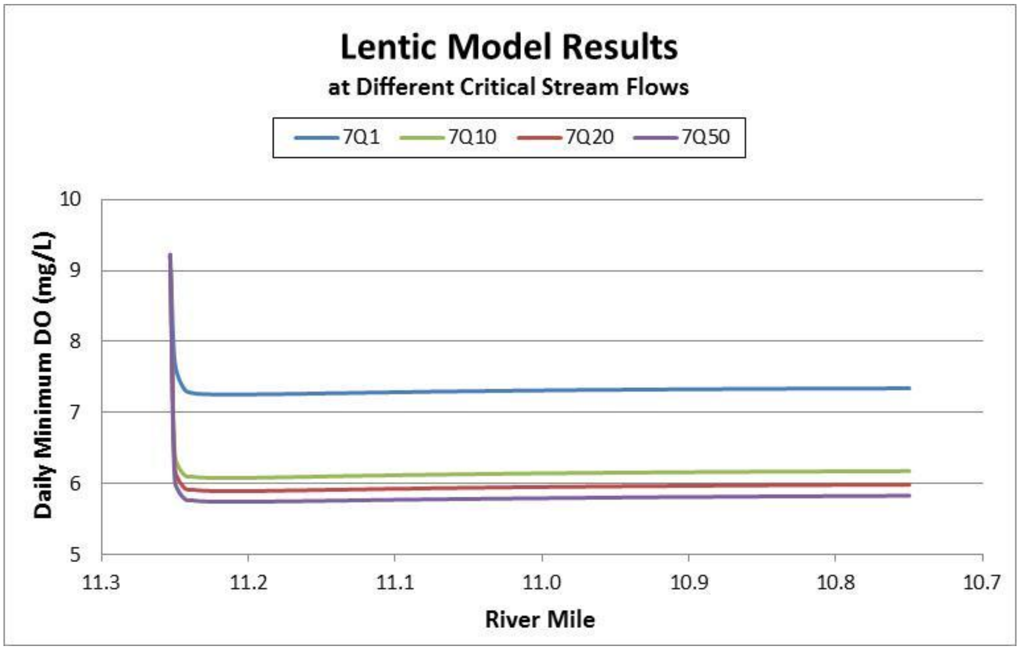

Figure 1. Lentic Model Results for Daily Minimum Dissolved Oxygen Concentrations at Different Critical Low Stream Flows by River Mile

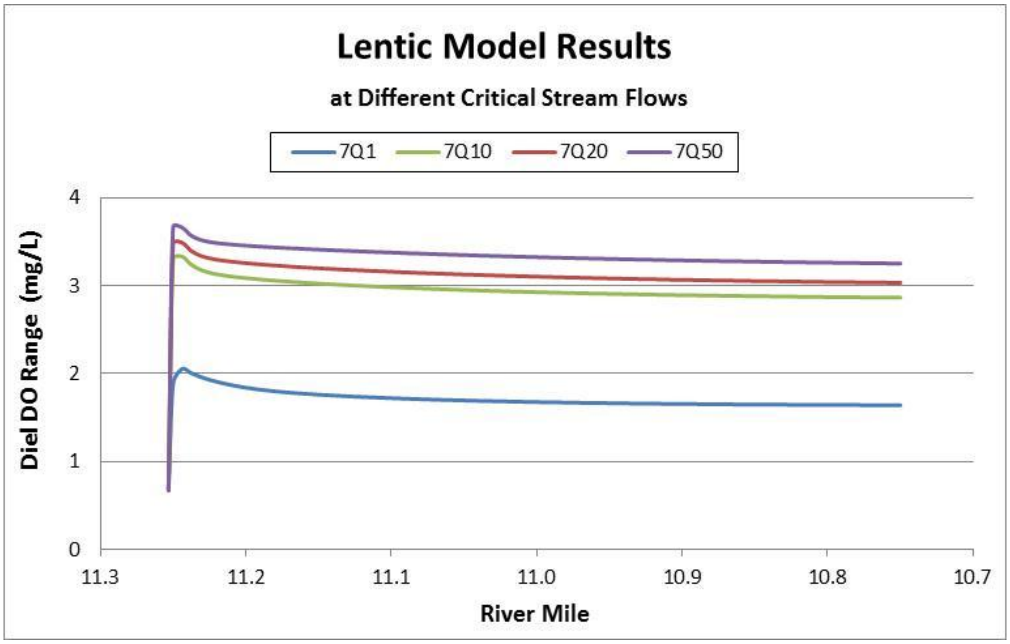

Figure 2. Lentic Model Results for the Diel Range of Dissolved Oxygen Concentrations at Different Critical Low Stream Flows by River Mile

