Technical Memorandum

Procedures and Methodologies for the Sensitivity and Uncertainty Analyses for Illinois River Watershed and Tenkiller Ferry Lake, Oklahoma

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INTRODUCTION

This document describes the model sensitivity analysis and uncertainty analysis performed for Illinois River Watershed HSPF model and Tenkiller Ferry Lake EFDC model. The sensitivity analysis provides the changes in model outputs in response to changes in values of input parameters. The uncertainty analysis evaluates and quantified the uncertainty in model predictions.

ILLINOIS RIVER WATERSHED ANALYSIS

When a natural system (e.g., a watershed) is modeled mathematically or physically, some degree of uncertainty is always present (Morgan and Henrion, 1990). The primary reason for this uncertainty is that the models represent only an approximation of reality, i.e., the real watershed systems that exist in the nature. The U.S. EPA (1999) noted that the model predictions cannot be any better than the accuracy of the observed data and the calibration and validation results, and therefore will always have some uncertainty associated with the output. Uncertainty analysis is a procedure to determine the confidence limits or reliability of model predictions with respect to the errors associated with observations and a model. Quantifying the uncertainty in modeling results is important to stakeholders and decision makers to have more information about the probability of achieving watershed management objectives. Stakeholders and decision makers can use the information about uncertainty in establishing a more accurate Margin of Safety (MOS) for the practices and procedures needed to achieve the watershed management objectives (Mishra et al., 2011).

Estimation of uncertainty requires the prior assessment of the model parameters and inputs to which the model is sensitive, to identify the primary parameters/inputs of concern, due to their critical impacts on watershed response and behavior. A sensitivity analysis is typically conducted to better understand how adjustments to the model parameters affect results. Sensitivity runs provide useful information regarding the physical, chemical and biological processes represented in a model and identify the most influential parameters and inputs for improving model accuracy. This type of analysis provides insight into forcing factors in models and how adjustments made will affect results, both for historical conditions and potential management scenarios. A sensitivity analysis is usually conducted independent of uncertainty analysis, but often as a precursor as noted above.

A sensitivity analysis measures the variability of model outputs caused by perturbations in model parameter values and input data, i.e., how sensitive is the model to changes in the input forcing functions (e.g., precipitation) and parameters that describe its characteristics. Informal sensitivity analyses (iterative parameter adjustments) are generally performed during model calibration to ensure that reasonable values for model parameters will be obtained, resulting in acceptable model results. The degree of allowable adjustment of any parameter is usually directly proportional to the uncertainty of its value and is limited to its expected range of values. Knowledge about the model sensitivity to the model parameters and inputs can help direct model parameter selection for additional investigation, support data collection planning efforts, aid in model calibration, and ultimately serve as a precursor for the uncertainty analysis.

This Technical Memorandum presents the procedures used in the sensitivity and uncertainty analyses performed for the Illinois River Watershed Model, along with the results of those analyses. For the sensitivity analyses, a sensitivity factor was calculated as the ratio of the percent change in model output to the percent change in input/parameter value, expressed as a percentage. These sensitivity factors allowed a ranking of the input and parameters in terms of the highest to lowest impacts on model outputs. This ranking provided the means for selecting the most sensitive inputs and parameters for the subsequent uncertainty analyses. The uncertainty analyses were conducted with a Monte Carlo procedure whereby the most sensitive parameters were assigned probability distributions, random values were drawn from these distributions, the model was run for each parameter selection combination, 1000 model runs were performed, and the model results were analyzed to produce the outputs with 90% confidence bounds reflecting and quantifying the model uncertainty for each output variable of interest.

WATERSHED MODEL SENSITIVITY ANALYSIS

For the Illinois River Watershed (IRW) modeling effort, a methodology adapted from Donigian and Love (2007) was used to conduct a sensitivity analysis (SA), followed by uncertainty analysis (UA). These steps were performed following the completion of the calibration and validation of the IRW model (based on the EPA HSPF model) so that the results of the SA were focused on model performance when it is providing a reasonable representation of the watershed behavior and response. The steps for SA are described in detail below, and depicted in the flowchart in Figure 1.

1. Critical model inputs and parameters were identified based on prior experience, literature review, and the specific calibration experience for the IRW. Table 1 lists the selected model inputs and parameters, their definitions, and relevant values from the calibration and SA perturbations.
2. Reasonable percent perturbations of model parameters and inputs from the calibrated values in both positive and negative directions were established based on the same experience/sources as noted above in #1.
3. Critical model output values of concern, at the sites within the Illinois River watershed, were identified to provide the targets, or metrics, for the sensitivity analysis. These analysis sites were limited to the AR/OK Stateline (Reach 630) and the Illinois River at Tahlequah (above Lake Tenkiller) (Reach 870). For both hydrology and water quality (including sediment), the metrics were selected from those assessed as part of the 'weight-of-evidence' approach to model calibration, and included annual runoff volume, highest 10% flows, lowest 25% flows, annual and daily sediment (TSS) loads and concentrations, and water quality (TN and TP) loads and concentrations (see Table 2 for a list of the model outputs analyzed).
4. Model simulations for a 10-year period (2000-2009), which included the calibration period (2001- 2009), were performed as a baseline run for the sensitivity analyses.
5. Using existing BASINS capabilities, the model parameters and inputs were changed in the IRW model with a one-at-a-time (OAT approach) according to the perturbation ranges identified in Step 2 (above). For every change in model inputs/parameters, HSPF simulations of IRW model were conducted, and the model outputs were processed to obtain the critical output values (metrics) identified in Step 3. These output values were saved in simple text files.

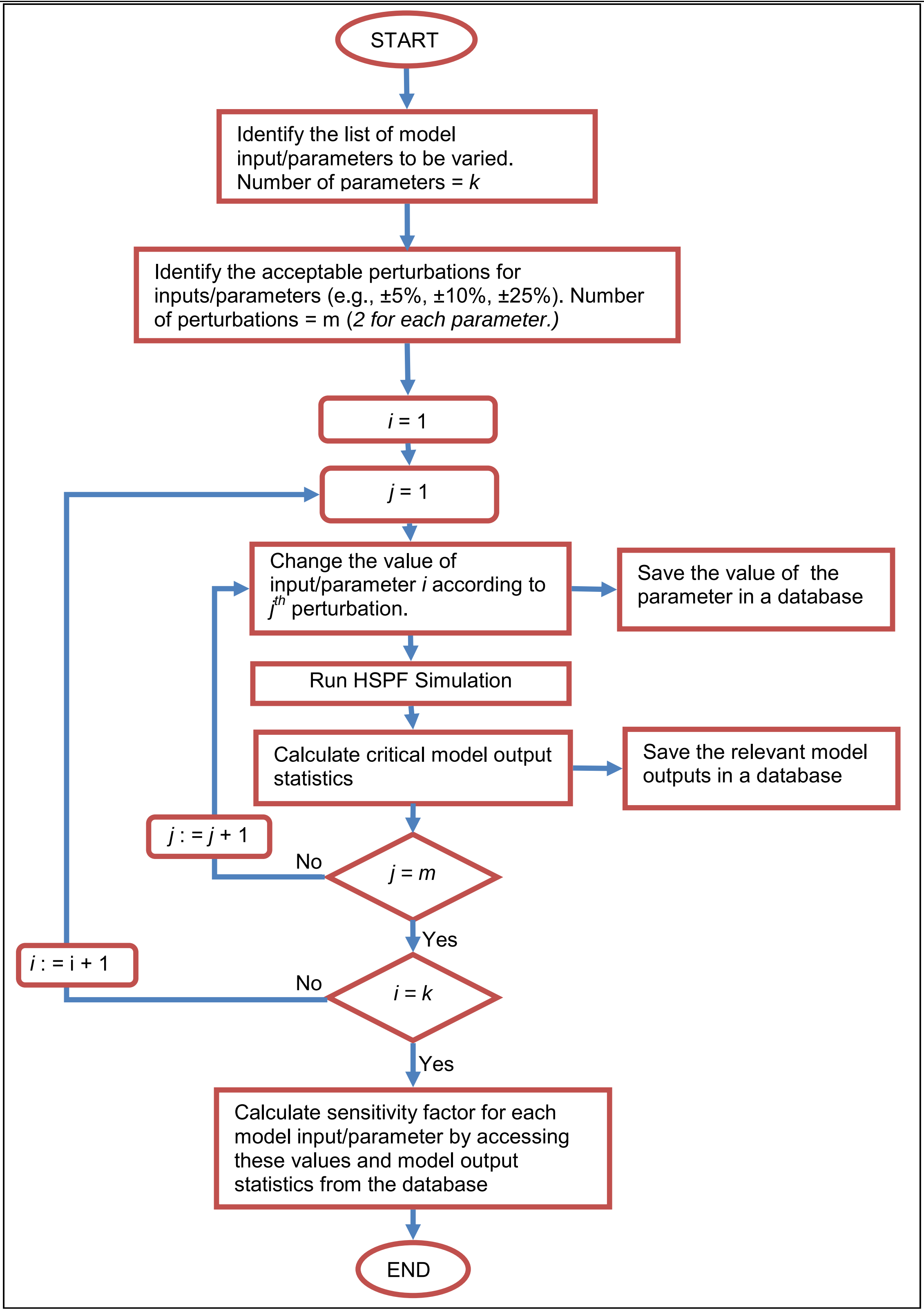

Figure 1. Steps for Conducting a Sensitivity Analysis

Table 1. List of HSPF parameters that were adjusted to assess model sensitivity for the IRW Model

			Calibration Value			%Change to the Calibrated Value		Parameter Value Range	
Category	**Model Input Parameter**	**Input/Parameter Definition**	**Weighted Mean**	**Min**	**Max**	**Decrease**	**Increase**	**Decrease**	**Increase**
Meteorologic Timeseries	Mean Precipitation, in/yr	Mean Annual Precipitation	43.6	30.3	56.9	85	115	25.7	65.4
	Mean Daily Air Temperature, F	Mean Daily Air Temperature	59.1	9.5	94.8	90	110	8.6	104.3
	Total Daily Solar Radiation, ly/day	Total Daily Solar Radiation	412.6	12.3	754.5	85	115	10.5	867.7
Hydrology	LZSN, in	Lower Zone Nominal Soil Moisture Storage	7	4	8.5	75	125	3.00	10.6
	INFILT, in/hr	Index to Infiltration Capacity of the Soil	0.097	0.035	0.3	50	150	0.02	0.45
	INTFW	Interflow Inflow Parameter	1.93	1	3.5	70	130	0.70	4.55
	LZETP	Lower Zone Evapotranspiration	0.395	0.1	0.75	75	125	0.08	0.94
	DEEPFR	Fraction of Groundwater Inflow to Deep Losses	0.19	0.03	0.35	50	150	0.02	0.53
	UZSN, in	Upper Zone Nominal Soil Moisture Storage	1.055	0.5	2	50	150	0.25	3.00
Sediment	KSER	Coefficient in Sediment Washoff Equation	0.245	0.04	1	50	150	0.02	1.50
	KRER	Coefficient in Soil Detachment Equation	0.313	0.109	0.452	50	150	0.05	0.68
	COVER*	Fraction of Land Protected From Raindrop Splash	0.83	0.6	0.97	75	125	0.45	1.00
	TAUCD, lb/ft2**	Critical Bed Shear Stress for Deposition	0.21	0.012	0.65	50	150	0.01	0.98
	TAUCS, lb/ft2**	Critical Bed Shear Stress for Scour	0.51	0.07	1.26	50	150	0.04	1.89
	M, lb/ft2.d	Bed/Bank Erodibility Factor	0.28	0.001	1	50	150	0.00	1.50
	KSAND	Coefficient in Sandload Equation	0.55	0.09	1.5	50	150	0.05	2.25
Water Temperature	CFSAEX*	Correction Factor for Solar Radiation on Water Surface	0.53	0.25	0.95	70	130	0.18	1.00
	LGTP1, degrees F	Lower Layer/Groundwater Soil Temperature	53.1	39	65	75	125	29.3	81.3
	KATRAD	Longwave Radiation Coefficient	15	15	15	75	125	11.3	18.8
	MUDDEP	Depth of Mud Layer in the Two Interface Model	1	1	1	75	125	0.75	1.25
	KMUD	Heat Conduction Coefficient Between Water and the Mud/Ground	30	30	30	75	125	22.50	37.5
	TGRND	Temperature of ground beneath stream bed	56.2	48	65	75	125	36	81.3
Water Quality Loadings (applies to BOD/Organics, NO3, NH4, PO4)	Loading of pollutants from Urban areas					50	150		
	Loading of pollutants from non-litter pasture land uses					50	150		
	Loading of pollutants from all litter pasture land uses					50	150		
	Loading of pollutants from point sources					50	120		

*These parameters were limited to the maximum value of 1. ** These parameters were changed jointly by the same percentage since they are correlated.

6. Following the completion of all the simulations (i.e., 63 simulations, including one for baseline and 62 for input/parameter changes), the sensitivity factor was calculated as the ratio of percent change in model output to the percent change in input/parameter value, expressed as a percentage.
7. Model input and parameters were ranked according to the value of the sensitivity factor (Table 3).

A sensitivity factor of 100% indicates that the model output changes in direct proportion, *i.e.,* one to one, to the change of the parameter value; whereas, a value of 200% indicates a 2:1 response, and a 10% indicates a relatively insensitive 0.1:1 response (i.e., a 10% change produces only a 1% change in model output). The results were graphically depicted in a "tornado diagram" for each model output (e.g. Figure 2 and Figure 3) for display and ease of interpretation. Table 3 lists the sensitivity factors for different outputs of interest at RCH 870, to the inputs/parameters. The sensitivity factors at RCH630 were very close to the sensitivity factors at RCH870. The table lists only the results where the sensitivity was greater than 20%. A complete set of tornado diagrams are presented in Appendix A for Reach 870 (Tahlequah) and Appendix B for Reach 630 (AR/OK Stateline).

Table 2. List of outputs of interest at RCH630 and RCH870 in Illinois River Watershed Model

Hydrology	**Water Quality**
Mean Annual Flow (cfs)	Mean Daily TSS Load (tons/day)
Annual Peak Daily Flow (cfs)	Mean TSS Conc. (mg/l)
Mean Annual Runoff (in)	Geom. Mean TSS Conc. (mg/l)
10% High Runoff Volume (in)	10% High TSS Conc. (mg/l)
25% High Runoff Volume (in)	50% Low TSS Conc. (mg/l)
50% High Runoff Volume (in)	Mean Daily TP Load (lbs/day)
50% Low Runoff Volume (in)	10% High TP Conc. (mg/l)
25% Low Runoff Volume (in)	50% Low TP Conc. (mg/l)
10% Low Runoff Volume (in)	Mean Daily TN Load (lbs/day)
5% Low Runoff Volume (in)	10% High TN Conc. (mg/l)
2% Low Runoff Volume (in)	50% Low TN Conc. (mg/l)
	Geom. Mean TP Conc. (mg/l)
	Mean Ann. TP Load (lbs/yr)
	Geom. Mean TN Conc. (mg/l)
	Mean TN Conc. (mg/l)
	Mean TP Conc. (mg/l)
	Mean Annual TN Load (lbs/yr)
	Mean Water Temp. (F)
	Mean Summer Water Temp. (F)

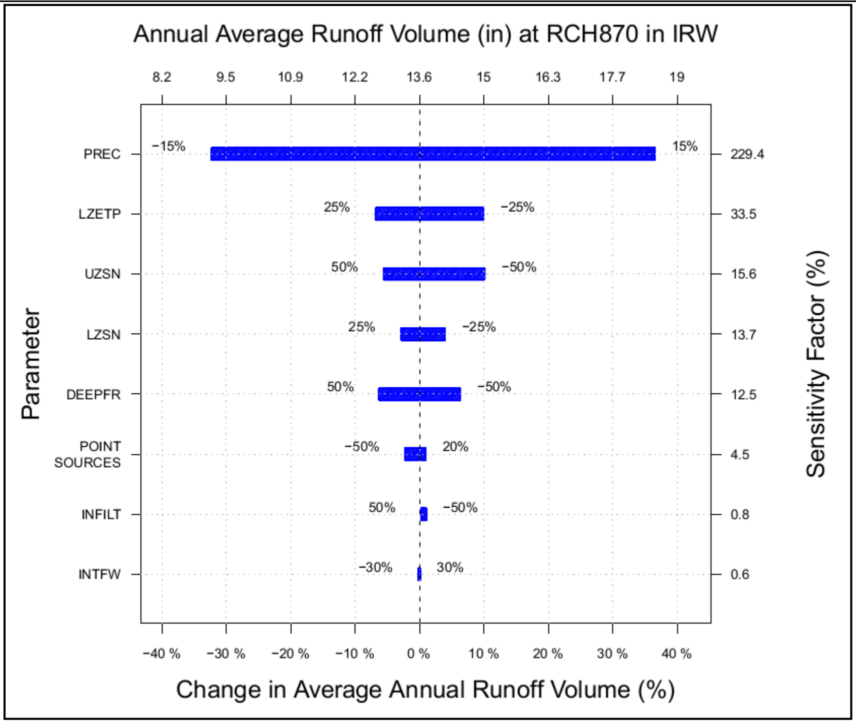

Figure 2. Tornado Diagram of parameter sensitivity for annual average runoff volume at RCH 870 (y-axis is not to scale)

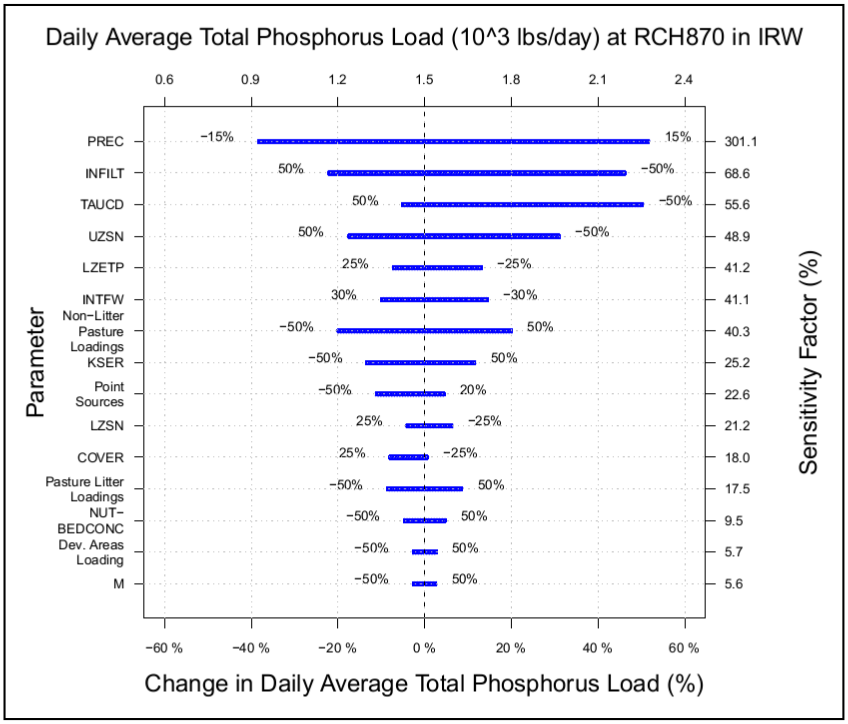

Figure 3. Tornado Diagram of parameter sensitivity for daily Total Phosphorus loading at RCH 870 (y-axis is not to scale).

Table 3. Sensitivity factors for hydrology and water quality outputs of interest for selected parameters (only factors greater than 20% are shown)

Hydrology Outputs

Inputs/ Parameters	Mean Annual runoff(in)	Annual Peak Flow (cfs)	Mean Annual (cfs)	10% High (in)	25% High (in)	50% High (in)	50% Low (in)	25% Low (in)	10% Low (in)
INFILT		53.8		25.4			26.7	27.2	24.0
INTFW		26.7							
LZETP	33.5	24.7	33.5	29.9	30.2	30.9	47.5	60.2	67.0
LZSN		26.2							
Point Sources									25.7
PREC	229.4	276.2	229.4	265.0	251.1	239.1	178.0	172.2	153.3
UZSN		29.3		26.9	21.7				

Water Quality Outputs

	Mean TSS Conc.(mg/l)	Geom. Mean TSS Conc. (mg/l)	Mean Daily TSS Load (tons/day)	Mean TN Conc. (mg/l)	Geom. Mean TN Conc. (mg/l)	Mean Daily TN Load (lbs/day)	Mean TP Conc. (mg/l)	Geom. Mean TP Conc. (mg/l)	Mean Daily TP Load (lbs/day)	Mean Water Temp. (F)	Mean Summer Water Temp. (F)
ATEMP										24.1	24.8
COVER	43.0		49.5								
INFILT	69.1		100.9				34.8	31.8	68.6		
INTFW	54.2		60.1						41.1		
KSAND		65.4									
KSER	58.2		66.6						25.2		
LGTP1				26.1	29.5						
LZETP	26.8	25.5	52.2			31.6			41.2		
LZSN			33.3			31.5			21.2		
Non-Litter Pasture Loadings				35.4	35.6	46.9			40.3		
Point Sources							61.9	61.9	22.6		
PREC	247.3	164.4	513.6	39.9	43.2	204.1	65.3	66.3	301.1		
TAUCS/TAUCD	350.9	566.5	158.6				31.0	26.2	55.6		
TGRND										42.5	37.7
UZSN	40.2		69.9			22.6			48.9		

WATERSHED MODEL SENSITIVITY ANALYSIS CONCLUSIONS

Review of the SA results summarized in Table 3, along with the tornado diagrams provided in Appendices A and B support the following conclusions:

a. As might be expected, the precipitation regime clearly dominates the SA results shown in Table 3 and the Appendices, compared to all the other inputs and parameters included in the SA, with Sensitivity Factors (SF) mostly in the range of 150% to over 250% for hydrology model outputs. The only cases when the precipitation sensitivity factor is less than 100% is for TN and TP concentration outputs, and this occurs because the precipitation perturbations impact both the load (i.e., numerator) and the flow (i.e., denominator) of the concentration calculation.
b. The only other parameters that come remotely close to the sensitivity of the model to precipitation are the instream shear stress scour and deposition thresholds (TAUCS, TAUCD), which control the degree of scour and deposition in the channel. TSS load and concentration are extremely sensitive to these parameters with SF values from 150% to over 500%.
c. Other than precipitation, the mean annual runoff volume was sensitive to LZETP due to its impact on the evapotranspiration component of the water balance; this is especially true during low flow conditions, e.g., 50% low, 25% low an10% low.
d. Peak flow rates are sensitive to many more parameters, as shown in Table 3, with the greatest sensitivity after precipitation being INFILT, the infiltration index in the model.
e. Those hydrology parameters that impact the flow regime the most, e.g., precipitation, INFILT, UZSN, LZETP, also affected the sediment/TSS outputs and sediment-associated nutrients, like TP.
f. The point source loadings appeared to have the greatest impact on TP concentrations and loadings, whereas the Non-Litter Pasture loadings had the greatest impacts on the TN concentrations and loadings.

The results of the SA for the IRW model are consistent with past experience with SA in other watersheds, and they provide a sound basis for selection of parameters for the UA.

WATERSHED MODEL UNCERTAINTY ANALYSIS

The parameters and inputs demonstrating the greatest sensitivity were then selected for further investigation in the uncertainty analysis. The sensitivity factor for precipitation was the highest for almost all the outputs of interest. The inclusion of precipitation in sensitivity analysis was to demonstrate its importance in model performance. However, precipitation was not selected for uncertainty analysis as it is an input climate forcing timeseries, and its impact was included in the uncertainty analysis through the 10-year simulations using actual precipitation data. Also, including it directly in uncertainty analysis would have masked the model uncertainty for most all of the other parameters.

The uncertainty analysis involved Monte Carlo simulation of IRW model with parameters randomly drawn from their respective statistical distributions. The parameters that resulted in greater than 50% sensitivity factors in all the outputs of interest were selected for the uncertainty analysis. The exceptions to this were LZSN, and the pollutant loadings from different sources, since LZSN is a major calibration parameter and pollutant loadings are key management options for water quality improvement. Thus, both LZSN and pollutant loadings were included in the uncertainty analysis.

Each selected parameter was assigned a probability distribution. The distribution of parameter represents a modeler's expectations of the range, variability, and distribution of the parameter value in nature. For uncertainty analyses conducted with watershed models like HSPF, bounded probability distributions (both normal and lognormal) are frequently used (Donigian and Love, 2007; Mishra et al. 2011), so that the parameters are confined to physically realistic values and remain within the computational limits of the HSPF model. Some model parameters may be correlated and their correlation may be provided while sampling the parameters from their respective distributions. Correlations may be provided explicitly using a covariance matrix (Donigian and Love, 2007) or the distribution can be derived in such a way that correlation among parameters is implicit, using any of the Bayesian techniques (Mishra et al., 2011). With the limited number and range of parameter values in the HSPF model, selected for the uncertainty analysis, the correlation among parameters was judged to not be important and therefore it was ignored in this uncertainty analysis. The steps for uncertainty analysis are described in the steps below and in Figure 4.

1. The model parameters resulting in sensitivity factors greater than 50% were selected, and then supplemented (as noted above) with some other important parameters for the focus of the uncertainty analysis (see Table 4).
2. A probability distribution, and value range limits were assigned to each model parameter. The assignment of probability distribution to the model parameters is based on the specific knowledge of the parameters, processes and algorithms used in the HSPF model; calibration experience with the Illinois River watershed model, and followed practices used by Donigian and Love (2007). The parameters were assumed to be independent of each other, i.e. they had no correlation.
   The parameters that are a function of soil and/or climate were assigned a lognormal (LN) distribution and the parameters that are a function of vegetation were assigned a normal distribution. The loadings from point sources were assumed to be uniformly distributed, within a range of 50% to 120% of their mean (i.e., same range as for the SA). For the water quality loadings from alternative land use categories, we assigned multiplication factors to the calibrated loadings based on the mean and range of loadings as calculated by the calibrated model for the calibration period.

   For the uncertainty analysis, the calibrated parameter range provided the basis for the range in which approximately 90% of these parameter values are expected. Based on this 90% range, standard deviation of these parameters were calculated as the range/3.3 (i.e. ±1.65 standard deviations from the mean of the normal distributions). For the LN distributions, standard deviation and mean of the underlying normal distributions were calculated based on the range, as follows:

   $$\text{std. dev} = \ln(\text{upper bound}/\text{lower bound})/3.3, \text{ and}$$
   $$\text{mean} = \ln(\text{lower bound}) + 1.645*\text{std. dev}).$$

   To get the resulting LN distributions, the values from the normal distribution obtained with mean and standard deviation calculated above, were individually exponentiated (i.e., assigned as exponent with base e). All of the distributions calculated above were truncated at their lower and upper limits (see Table 4) to avoid breaching physically realistic values and associated computational limits of HSPF. As examples, Figures 5 and 6 show the resulting NO and LN distributions of two parameters, LZETP and INTFW.

3. Random model parameter values were drawn based on their respective distributions and range limits, using the 'pse' package (Chalom and Prado, 2014) in R (R Core Team, 2014). The 'pse' package provides the flexibility to draw samples from a distribution using a Latin Hypercube Sampling (LHS) scheme. The LHS scheme ensures that the entire parameter space is sampled efficiently.
4. In Monte Carlo simulations, the number of parameter draws should be enough to converge on an estimate of the probability distribution of the output variables (Gardner and O'Neill, 1983). This number is generally achieved by trial and error and increases with the number of parameters and their variability. Mishra et al., 2011 conducted Monte Carlo simulation with about 26 parameters and the number of simulations were 12,000. Donigian and Love (2007) performed a series of tests with the number of runs ranging from 150 to 1500, and found that a stable output distribution could be obtained with about 500-600 runs; their subsequent uncertainty analyses for about 30 parameters/inputs was based on 600 runs.
   To ensure an adequate number of simulations, we started with a set of 1000 parameter draws. We calculated various output metrics (mean, standard deviation, 5 percentile, 95 percentile, and probability density function) after the end of 50, 100, 200, 500, and 1000 simulations. There was no significant difference in output metrics after 500 and 1000 simulations for all the outputs of interest, indicating that we had conducted a sufficient number of simulations (see Figure 7). Also, In the Monte Carlo Simulation code, checks were provided to ensure that the allowed limits of parameters were never breached. These variables were COVER and CFSAEX. The maximum possible values of these parameters were limited to 1. In addition, selected parameters were varied jointly to preclude any physical unrealistic values. Thus, the TAUCD and TAUCS values for each reach were varied by the same multiplication factor to avoid physically unrealistic conditions.

5. In the IRW model, the parameters vary spatially, and therefore a single value cannot be provided to each individual parameter. Therefore, the parameter sets generated in the previous steps were normalized by dividing them with their respective mean values to generate a multiplication factor for each parameter. For each HSPF simulation, the existing parameters were multiplied by these multiplication factors.
6. In the BASINS development environment in VB.net, the UCI file for each HSPF simulation of the IRW model was re-generated using the multiplication factors for each parameter from the previous step, a model simulation was conducted, and the relevant output was saved in a text file for later processing.
7. Various statistics for the outputs of interest were calculated from all the runs, including different percentiles, uncertainty, and probability density functions (Table 5 and Table 6).

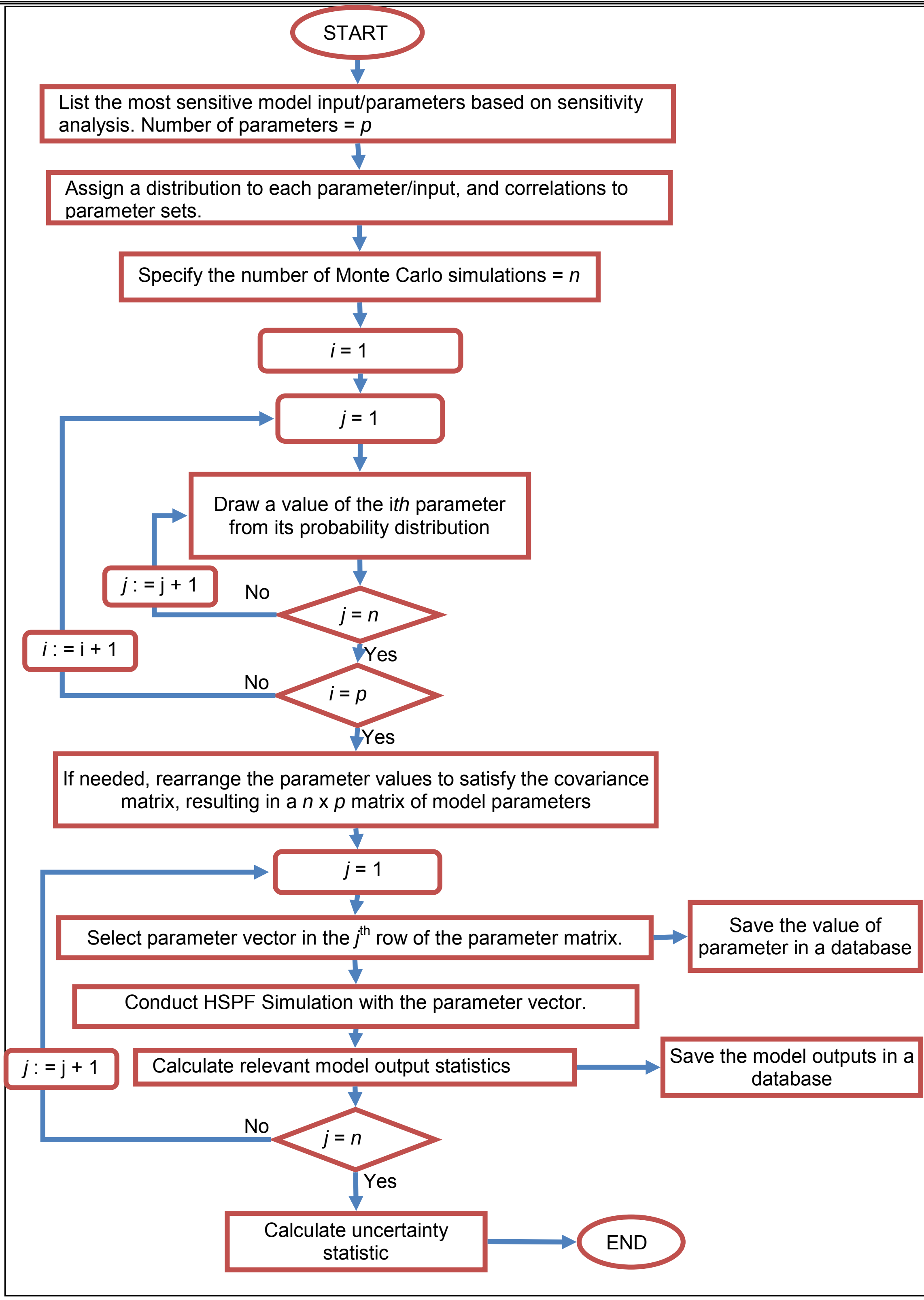

Figure 4 Steps for conducting an uncertainty analysis.

Table 4. List of parameters that were varied for uncertainty analysis

Parameter Details					Calibrated Values					Distribution Parameters		
Category	**Name**	**Definition**	**Type**	**Distribution Type**	**Min**	**Max**	**Mean**	**90% Range**	**Std. Dev. (90% Range/ 3.3)**	**Lower and upper limits**	**Std. Dev. For Underlying Normal Distribution**	**Mean for Underlying Normal Distribution**
Hydrology	INFILT, in/hr	Index to Infiltration Capacity of the Soil	Soil/ Climate	LN	0.035	0.300	0.10	0.03 – 0.30	0.08	0.01 – 0.50	0.75	-2.45
	INTFW	Interflow Inflow Parameter	Soil/ Climate	LN	1.00	3.50	1.93	1.00 – 3.50	0.76	0.50 – 6.00	0.38	0.62
	UZSN, in	Upper Zone Nominal Soil Moisture Storage	Soil	LN	0.50	2.00	0.97	0.50 – 2.00	0.45	0.20 – 3.00	0.42	0.00
	LZSN	Lower Zone Nominal Storage	Soil/ Climate	LN	4.00	8.50	7.00	4.00 – 8.50	1.36	2.50 – 9.00	0.23	1.76
	LZETP	Lower Zone Evapotranspiration	Vegetation	NO	0.10	0.75	0.40	0.10 – 0.80	0.21	0.05 – 0.90		
Soils/ Sediment	KSER	Coefficient in Sediment Washoff Equation	Soil/ Vegetation	LN	0.04	1.00	0.25	0.04 – 2.00	0.59	0.01 -10.00	1.19	-1.27
	COVER	Fraction of Land Protected from Raindrop Splash	Vegetation	NO	0.60	0.97	0.83	0.30 – 0.99	0.21	0.05 – 1.00		
	TAUCD, lb/ft2*	Critical Bed Shear Stress for Deposition	Soil/ Sediment	LN	0.012	0.650	0.21	0.05 - 0.50	0.14	0.01 – 1.00	0.70	-1.85
	TAUCS, lb/ft2*	Critical Bed Shear Stress for Scour	Soil/ Sediment	LN	0.07	1.26	0.51	0.10 – 1.50	0.42	0.05 – 2.00	0.82	-0.95
	KSAND	Coefficient in Sandload equation	Soil/ Sediment	LN	0.09	1.50	0.55	0.05 – 2.00	0.59	0.01 – 5.00	1.12	-1.16
Nutrient Loadings	Point Sources	Loading from Point Sources to the reach	Nutrient Loading	UN				0.5 – 1.2	0.21	0.50 -1.20		
	Dev. Areas Loading	Loading of N and P from Developed Areas	Nutrient Loading	LN				0.6 – 1.5	0.27	0.50 – 1.60	0.28	-0.05
	Pasture Litter Loading	Loading of N and P from Pasture areas treated with Litter	Nutrient Loading	LN				0.4 – 2.5	0.64	0.30 – 2.60	0.56	0.00
	Non-Litter Pasture Loadings	Loading of N and P from Pasture areas not treated with Litter	Nutrient Loading	LN				0.4 – 2.0	0.48	0.30 – 2.10	0.49	-0.11

- -- These parameters were changed jointly by the same percentage since they are correlated.

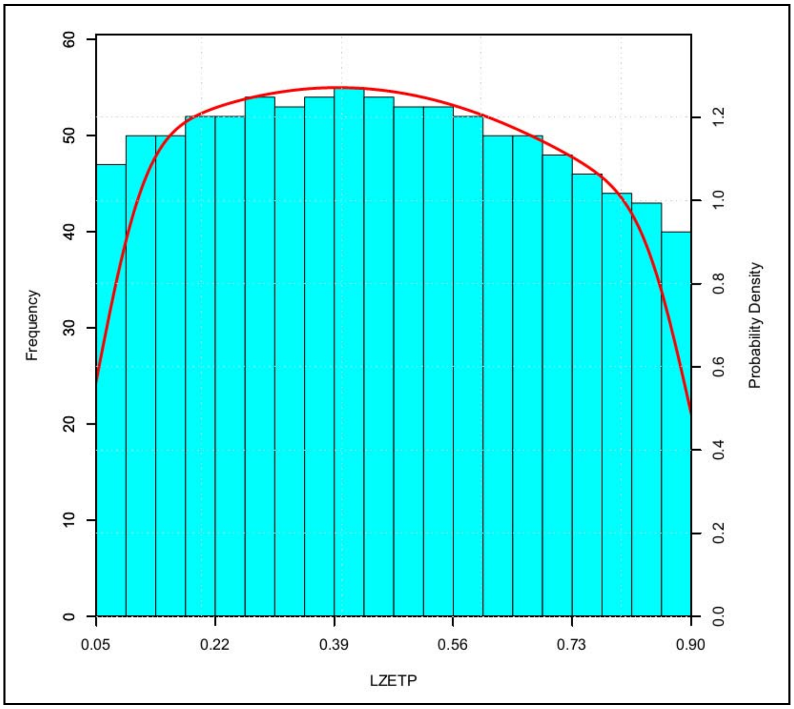

Figure 5. Histogram and probability density function of bounded and normally distributed parameter, LZETP.

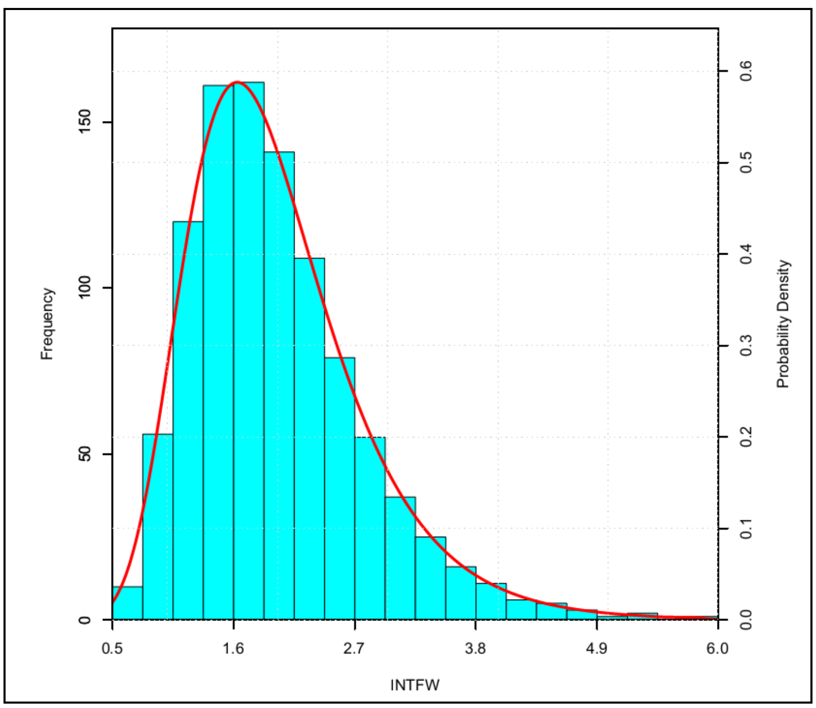

Figure 6. Histogram and probability density function of bounded and log-normally distributed parameter, INTFW.

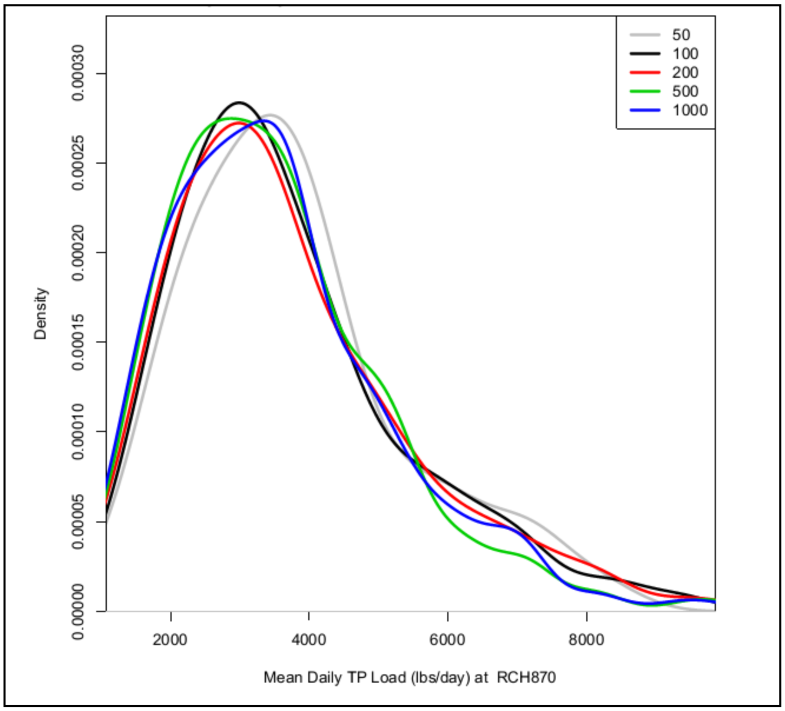

Figure 7. Probability density function of mean daily Total Phosphorus load (lbs/day) in RCH870 generated with different number of Monte Carlo simulations.

WATERSHED MODEL UNCERTAINTY ANALYSIS RESULTS

Tables 5 and 6 show the primary uncertainty analysis results. The results are shown at both the AR/OK Stateline (Reach 630) and at the Illinois River at Tahlequah (Reach 870). As noted above, for each output metric, the table includes the mean value, the 5th and 95th percentile values, and the overall "Percent Uncertainty" which is calculated as the average deviation from the mean value, i.e. the sum of the 5th percentile minus the Mean, and the 95th percentile minus the mean, divided by 2. This Percent Uncertainty represents the average deviation from the mean value for the 90% confidence range.

Thus, the overall uncertainty in hydrology outputs varied from 11% to 45%, but the uncertainty in water quality outputs varied from about 1% to 150%. The TSS concentration and loads had the greatest uncertainty, which is often the case, followed by TP, TN, and water temperature. The major output of concern for this study is the TP load and it has an uncertainty between 70 and 80% at the two locations of interest.

Frequency duration curves of flow were also plotted to illustrate the uncertainty in flow simulation for the entire range of flows (see Figure 7). The curves were plotted with 5th and 95th percentile curves. It is evident from Figure 7 that the uncertainty increases for low flow conditions and high flow events, with the lowest uncertainty for the moderate flow ranges.

Table 3. Mean, 5th and 95th percentiles, and uncertainty of hydrology outputs of interest at RCH630, and RCH870 in the IRW model.

RCH630	Annual Peak Flow (cfs)	Mean Annual (cfs)	Mean Annual runoff(in)	10% High (in)	25% High (in)	50% High (in)	50% Low (in)	25% Low (in)	10% Low (in)	5% Low (in)
5th Percentile	13905.9	722.0	17.3	7.9	11.6	14.8	1.6	0.6	0.2	0.1
Mean	20940.2	814.7	19.5	10.5	14.0	16.9	2.6	0.9	0.3	0.1
95th Percentile	27342.2	907.8	21.7	13.5	16.5	19.2	3.7	1.3	0.4	0.2
% Uncertainty	32.1	11.4	11.4	26.6	17.4	13.1	40.0	40.4	39.0	36.9
RCH870										
5th Percentile	17919.6	1183.0	16.9	7.5	11.2	14.5	1.6	0.5	0.2	0.1
Mean	29616.2	1335.8	19.1	9.8	13.6	16.5	2.6	0.9	0.3	0.1
95th Percentile	40758.8	1490.8	21.3	12.4	16.0	18.9	3.7	1.3	0.4	0.2
% Uncertainty	38.6	11.5	11.5	25.0	17.8	13.4	40.8	44.0	44.6	43.4

Table 4. Mean, 5th and 95th percentiles, and uncertainty of water quality outputs of interest at RCH630, and RCH870 in the IRW model.

RCH630	10% High TSS Conc.(mg/l)	Mean TSS Conc.(mg/l)	Mean Daily TSS Load (tons/day)	10% High TN Conc.(mg/l)	Mean TN Conc. (mg/l)	Mean Daily TN Load (lbs/day)	10% High TP Conc.(mg/l)	Mean TP Conc. (mg/l)	Mean Daily TP Load (lbs/day)	Mean Summer Water Temp. (F)	Mean Water Temp. (F)
5th Percentile	16.6	8.54	146.94	3.1	2.25	8414.50	0.4	0.17	871.70	75.47	61.40
Mean	246.8	94.37	822.10	4.5	3.15	13935.40	0.7	0.30	2134.50	76.22	61.79
95th Percentile	779.2	300.59	1894.19	6.8	4.43	23048.93	1.2	0.47	4181.14	76.78	62.10
% Uncertainty	154.5	154.70	106.30	40.9	34.60	52.50	55.1	50.90	77.50	0.90	0.60
RCH870											
5th Percentile	28.2	15.57	266.07	3.0	2.10	13328.30	0.3	0.15	1446.87	77.33	62.97
Mean	376.7	131.32	1560.07	4.2	2.88	21235.12	0.6	0.28	3559.89	77.75	63.19
95th Percentile	1133.5	382.04	3389.88	6.5	4.07	33808.28	1.1	0.48	6774.10	78.05	63.35
% Uncertainty	146.7	139.50	100.10	40.8	34.30	48.20	61.4	58.90	74.80	0.50	0.30

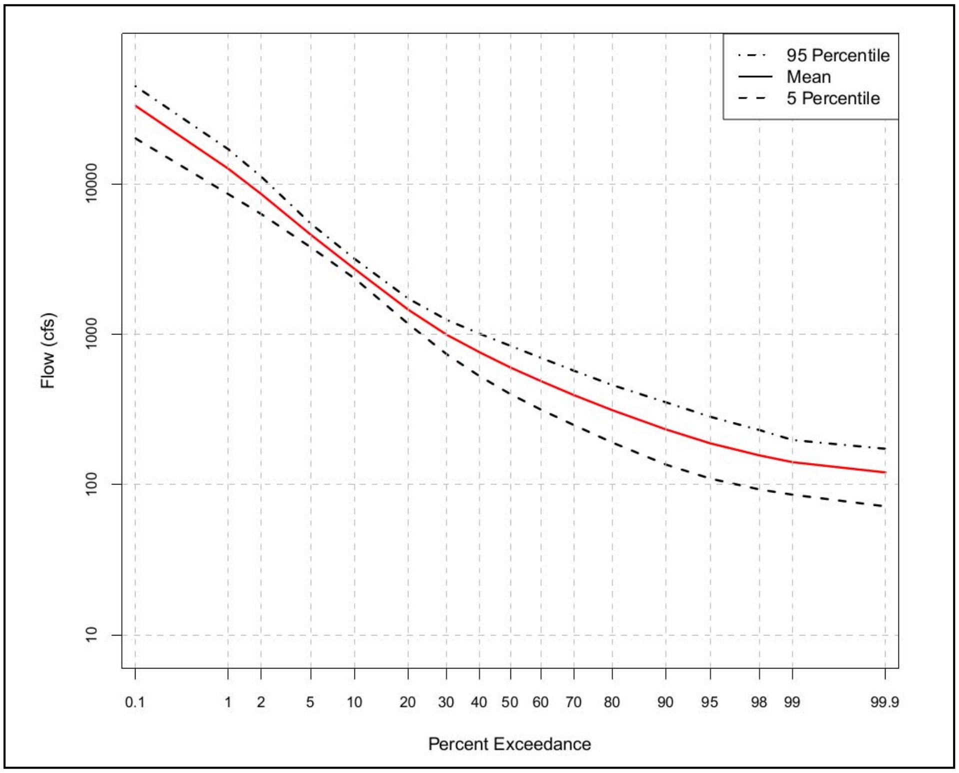

Figure 8. Frequency duration curves at RCH870 with 5% and 95% percentile curves to illustrate the model uncertainty.

WATERSHED MODEL UNCERTAINTY ANALYSIS CONCLUSIONS

From the UA results shown in Tables 5 and 6, the following conclusions are derived:

a. Model uncertainty increases from the hydrology outputs, to nutrient outputs, to sediment/TSS outputs.

b. Ranges of % Uncertainty are about: 10% to 45% for hydrology, 35% to 75% for nutrients, and 100% to 150% for sediment/TSS. These ranges also reflect the relative difficulties in modeling the corresponding variables, with flow being the least difficult and sediment being the most difficult.

c. Uncertainty estimates at Tahlequah (Reach 870) and the AR/OK Stateline (Reach 630) are essentially the same; the differences in the % Uncertainty between these two sites is not considered significant.

d. The very low uncertainty values for water temperature are likely understated due to the calculations being based on mean temperatures. However, it is also true that water temperature simulation is usually the most accurate, and thus would be expected to have the lowest degree of uncertainty.

e. The large range between the 5^{th} and 95^{th} percentile daily loads for TN, TP, and TSS is realistic and reflects the dynamics and variability inherent in the IRW system.

Based on experience with UA with HSPF in other watersheds, the results presented here are reasonable and realistic.

TENKILLER FERRY LAKE EFDC WATER QUALITY MODEL ANALYSIS

This section describes the procedure used Tenkiller

LAKE EFDC MODEL SENSITIVITY ANALYSIS

The purpose of the Tenkiller Ferry Lake EFDC water quality model sensitivity analysis is to better understand how adjustments to the model input parameters affect modeling results. The sensitivity analysis provides useful information regarding the physical, chemical and biological processes represented in the model and identifies the most influential parameters for improving model accuracy.

Specifically, sensitivity analysis is a procedure to determine the changes in model output with respect to changes in model input parameters. This analysis will provide useful information on the model responses to changes in different model input parameters and coefficients.

The selected key kinetic coefficients and model input parameters and sensitivity analysis results for the Tenkiller Ferry Lake EFDC water quality model are summarized in this technical memorandum.

The purpose of the uncertainty analysis of the Tenkiller Ferry Lake EFDC water quality model is to determine the confidence limits, or reliability of model predictions, with respect to the errors associated with observations and the computational model. The selected kinetic coefficients and model input parameters and uncertainty analysis results of the Tenkiller Ferry Lake EFDC water quality model are summarized in this technical memorandum.

Lake Model Sensitivity Analysis Procedure

The Tenkiller Ferry Lake EFDC water quality model was calibrated in the year of 2006 because more observed water quality data were available in 2006 (DSLLC, 2014). The calibration simulation was selected as a baseline simulation. The following steps were performed to assess the sensitivity of the Tenkiller Ferry Lake EFDC water quality model.

(1) Identify the critical model input coefficient and parameters;
(2) Determine the reasonable low and high perturbation levels for each model input coefficient and parameter;
(3) Make sure each perturbation of model input coefficient and parameter value is within a reasonable range;
(4) Run the EFDC model for each low and high perturbation of model input coefficient and parameter;

(5) Calculate the percent difference from the baseline for each model input coefficient and parameter value;
(6) Rank the model input coefficients and parameters by normalized sensitivity coefficients (NSCs);
(7) Plot time series, compute summary statistics, and prepare Box and Whisker plots for each model input coefficient and parameter value; and
(8) Use NSCs to plot Tornado Diagrams to summarize response to each model input coefficient and parameter value for selected response variables. The tornado diagram was created to rank the model input and parameters based on NSCs following the methodology by Donigian and Love (2007).

As described above low and high values are selected to specify the perturbation of each model parameter selected for the sensitivity analysis. This approach is a valid statistical expression of the Point Estimate Method originally developed by Rosenblueth (1981) and subsequently modified and applied by Harr (1989), Li (1992), and Christian and Baecher (1999). In the Point Estimate Method, three values -- low, middle and high-- of the perturbed parameter are required. The three values, usually taken to be the mean and ± 1σ or ± 2σ, for each input parameter, are used to construct a pseudo-PDF from model outputs by joint probability calculations. The low and high values can be based on the middle value ± some percentage or the low and high values can be based on statistics for the model parameter (e.g., mean ± 1σ; mean ± 2σ). In applying the Point Estimate Method for the sensitivity analysis of the Tenkiller Ferry Lake model, a simple percentage was specified as ±50% of the model calibration parameter values to assign low and high parameter values around the middle calibrated parameter values.

In their sensitivity and uncertainty analysis for a lake model, Missaghi et al. (2013) identified the highest ranked kinetic parameters that contributed to most of the variance of the total lake model output uncertainty. Two of the three kinetic parameters selected for the sensitivity analysis (benthic phosphate flux and half-saturation constant for phosphorus) were identified by Missaghi et al. as the highest ranked kinetic parameters for their lake model. Despite the limited number of model parameters selected for the lake model sensitivity analysis, the parameters selected were consistent with the parameters shown by Missaghi et al. to be very important for their lake model.

Response Variables and Selected Stations

The state variables for the Tenkiller Ferry Lake EFDC water quality model selected for the sensitivity analysis include dissolved oxygen (DO), chlorophyll a, and total phosphorus (TP). These state variables are chosen for the sensitivity analysis because dissolved oxygen, chlorophyll a and the Trophic State Index (computed as a function of chlorophyll a) are the water quality targets for determination of the TMDLs for Tenkiller Ferry Lake. Total Phosphorus is the water quality target for determination of the TMDLs for the Illinois River watershed. Considering the nature of these state variables, DO was evaluated for the bottom layer of the water column with the thickness based on the lower 25% of the total water column. Chlorophyll a was evaluated for the surface layer of the water column with the thickness based on the upper 25% of the total water column. TP was evaluated as a depth-averaged parameter for the whole water column.

For sensitivity analysis, EFDC water quality model results were extracted from the cells where two observed stations LK-01 and LK-03 (DSLLC, 2014) are located (Figure 1). Stations LK-01 and LK-03 represent two different areas of Tenkiller Ferry Lake: LK-01 is located in the forebay area in the lacustrine zone and LK-03 is in the transition zone close to the riverine sections of the upstream rivers: the Illinois River and Baron Fork Creek.

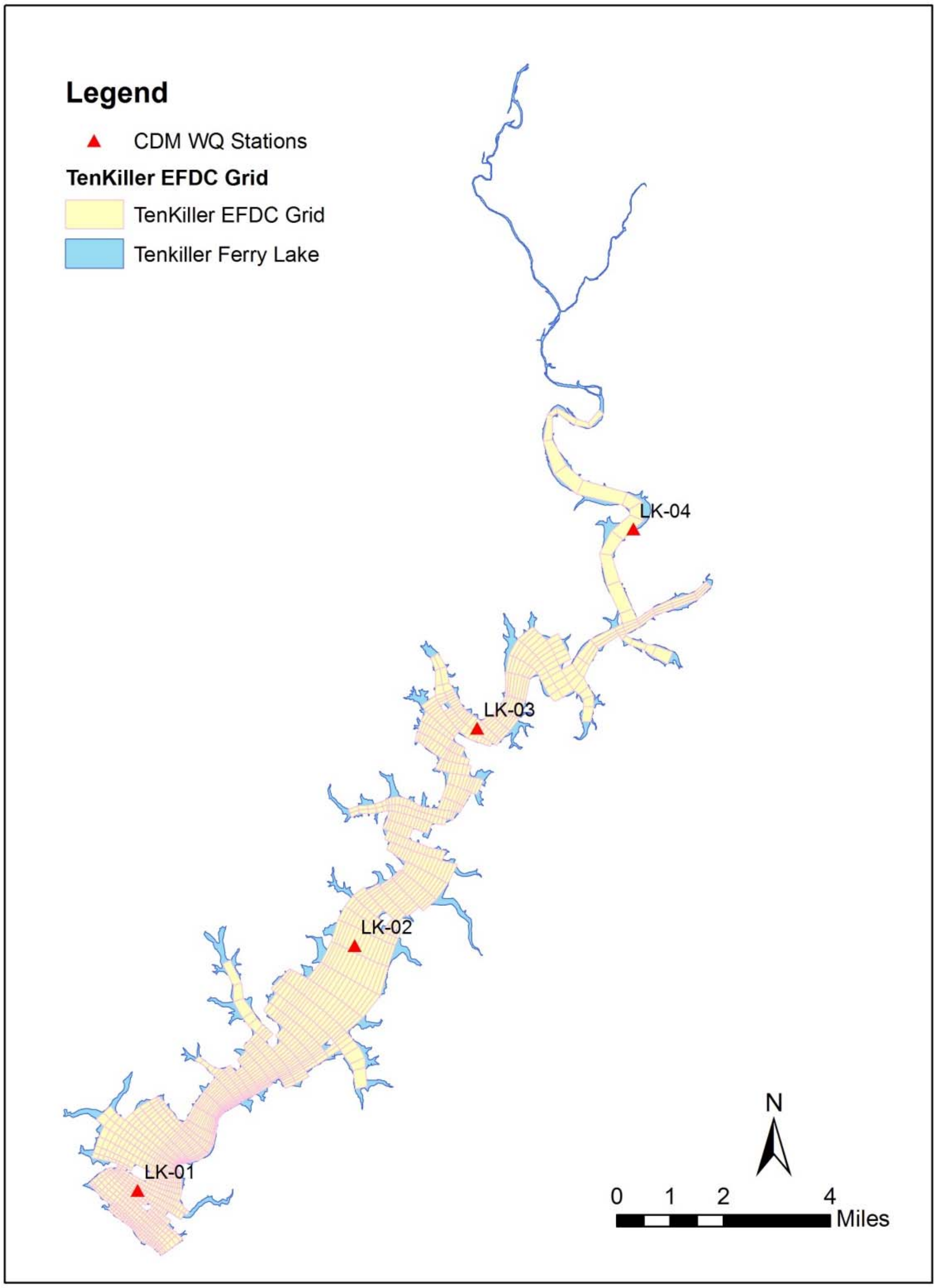

Figure 9 Location of the CDM Water Quality Monitoring Stations in Tenkiller Ferry Lake

Selected Model Input/Parameters and Perturbation Levels

Based on the experience gained from numerous model runs during the model calibration task, kinetic coefficients and model input parameters that significantly influenced the model results included the maximum algae growth rate, phosphorus half saturation constant for nutrient uptake by algae, and PO4 sorption enhancement factor for the sediment flux of phosphate from the sediment diagenesis model along with the watershed total phosphorus (TP) loads. Model results for surface layer algae chlorophyll a are directly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and indirectly related to changes in the PO4 sorption enhancement factor through changes in the sediment release of phosphate to the water column. Model results for depth-averaged TP are directly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and changes in the PO4 sorption enhancement factor through changes in the sediment release of phosphate to the water column. Model results for bottom layer DO are controlled significantly by the onset and erosion of seasonal stratification with seasonal hypoxic conditions observed and simulated during the summer months. As a result of changes in oxygen demand below the thermocline during the summer from changes in algae biomass, model results for bottom DO are indirectly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and changes in the PO4 sorption enhancement factor. The two perturbation levels that were determined for the analysis are 50% increase and 50% decrease from the calibration values as shown in Table 1.

Table 5 Selected Kinetic Coefficients and Input Parameters for Sensitivity Analysis

Variables	Perturbation Level		
	Low	Baseline (calibration)	High
Watershed TP Loads (kg/day)	Decreased by 50%	HSPF Model	Increased by 50%
Maximum Algae Growth Rate (day^{-1})	Decreased by 50%	Zone-specific: 1-1.4	Increased by 50%
PO4 Sorption Enhancement Factor in Sediment Diagenesis (multiplier)	Decreased by 50%	Zone-specific: 300-900	Increased by 50%
P Half Saturation Constant for Algae (mg/L)	Decreased by 50%	0.005	Increased by 50%

Normalized Sensitivity Coefficients

Normalized sensitivity coefficient (NSC) is calculated as the percent change of the average absolute percent change in model output for the two runs divided by the average absolute percent change in input/parameter value. A NSC value of 100 indicates a 1:1 sensitivity with the model producing a result in direct proportion to the input/parameter change (Donigian and Love, 2007). For example, a perturbation of decrease/increase in input/parameter by 50% will produce a response of increase/decrease by 50% in the model output. The higher the NSC is, the more sensitive the input/parameter is.

LAKE MODEL SENSITIVITY ANALYSIS RESULTS

Sensitivity analyses were conducted with the calibrated model for year 2006. The responsive variables, evaluated for the entire year, are chlorophyll a, TP, and DO. The four model input/parameters examined are watershed TP loads, maximum algae growth rate, PO4 sorption enhancement factor of sediment flux of phosphate, and P half-saturation constant for algae.

Time series plots, Box-Whisker-Plots, and torpedo diagrams are provided for all three responsive variables. Compared with time series plots, Box-Whisker-plots provide much better visualization of the distribution of data. For a Box-Whisker-plot, the blue star indicates the minimum value of the dataset; the lower end of the Whisker is the 10 percentile of the dataset; the lower end of the Box indicates the 25% percentile; the bar in the Box is the median value; the diamond shows the mean value; the upper end of the Box is the 75 percentile; the upper end of the Whisker is the 90% percentile; and the brown star is the maximum value of the dataset. Figure 3 shows an example of the Box and Whisker plot.

As shown in Figure 10 as an example of the tornado diagram, the y-axis is the calculated NSC in percentage and the x-axis is the percent difference of modeled responsive variables from mean in percentage. The NSC was calculated based on two perturbation levels: +50% (50% increase from the baseline value) and -50% (50% decrease from the baseline value), as shown in the torpedo diagram. The model input-parameters are listed on the right side of the plot in the order of from high to low sensitivity level.

Sensitivity Analysis of Chlorophyll a

The time series plots and Box-Whisker-Plots of modeled chlorophyll a under different perturbation levels of these four model input/parameters at stations LK-01 and LK-03 are given in Figures 2 through 9 and Figures 11 through 18, respectively. The tornado diagrams of sensitivity analyses results of modeled chlorophyll a at station LK-01 and LK-03 are given in Figure 10 and Figure 19, respectively. The calculated NSCs are also given in Table 2.

At station LK-03, perturbations in watershed TP loads and maximum algal growth rate showed similar impact on modeled chlorophyll a, as shown by the similar values of NSCs (Table 2 and Figures 11-18). PO4 sorption enhancement factor and P half-saturation for algae showed much lower impact on modeled chlorophyll a compared with watershed TP loads and maximum algal growth rate (Table 2 and Figures 11-18).

At station LK-01 in the forebay area of the lake, maximum algal growth rate is the single most sensitive parameter, with the calculated NSC of 93.5, as shown in Table 2. Watershed TP loads only rank third in the order of calculated NSC). All the kinetics parameters in this analysis showed relatively higher NSCs at station LK-01 than station LK-03 (Table 2).

Table 6 Calculated Normalized Sensitivity Coefficients (%) for Modeled Chlorophyll a at Stations LK-01 and LK-03 in the Surface Layer

Model Input/Parameters	LK-01	LK-03
Watershed TP loads	39.83	65.03
Maximum algal growth rate	93.50	70.01
PO4 sorption enhancement factor	21.07	12.39
P half-saturation constant for algae	42.09	18.35

At both LK-01 and LK-03, the positive perturbations in the watershed TP loads and maximum algal growth rate result in the positive response in the average modeled chlorophyll a, or vice versa (Figures 10 and 19). The positive perturbation in the watershed TP loads increases the amount of PO4, an essential nutrient for algal growth, which will stimulate the algal growth and result in the increase in the chlorophyll a concentration in the water column.

At both LK-01 and LK-03, the positive perturbation in PO4 sorption enhancement factor and P half-saturation for algae lead to negative response in the average modeled chlorophyll a, or vice versa (Figures 10 and 19). The positive perturbation in PO4 sorption enhancement factor decreases the amount of PO4 released from sediment bed to water column, which in turn inhibits the algal growth and results in the decrease in the chlorophyll a concentration. The positive perturbation in P half-saturation for algae decreases the algal growth and results in the decrease in modeled chlorophyll a concentration.

Sensitivity Analysis of TP

The time series plots and Box-Whisker-Plots of modeled TP under different perturbation levels of these four model input/parameters at stations LK-01 and LK-03 are given in Figures 20 through 27 and Figures 29 through 36, respectively. The tornado diagrams of sensitivity analyses results of TP at stations LK-01 and LK-03 are given in Figure 28 and Figure 37, respectively. The calculated NSCs are also given in Table 3.

At station LK-01, perturbations in watershed TP loads and maximum algae growth rate showed much higher impact on the modeled TP than that in PO4 sorption enhancement factor and P half-saturation for algae, as shown by the higher values of NSCs in Table 3 and Figures 20-27. At station LK-03, which is close to the upstream riverine area, watershed TP loads becomes the single most important factor affecting the modeled TP than the other three parameters (Table 3 and Figures 29-36).

Table 7 Calculated Normalized Sensitivity Coefficients (%) for Modeled TP at Stations LK-01 and LK-03 for Depth-Averaged water Column

Model Input/Parameters	LK-01	LK-03
Watershed TP loads	65.88	100.10
Maximum algal growth rate	74.34	25.76
PO4 sorption enhancement factor	20.89	6.56
P half-saturation constant for algae	17.89	2.05

Illinois River and Baron Fork Creek are the two largest tributaries that contribute flow and nutrients to Tenkiller Ferry Lake. Since station LK-03 is close to both rivers, the nutrient loads from upstream rivers dominate the nutrient transport and fate process at this location compared with the other kinetic parameters. This might explain that the poor EFDC TPO4 calibration results at station LK-03 is caused by the inaccurate HSPF-simulated TPO4 boundary at Illinois River and Baron Fork Creek.

The kinetics parameters play much more important roles in the nutrient transport and fate process at station LK-01 in the forebay area of the lake than at station LK-03. The calculated NSCs for maximum algal growth rate, PO4 sorption enhancement factor, and P half-saturation for algae are 74.34, 20.89, and 17.89 at LK-01, whereas the calculated NSCs at LK-03 are 25.76, 6.56, and 2.05.

At both stations LK-01 and LK-03, the positive perturbation in watershed TP loads results in the positive response in modeled TP concentration or vice versa as shown in Figures 28 and 37. However, the positive perturbation in maximum algal growth rate results in the negative response in modeled TP concentration or vice versa (Figures 28 and 37). The positive perturbation in maximum algal growth rate increases the algal mass in the water column. The algae in the water column continue to settle onto the sediment bed; hence, the TP concentration decreases due to the loss of TP in the algal mass.

Sensitivity Analysis of DO

The time series plots and Box-Whisker-Plots of modeled DO under different perturbation levels of these four model input/parameters at stations LK-01 and LK-03 are given in Figures 38 through 45 and Figures 47 through 54, respectively. The tornado diagrams of sensitivity analyses results of modeled DO at station LK-01 and LK-03 are given in Figure 46 and Figure 55, respectively. The calculated NSCs are also given in Table 4.

Compared with modeled TP and chlorophyll a, the values of calculated NSCs are much smaller: all values are less than 10 (Table 4). Hence, the modeled DO results are not as sensitive to perturbations in modeled input/parameters as modeled TP and chlorophyll a. Maximum algal growth rate is a relatively sensitive parameter with higher value of NSC compared with the other three model input/parameters (Table 4).

At both stations of LK-01 and LK-03, maximum algal growth rate is the most sensitive parameter, as shown by the largest value of calculated NSCs in Table 4. At both stations, PO4 sorption enhancement factor is the least sensitive parameter (Table 4). At LK-03, watershed TP loads ranks second in the magnitude of NSC; only second to maximum algal growth rate (Table 4).

Table 8 Calculated Normalized Sensitivity Coefficients (%) for Modeled DO at Stations LK-01 and LK-03 for Bottom Layer

Model Input/Parameters	LK-01	LK-03
Watershed TP loads	1.07	2.27
Maximum algal growth rate	7.10	6.55
PO4 sorption enhancement factor	0.68	0.44
P half-saturation constant for algae	3.73	1.41

At station LK-01, the positive perturbation in maximum algal growth rate results in the negative response in the modeled DO concentration or vice versa (Figure 46). However, at station LK-03, the positive perturbation in maximum algal growth rate results in the positive response in the modeled DO concentration or vice versa (Figure 55).

LAKE MODEL SENSITIVITY ANALYSIS SUMMARY AND CONCLUSIONS

Sensitivity analyses were conducted with the calibrated Tenkiller Ferry Lake EFDC water quality model in year 2006. Sensitivity analyses were conducted to evaluate the responses for TP, chlorophyll a, and DO under two perturbation levels (decrease and increase by 50% from the baseline calibration) of four model input coefficients or parameters for the model calibration year of 2006. These four model input coefficients or parameters are watershed TP loads, maximum algae growth rate, PO4 sorption enhancement factor of benthic phosphate flux in the sediment diagenesis model, and P half-saturation constant for algae.

In performing a sensitivity and uncertainty analysis for a lake model, Missaghi et al. (2013) identified the highest ranked kinetic parameters that contributed to most of the variance of the total lake model output uncertainty. Two of the three kinetic parameters selected for the sensitivity analysis of the Tenkiller Ferry lake model (benthic phosphate flux and half-saturation constant for phosphorus) were identified by Missaghi et al. as the highest ranked kinetic parameters for their lake model. The sensitivity analysis developed for the Tenkiller Ferry Lake model is based on watershed loading of phosphorus and three kinetic parameters. It is noteworthy that two of the three kinetic parameters selected for the sensitivity analysis of

Tenkiller Ferry Lake were shown by Missaghi et al. (2013) to be the most important model parameters for the sensitivity and uncertainty analysis of their lake model.

The time series plots, Box-Whisker-Plots, and torpedo diagrams are presented for visual comparison of the sensitivity analysis results. The calculated NSCs are used for quantitative and graphical comparison of the sensitivity of model input coefficients and parameters. Sensitivity analyses results are given at two CDM stations: LK-01 and LK-03. Station LK-01 is located in the forebay area in the lacustrine zone and LK-03 in the transition zone is close to the riverine sections of the upstream rivers: the Illinois River and Baron Fork Creek.

Based on the NSCs shown in the torpedo diagrams for both LK-01 and LK-03 for each state variables, the maximum growth rate of algae and the watershed loading of TP results in sensitivity analysis responses are greater than 50% for surface layer chlorophyll a and water column TP and greater than 5% for bottom DO. The sensitivity response of changes to the half saturation constant for P and the PO4 enhancement factor for sediment flux of phosphate are less than 50% for chlorophyll a and TP and less than 5% for DO.

In the transition zone station LK-03, the TP load from the watershed has a very large impact on the sensitivity results for TP (100%) and chlorophyll a (65%). The maximum algal growth rate has a large impact on chlorophyll a (70%) with a smaller impact on TP (25%). Changes in TP loading from the watershed directly affect the availability of inorganic phosphate for algal uptake and resulting algae biomass. Changes in the maximum algae growth rate directly affect algae biomass through more or less photosynthetic production while TP is impacted through more or less uptake of inorganic phosphate and more or less organic phosphorus from changes in algae biomass.

In the lacustrine zone station LK-01, the TP load from the watershed has less of an impact on the sensitivity results for TP (66%) than in the transition zone LK-03 station (100%). In comparison to the transition zone LK-03 station, there is also a smaller impact of TP loading on chlorophyll a (40%) at the LK-01 station. In contrast to the transition zone LK-03 station, changes in the maximum algal growth rate have a very large impact on chlorophyll a (94%) and TP (74%) at the LK-01 station.

The effect of the PO4 enhancement factor on the sediment flux of phosphate would show the greatest response for bottom layer PO4 during the summer stratified months when the bottom layer is hypoxic. On an annual averaged basis and on a depth-averaged water column basis for TP, the sensitivity of water column TP to the PO4 enhancement is diminished because of the indirect connection of TP to this model parameter and changes in bottom layer PO4 that are greatest during the summer stratified months.

The half saturation constant for nutrient uptake affects the algal growth rate as a multiplier of the maximum growth rate that is dependent on the phosphate concentration. The sensitivity analysis results for LK-01 and LK-03 demonstrate an impact of this parameter of ranging from 2 to 18% for chlorophyll a and TP but the impact of this parameter is not as great as changes in the maximum growth rate for algae.

In contrast to the significant changes demonstrated for chlorophyll a and TP, the sensitivity analysis results for bottom layer DO exhibit responses that are less than 10% and are not greatly impacted by the changes in the model input coefficients and parameters. Model results for bottom layer DO are controlled rather by seasonal stratification that cuts off surface layer dissolved oxygen and results in hypoxic conditions during the summer months. The sensitivity analysis results for bottom DO are controlled by changes in oxygen demand below the summer thermocline from changes in algae biomass, algae respiration, and changes in SOD from deposition of algal related particulate organic matter to the sediment bed. The sensitivity analysis demonstrates that changes in the maximum algal growth rate result in the largest response of ~7% for bottom layer DO.

LAKE MODEL UNCERTAINTY ANALYSIS

Uncertainty Analysis Procedure

The Tenkiller Ferry Lake EFDC water quality model was calibrated for the year of 2006 because more observed water quality data were available in 2006 than in 2005 (DSLLC, 2014). The calibration simulation was selected as a baseline simulation for the sensitivity and uncertainty analyses. The following steps were performed to assess the uncertainty of the Tenkiller Ferry Lake EFDC water quality model.

(1) Select the model input coefficient and parameters for uncertainty analysis based on the sensitivity analysis results and specific calibration experience for the Tenkiller Ferry Lake EFDC water quality model;
(2) Determine the reasonable perturbation levels for each model input coefficient and parameter;
(3) Make sure each perturbation of model input coefficient and parameter value is within a reasonable range;
(4) Run the EFDC models for each perturbation of model input coefficient and parameter;
(5) Determine the 90 percent confidence interval, representing the values between 5th and 95th percentiles of responsive water quality variables;
(6) Generate the exceedance curve for each responsive water quality variable at stations LK-01 and LK-03, and;
(7) Calculate the percent uncertainty with the following equation (Donigian and Love, 2007).

$$Percent\ Uncertainty = \left(\frac{95th\ Percentile - 5th\ Percentile}{Mean * 2}\right) * 100$$

Response Variables and Selected Stations

The state variables for the Tenkiller Ferry Lake EFDC water quality model selected for the uncertainty analysis include dissolved oxygen (DO), chlorophyll a, and total phosphorus (TP). These state variables are chosen for the uncertainty analysis because dissolved oxygen, chlorophyll a and the Trophic State Index (computed as a function of chlorophyll a) are the water quality targets for determination of the TMDLs for Tenkiller Ferry Lake while total phosphorus (TP) is the water quality target for determination of the TMDLs for the Illinois River watershed. Considering the nature of these state variables, DO was evaluated for the bottom layer of the water column with the thickness based on the lower 25% of the total water column. Chlorophyll a was evaluated for the surface layer of the water column with the thickness based on the upper 25% of the total water column. TP was evaluated on a depth-averaged basis for the whole water column.

For the uncertainty analysis, EFDC water quality model results were extracted from the cells where two observed stations LK-01 and LK-03 (DSLLC, 2014) are located (Figure 1). Stations LK-01 and LK-03 represent different areas of Tenkiller Ferry Lake: LK-01 is located in the forebay area in the lacustrine zone and LK-03 is in the transition zone close to the riverine sections of the upstream rivers: the Illinois River and Baron Fork Creek.