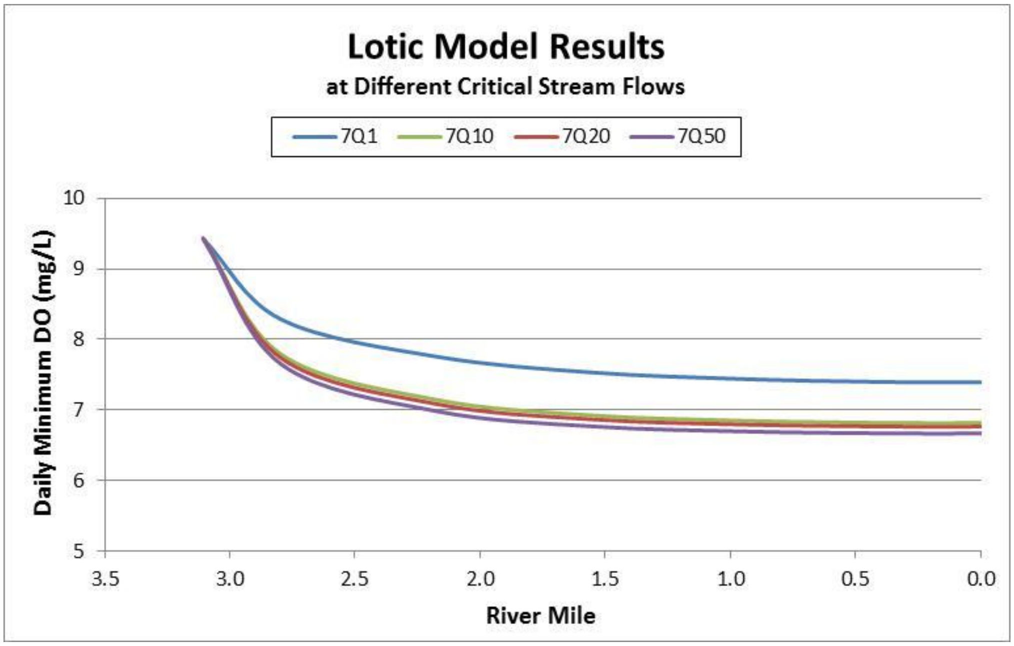

Figure 3. Lotic Model Results for Daily Minimum Dissolved Oxygen at Different Critical Low Stream Flows by River Mile

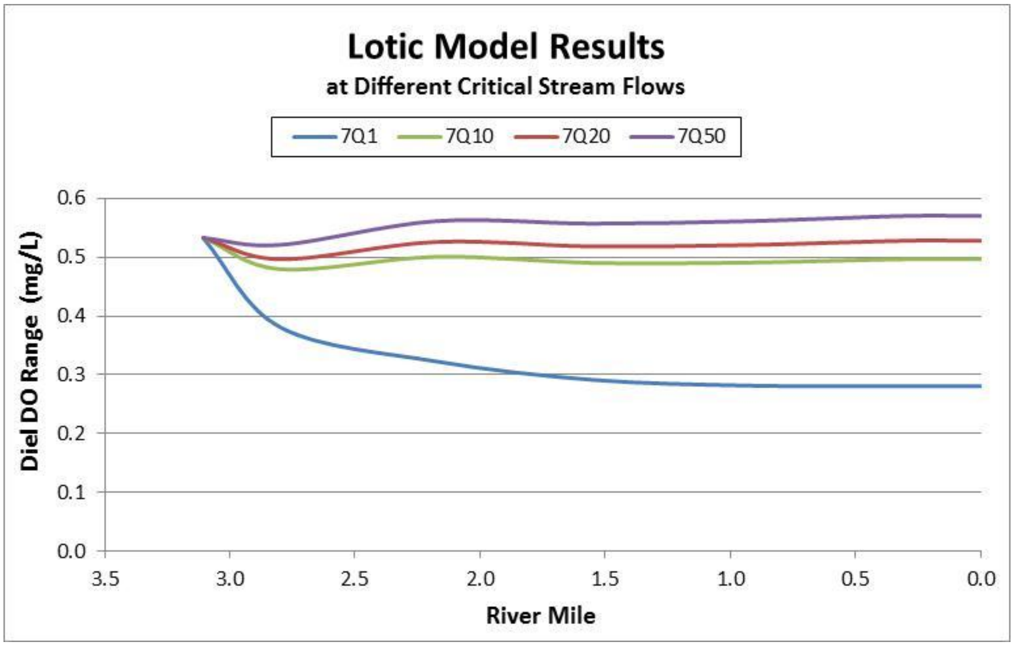

Figure 4. Lotic Model Results for the Diel Range of Dissolved Oxygen Concentrations at Different Critical Low Stream Flows by River Mile