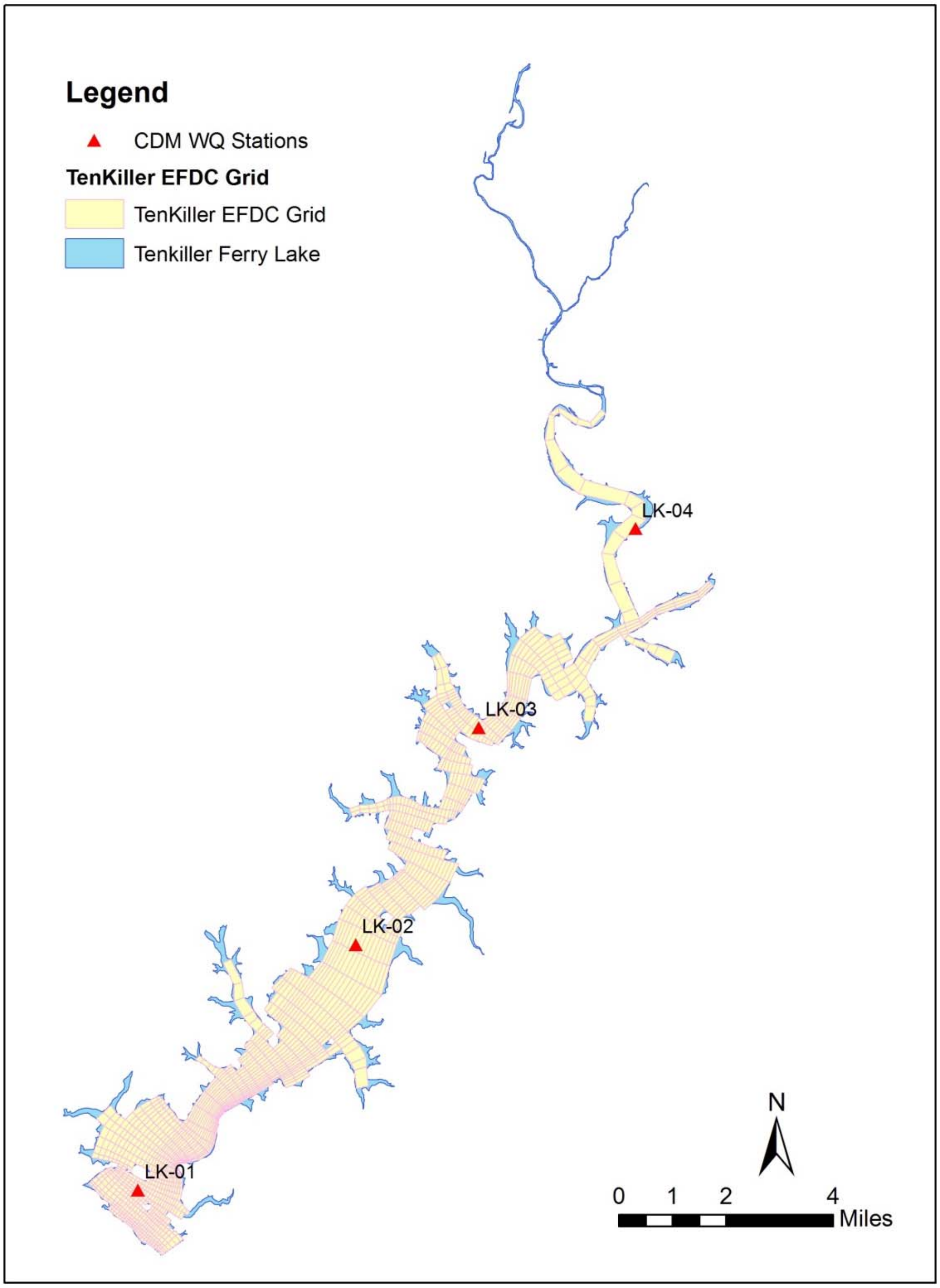

Figure 10. Location of the CDM Water Quality Monitoring Stations in Tenkiller Ferry Lake

Selected Model Input/Parameters and Perturbation Levels

Based on the experience gained from numerous model runs during the model calibration and sensitivity analysis tasks, kinetic coefficients and model input parameters that significantly influenced the model results included the maximum algae growth rate, phosphorus half saturation constant for nutrient uptake by algae, and PO4 sorption enhancement factor for the sediment flux of phosphate from the sediment diagenesis model along with the total phosphorus (TP) loads from the watershed.

Model results for surface layer algae chlorophyll a are directly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and indirectly related to changes in the PO4 sorption enhancement factor through changes in the sediment release of phosphate to the water column. Model results for depth-averaged TP are directly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and changes in the PO4 sorption enhancement factor through changes in the sediment release of phosphate to the water column. Model results for bottom layer DO are controlled significantly by the onset and erosion of seasonal stratification with seasonal hypoxic conditions observed and simulated during the summer months. As a result of changes in oxygen demand below the thermocline during the summer from changes in algae biomass, model results for bottom DO are indirectly related to changes in the maximum algae growth rate, the half saturation constant, watershed loading of TP and changes in the PO4 sorption enhancement factor. Two model runs with two perturbation levels based on a 50% increase and 50% decrease from the baseline calibration values were used for the sensitivity analysis. In order to derive more robust statistics for the uncertainty analysis, two additional sets of model runs were set up based on middle-low and middle-high values for each model input/parameter evaluated for the sensitivity analysis. Perturbations of all selected model input/parameters are shown in Table 1. A total of seventeen (17) model runs, including the calibration run, were assessed for the model uncertainty analysis.

It should be noted that the output of the watershed model TP loads becomes the input to the EFDC lake model. Effort was made to confirm that the percentages of increase and decrease of input TP concentrations from the baseline for the lake model uncertainty analysis are in line with the results of the uncertainty analysis of the HSPF watershed model (Aqua Terra, 2014). However, the input TP concentrations of 50% increase and 50% decrease from the baseline for the lake model cannot be directly compared to the 95th and 5th percentile of TP concentrations of the uncertainty analysis for the watershed model for the following two reasons:

1. Ten-year period of 2000 to 2009, which includes dry, wet and average hydrological conditions, were used in the watershed model uncertainty analysis while a one-year period of 2006, which is a dry year, was used in the lake model uncertainty analysis; and

2. The input TP concentrations of 50% increase and 50% decrease from the baseline for the lake model were calculated based on the TP concentration results of the watershed calibration model for the dry year period of 2006 while the 95th and 5th percentile of TP concentrations of the uncertainty analysis for the watershed model were calculated based on the results of the watershed model simulation for 2000-2009 with a number of different perturbations of watershed model parameters and inputs.

The results of uncertainty analysis of the watershed HSPF model at Tahlequah (RCH870) for ten-year period of 2000-2009 showed that the 5th percentile, mean, and 95th percentile concentrations are 0.15, 0.28, and 0.48 mg/l, respectively. The mean TP concentrations of 50% decrease, and 50% increase from the baseline and the mean TP concentration of the baseline at RCH 890 for year 2006 for lake model sensitivity and uncertainty analyses are 0.09 mg/L (50% decrease), 0.27 mg/L (50% increase) and 0.18 mg/L (mean), respectively. To determine if the percentages of TP increase and decrease from the baseline in the lake model are reasonable when compared to the TP concentrations corresponding to the 95th , mean and 5th percentile of TP concentrations derived from the watershed uncertainty analysis, recognition of the hydrologic variability of the watershed model uncertainty analysis, which incorporates a mix of dry, average and wet years for the 2000-2009 watershed simulation, is the key issue for evaluation of the lake model uncertainty analysis. During dry hydrologic conditions, the TP loading from the watershed is considerably less than the TP loading during average or wet hydrologic conditions. The input TP concentration for watershed loading to the lake model for the uncertainty analysis, based on 2006 dry year conditions, ranges from 0.09 to 0.27 mg/L for the 50% decrease to the 50% increase scenarios. The TP range for the lake uncertainty analysis is therefore comparable to the watershed model range for the 5th percentile (0.15 mg/L) and mean (0.28 mg/L) TP concentrations at Tahlequah for the watershed model uncertainty analysis which is based on dry, average and wet year conditions from 2000-2009.

Table 9 Selected Kinetic Coefficients and Input Parameters for Uncertainty Analysis

Variables	Perturbation Level				
	Low	Medium low	Baseline (calibration)	Medium high	High
Watershed TP Loads (kg/day)	Decreased by 50%	Decreased by 25%	HSPF Model	Increased by 25%	Increased by 50%
Maximum Algae Growth Rate (day^{-1})	Decreased by 50%	Decreased by 25%	Zone-specific: 1.0-1.4	Increased by 25%	Increased by 50%
PO4 Sorption Enhancement Factor in Sediment Diagenesis (multiplier)Factor in Sediment Diagenesis	Decreased by 50%	Decreased by 25%	Zone-specific: 300-900	Increased by 25%	Increased by 50%
P Half Saturation constant for Algae (mg/L)	Decreased by 50%	Decreased by 25%	0.005	Increased by 25%	Increased by 50%

Selected Modeling Periods for Uncertainty Analyses

Uncertainty analysis was conducted for the entire calibration period of 2006 from January 1 to December 31. To better understand the model uncertainty under stratified conditions, uncertainty analysis was also conducted for the stratified period. Detailed examination of the calibration plots of water temperature profile at stations LK-01 and LK-02 reveals that the stratified period for 2006 is from April 1 to October 31.

LAKE MODEL UNCERTAINTY ANALYSIS RESULTS

Uncertainty Analyses Results for the Entire Calibration Period

Uncertainty analysis was conducted with the calibrated EFDC model in year 2006. The responsive variables are chlorophyll a, TP, and DO. The four model input coefficients and parameters examined are watershed TP loads, maximum algae growth rate, PO4 sorption enhancement factor of sediment diagenesis, and P half-saturation constant for algae.

Exceedance curves are provided for all three responsive variables at stations LK-01 and LK-03. The exceedance curve shows the mean model output bounded by the 5^{th} and 95^{th} percentile values, which is the 90% confidence interval.

An example of an exceedance curve is given in Figure 2. Mean, 5^{th} and 95^{th} percentile values are calculated for a total of nineteen (19) exceedance levels (from 5% to 95% with an interval of 5%) to generate the exceedance curve. The exceedance level of 50% is used as an example to show how to calculate the mean, 5^{th} and 95^{th} percentile values presented in the plots. The 50^{th} percentile values are calculated for each of the seventeen (17) EFDC model runs; hence, there are a total of seventeen (17) 50^{th} percentile values. Finally, the mean, 5^{th}, and 95^{th} percentile values are calculated from the above seventeen (17) 50^{th} percentile values. Mean, 5^{th}, and 95^{th} percentile values for other exceedance level can be calculated following the similar approach. One additional step, however, needs to be done. For example, mean, 5^{th}, and 95^{th} percentile values calculated from the seventeen (17) 5^{th} percentile values are plotted as the mean, 5^{th}, and 95^{th} percentile values for the exceedance level of 95%.

The mean model output, 5^{th} percentile, 95^{th} percentile, and percent uncertainty for chlorophyll a, TP, and DO at stations LK-01 and LK-03 for the entire calibration period are given in Table 2. The exceedance curves of chlorophyll a, TP, and DO at stations LK-01 and LK-03 are shown in Figures 2 through 8.

Table 10 List of 5th to 95th Percentile Ranges and Percent Uncertainty of Responsive Variables for the Entire Calibration Period

Responsive variables	Chlorophyll a (µg/L)	TP (mg/L)	DO (mg/L)
LK-01			
5th Percentile	2.5	0.008	6.6
Mean	3.5	0.010	6.8
95th Percentile	4.7	0.014	6.9
Percent Uncertainty	29.1%	28.1%	2.2%
LK-03			
5th Percentile	12.7	0.044	8.2
Mean	20.1	0.064	8.4
95th Percentile	25.4	0.082	8.6
Percent Uncertainty	31.6%	29.8%	2.0%

For the Tenkiller Ferry Lake EFDC water quality model, the overall level of uncertainty is low for the water quality variable of DO with the calculated percent uncertainty less than 5% at both stations LK-01 and LK-03. However, water quality variables of chlorophyll a and TP show much higher value of percent uncertainty ranging from 28.1% to 31.6%, as shown in Table 2.

The Normalized Sensitivity Coefficient (NSC) is calculated as the percent change of the average absolute percent change in model output for the two runs divided by the average absolute percent change in input coefficient or parameter value. As shown in Table 3, modeled DO showed much lower values of normalized sensitivity coefficients compared with chlorophyll a and TP at both stations LK-01 and LK-03, indicating the perturbation of model input coefficients and parameters caused much smaller response in modeled DO than in modeled chlorophyll a and TP. This explains why modeled DO showed a much narrower range in the 90 percent confidence interval, as shown in Figures 2 through 8.

As seen in Table 2, responsive variables showed similar magnitude of percent uncertainty at both stations LK-01 and LK-03. Even though mean, 5^{th} percentile, 95^{th} percentile values of chlorophyll a and TP at station LK-03 are significantly higher than those at station LK-01, chlorophyll a and TP show similar magnitude of percent uncertainty, as shown in Table 2. For example, the 5^{th} percentile, mean, and 95^{th} values of chlorophyll a at station LK-01 are 2.5, 3.5, and 4.7 µg/L, respectively, whereas the 5^{th} percentile, mean, and 95^{th} values of chlorophyll a at station LK-03 are 12.7, 20.1, and 25.4 µg/L, respectively (Table 2). As shown in Table 2, the calculated values of percent uncertainty are very similare at station LK-01 (29%) and station LK-03 (32%).

Table 11 Calculated Normalized Sensitivity Coefficients at Stations LK-01 and LK-03

Model Input/Parameter	Chlorophyll a	TP	DO
LK-01			
Watershed TP loads	39.83	65.88	1.07
Maximum algal growth rate	93.50	74.34	7.10
PO4 sorption enhancement factor	21.07	20.89	0.68
P half-saturation for algae	42.09	17.89	3.73
LK-03			
Watershed TP loads	65.03	100.10	2.27
Maximum algal growth rate	70.01	25.76	6.55
PO4 sorption enhancement factor	12.39	6.56	0.44
P half-saturation for algae	18.35	2.05	1.41

Uncertainty Analyses Results for the Stratified Period

The mean model output, 5th percentile, 95th percentile, and percent uncertainty for chlorophyll a, TP, and DO at stations LK-01 and LK-03 for the stratified period (April 1 – Oct.31) are given in Table 4. Exceedance curves are provided for all three responsive variables at stations LK-01 and LK-03 for the stratified period, as shown in Figures 7 through 12.

At station LK-03 in the transition zone, there is not much difference in the mean value and percent uncertainty of chlorophyll a and TP concentrations between the entire calibration period and the stratified period, as shown in Tables 3 and 4. However, the mean DO concentration (6.2 mg/L) for the stratified period is much lower than that for the entire calibration period (8.4 mg/L); yet, the values of the calculated percent uncertainty for these two periods are very similar, as shown in Tables 3 and 4.

At station LK-01 in the lacustrine zone, the mean values of chlorophyll a, TP, and DO at the stratified period are all relatively lower than those at the entire calibration period, as shown in Tables 3 and 4. Calculated values of percent uncertainty for chlorophyll a and TP are similar between the stratified period and the entire calibration period. However, the percent uncertainty of DO for the stratified period (5.5%), although quite low, is higher than the percent uncertainty for the entire calibration period (2.2%).

The relatively lower mean DO concentrations for stratified conditions are expected. During the summer stratified conditions, low bottom layer DO results from higher water temperature and renewal of bottom layer DO that is cut off from the surface layer by water column stratification.

Table 12 List of 5th to 95th Percentile Ranges and Percent Uncertainty of Responsive Variables for Stratified Period (April 1 – October 31)

Responsive variables	Chlorophyll a (µg/L)	TP (mg/L)	DO (mg/L)
LK-01			
5th Percentile	1.8	0.004	4.4
Mean	2.5	0.005	4.6
95th Percentile	3.2	0.007	4.9
Percent Uncertainty	28.0%	32.3%	5.5%
LK-03			
5th Percentile	12.1	0.052	6.1
Mean	20.4	0.074	6.2
95th Percentile	25.3	0.095	6.3
Percent Uncertainty	32.5%	29.5%	1.9%

Sensitivity Analysis Results

Time series plots and Box-Whisker-Plots are provided for all three responsive variables at stations LK-01 and LK-03. Sensitive parameters can be identified for each responsive water quality variable from the time series and Box-Whisker-Plots. For a Box-Whisker-plot, the blue star indicates the minimum value of the dataset; the lower end of the Whisker is the 10 percentile of the dataset; the lower end of the Box indicates the 25% percentile; the bar in the Box is the median value; the diamond shows the mean value; the upper end of the Box is the 75 percentile; the upper end of the Whisker is the 90% percentile; and the brown star is the maximum value of the dataset. The time series plots and Box-Whisker-Plots of modeled chlorophyll a, modeled TP, and modeled DO under different perturbation levels of these four model input coefficients and parameters at stations LK-01 and LK-03 are given in Figures 14 through 29 (chlorophyll a), Figures 30 through 45 (TP), and Figures 46 through 61 (DO), respectively.

As shown in Figures 14 through 29, for modeled chlorophyll a at station LK-03, watershed TP loads and maximum algal growth rate are the most sensitive parameters, while maximum algal growth rate is the single most sensitive parameter at station LK-01. For modeled TP at station LK-03, watershed TP load is the single most sensitive parameter, while watershed TP loads and maximum algal growth rate are the most sensitive parameters at station LK-01, as shown in Figure 30 through 45. Perturbations in all model inputs and parameters produce a much lower response in modeled DO than modeled chlorophyll a and TP (Figures 46 through 61). The maximum algal growth rate is seen to be the most sensitive parameter for DO.

LAKE MODEL UNCERTAINTY ANALYSIS SUMMARY AND CONCLUSIONS

Uncertainty analyses of the Tenkiller Ferry Lake EFDC water quality model were performed for three responsive variables of TP, chlorophyll a, and DO. Four perturbation levels (decrease by 50%, decrease by 25%, increase by 25%, and increase by 50% from the baseline) of four model input coefficients and parameters were evaluated with the calibrated EFDC lake model for the year 2006.

The four model input coefficients and parameters are watershed TP loads, maximum algae growth rate, PO4 sorption enhancement factor of sediment diagenesis, and P half-saturation constant for algae. The uncertainty analyses were conducted for both the entire 2006 calibration period (January 1 to December 31) and the stratified period for 2006 from April 1 to October 31.

Exceedance curves are given for visual inspection of the 90% confidence interval of EFDC-simulated water quality variables. The percent uncertainty is also calculated for each water quality responsive variable at both stations LK-01 and LK-03. Station LK-01 is located in the forebay area in the lacustrine zone and station LK-03 is in the transition zone close to the riverine sections of the upstream lake: the Illinois River and Baron Fork Creek.

For the Tenkiller Ferry Lake EFDC water quality model, the overall level of uncertainty is very low for the water quality variable of DO with values of calculated percent uncertainty less than 6%, while chlorophyll a and TP show higher percent uncertainty ranging from 28.0% to 32.5% for both the entire calibration period and the stratified period. All responsive water quality variables show a similar magnitude of percent uncertainty at both stations LK-01 and LK-03 even though there are significant differences in the magnitude of water quality variables between the two stations for both the entire calibration period and the stratified period.

At station LK-01 in the lacustrine zone, the mean values of chlorophyll a, TP, and DO for the stratified period are relatively lower than those for the entire calibration period. However, the values of percent uncertainty for chlorophyll a and TP are similar between the stratified period and the entire calibration period. The value of percent uncertainty for DO is higher for the stratified period than the entire calibration period.

At station LK-03 in the transition zone, there is not much difference in the mean values and calculated percent uncertainty for chlorophyll a, TP, and DO between the stratified period and the entire calibration period. The expected exception, however, is that the mean bottom layer DO concentration for the stratified period is lower than the mean bottom layer DO for the entire calibration period.

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Donigian, A.S. Jr. and J.T. Love. 2007. The Housatonic River Watershed Model: Model Application and Sensitivity/Uncertainty Analysis. 7th International IWA Symposium on System Analysis and Integrated Assessment in Water Management, May 7-9, 2007. Washington, DC. WATERMATEX Proceedings on CD-ROM.

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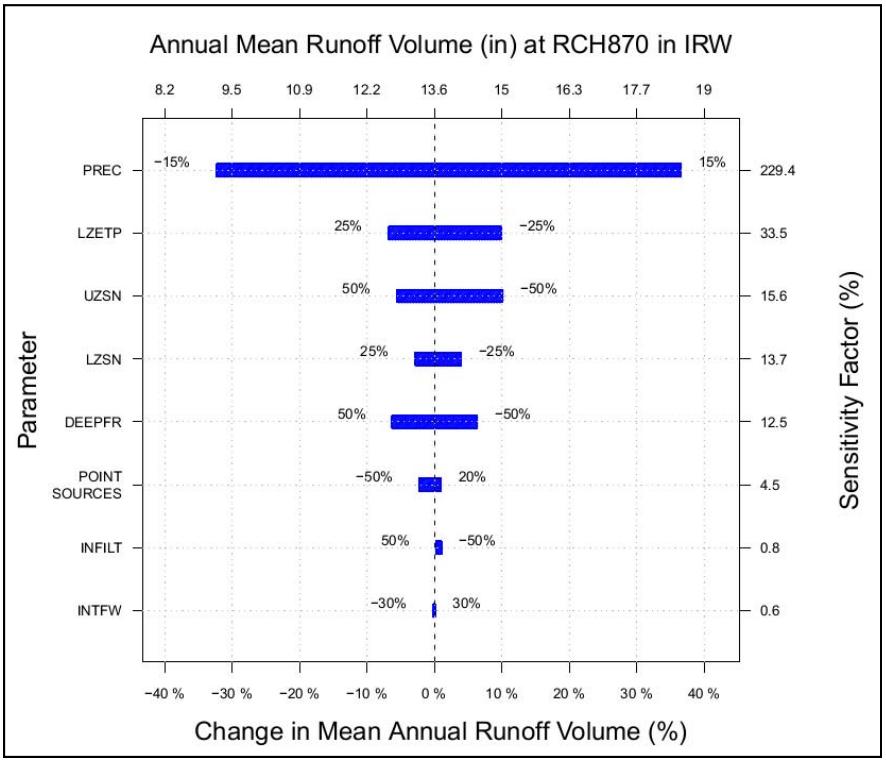
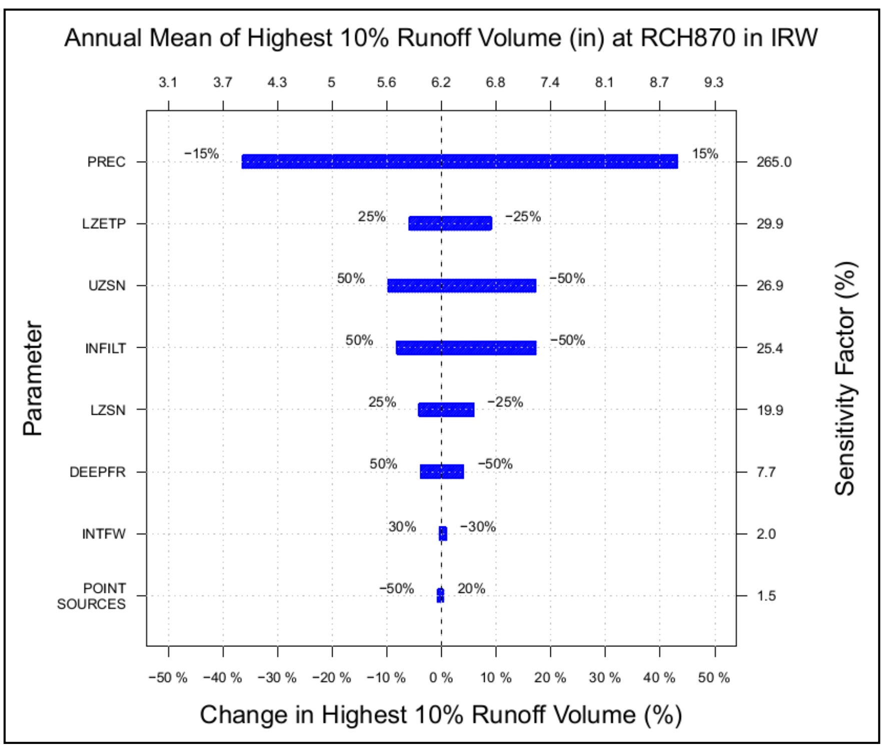
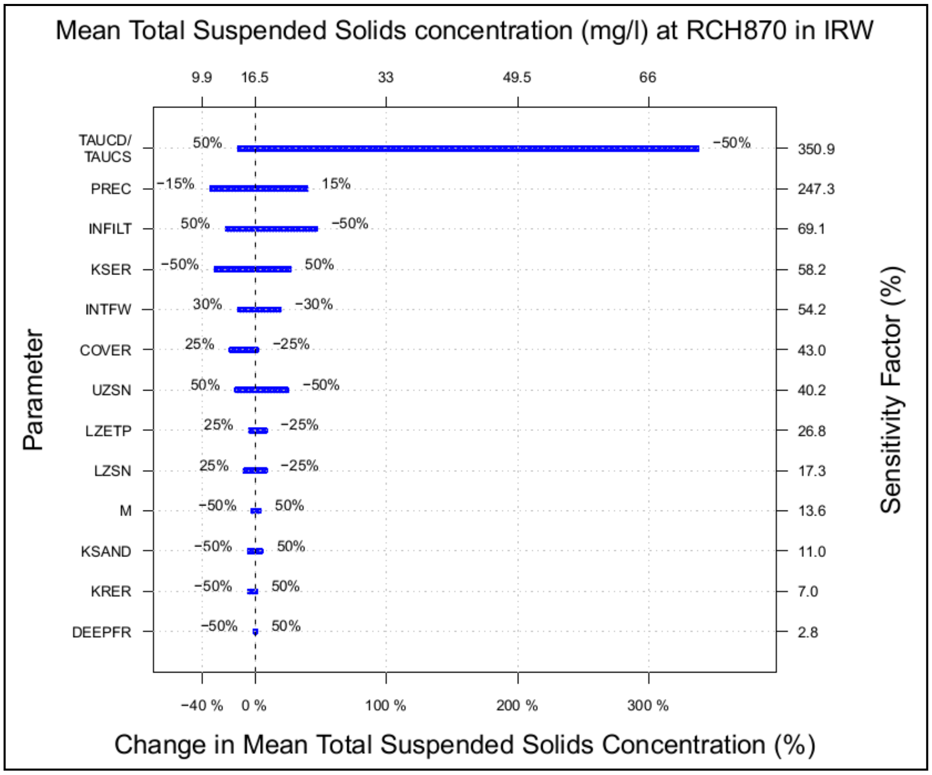
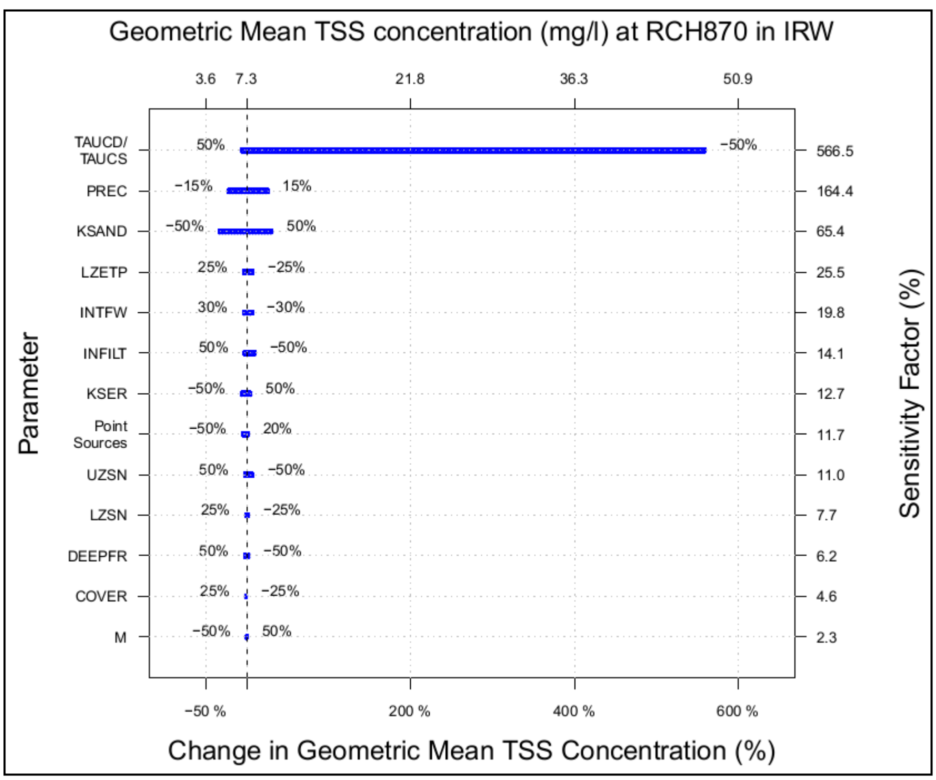
APPENDIX A

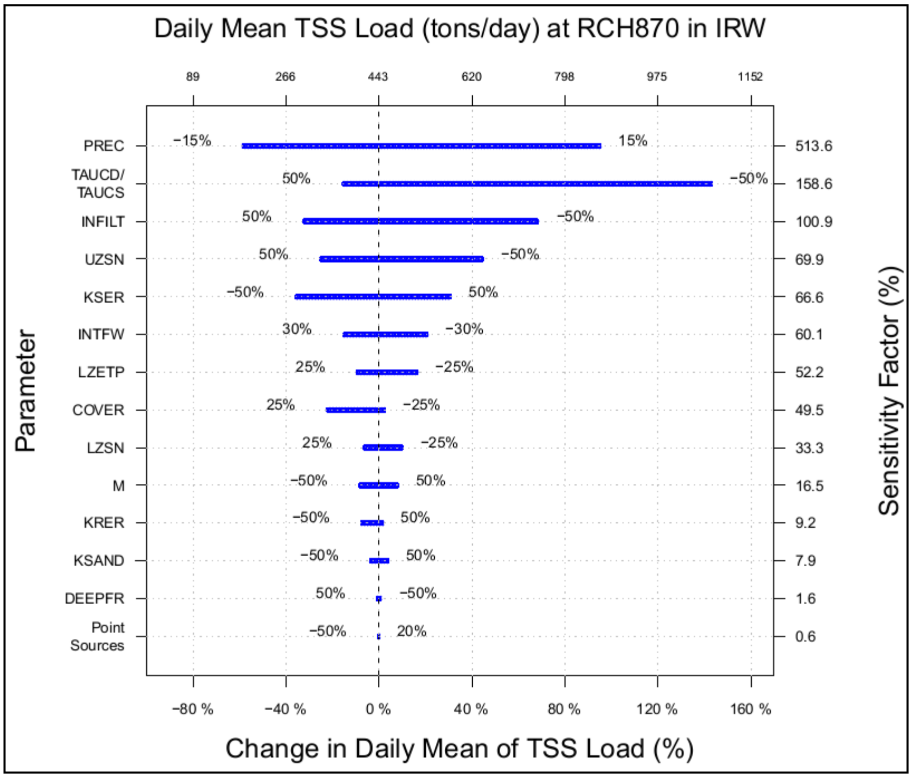
Tornado Diagrams of some key outputs of interest at RCH870 in the Illinois River Watershed. Please note that the Y-axis is not to scale.

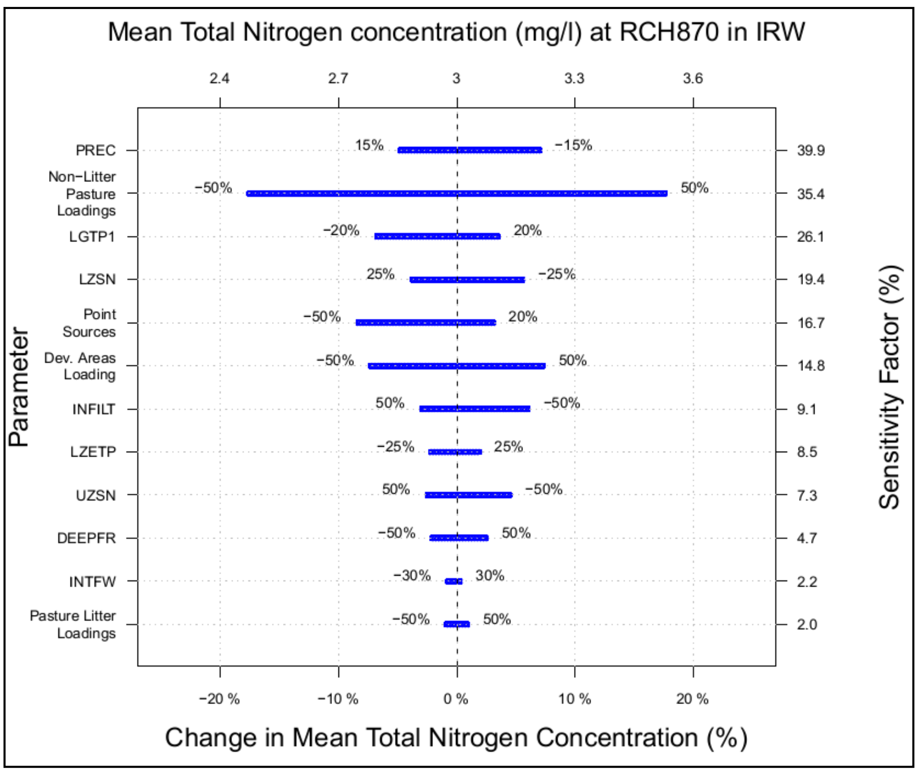


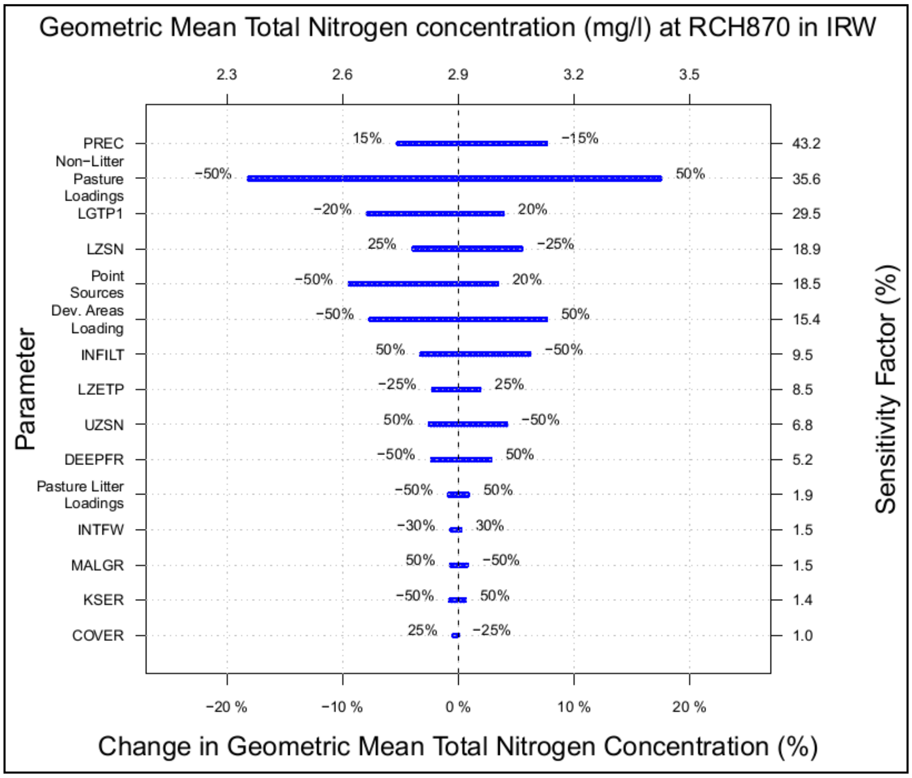


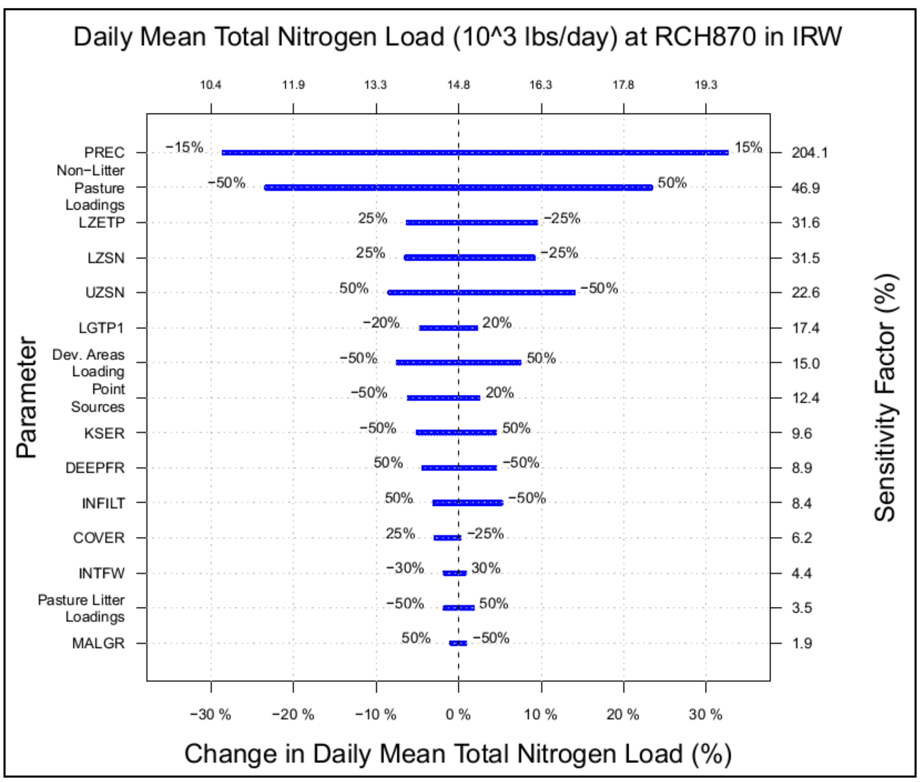

Mean Total Suspended Solids concentration (mg/l) at RCH870 in IRW
9.9
16.5
33
49.5
66
TAUCD/ TAUCS 50% −50% 350.9
PREC −15% 15% 247.3
INFILT 50% −50% 69.1
KSER −50% 50% 58.2
INTFW 30% −30% 54.2
COVER 25% −25% 43.0
UZSN 50% −50% 40.2
LZETP 25% −25% 26.8
LZSN 25% −25% 17.3
M −50% 50% 13.6
KSAND −50% 50% 11.0
KRER −50% 50% 7.0
DEEPFR −50% 50% 2.8
Parameter
Sensitivity Factor (%)
−40 %
0 %
100 %
200 %
300 %
Change in Mean Total Suspended Solids Concentration (%)

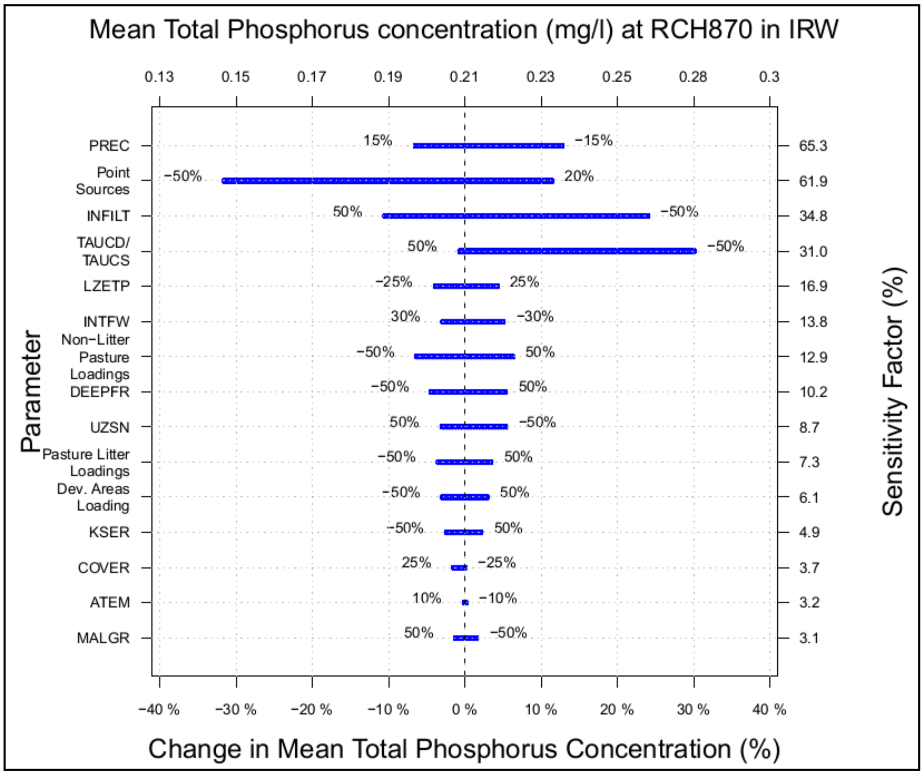

Geometric Mean TSS concentration (mg/l) at RCH870 in IRW
3.6
7.3
21.8
36.3
50.9
TAUCD/ TAUCS 50% −50% 566.5
PREC −15% 15% 164.4
KSAND −50% 50% 65.4
LZETP 25% −25% 25.5
INTFW 30% −30% 19.8
INFILT 50% −50% 14.1
KSER −50% 50% 12.7
Point Sources −50% 20% 11.7
UZSN 50% −50% 11.0
LZSN 25% −25% 7.7
DEEPFR 50% −50% 6.2
COVER 25% −25% 4.6
M −50% 50% 2.3
Parameter
Sensitivity Factor (%)
−50 %
200 %
400 %
600 %
Change in Geometric Mean TSS Concentration (%)

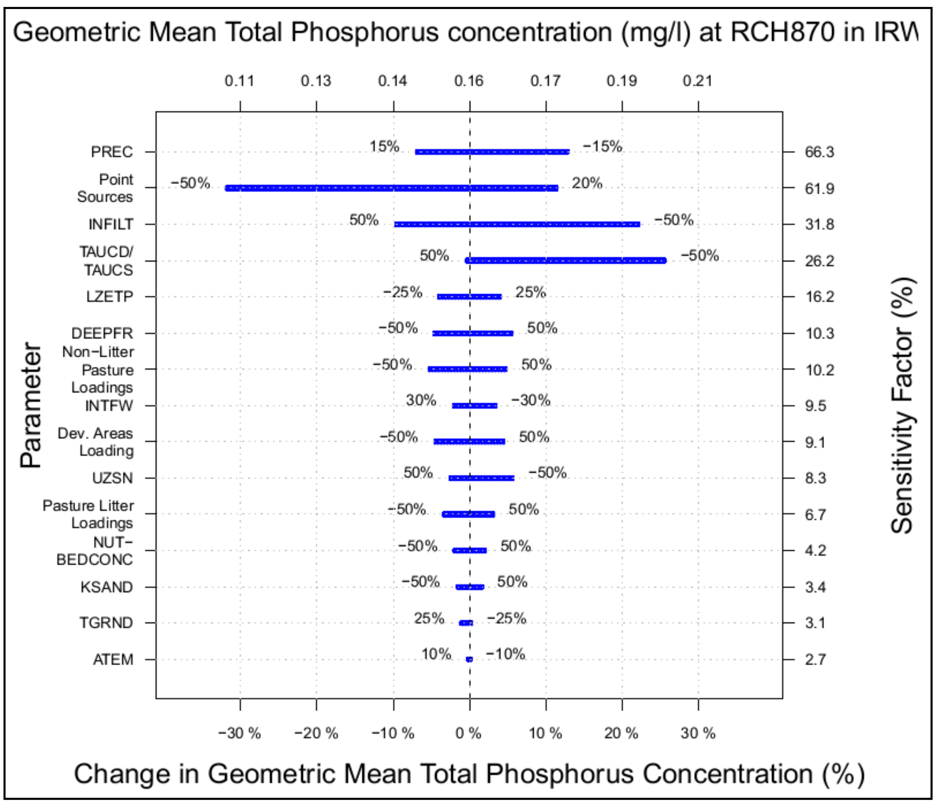

Daily Mean TSS Load (tons/day) at RCH870 in IRW
89
266
443
620
798
975
1152
PREC
TAUCD/ TAUCS
INFILT
UZSN
KSER
INTFW
LZETP
COVER
LZSN
M
KRER
KSAND
DEEPFR
Point Sources
Parameter
Sensitivity Factor (%)
513.6
158.6
100.9
69.9
66.6
60.1
52.2
49.5
33.3
16.5
9.2
7.9
1.6
0.6
−80 %
−40 %
0 %
40 %
80 %
120 %
160 %
Change in Daily Mean of TSS Load (%)

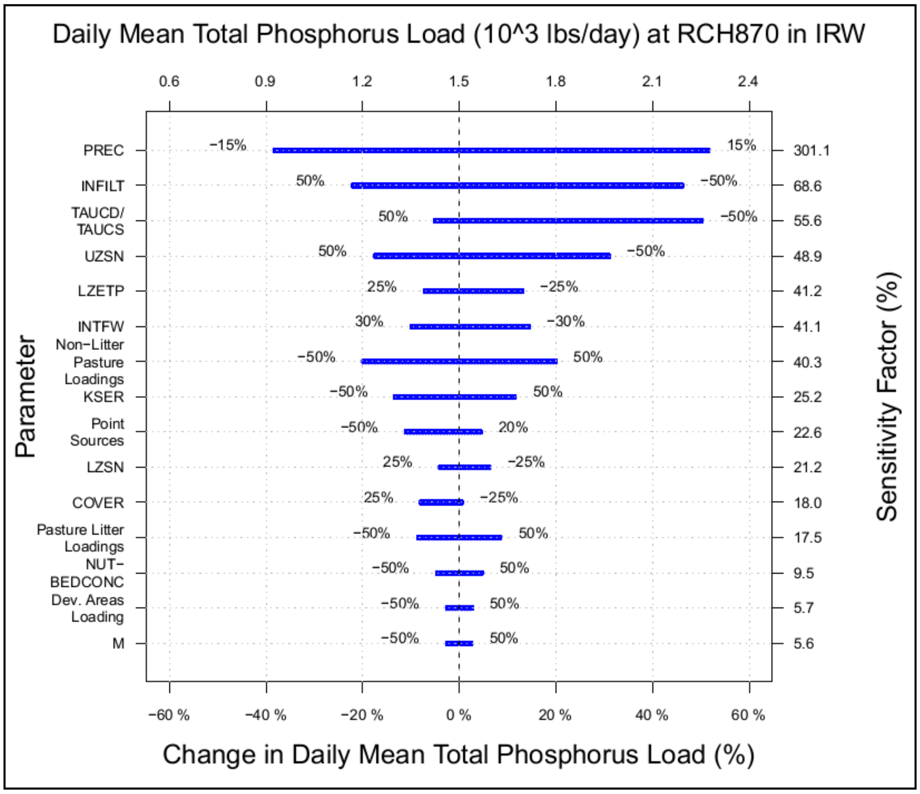

Mean Total Nitrogen concentration (mg/l) at RCH870 in IRW
2.4
2.7
3
3.3
3.6
PREC
Non−Litter Pasture Loadings
LGTP1
LZSN
Point Sources
Dev. Areas Loading
INFILT
LZETP
UZSN
DEEPFR
INTFW
Pasture Litter Loadings
Parameter
Sensitivity Factor (%)
39.9
35.4
26.1
19.4
16.7
14.8
9.1
8.5
7.3
4.7
2.2
2.0
−20 %
−10 %
0 %
10 %
20 %
Change in Mean Total Nitrogen Concentration (%)


Geometric Mean Total Nitrogen concentration (mg/l) at RCH870 in IRW
2.3
2.6
2.9
3.2
3.5
Parameter
PREC
Non−Litter Pasture Loadings
LGTP1
LZSN
Point Sources
Dev. Areas Loading
INFILT
LZETP
UZSN
DEEPFR
Pasture Litter Loadings
INTFW
MALGR
KSER
COVER
Sensitivity Factor (%)
43.2
35.6
29.5
18.9
18.5
15.4
9.5
8.5
6.8
5.2
1.9
1.5
1.5
1.4
1.0
−20 %
−10 %
0 %
10 %
20 %
Change in Geometric Mean Total Nitrogen Concentration (%)


Daily Mean Total Nitrogen Load (10^3 lbs/day) at RCH870 in IRW
10.4
11.9
13.3
14.8
16.3
17.8
19.3
Parameter
PREC
Non−Litter Pasture Loadings
LZETP
LZSN
UZSN
LGTP1
Dev. Areas Loading
Point Sources
KSER
DEEPFR
INFILT
COVER
INTFW
Pasture Litter Loadings
MALGR
Sensitivity Factor (%)
204.1
46.9
31.6
31.5
22.6
17.4
15.0
12.4
9.6
8.9
8.4
6.2
4.4
3.5
1.9
−30 %
−20 %
−10 %
0 %
10 %
20 %
30 %
Change in Daily Mean Total Nitrogen Load (%)


Mean Total Phosphorus concentration (mg/l) at RCH870 in IRW
0.13
0.15
0.17
0.19
0.21
0.23
0.25
0.28
0.3
PREC
Point Sources
INFILT
TAUCD/ TAUCS
LZETP
INTFW
Non−Litter Pasture Loadings
DEEPFR
UZSN
Pasture Litter Loadings
Dev. Areas Loading
KSER
COVER
ATEM
MALGR
Parameter
Sensitivity Factor (%)
65.3
61.9
34.8
31.0
16.9
13.8
12.9
10.2
8.7
7.3
6.1
4.9
3.7
3.2
3.1
−40 %
−30 %
−20 %
−10 %
0 %
10 %
20 %
30 %
40 %
Change in Mean Total Phosphorus Concentration (%)


Geometric Mean Total Phosphorus concentration (mg/l) at RCH870 in IRW
0.11
0.13
0.14
0.16
0.17
0.19
0.21
PREC
Point Sources
INFILT
TAUCD/ TAUCS
LZETP
DEEPFR
Non−Litter Pasture Loadings
INTFW
Dev. Areas Loading
UZSN
Pasture Litter Loadings
NUT− BEDCONC
KSAND
TGRND
ATEM
Parameter
Sensitivity Factor (%)
66.3
61.9
31.8
26.2
16.2
10.3
10.2
9.5
9.1
8.3
6.7
4.2
3.4
3.1
2.7
−30 %
−20 %
−10 %
0 %
10 %
20 %
30 %
Change in Geometric Mean Total Phosphorus Concentration (%)


Daily Mean Total Phosphorus Load (10^3 lbs/day) at RCH870 in IRW
0.6
0.9
1.2
1.5
1.8
2.1
2.4
Parameter
PREC
INFILT
TAUCD/ TAUCS
UZSN
LZETP
INTFW
Non−Litter Pasture Loadings
KSER
Point Sources
LZSN
COVER
Pasture Litter Loadings
NUT− BEDCONC
Dev. Areas Loading
M
−15%
15%
50%
−50%
50%
−50%
50%
−50%
25%
−25%
30%
−30%
−50%
50%
−50%
50%
−50%
20%
25%
−25%
25%
−25%
−50%
50%
−50%
50%
−50%
50%
−50%
50%
Sensitivity Factor (%)
301.1
68.6
55.6
48.9
41.2
41.1
40.3
25.2
22.6
21.2
18.0
17.5
9.5
5.7
5.6
−60 %
−40 %
−20 %
0 %
20 %
40 %
60 %
Change in Daily Mean Total Phosphorus Load (%)

APPENDIX B

Tenkiller Ferry Lake EFDC Water Quality Model Sensitivity Analysis and Uncertainly Analysis Results

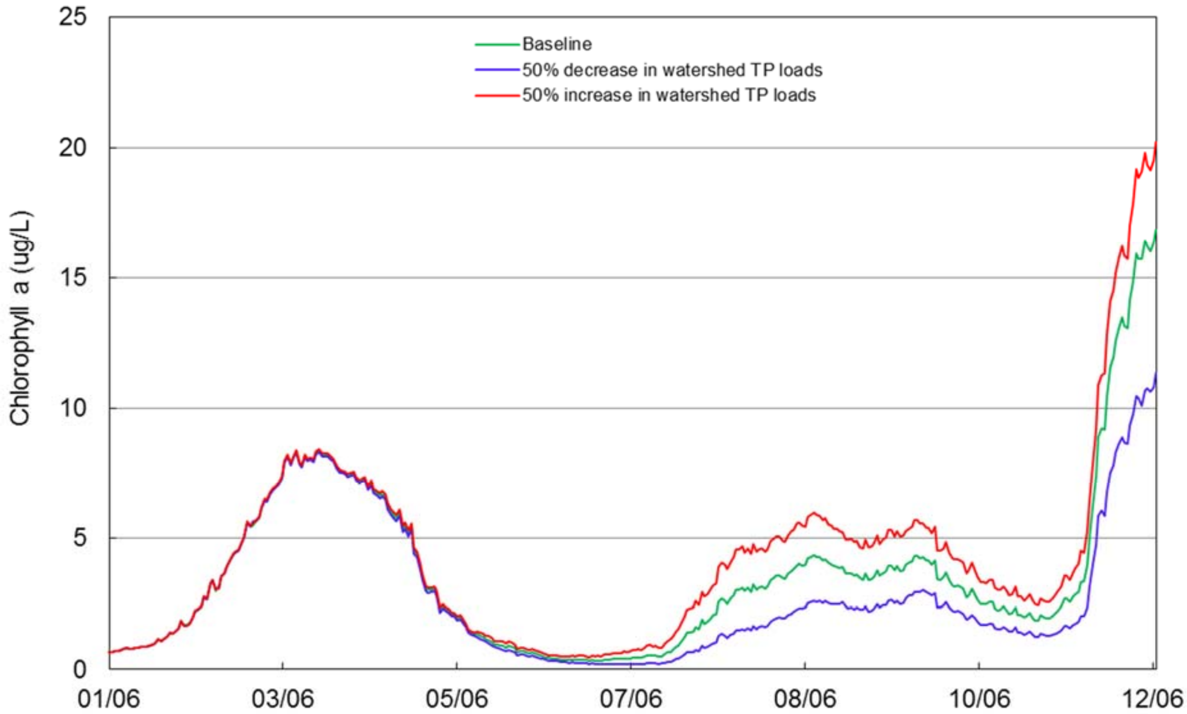


Figure 11 Modeled Surface Chlorophyll a at LK-01 under Perturbation Levels of Watershed TP Loads

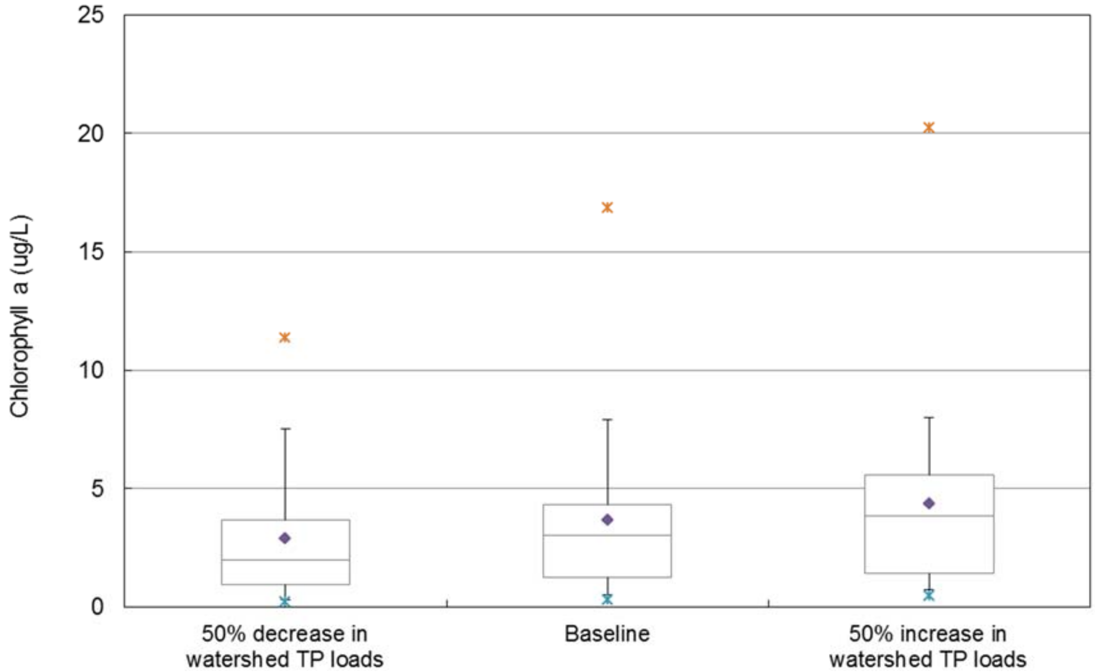


Figure 12 Box-Whisker-Plot of Surface Chlorophyll a at LK-01 under Watershed TP Loads Perturbation

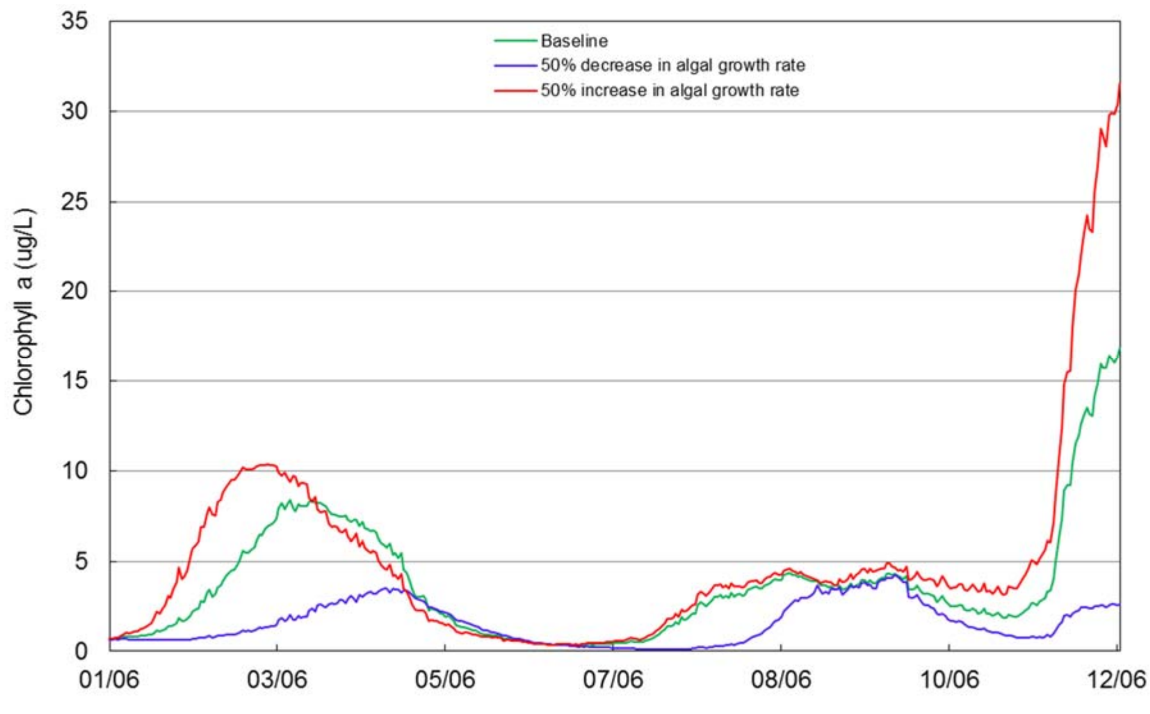


Figure 13 Modeled Surface Chlorophyll a at LK-01 under Perturbation Levels of Algal Growth Rate

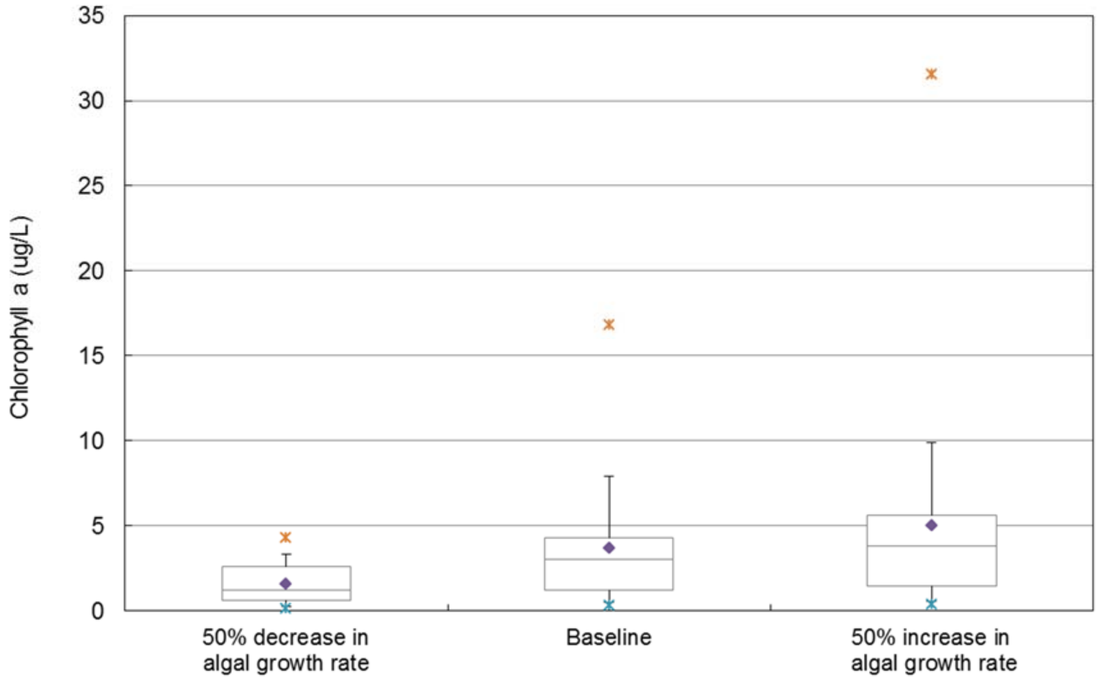


Figure 14 Box-Whisker-Plot of Surface Chlorophyll a at LK-01 under Algal Growth Rate Perturbation

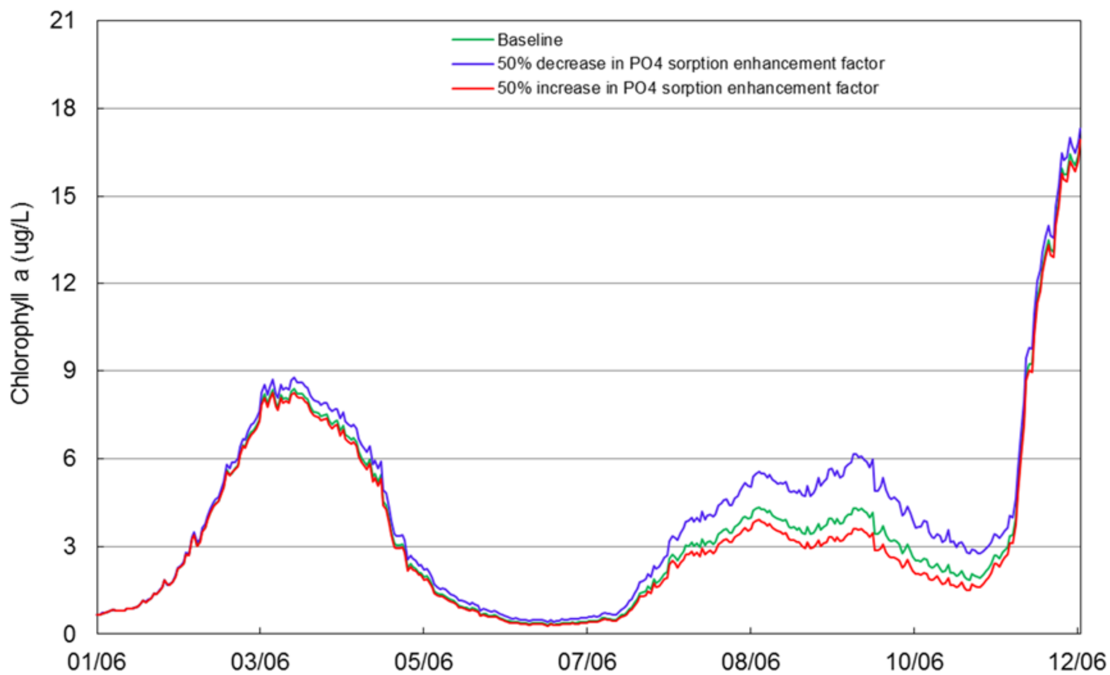


Figure 15 Modeled Surface Chlorophyll a at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

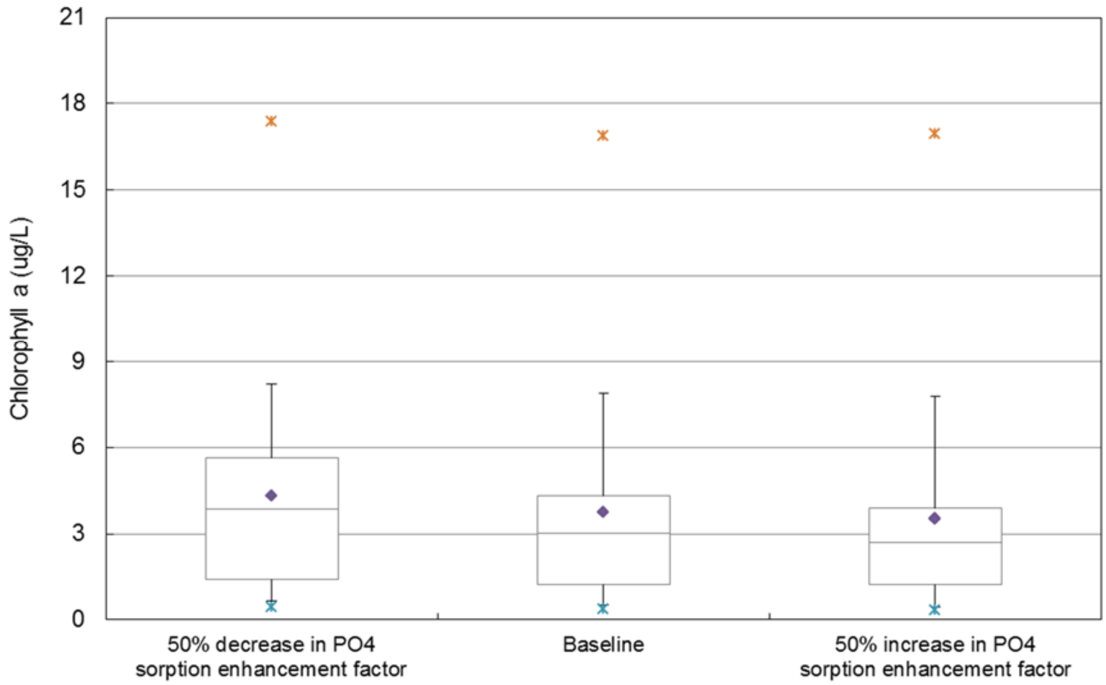


Figure 16 Box-Whisker-Plot of Surface Chlorophyll a at LK-01 under PO4 Sorption Enhancement Factor Perturbation

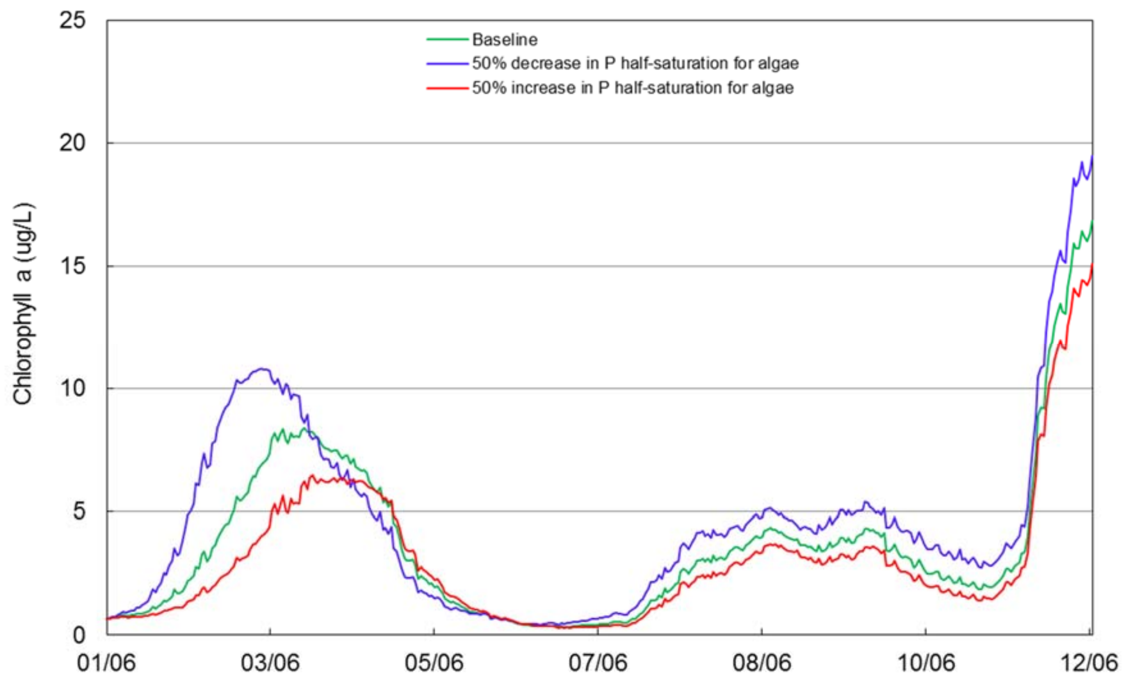


Figure 17 Modeled Surface Chlorophyll a at LK-01 under Perturbation of P Half-saturation for Algae

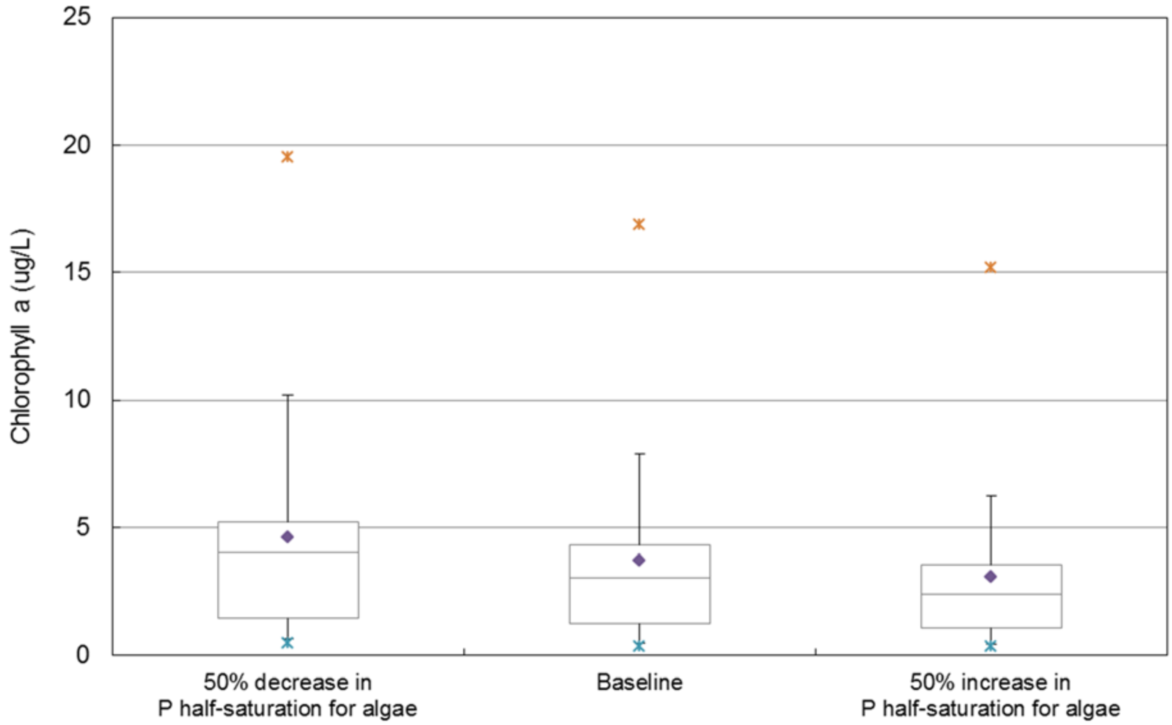


Figure 18 Box-Whisker-Plot of Surface Chlorophyll a at LK-01 under P Half-saturation for Algae Perturbation

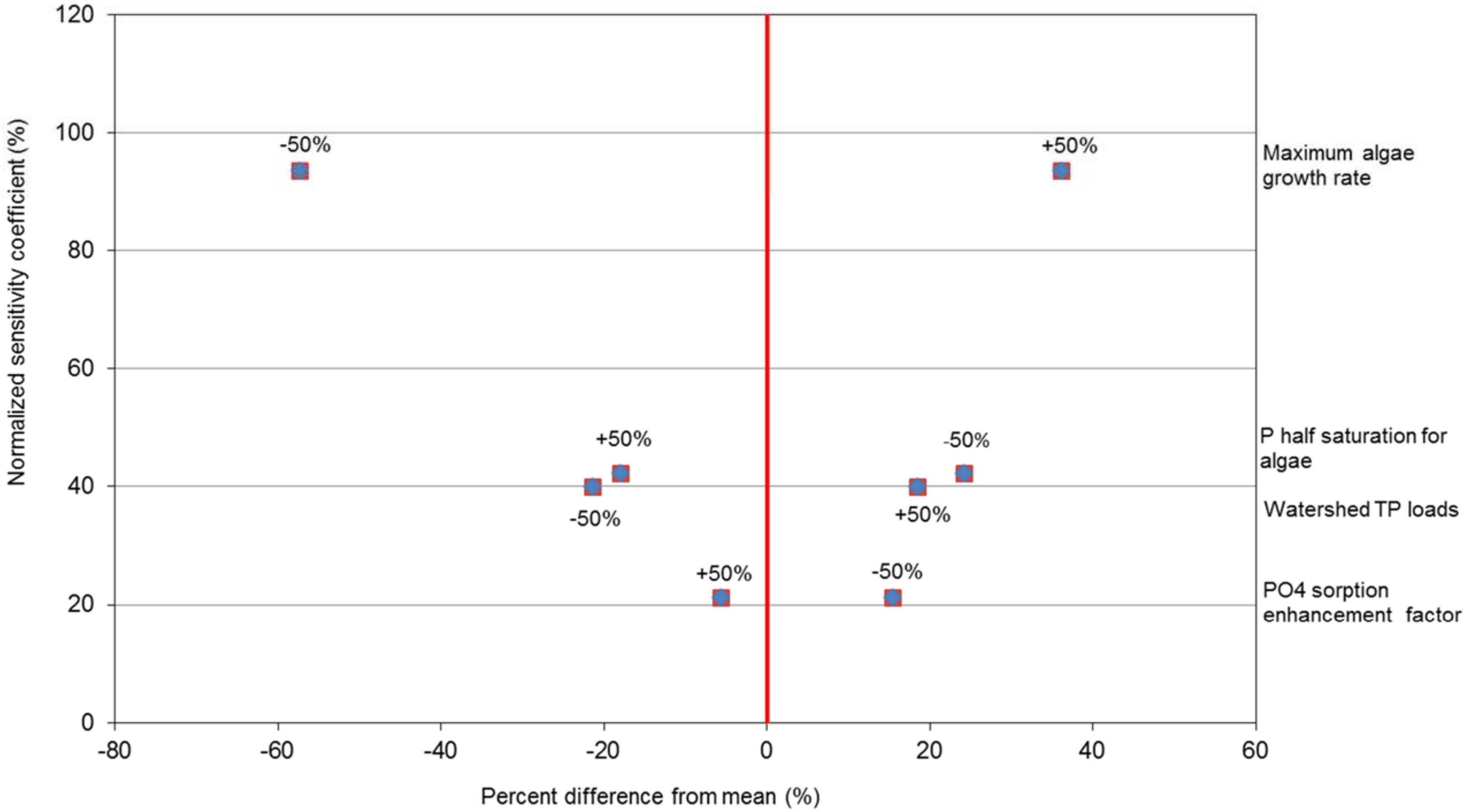


Figure 19 Tornado Diagram for Sensitivity Analysis of Modeled Surface Chlorophyll a at LK-01