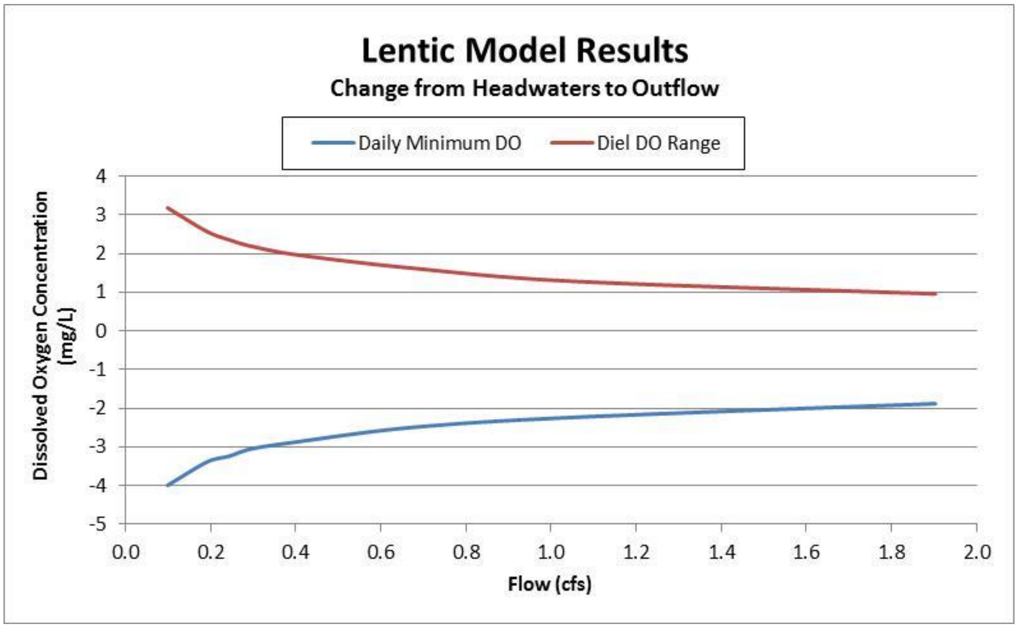

Figure 5. Lentic Model Results for the Change in Daily Minimum and the Diel Range of Dissolved Oxygen Concentration from the Headwaters to the Outflow

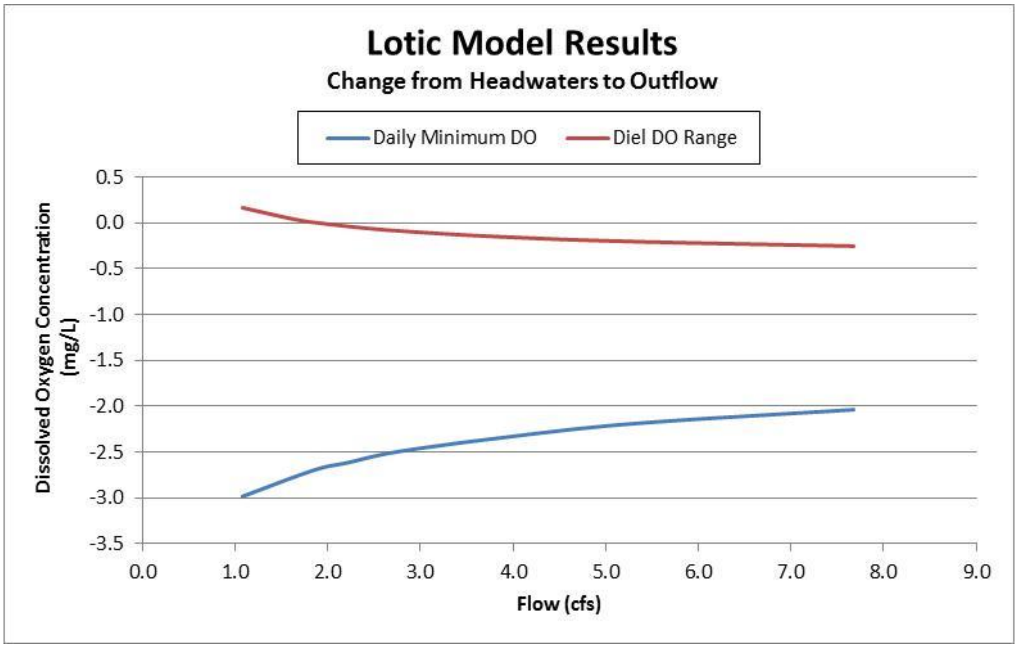

Figure 6. Lotic Model Results for the Change in Daily Minimum and the Diel Range of Dissolved Oxygen Concentration from the Headwaters to the Outflow

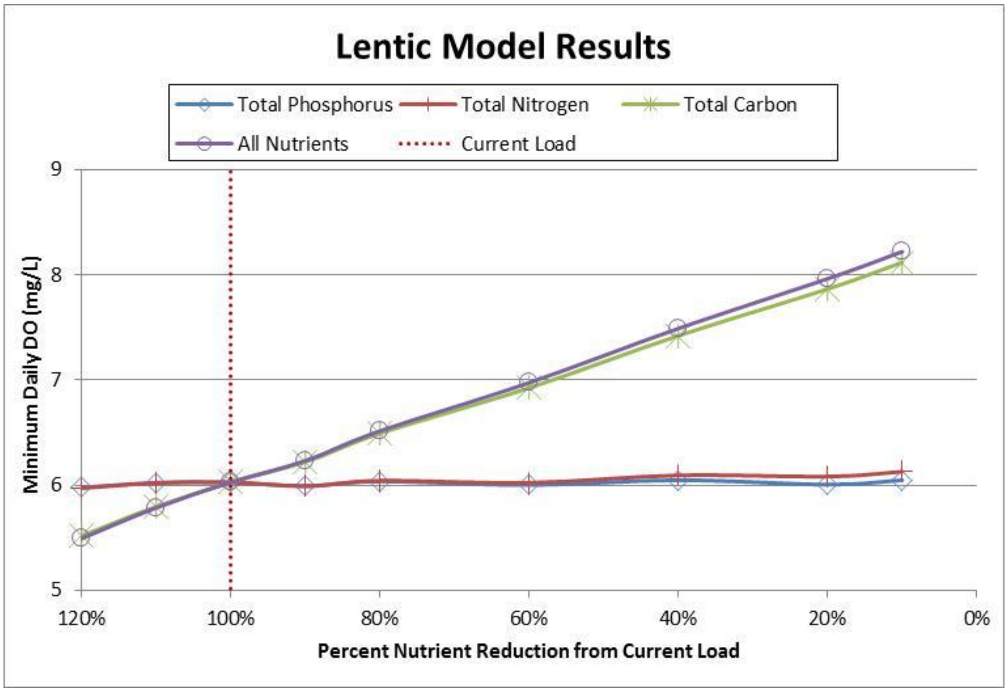

Figure 7. Lake Jonive Model Results for Daily Minimum Dissolved Oxygen Concentrations at Different Percent Nutrient Loads