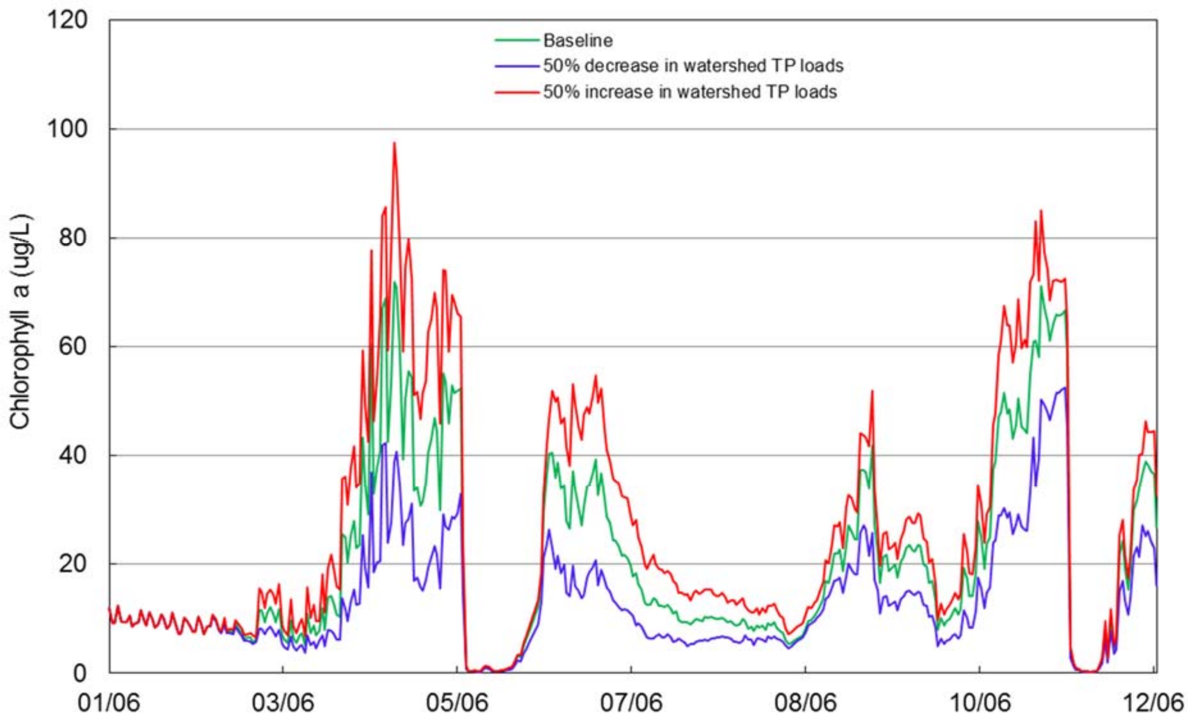


Figure 20 Modeled Surface Chlorophyll a at LK-03 under Perturbation Levels of Watershed TP Loads

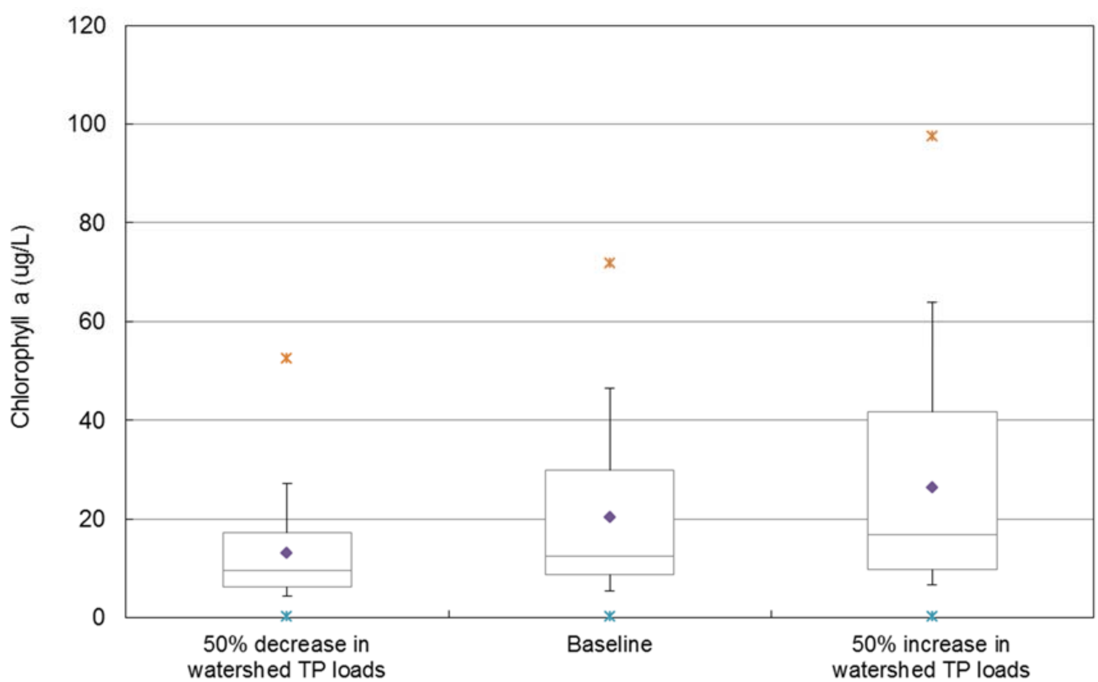


Figure 21 Box-Whisker-Plot of Surface Chlorophyll a at LK-03 under Watershed TP Loads Perturbation

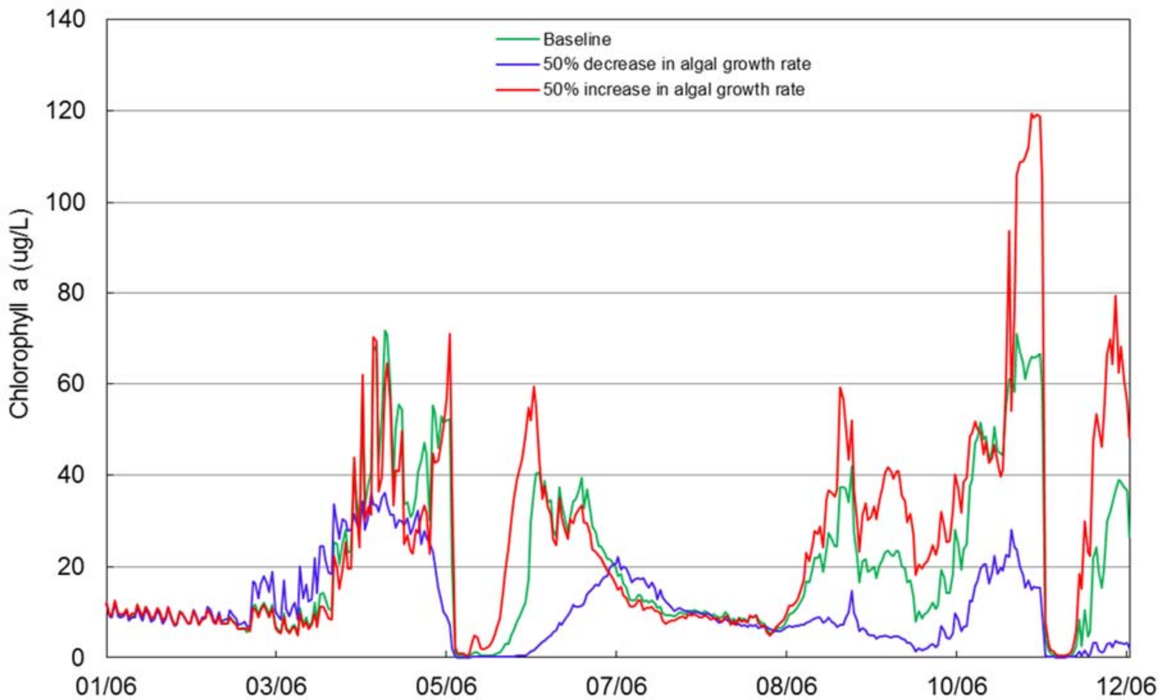


Figure 22 Modeled Surface Chlorophyll a at LK-03 under Perturbation Levels of Algal Growth Rate

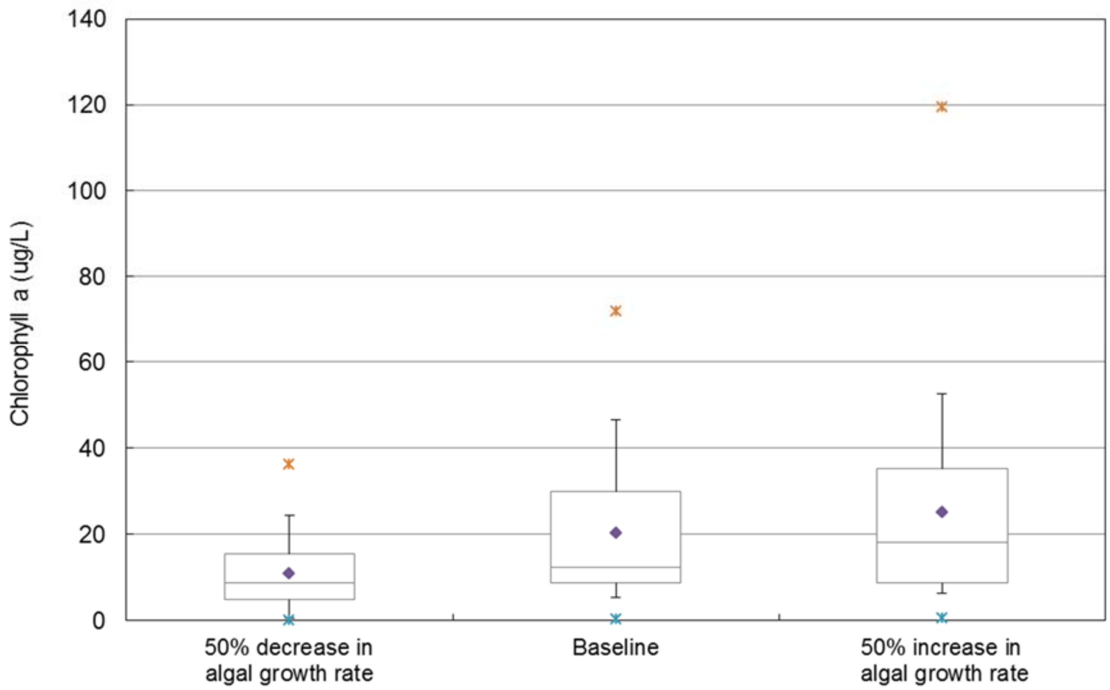


Figure 23 Box-Whisker-Plot of Surface Chlorophyll a at LK-03 under Algal Growth Rate Perturbation

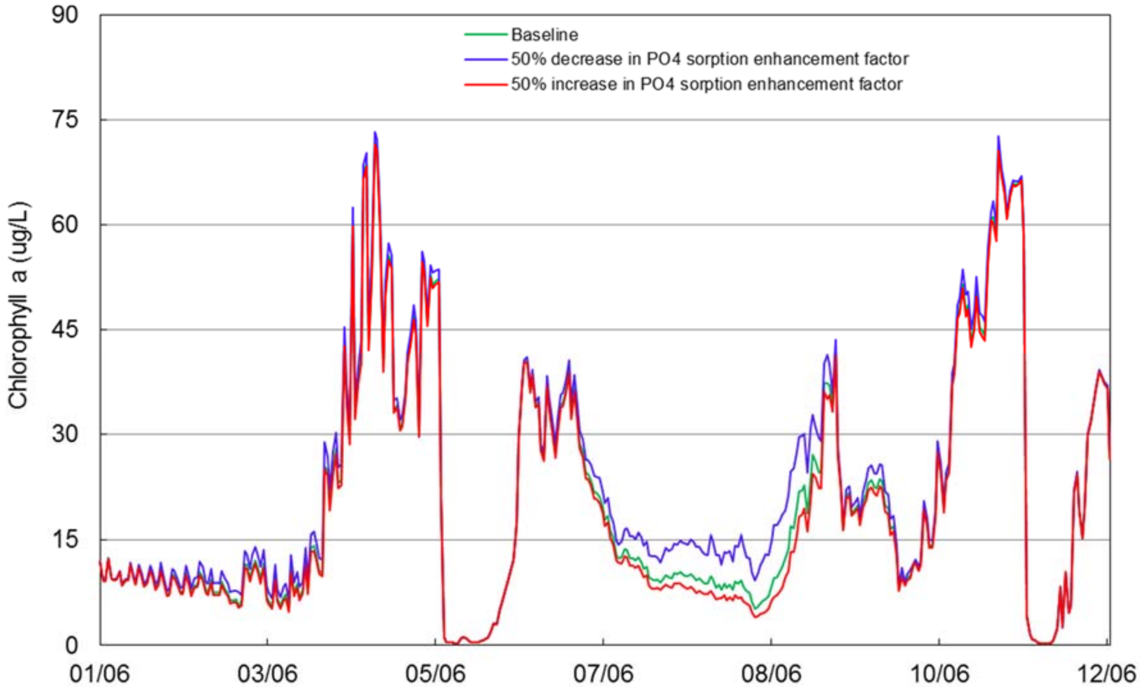


Figure 24 Modeled Surface Chlorophyll a at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

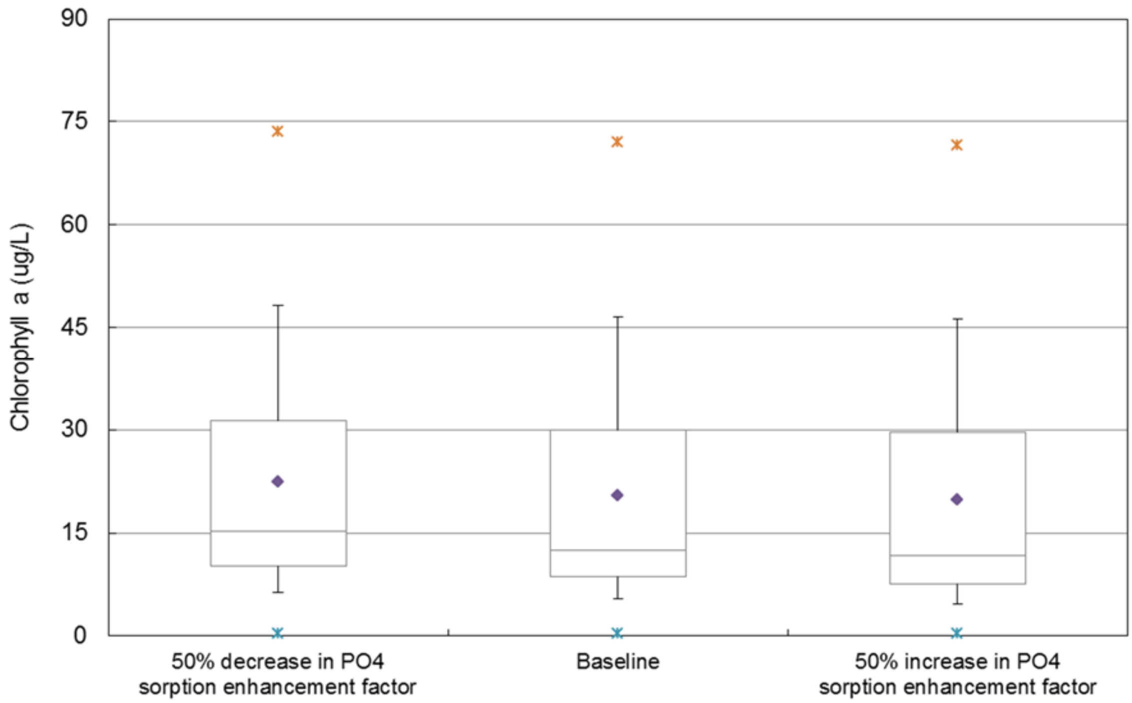


Figure 25 Box-Whisker-Plot of Surface Chlorophyll a at LK-03 under PO4 Sorption Enhancement Factor Perturbation

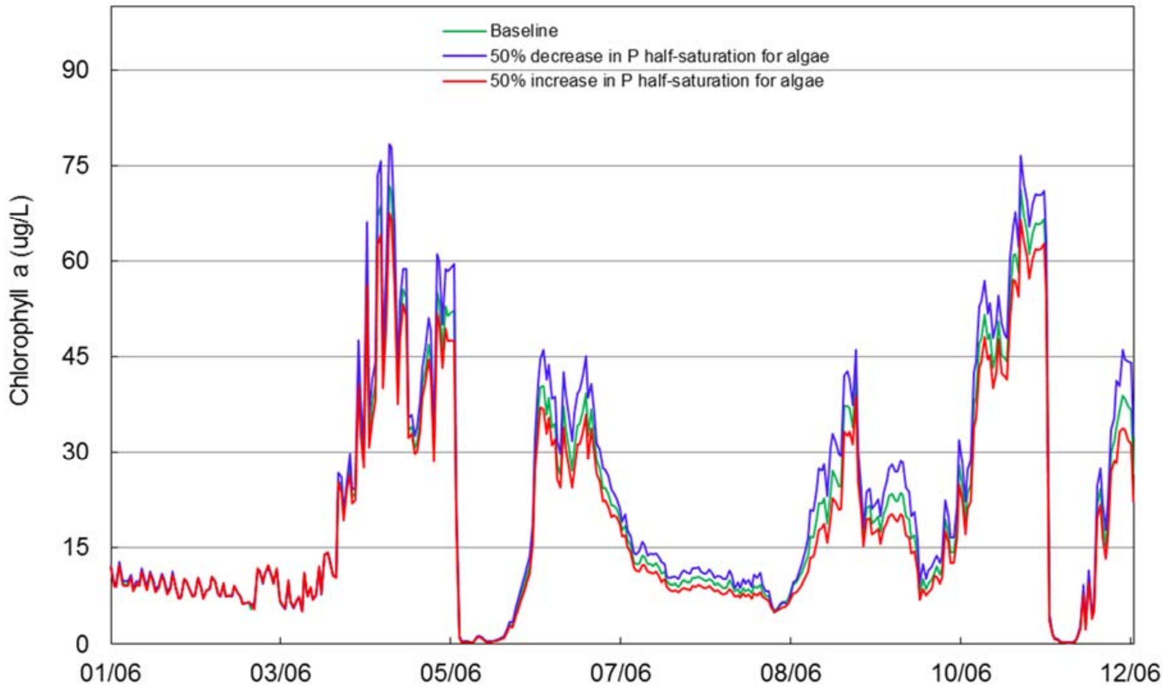


Figure 26 Modeled Surface Chlorophyll a at LK-03 under Perturbation of P Half-saturation for Algae

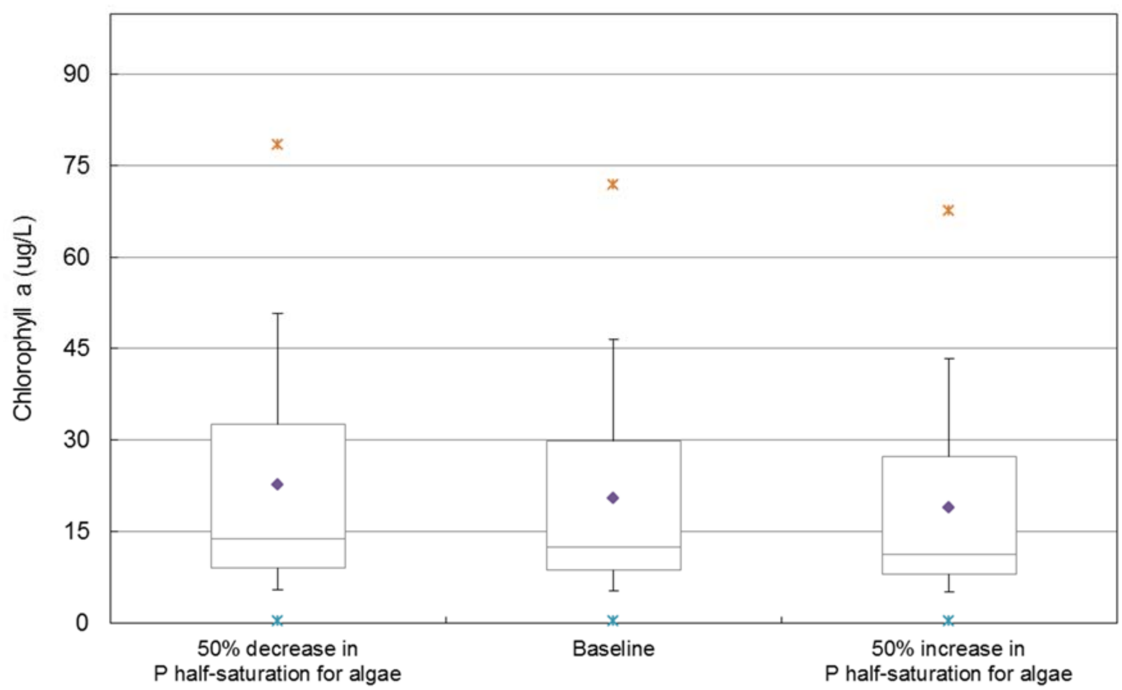


Figure 27 Box-Whisker-Plot of Surface Chlorophyll a at LK-03 under P Half-saturation for Algae Perturbation

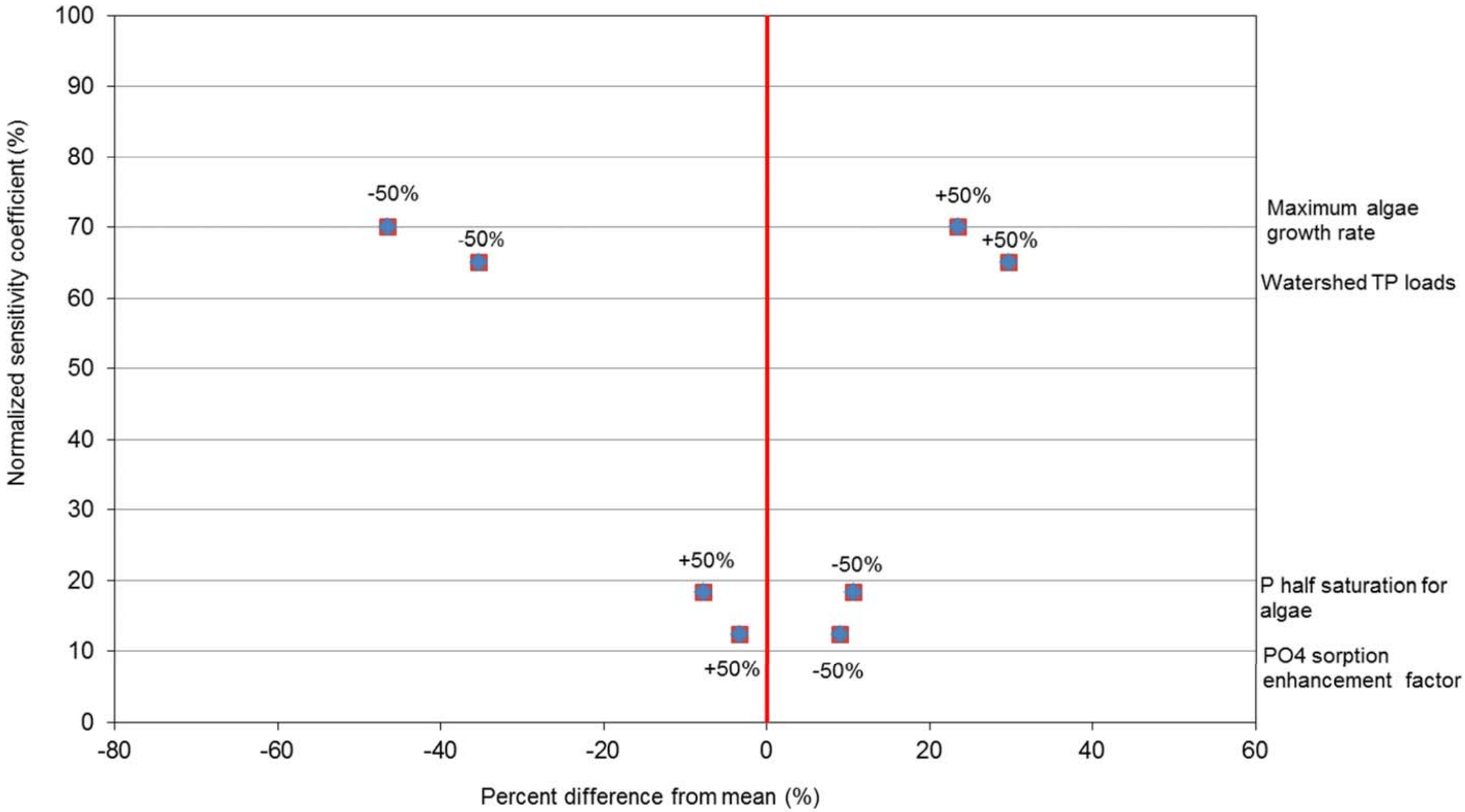


Figure 28 Tornado Diagram for Sensitivity Analysis of Modeled Surface Chlorophyll a at LK-03

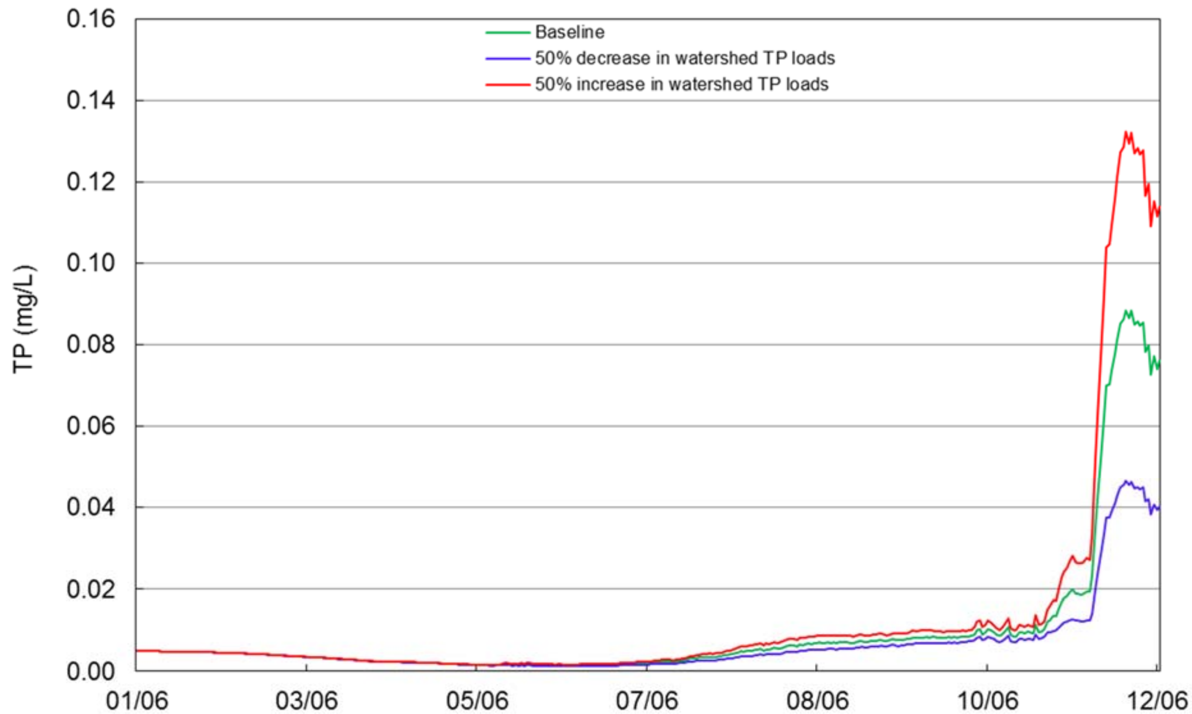


Figure 29 Modeled Depth-averaged TP at LK-01 under Different Perturbation Levels of Watershed TP Loads

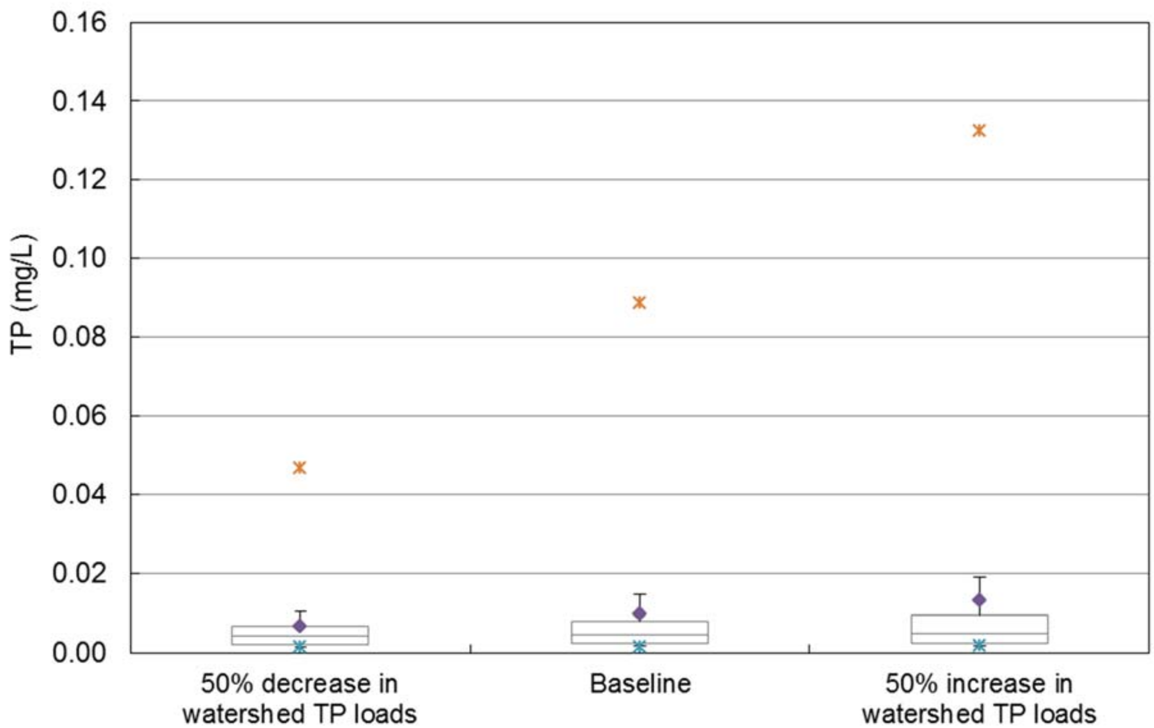


Figure 30 Box-Whisker-Plot of Depth-averaged TP at LK-01 under Different Watershed TP Loads Perturbation

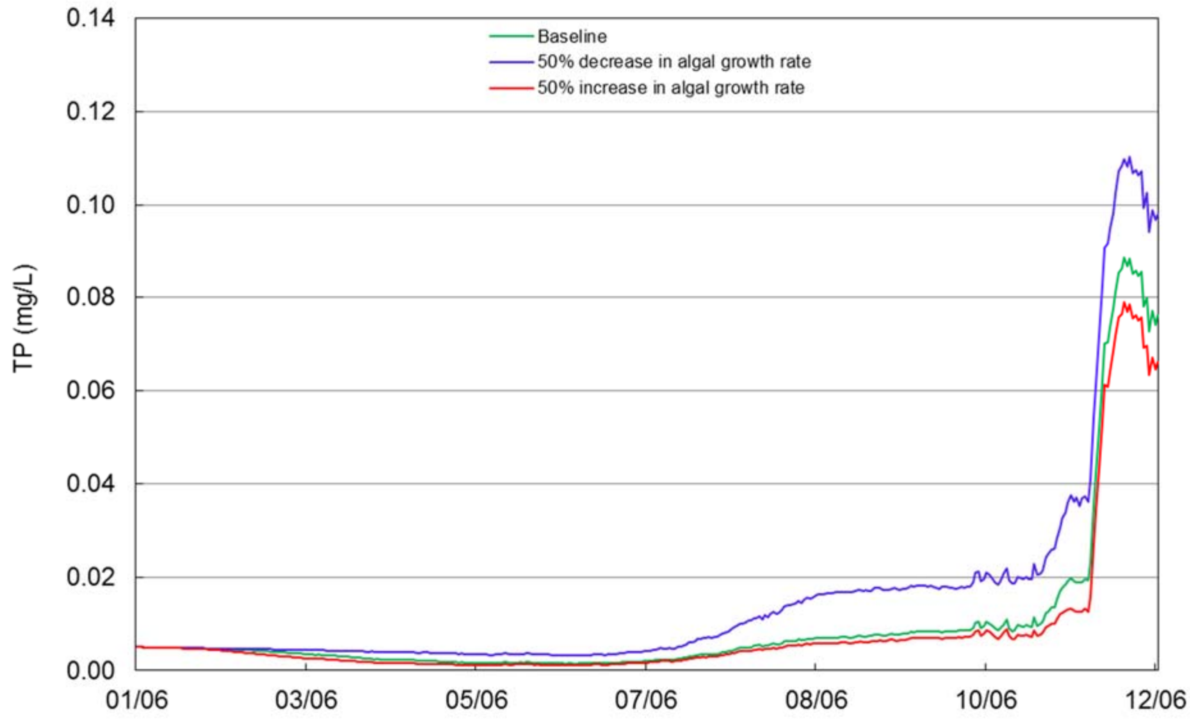


Figure 31 Modeled Depth-averaged TP at LK-01 under Different Perturbation Levels of Algal Growth Rate

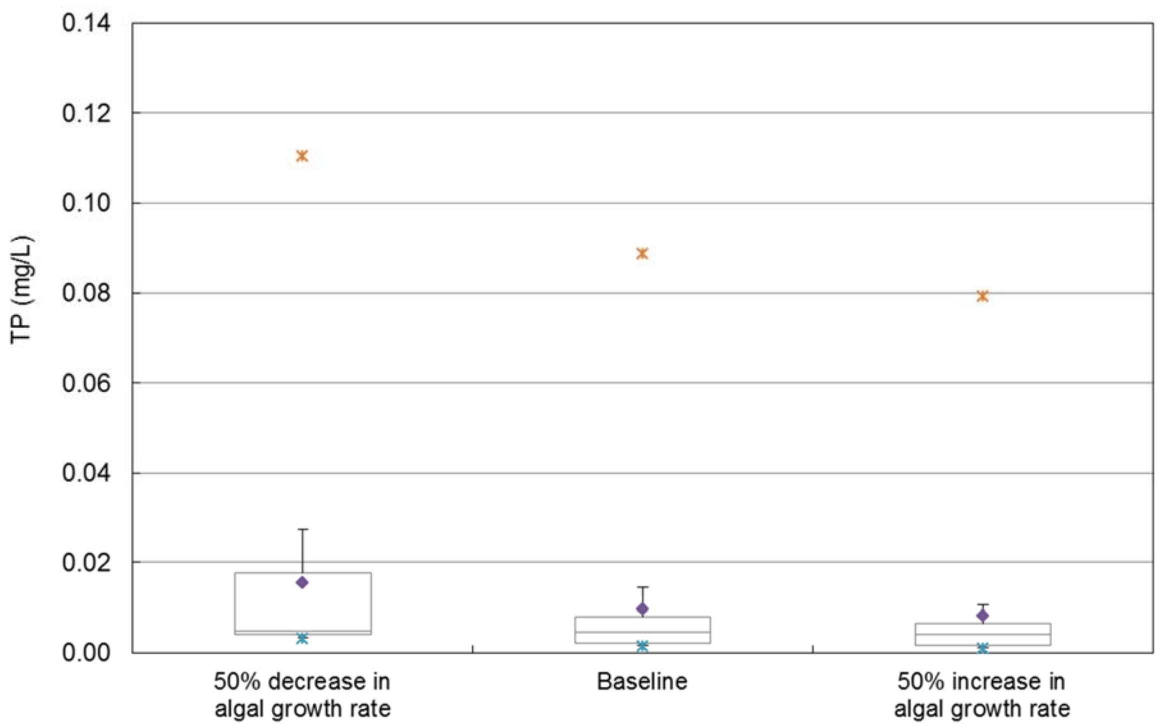


Figure 32 Box-Whisker-Plot of Depth-averaged TP at LK-01 under Different Algal Growth Rate Perturbation

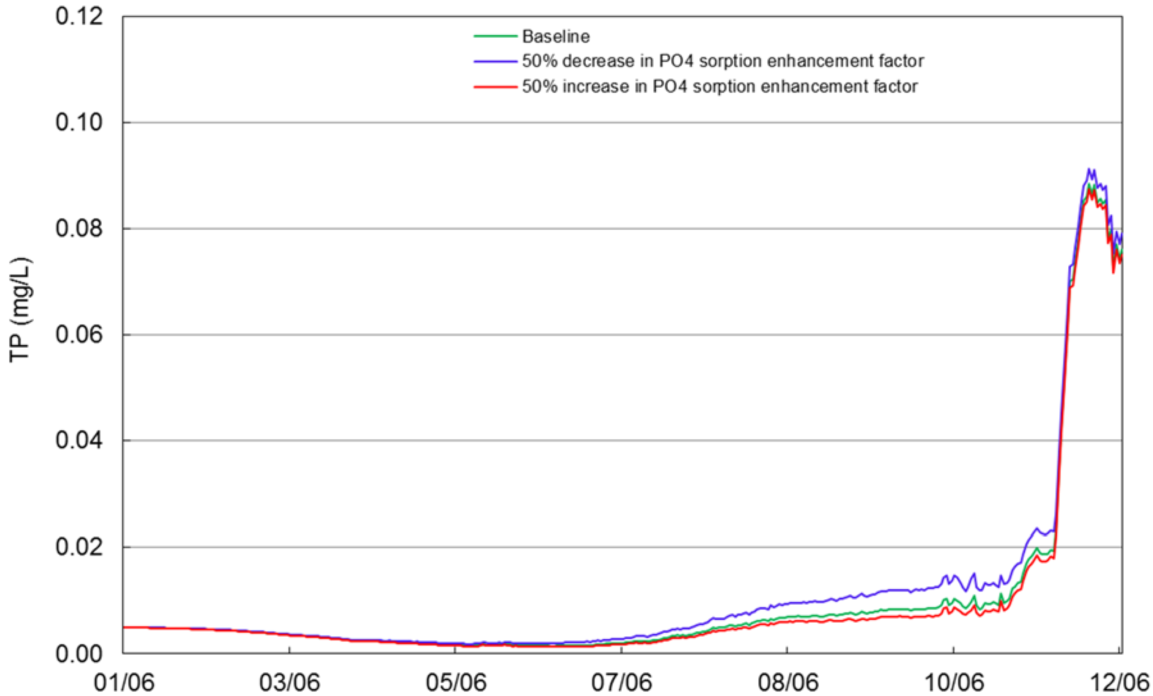


Figure 33 Modeled Depth-averaged TP at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

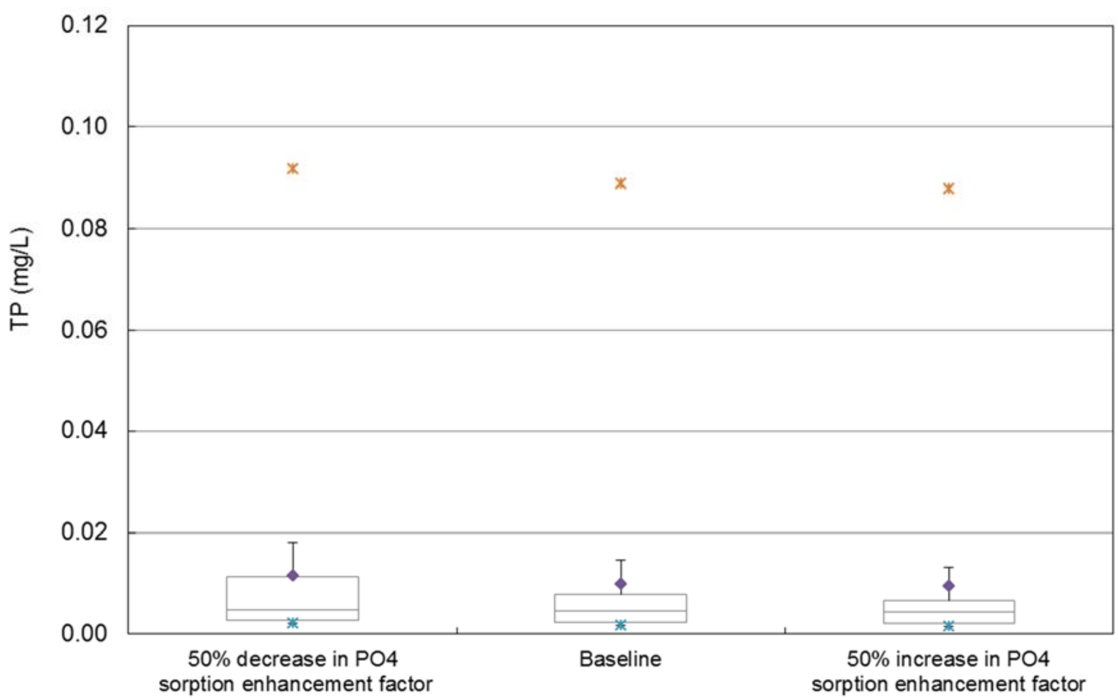


Figure 34 Box-Whisker-Plot of Depth-averaged TP at LK-01 under PO4 Sorption Enhancement Factor Perturbation

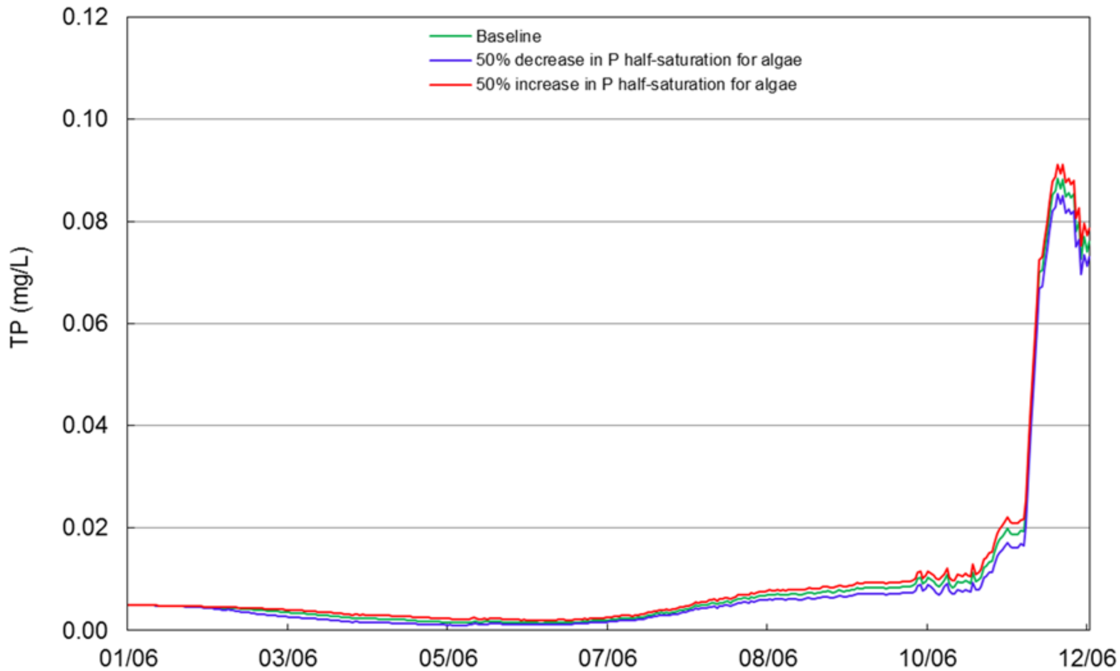


Figure 35 Modeled Depth-averaged TP at LK-01 under Different Perturbation of P Half-saturation for Algae

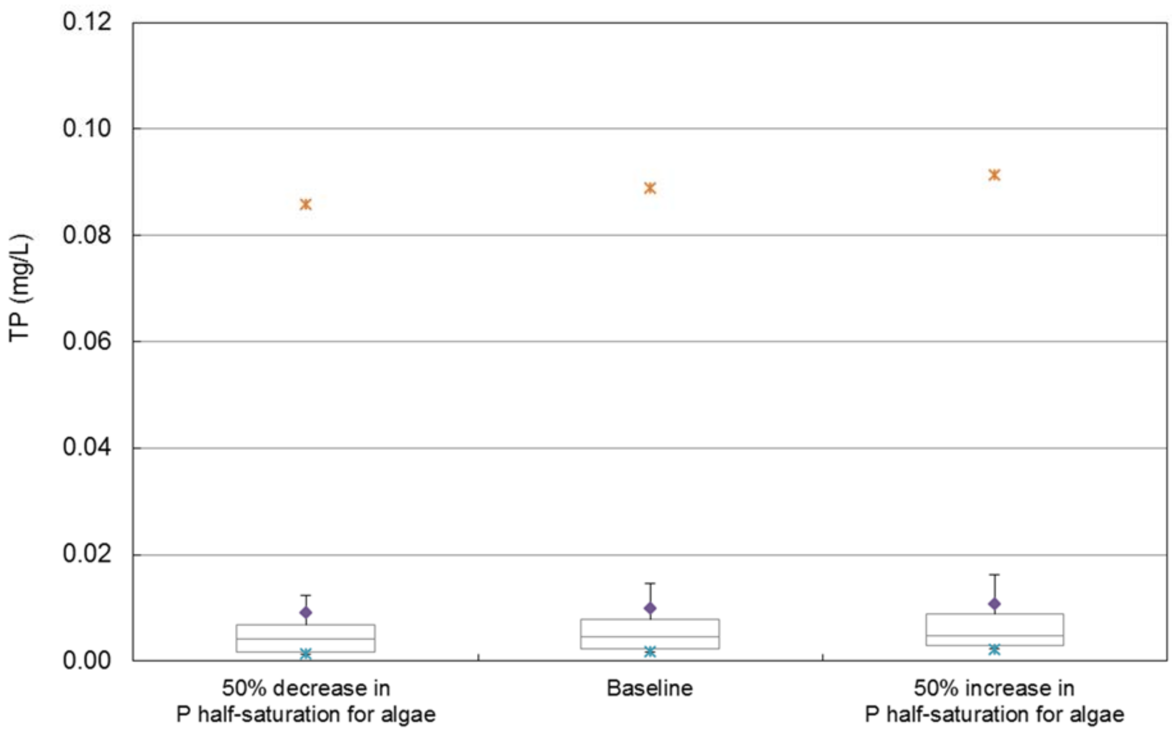


Figure 36 Box-Whisker-Plot of Depth-averaged TP at LK-01 under P Half-saturation for Algae Perturbation

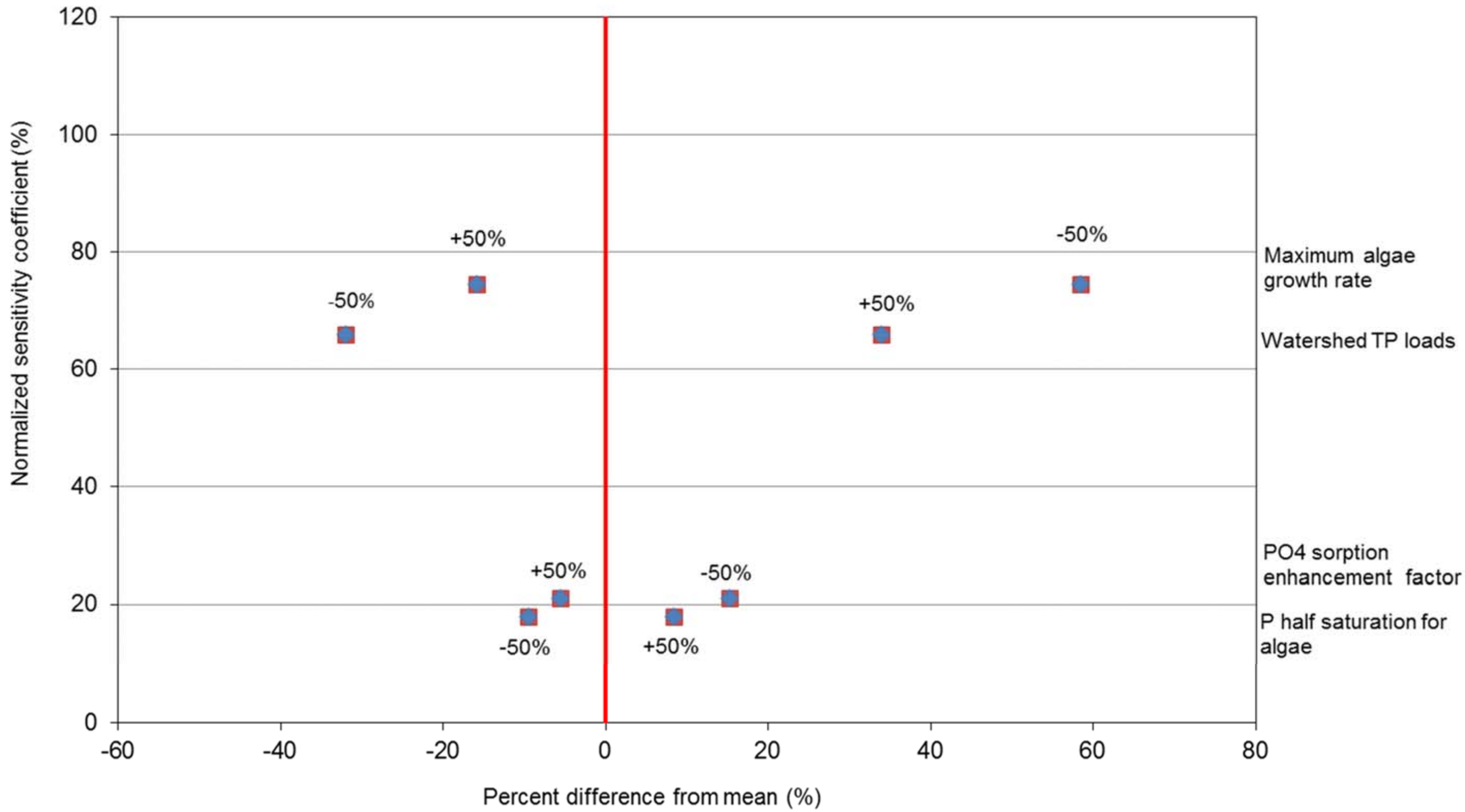


Figure 37 Tornado Diagram for Sensitivity Analysis of Modeled Depth-averaged TP at LK-01

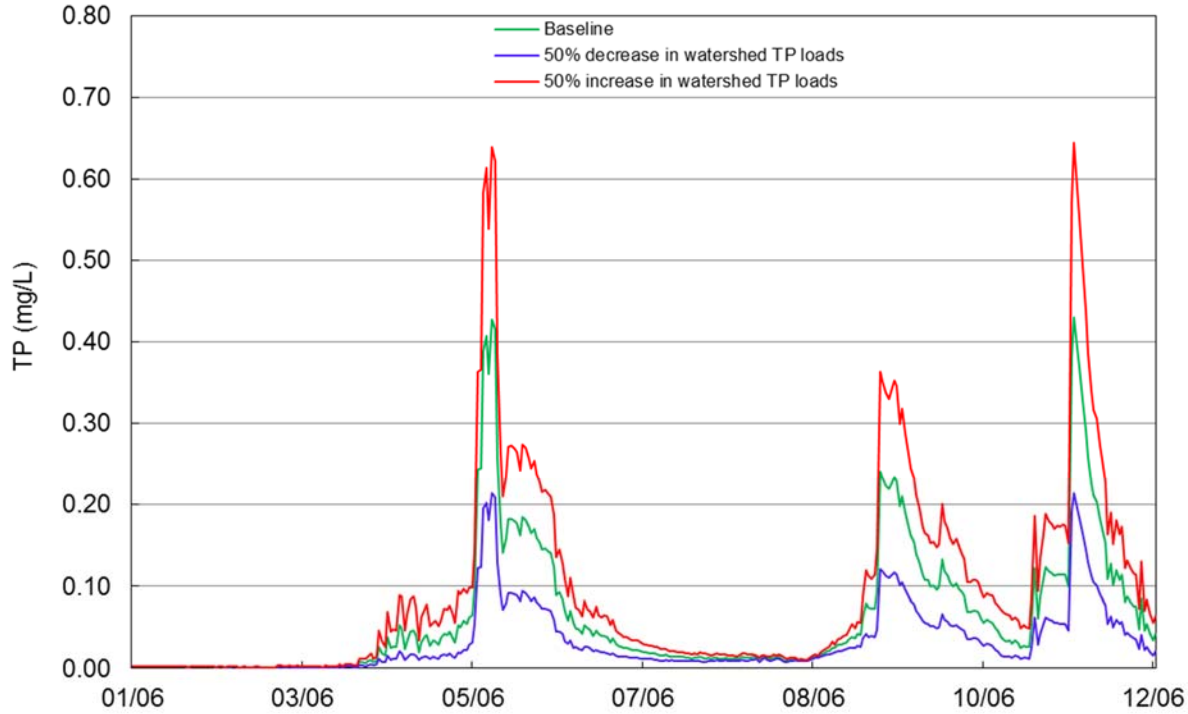


Figure 38 Modeled Depth-averaged TP at LK-03 under Different Perturbation Levels of Watershed TP Loads

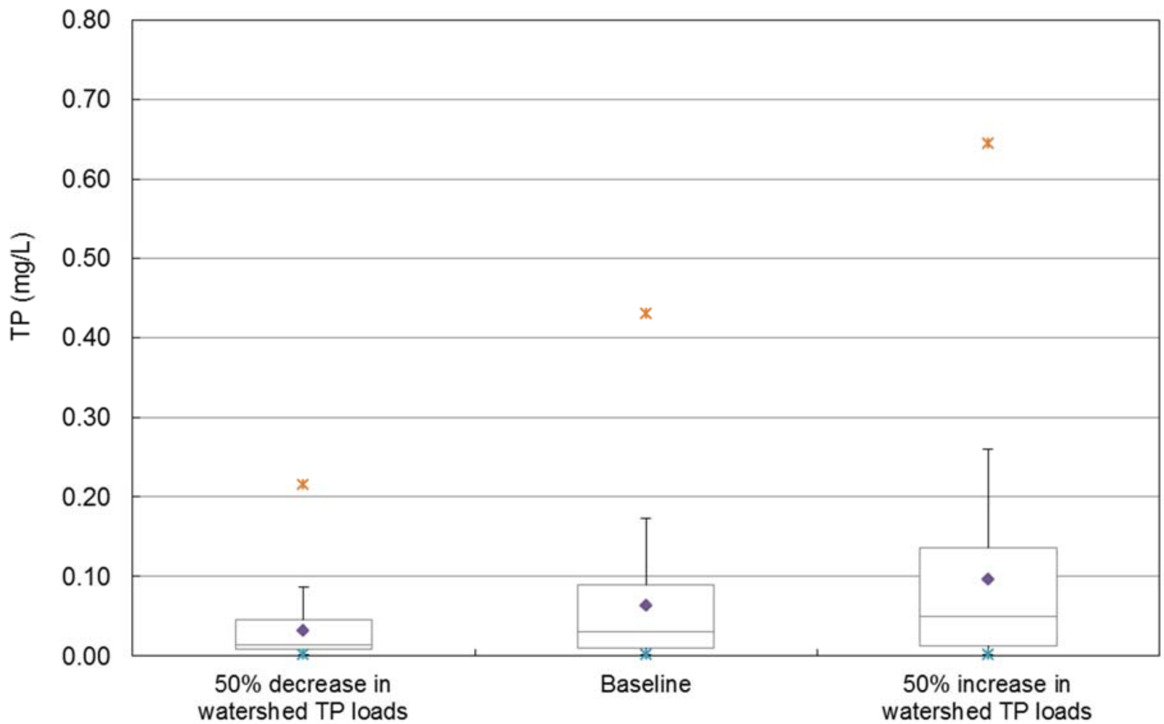


Figure 39 Box-Whisker-Plot of Depth-averaged TP at LK-03 under Different Watershed TP Loads Perturbation

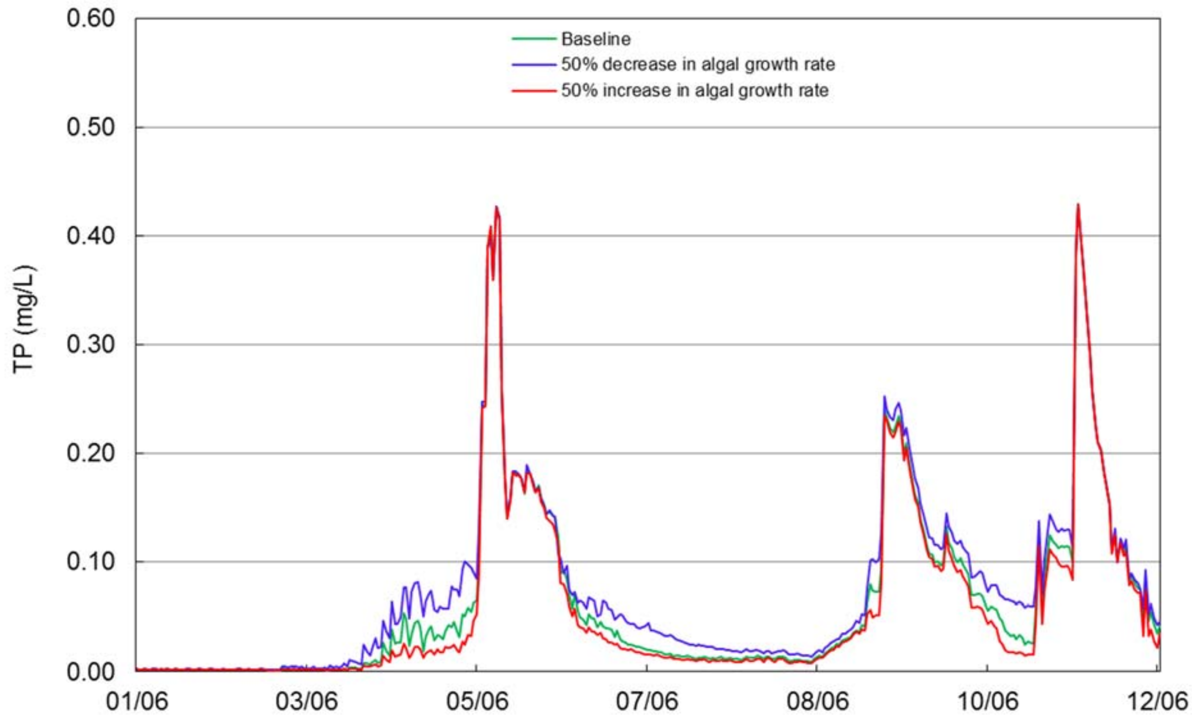


Figure 40 Modeled Depth-averaged TP at LK-03 under Different Perturbation Levels of Algal Growth Rate

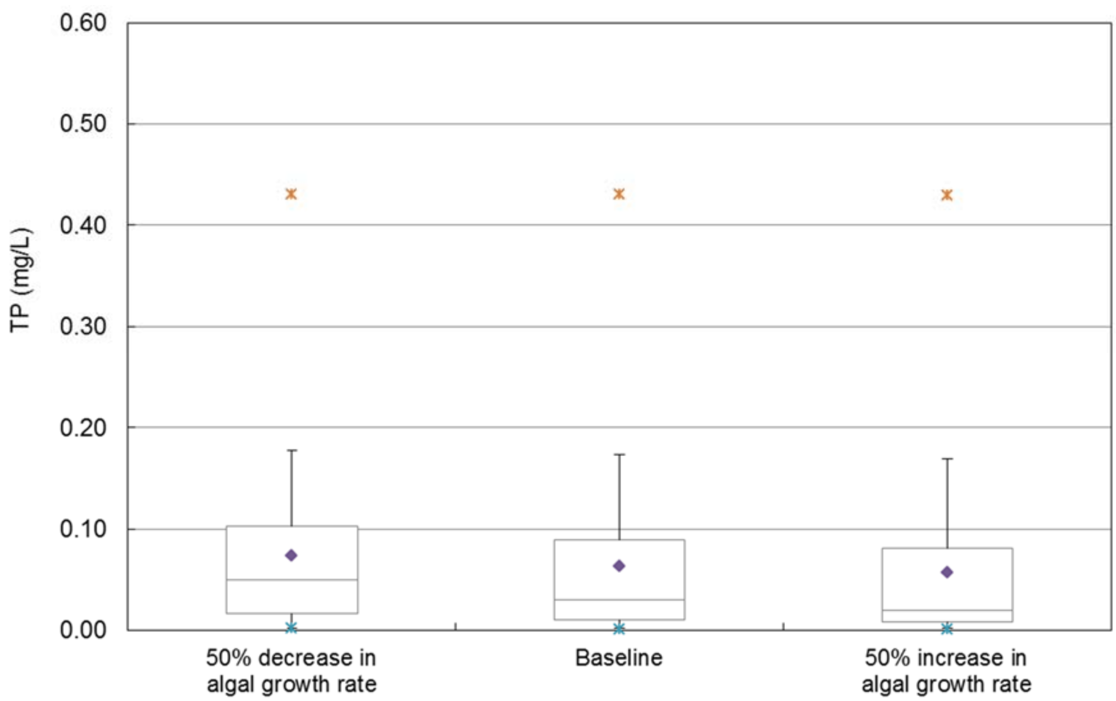


Figure 41 Box-Whisker-Plot of Depth-averaged TP at LK-03 under Different Algal Growth Rate Perturbation

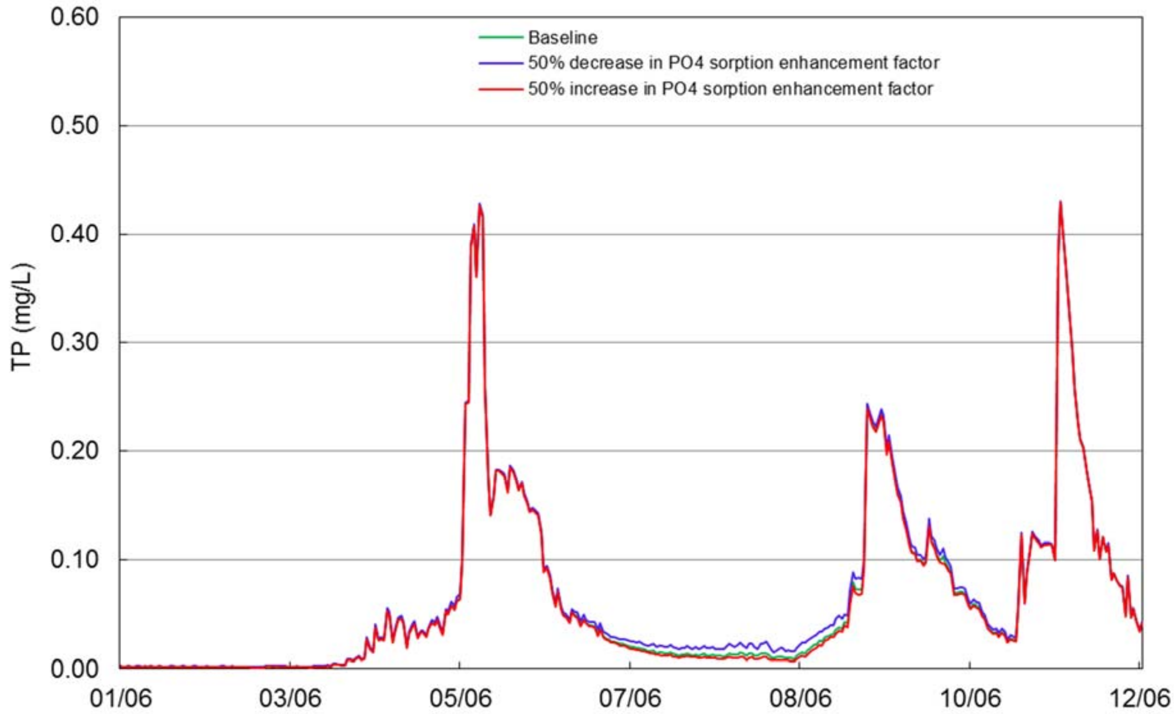


Figure 42 Modeled Depth-averaged TP at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

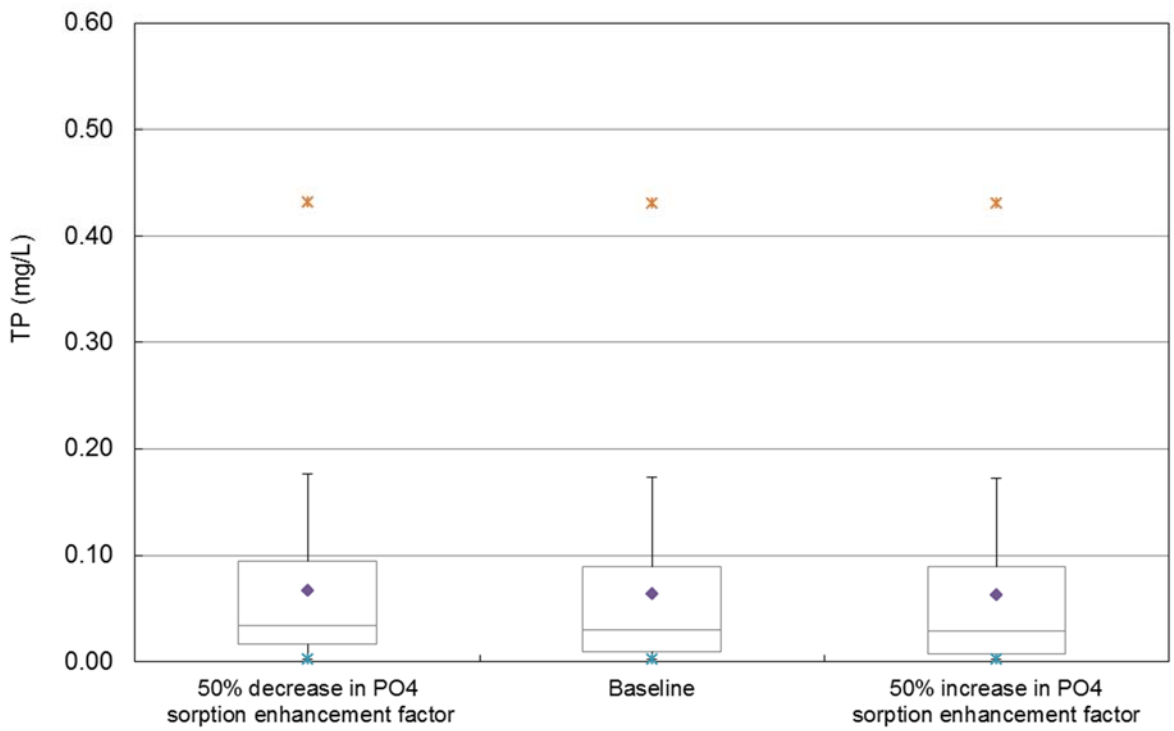


Figure 43 Box-Whisker-Plot of Depth-averaged TP at LK-03 under PO4 Sorption Enhancement Factor Perturbation

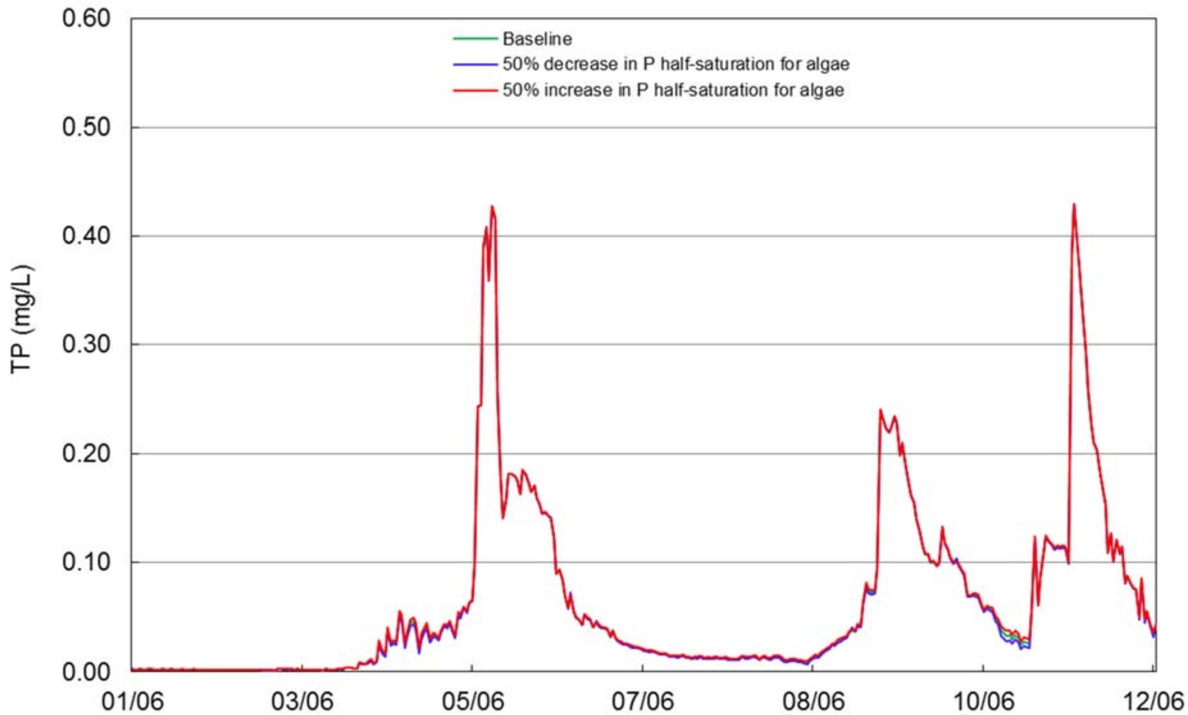


Figure 44 Modeled Depth-averaged TP at LK-03 under Different Perturbation of P Half-saturation for Algae

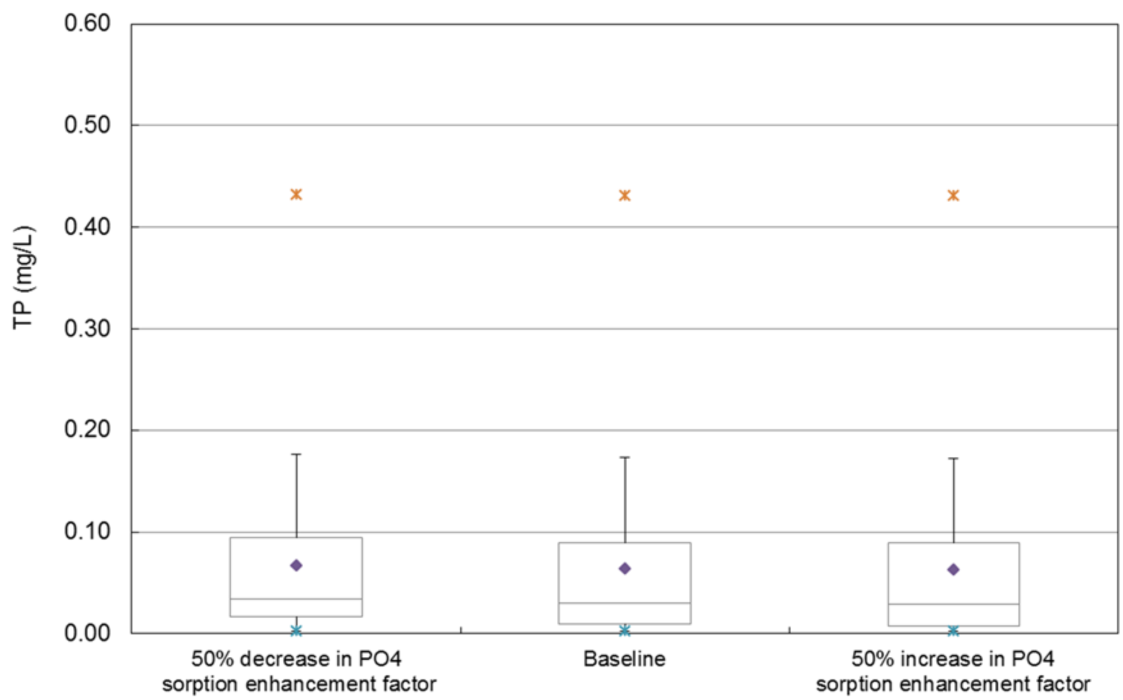


Figure 45 Box-Whisker-Plot of Depth-averaged TP at LK-03 under P Half-saturation for Algae Perturbation

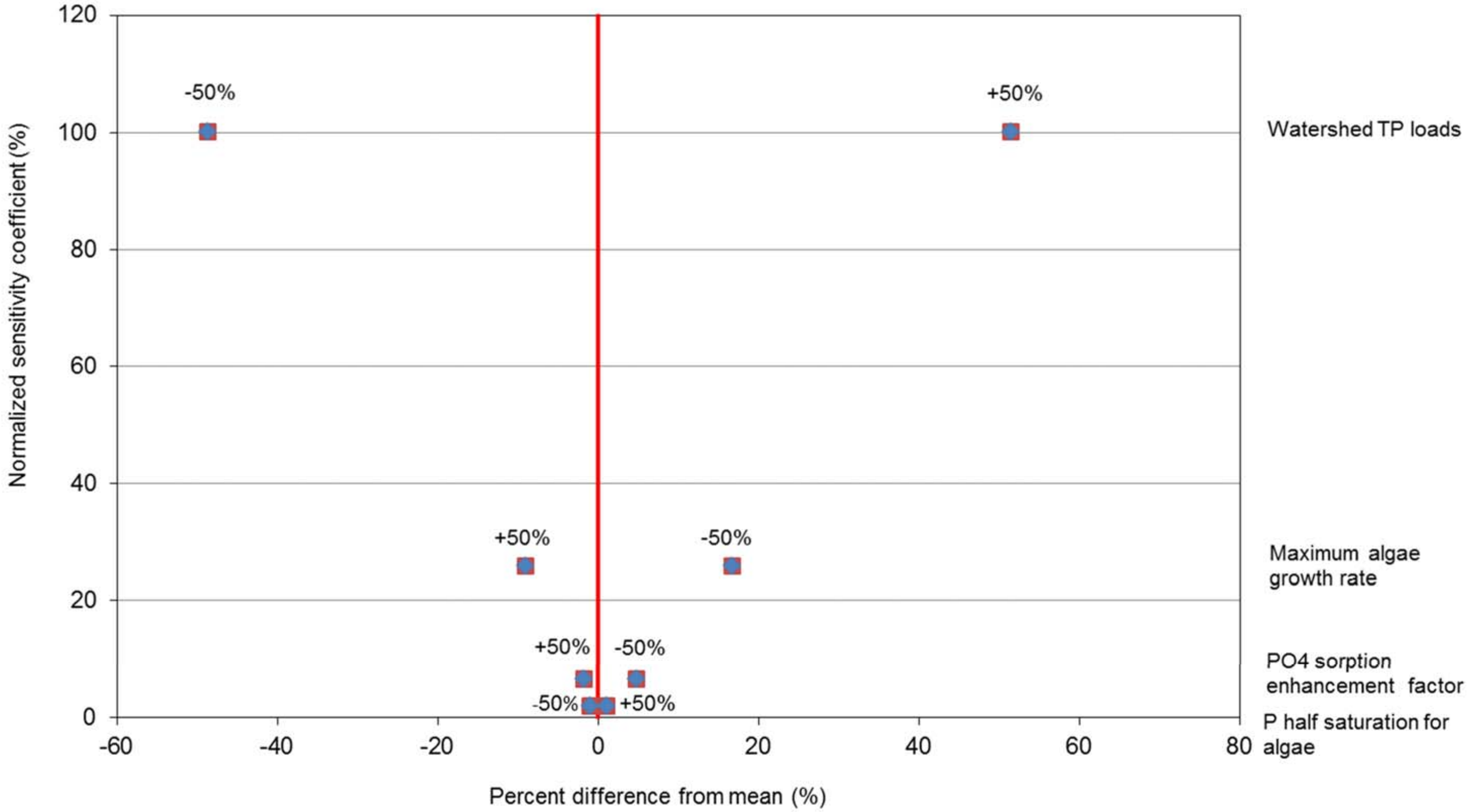


Figure 46 Tornado Diagram for Sensitivity Analysis of Modeled Depth-averaged TP at LK-03