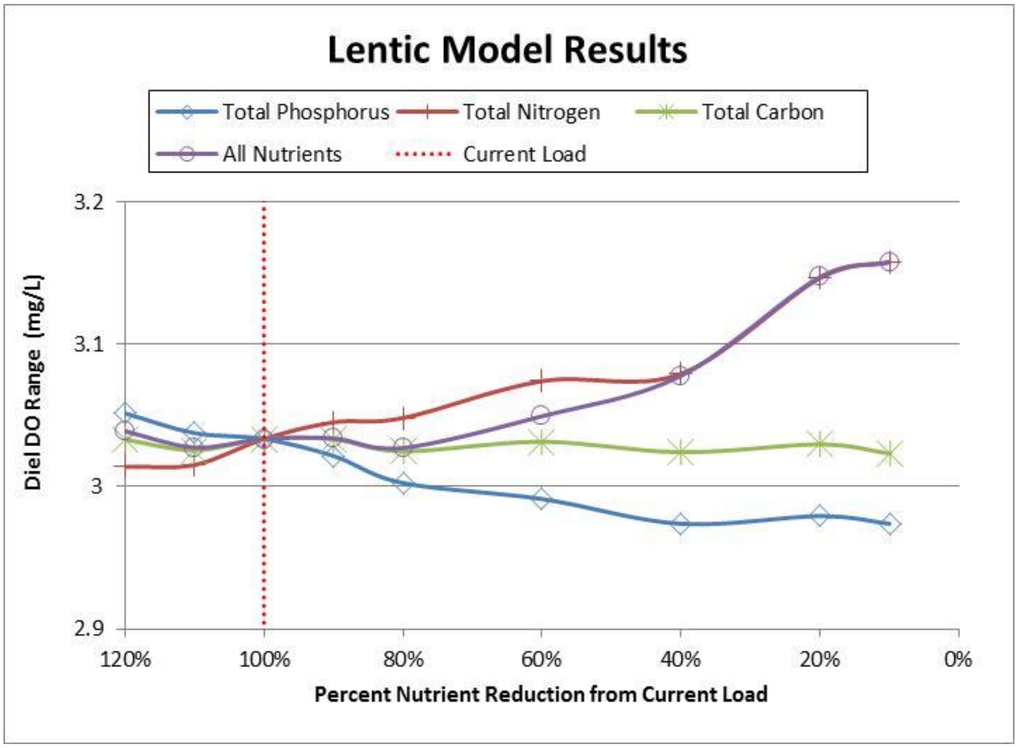

Figure 8. Lake Jonive Model Results for the Diel Range of Dissolved Oxygen Concentrations at Different Percent Nutrient Loads

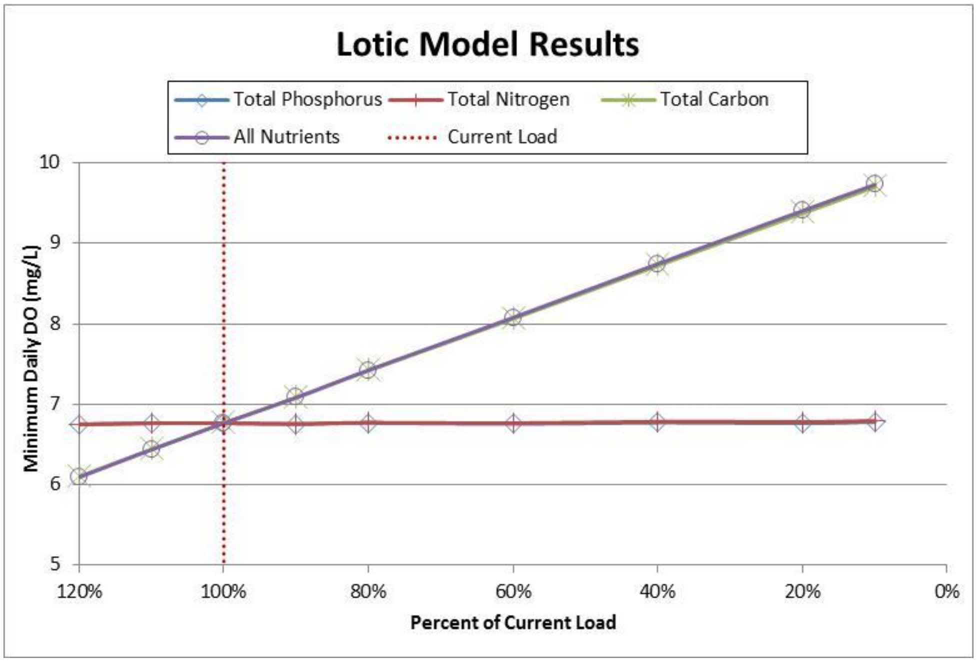

Figure 9. Lotic Model Results for Daily Minimum Dissolved Oxygen Concentrations at Different Percent Nutrient Loads