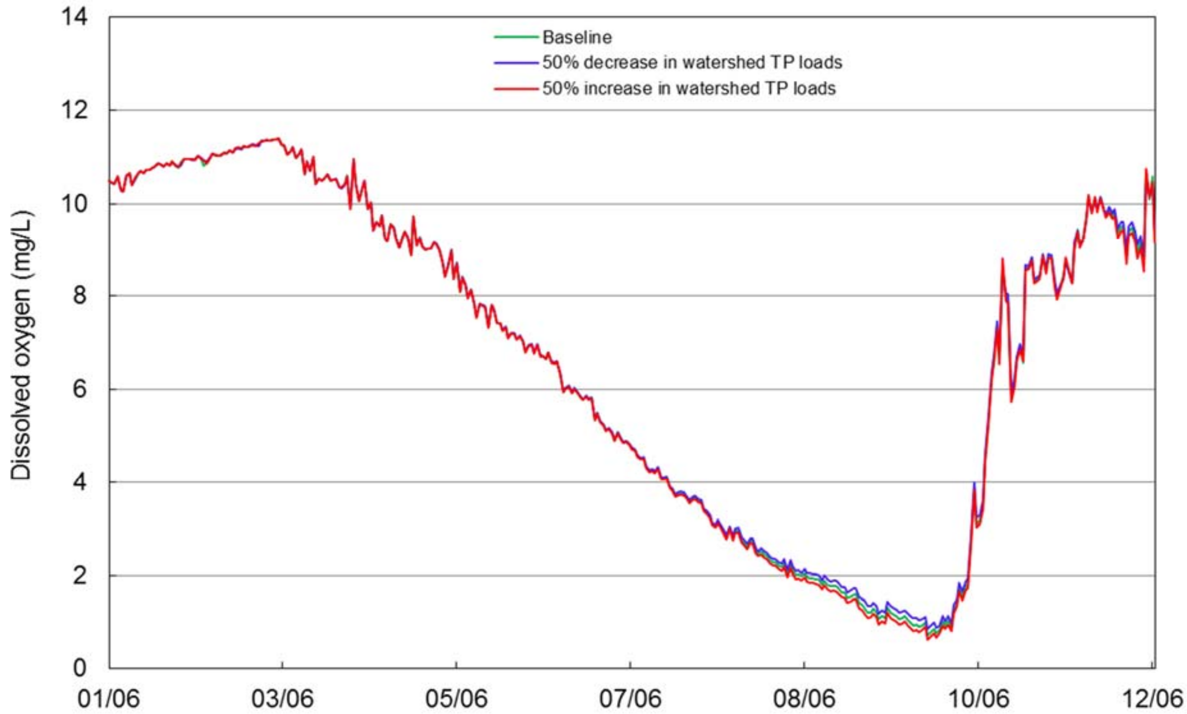


Figure 47 Modeled Bottom DO at LK-01 under Different Perturbation Levels of Watershed TP Loads

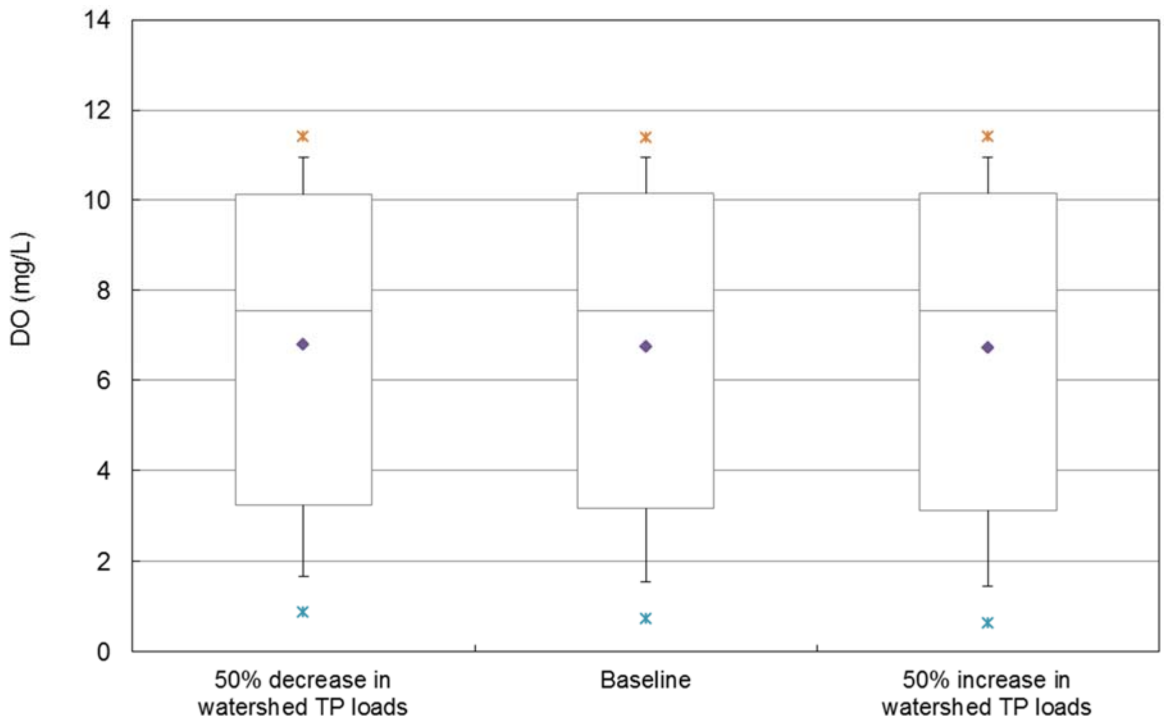


Figure 48 Box-Whisker-Plot of Bottom DO at LK-01 under Different Watershed TP Loads Perturbation

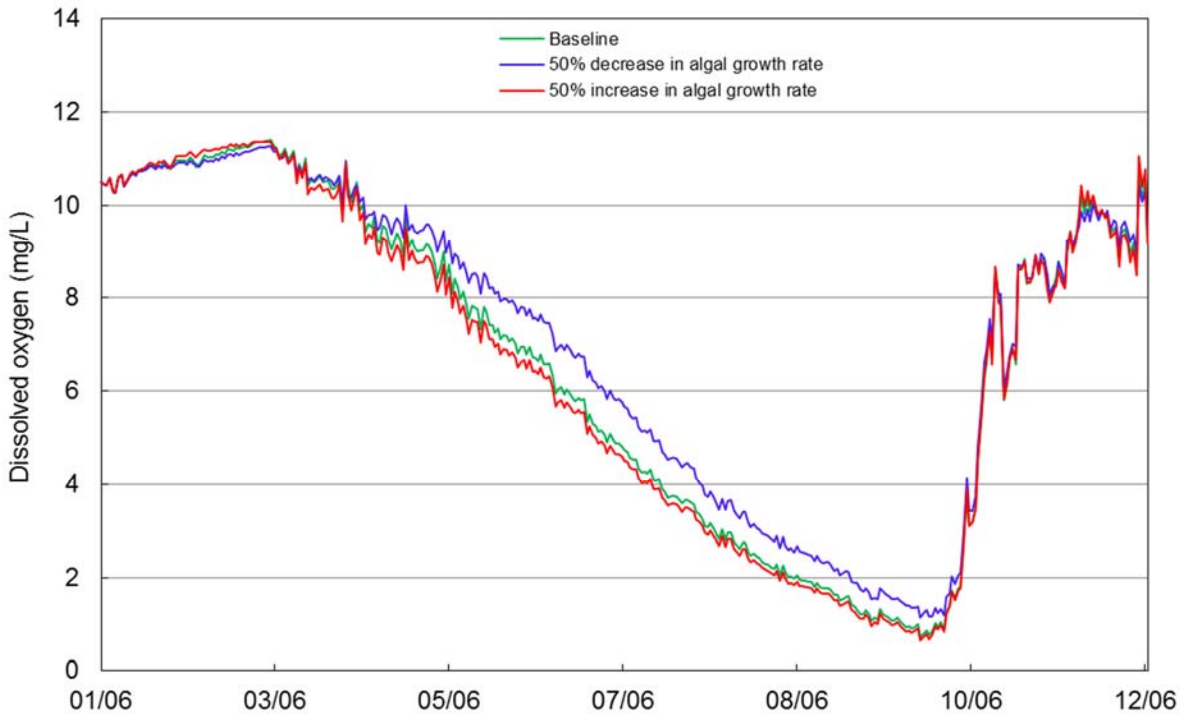


Figure 49 Modeled Bottom DO at LK-01 under Different Perturbation Levels of Algal Growth Rate

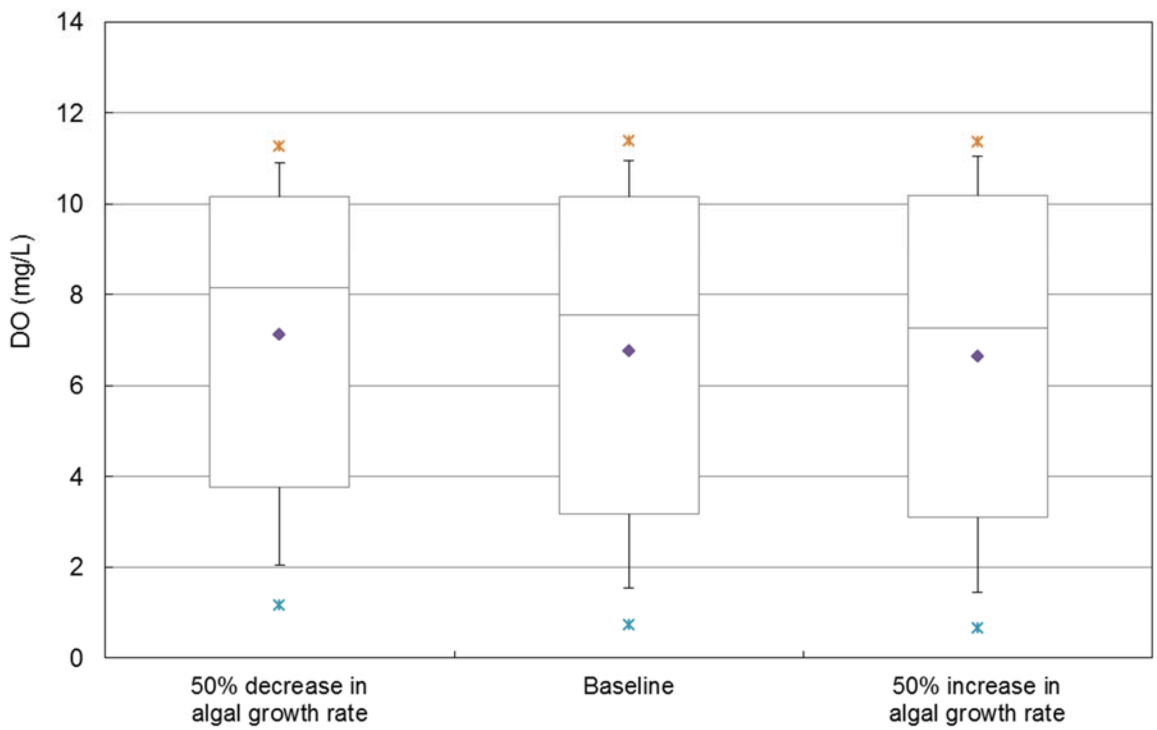


Figure 50 Box-Whisker-Plot of Bottom DO at LK-01 under Different Algal Growth Rate Perturbation

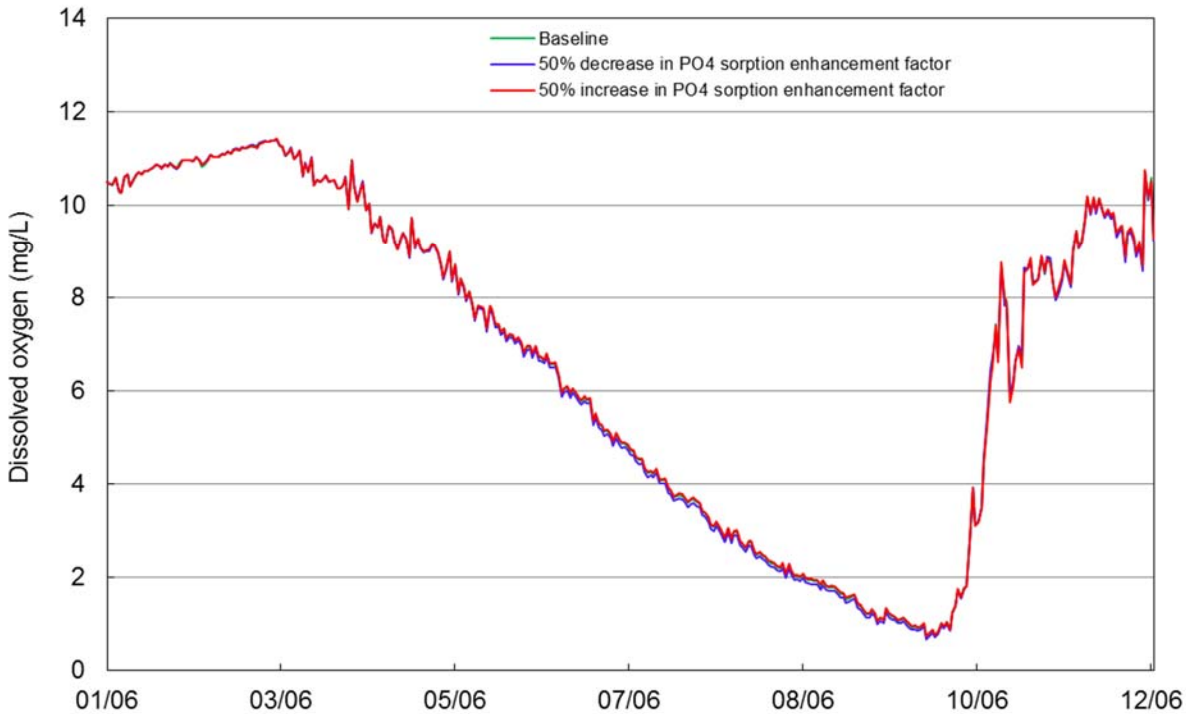


Figure 51. Modeled Bottom DO at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

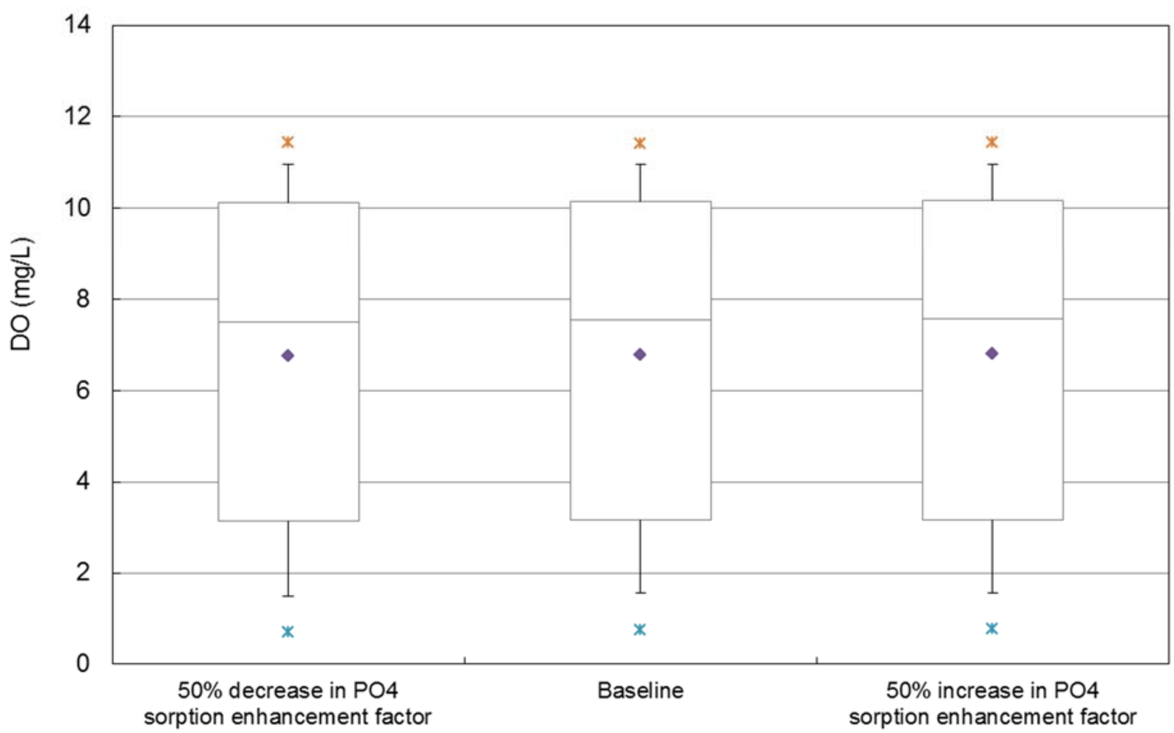


Figure 52. Box-Whisker-Plot of Bottom DO at LK-01 under PO4 Sorption Enhancement Factor Perturbation

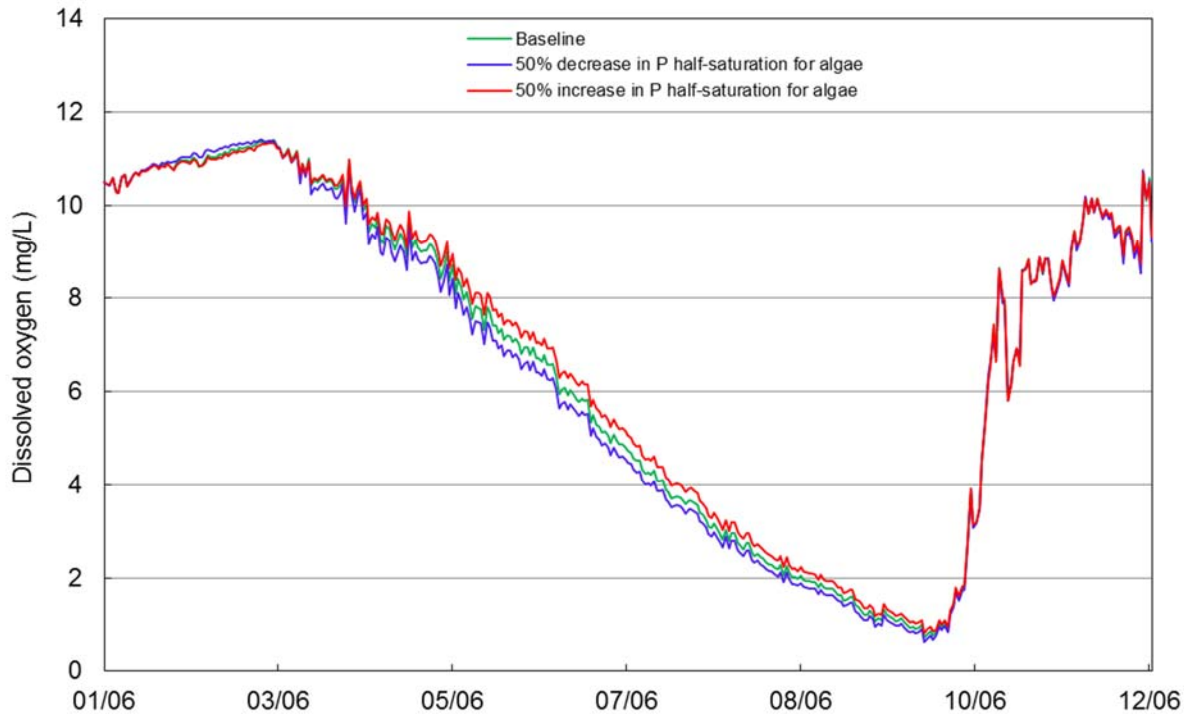


Figure 53 Modeled Bottom DO at LK-01 under Different Perturbation of P Half-saturation for Algae

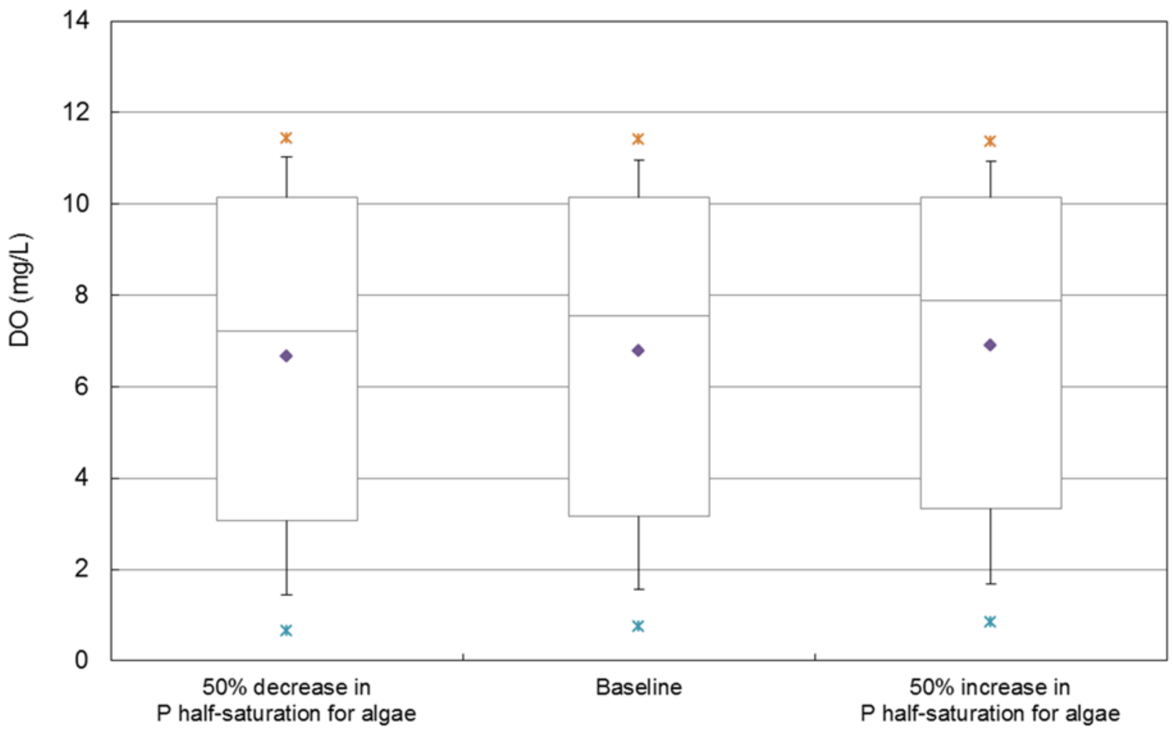


Figure 54 Box-Whisker-Plot of Bottom DO at LK-01 under P Half-saturation for Algae Perturbation

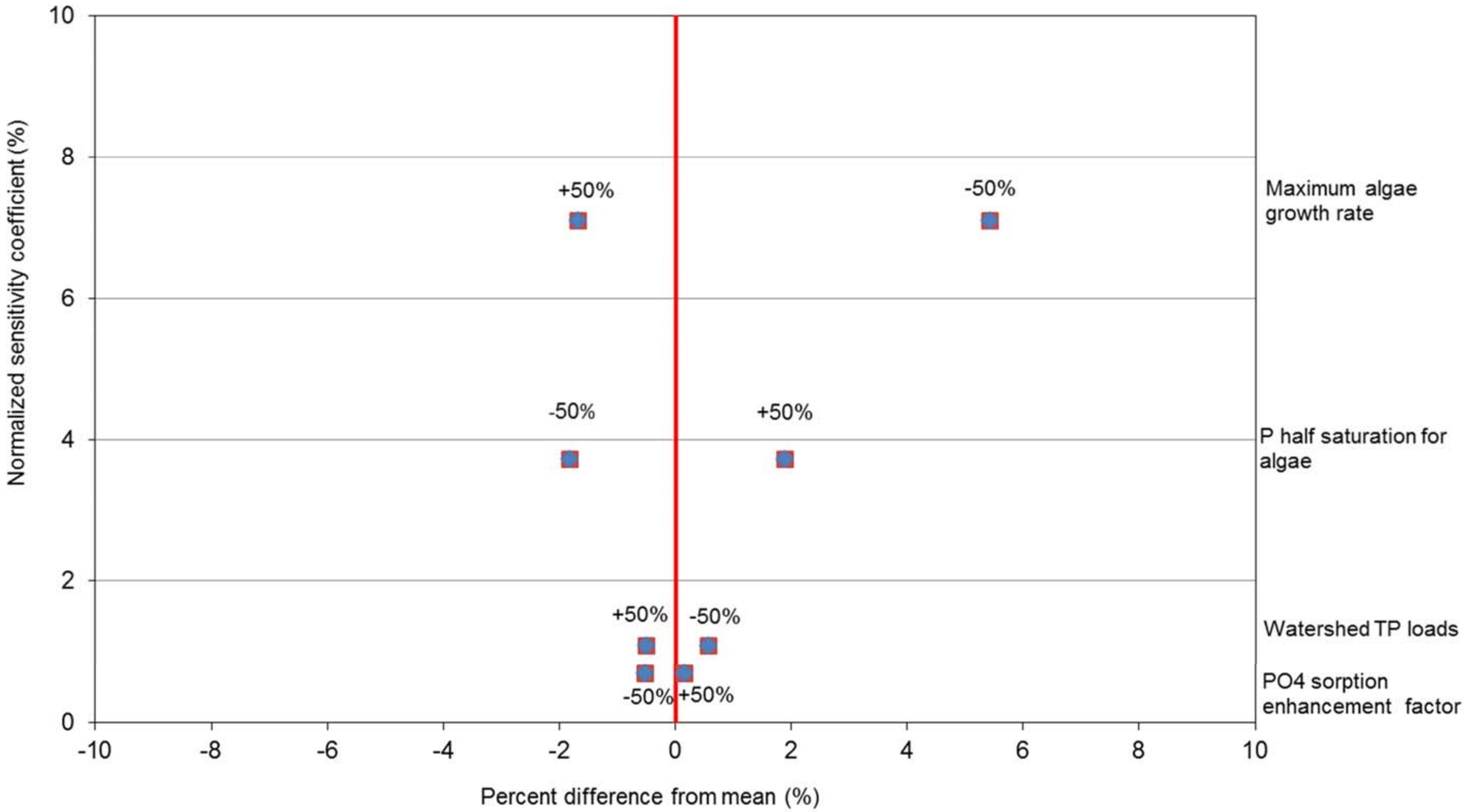


Figure 55 Tornado Diagram for Sensitivity Analysis of Modeled Bottom DO at LK-01

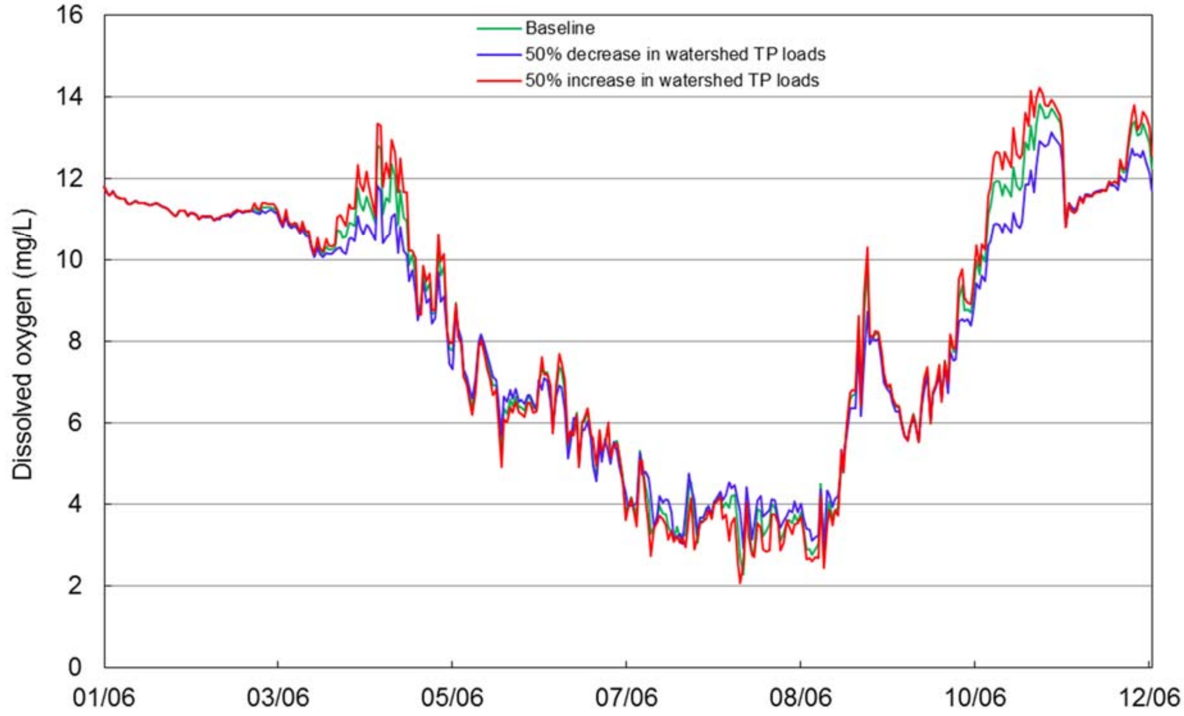


Figure 56 Modeled Bottom DO at LK-03 under Different Perturbation Levels of Watershed TP Loads

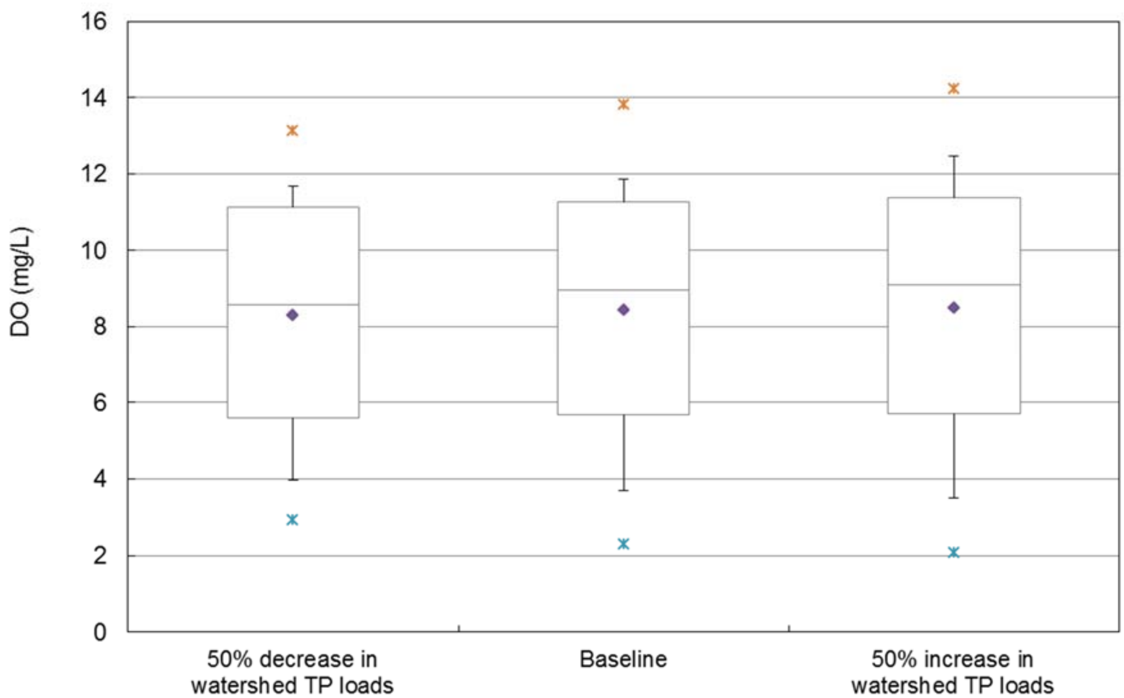


Figure 57 Box-Whisker-Plot of Bottom DO at LK-03 under Different Watershed TP Loads Perturbation

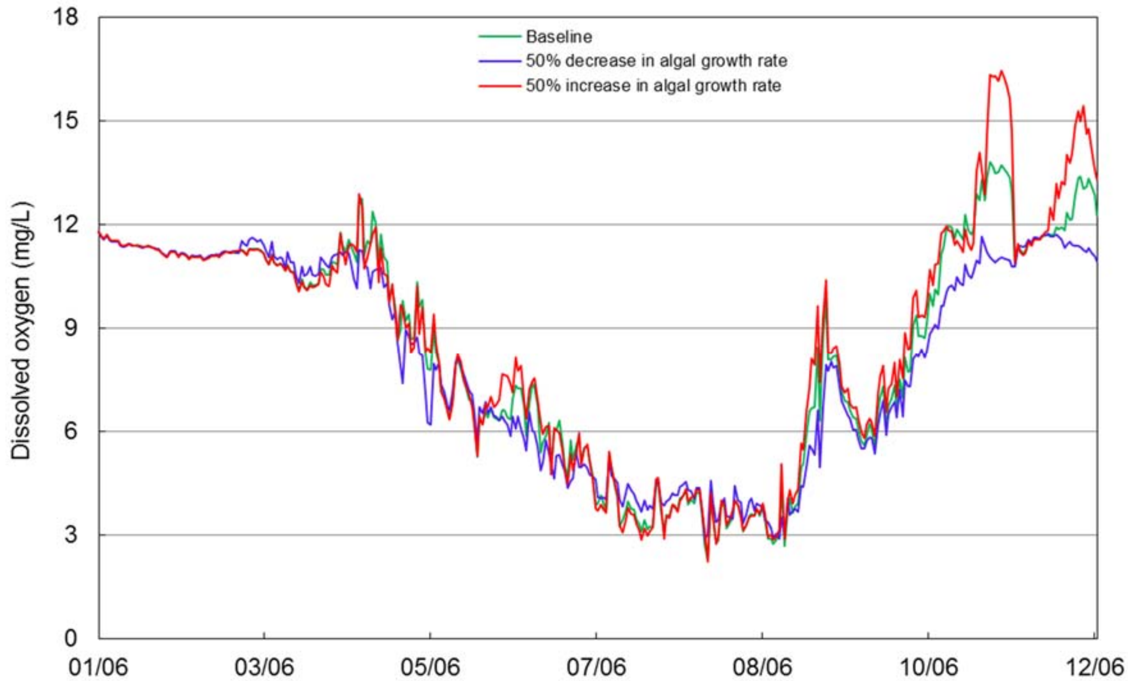


Figure 58 Modeled Bottom DO at LK-03 under Different Perturbation Levels of Algal Growth Rate

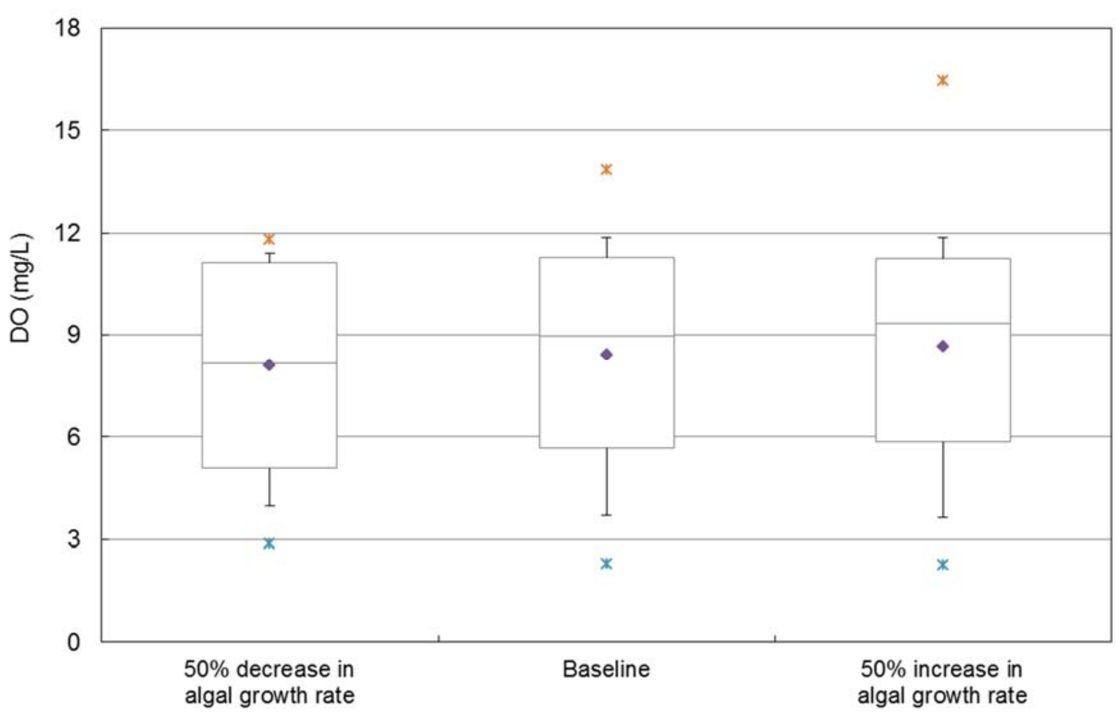


Figure 59 Box-Whisker-Plot of Bottom DO at LK-03 under Different Algal Growth Rate Perturbation

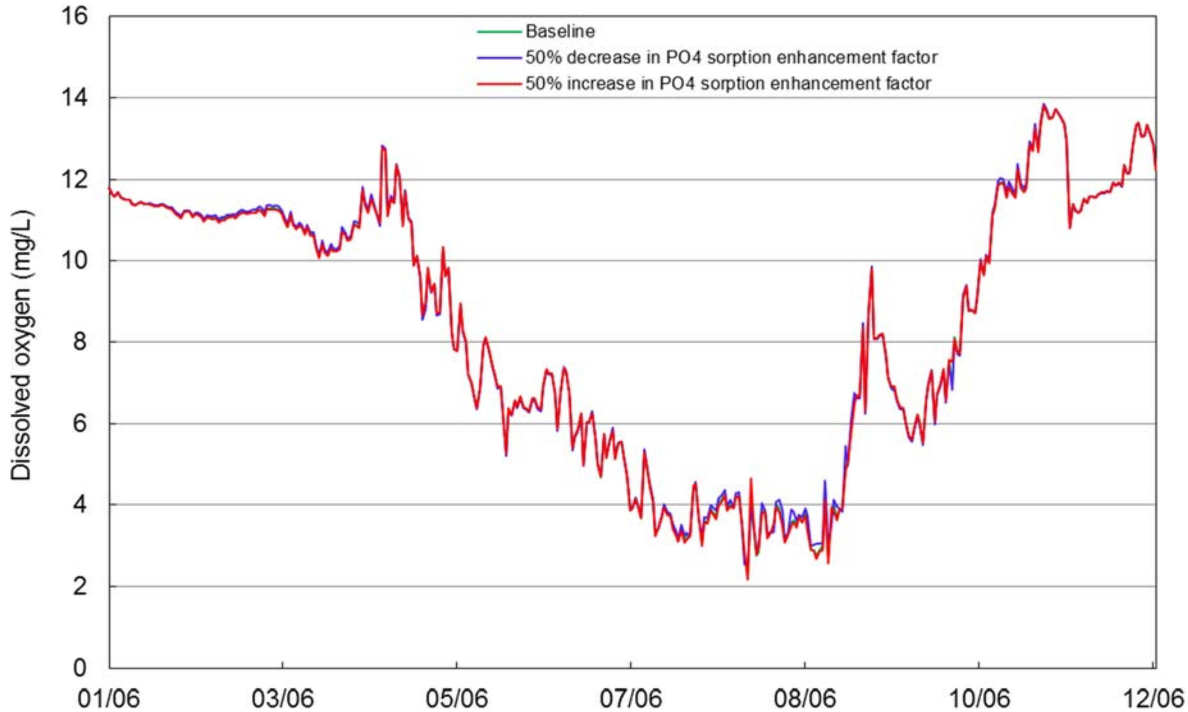


Figure 60 Modeled Bottom DO at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