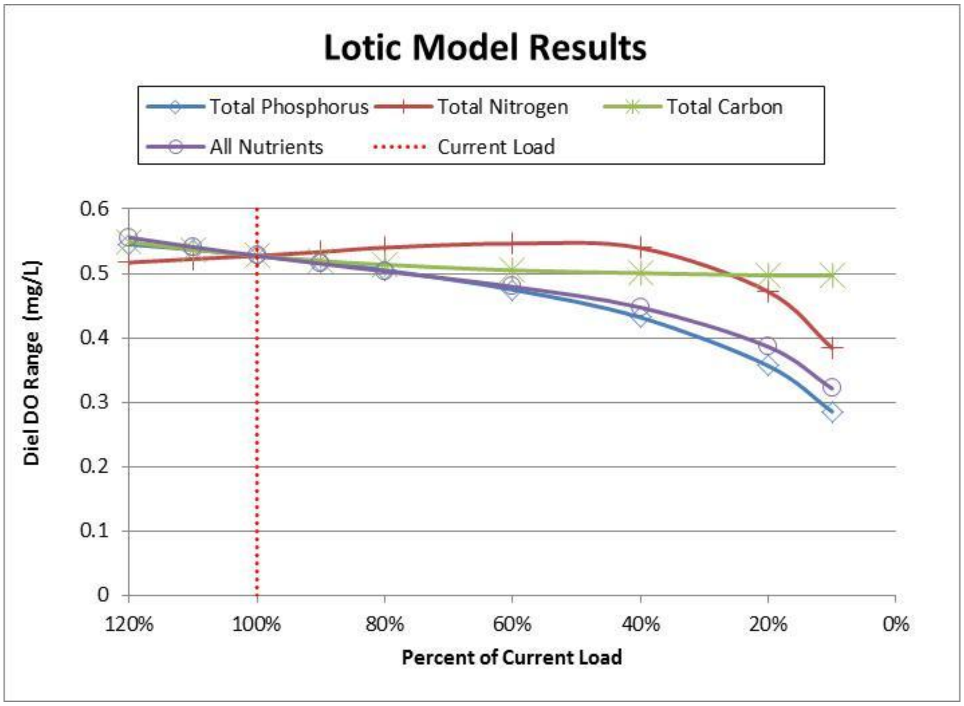

Figure 10. Lotic Model Results for the Diel Range of Dissolved Oxygen Concentrations at Different Percent Nutrient Loads

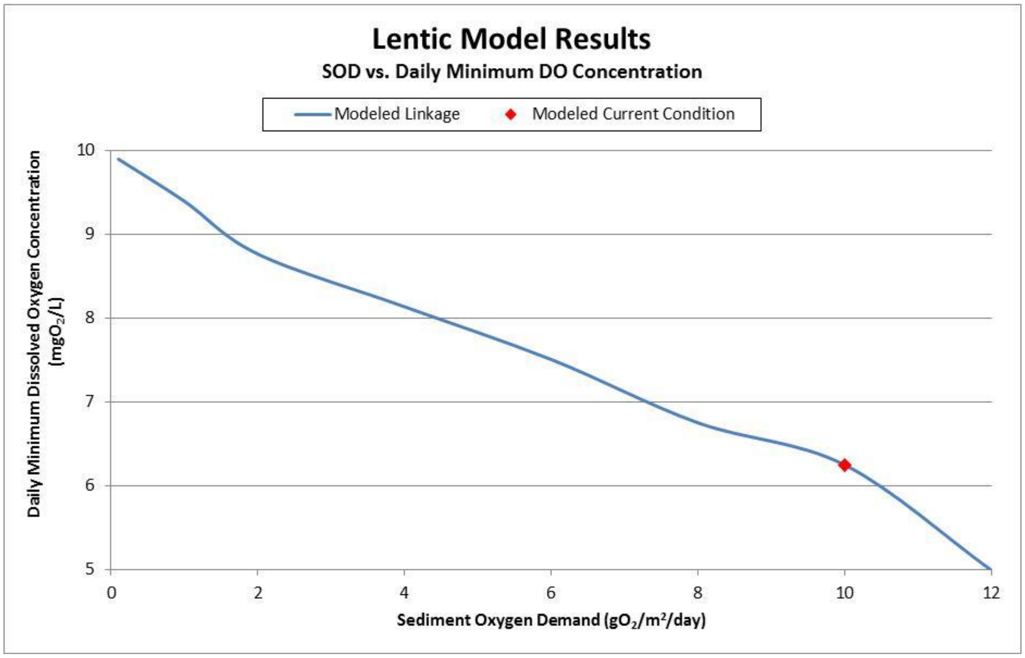

Figure 11. Lentic Model Results showing the Linkage between Sediment Oxygen Demand and the Daily Minimum Dissolved Oxygen Concentrations.

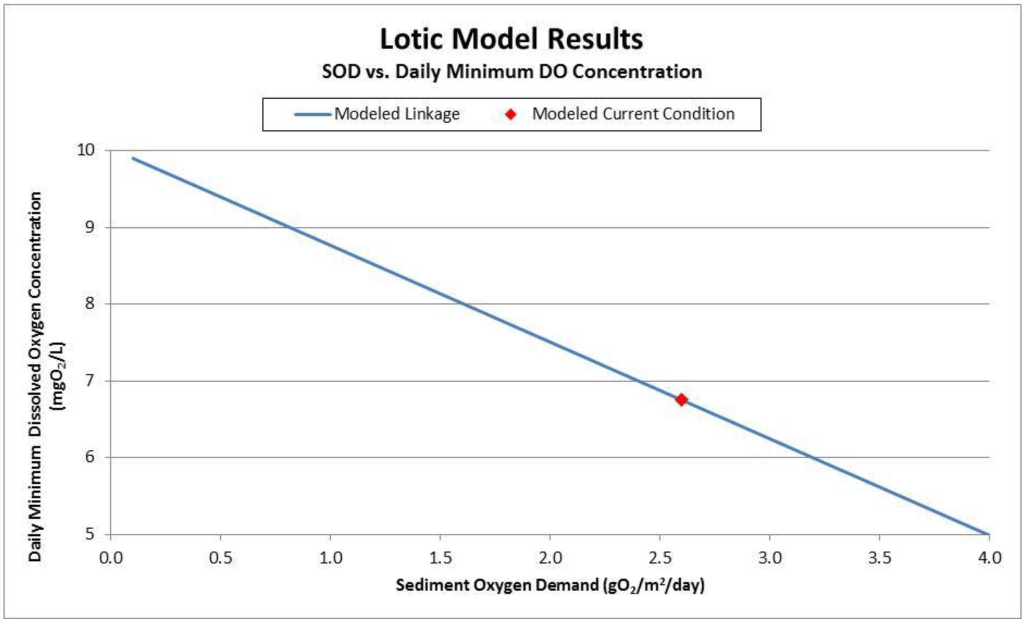

Figure 12. Lotic Model Results showing the Linkage between Sediment Oxygen Demand and the Daily Minimum Dissolved Oxygen Concentrations.

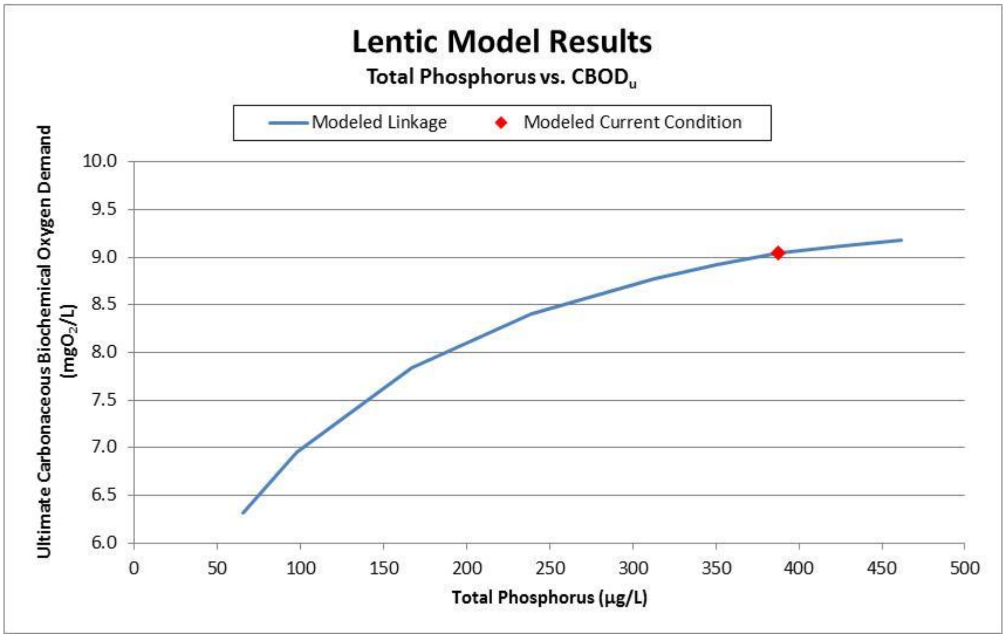

Figure 13. Lentic Model Results showing the Linkage between Total Phosphorus and Ultimate Carbonaceous Biochemical Oxygen Demand.

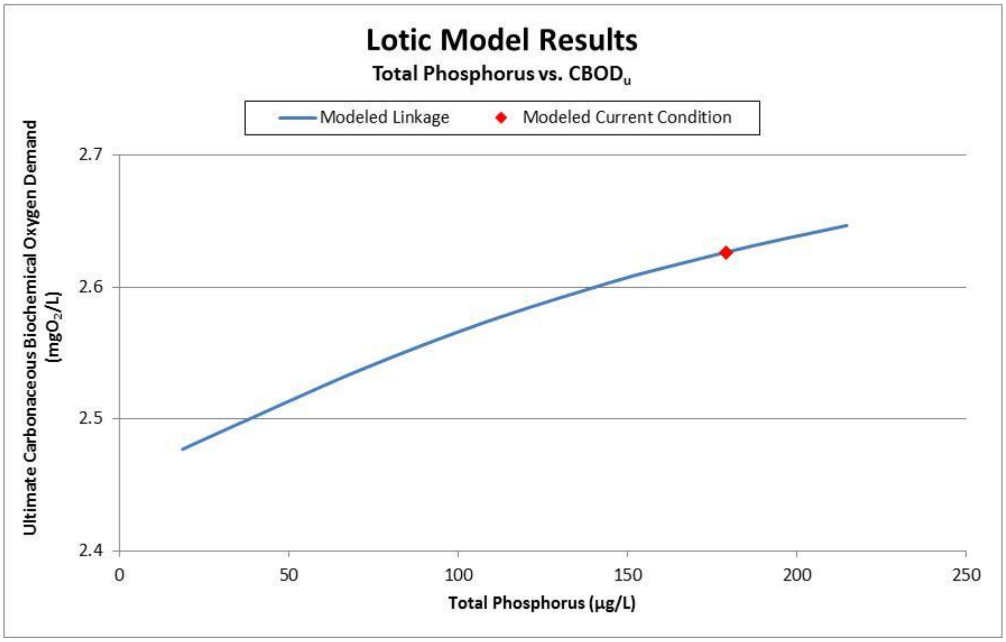

Figure 14. Lotic Model Results showing the Linkage between Total Phosphorus concentration and Ultimate Carbonaceous Biochemical Oxygen Demand.

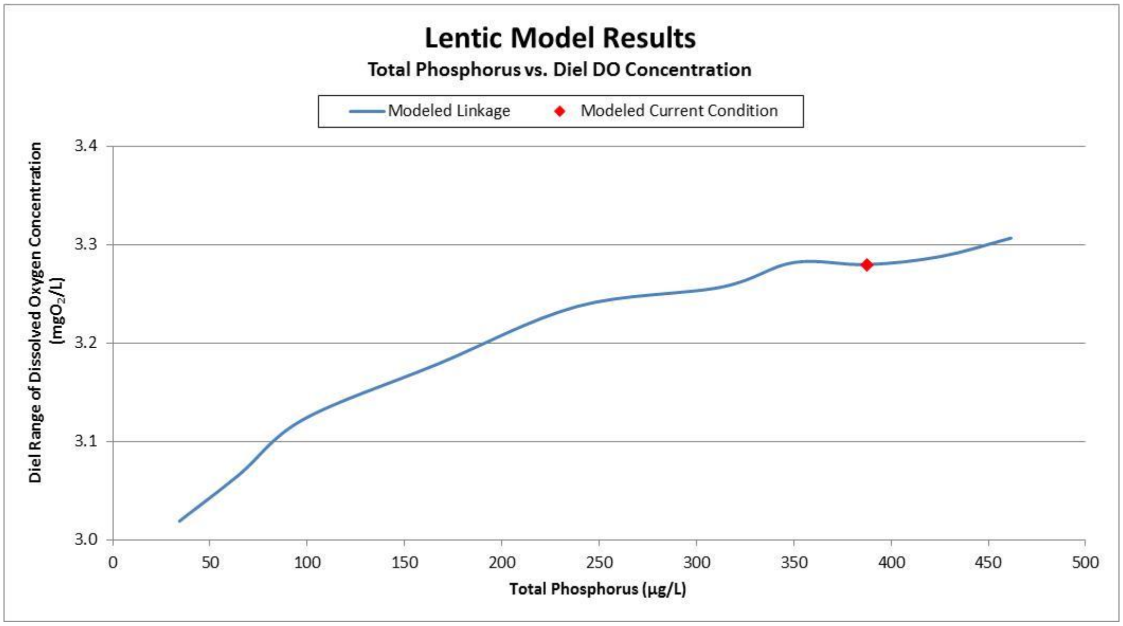

Figure 15. Lentic Model Results showing the Linkage between Total Phosphorus Concentration and the Diel Range of Dissolved Oxygen Concentration.

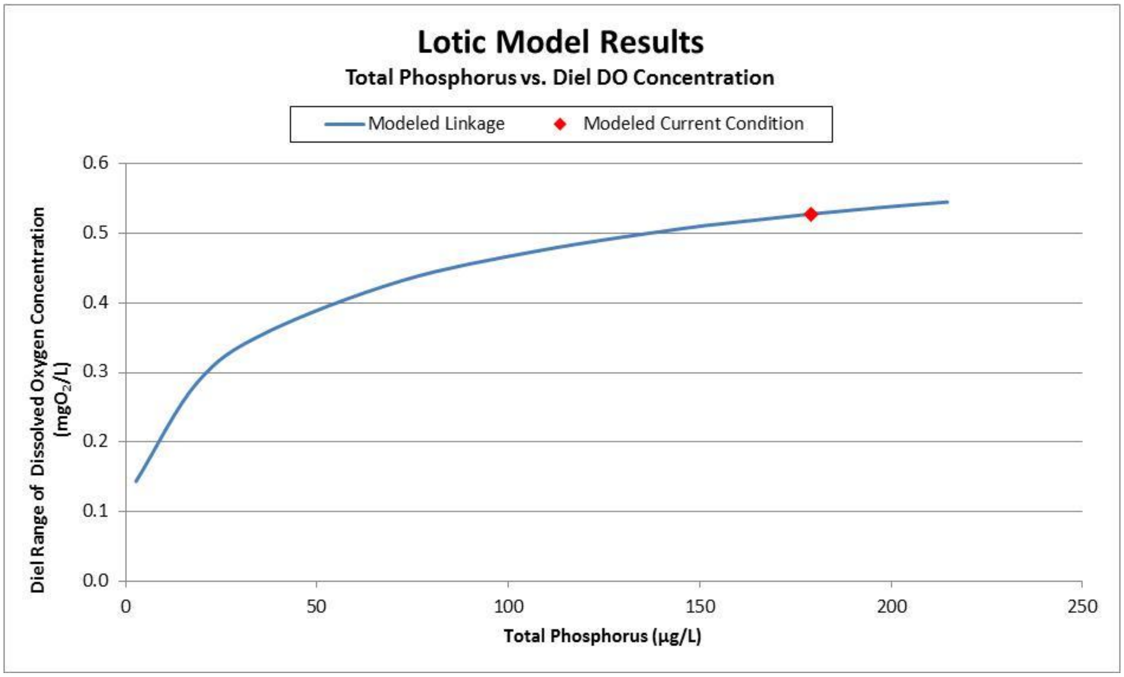

Figure 16. Lotic Model Results showing the Linkage between Total Phosphorus Concentration and the Diel Range of Dissolved Oxygen Concentration and.

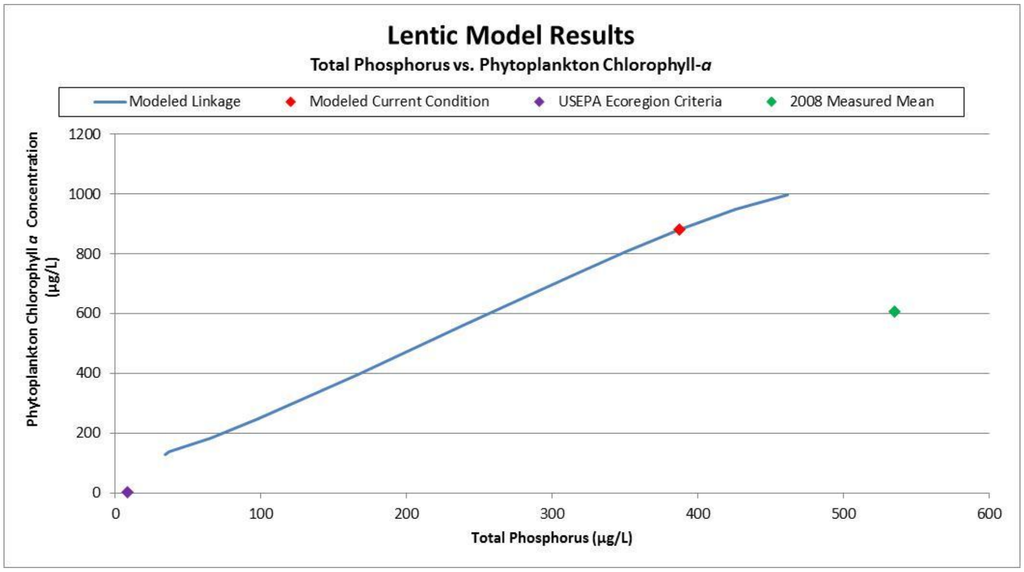

Figure 17. Lentic Model Results showing the Linkage between Total Phosphorus and Phytoplankton Chlorophyll-*a* Concentration.

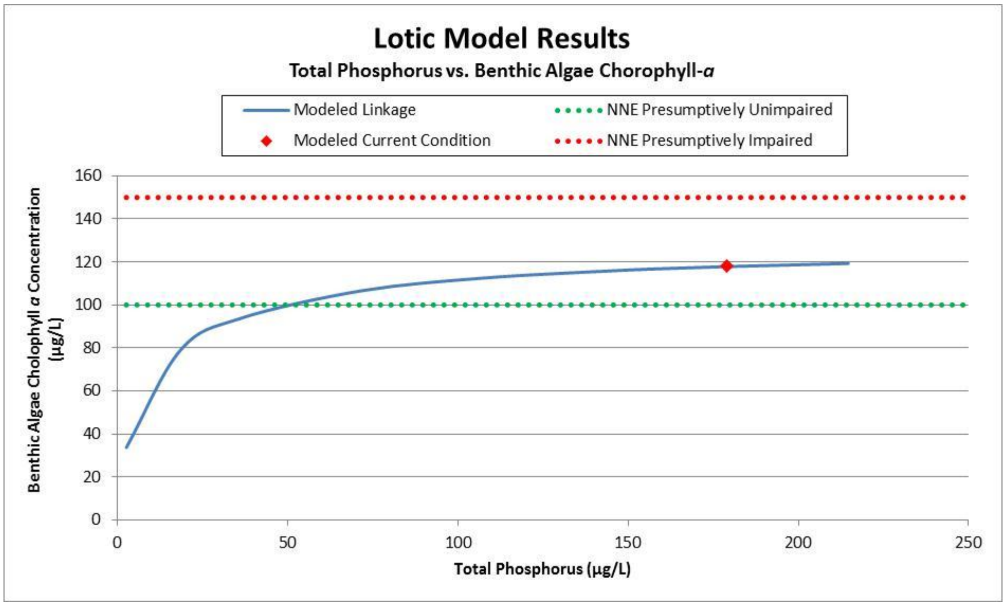

Figure 18. Lotic Model Results showing the Linkage between Total Phosphorus and Benthic Algal Chlorophyll-*a* Concentration.