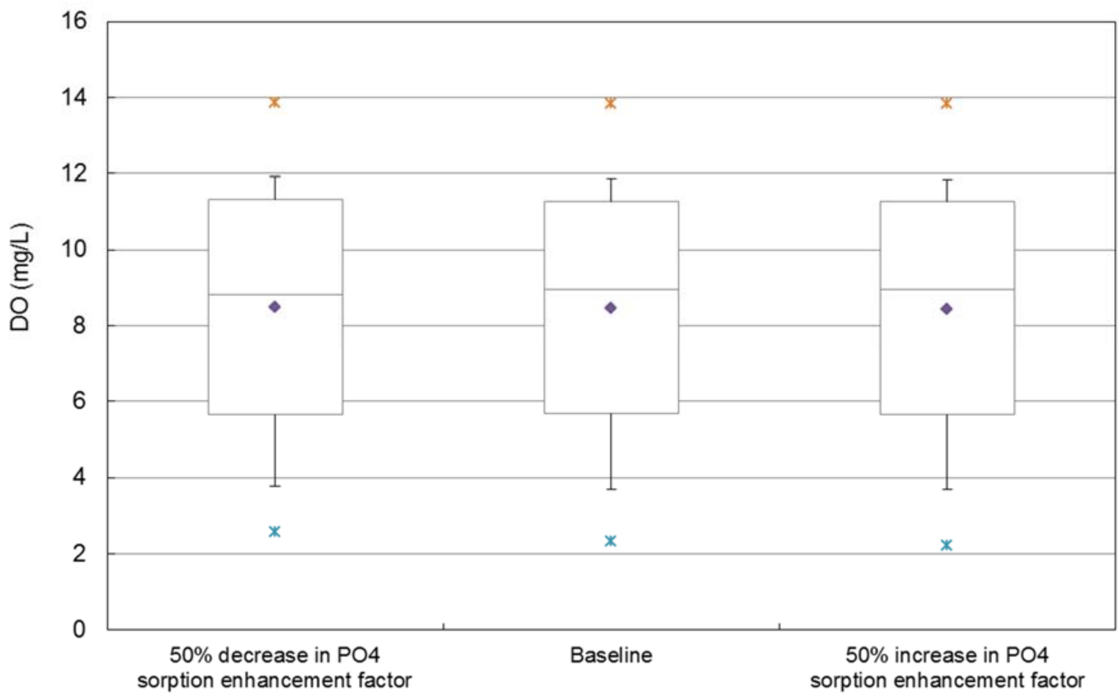


Figure 61 Box-Whisker-Plot of Bottom DO at LK-03 under PO4 Sorption Enhancement Factor Perturbation

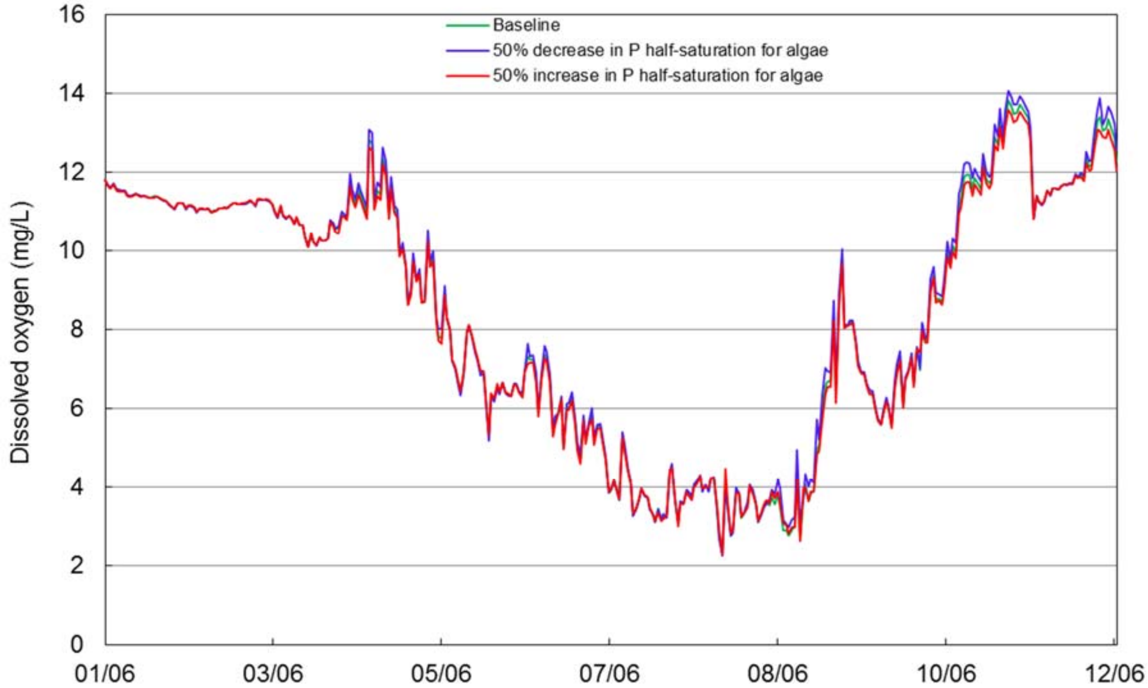


Figure 62 Modeled Bottom DO under at LK-03 Different Perturbation of P Half-saturation for Algae

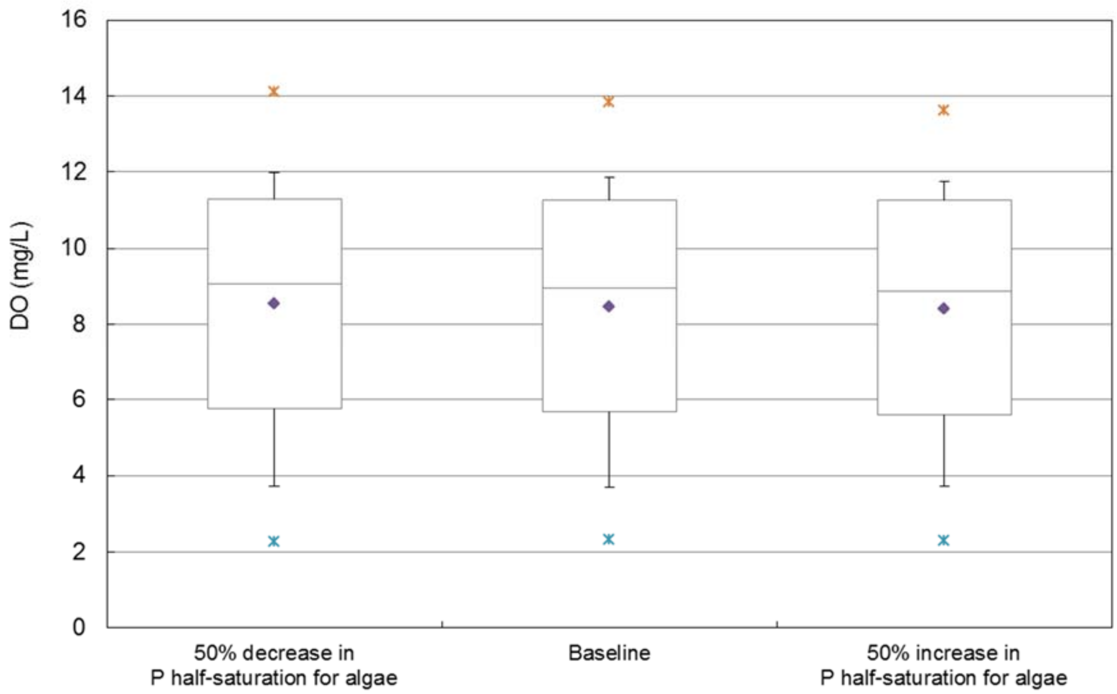


Figure 63 Box-Whisker-Plot of Bottom DO at LK-03 under P Half-saturation for Algae Perturbation

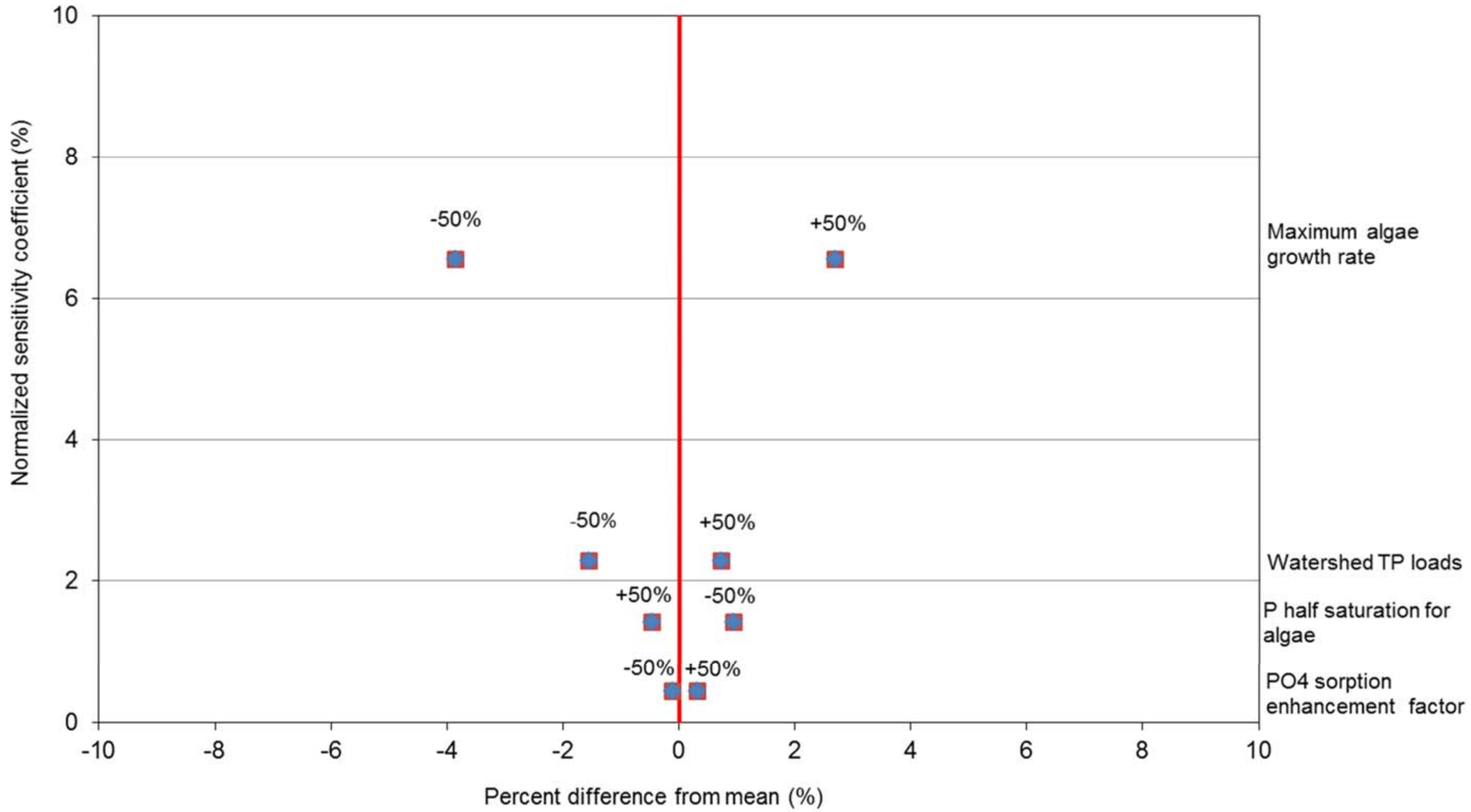


Figure 64 Tornado Diagram for Sensitivity Analysis of Modeled Bottom DO at LK-03

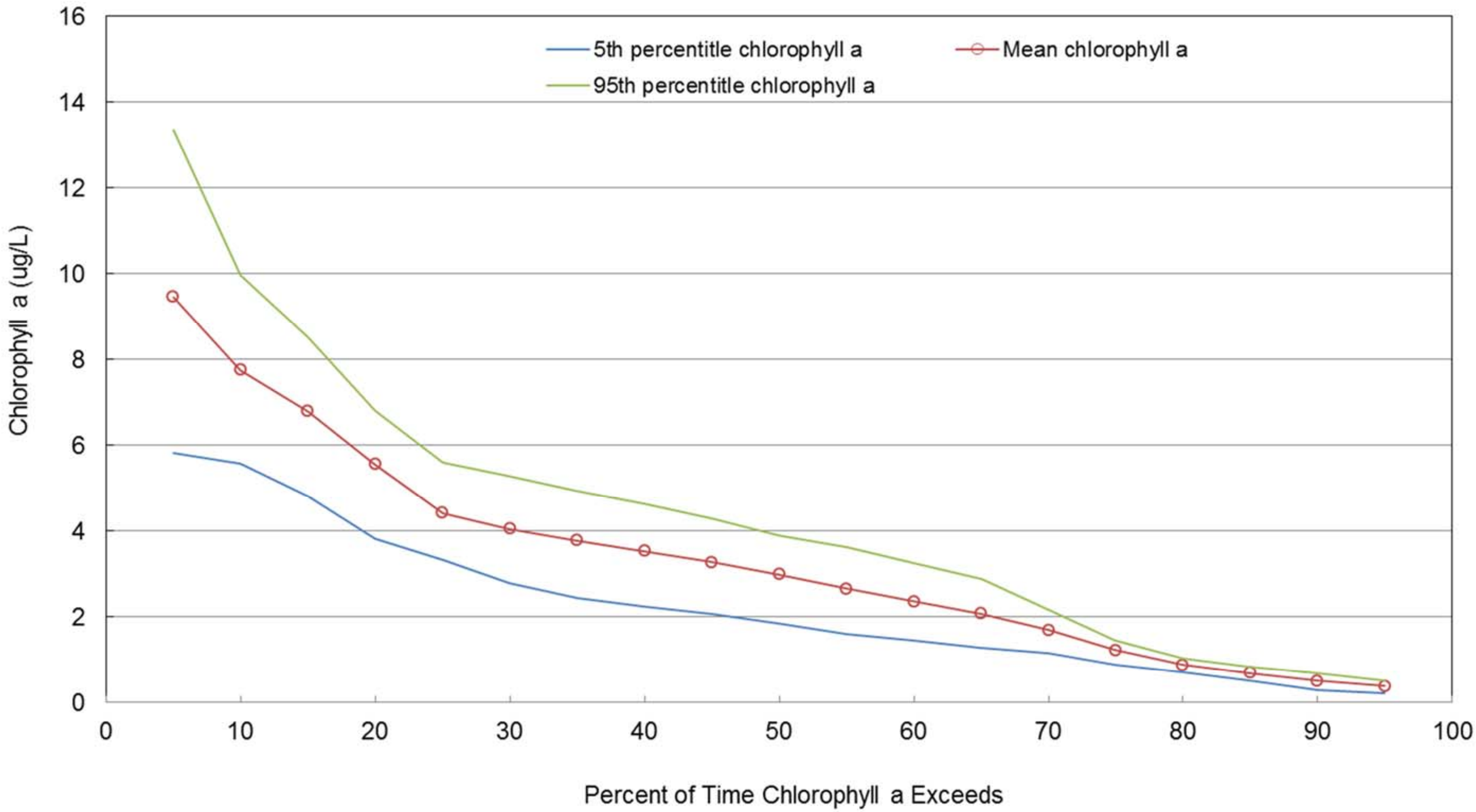


Figure 65 Chlorophyll a Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

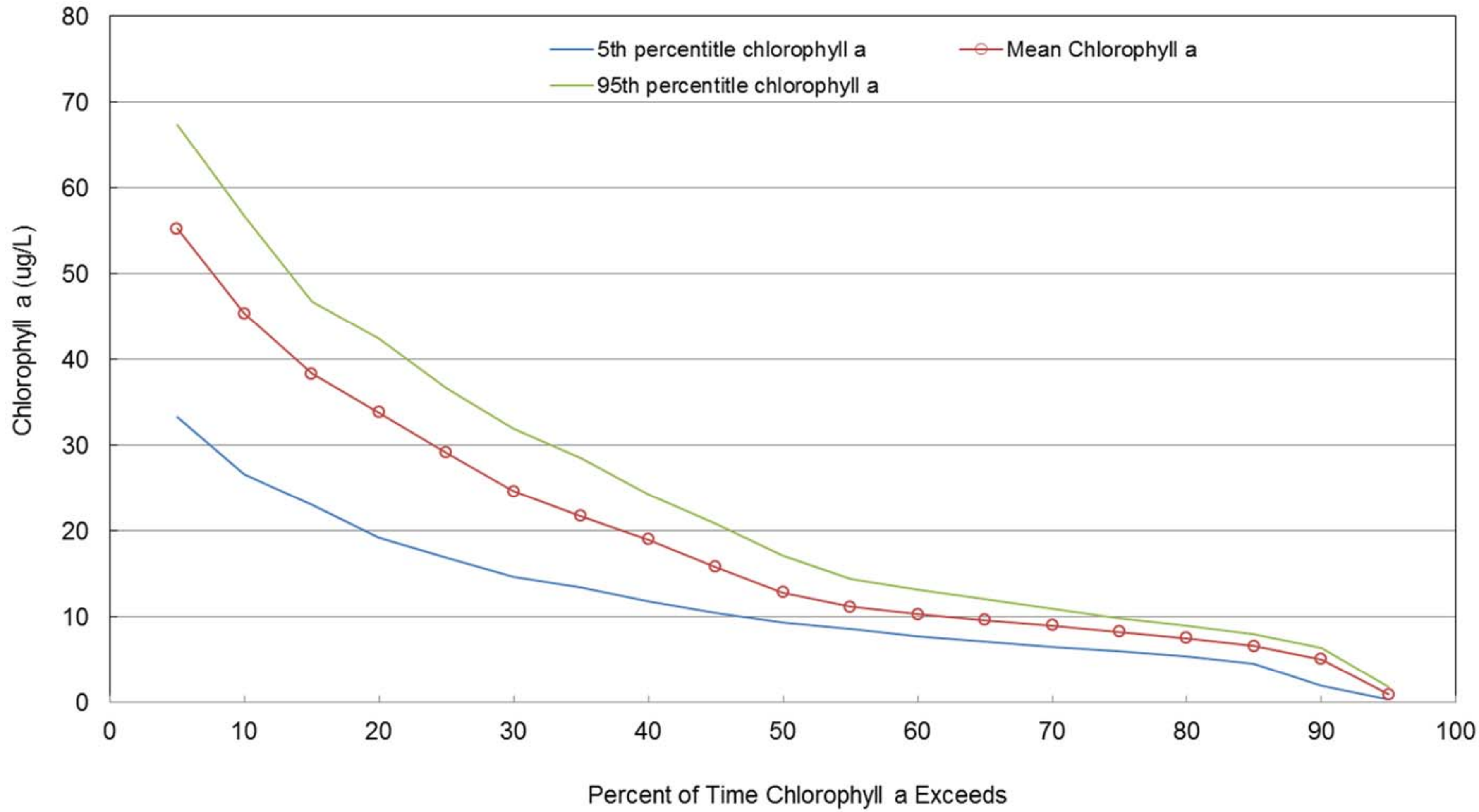


Figure 66 Chlorophyll a Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

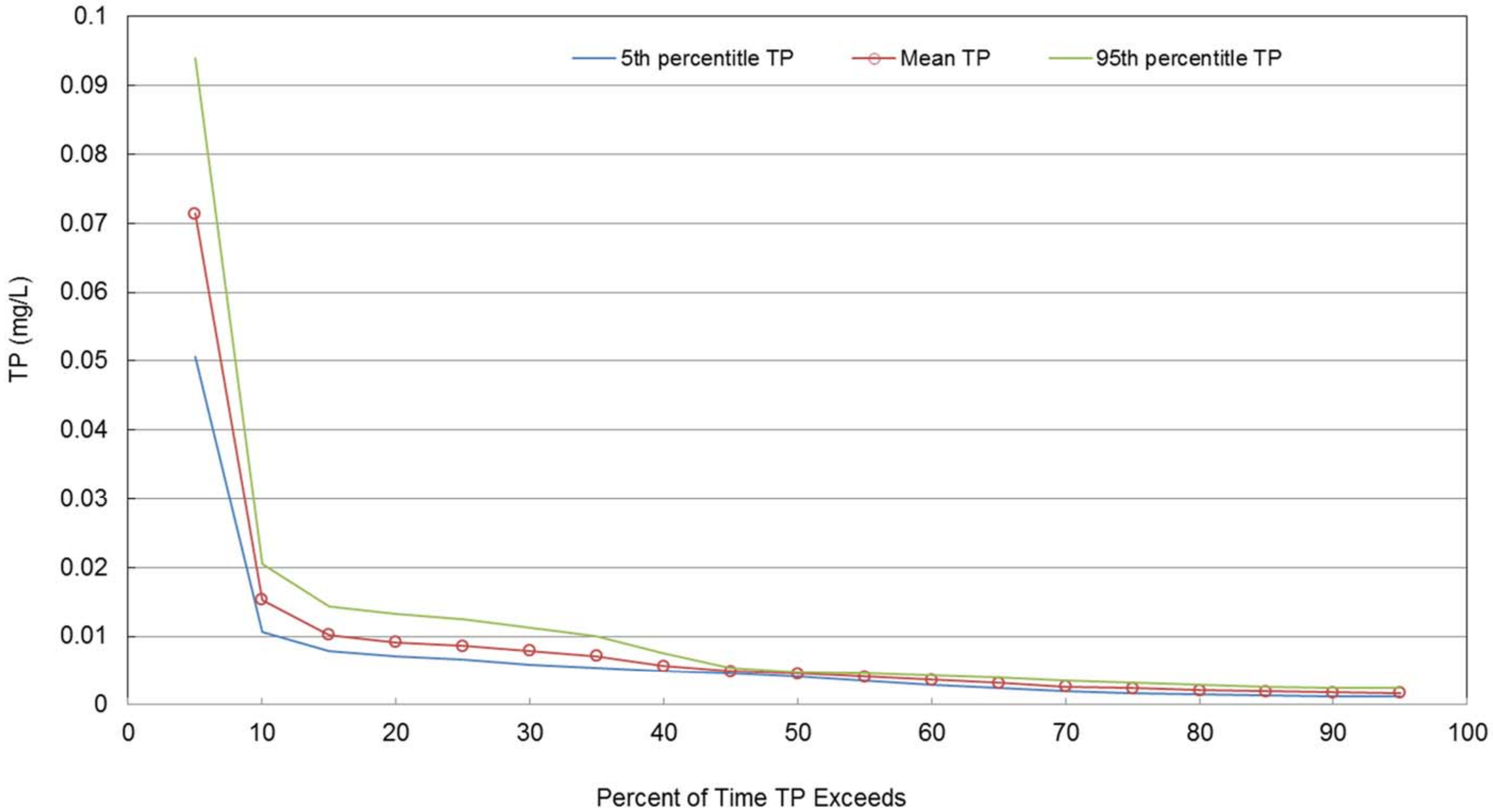


Figure 67 TP Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

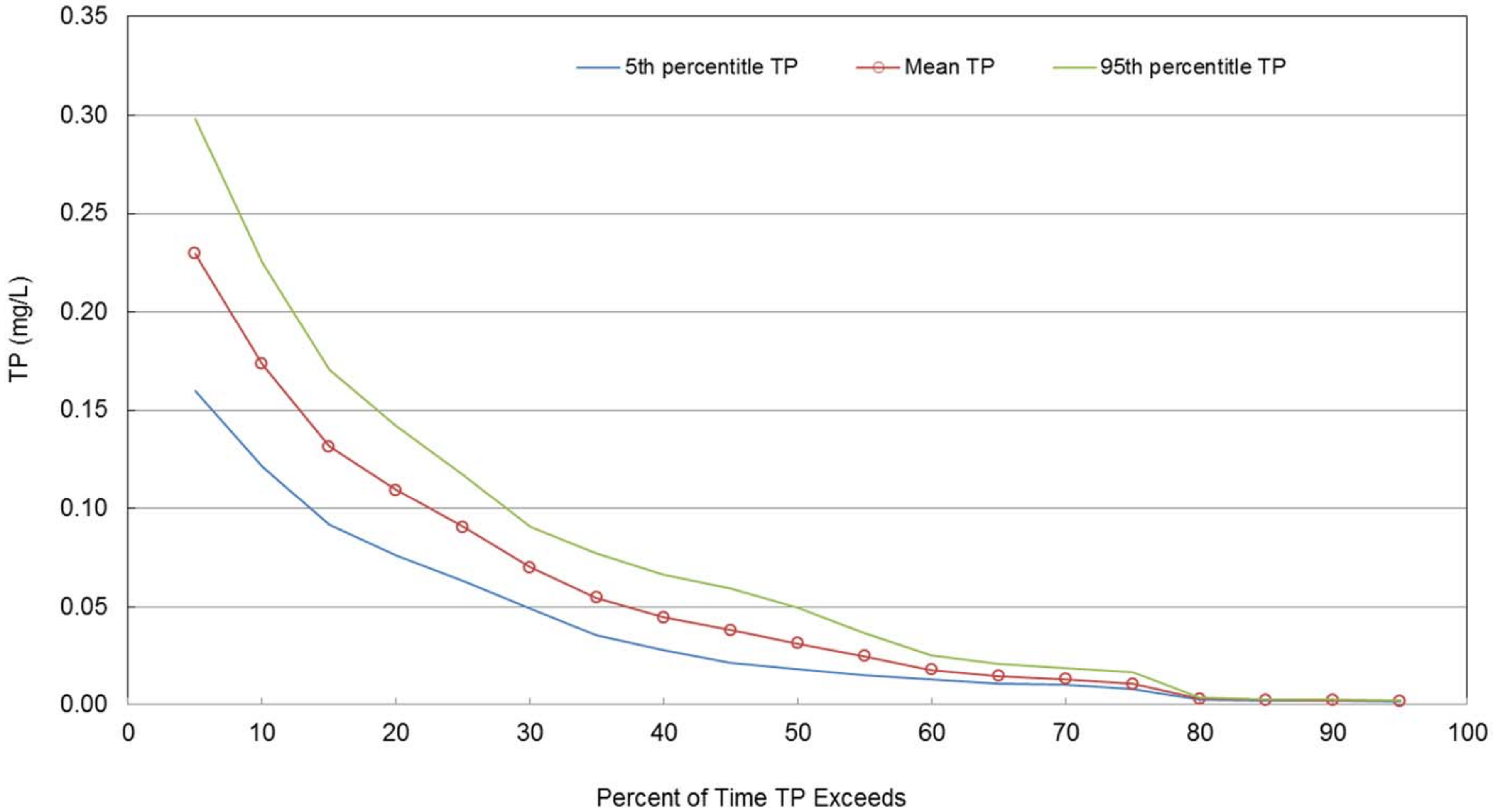


Figure 68 TP Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

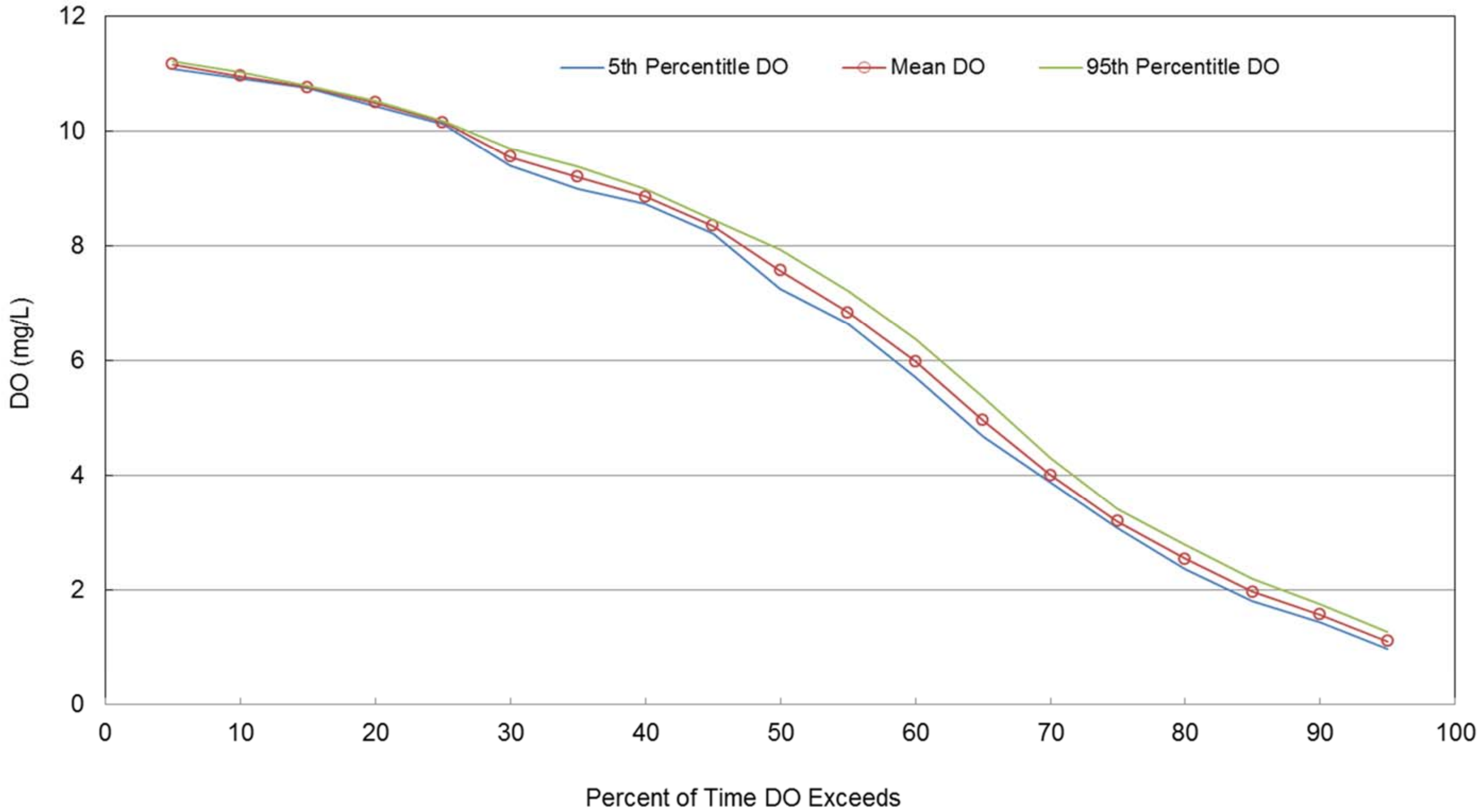


Figure 69 DO Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

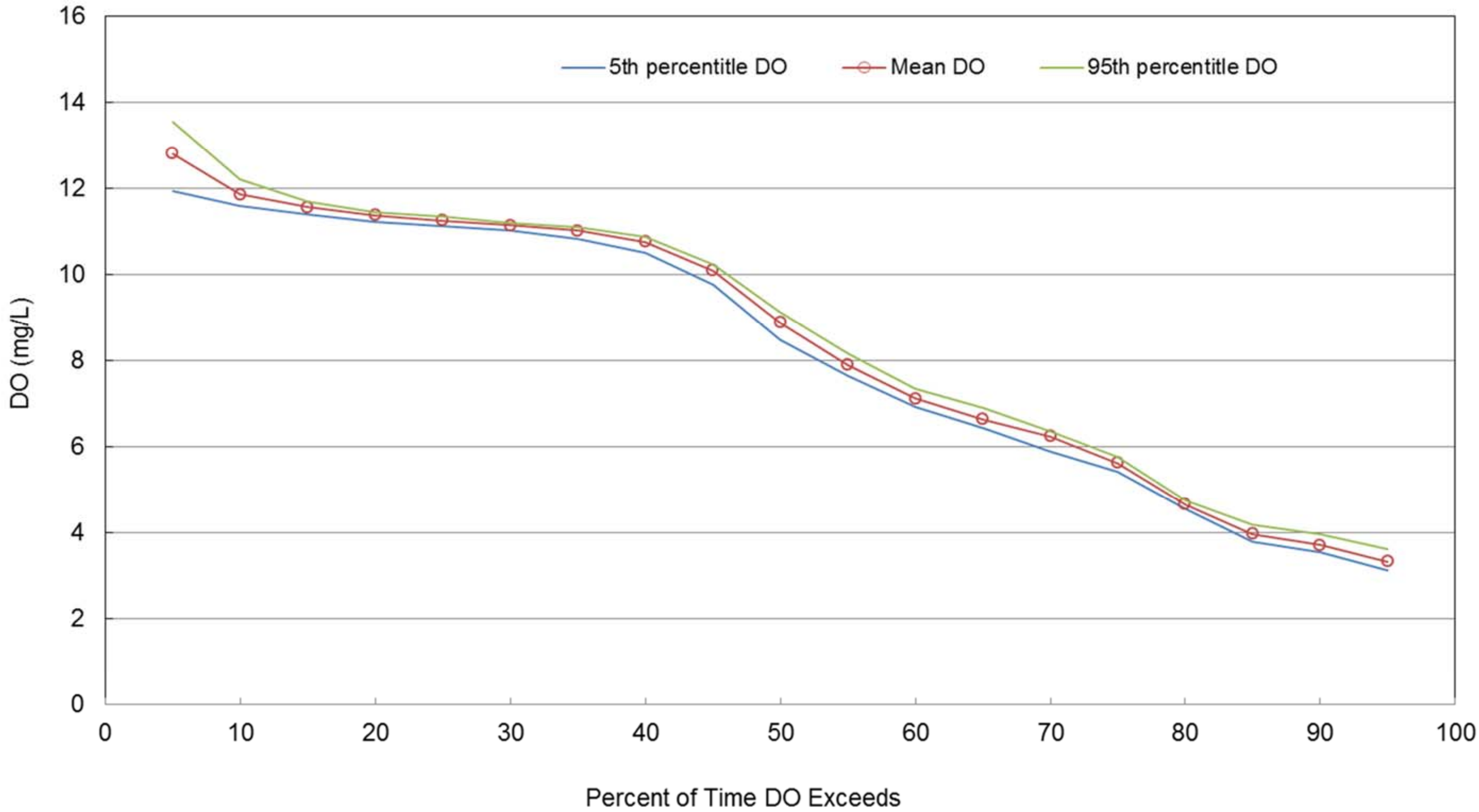


Figure 70 DO Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Entire Simulation Period

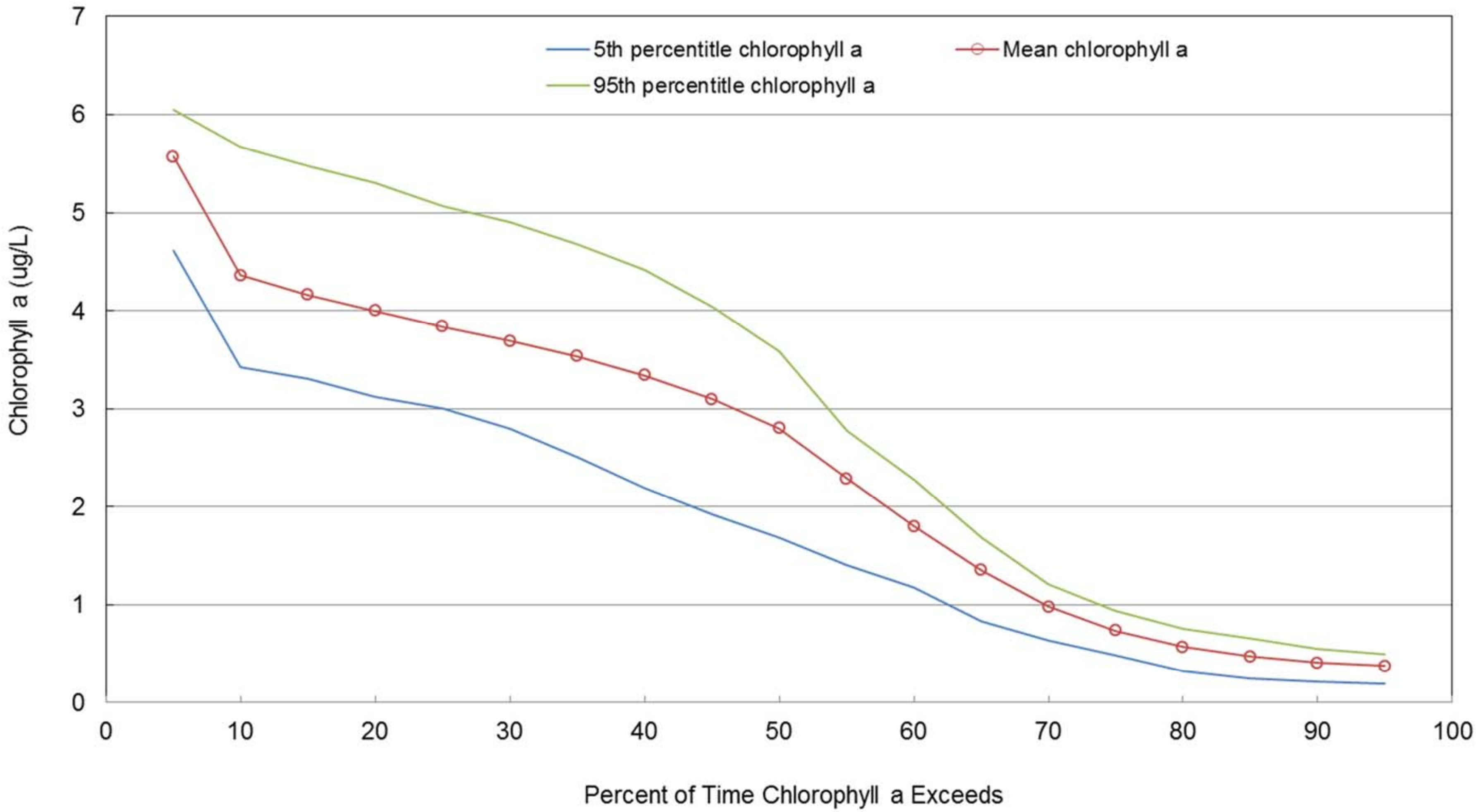


Figure 71 Chlorophyll a Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

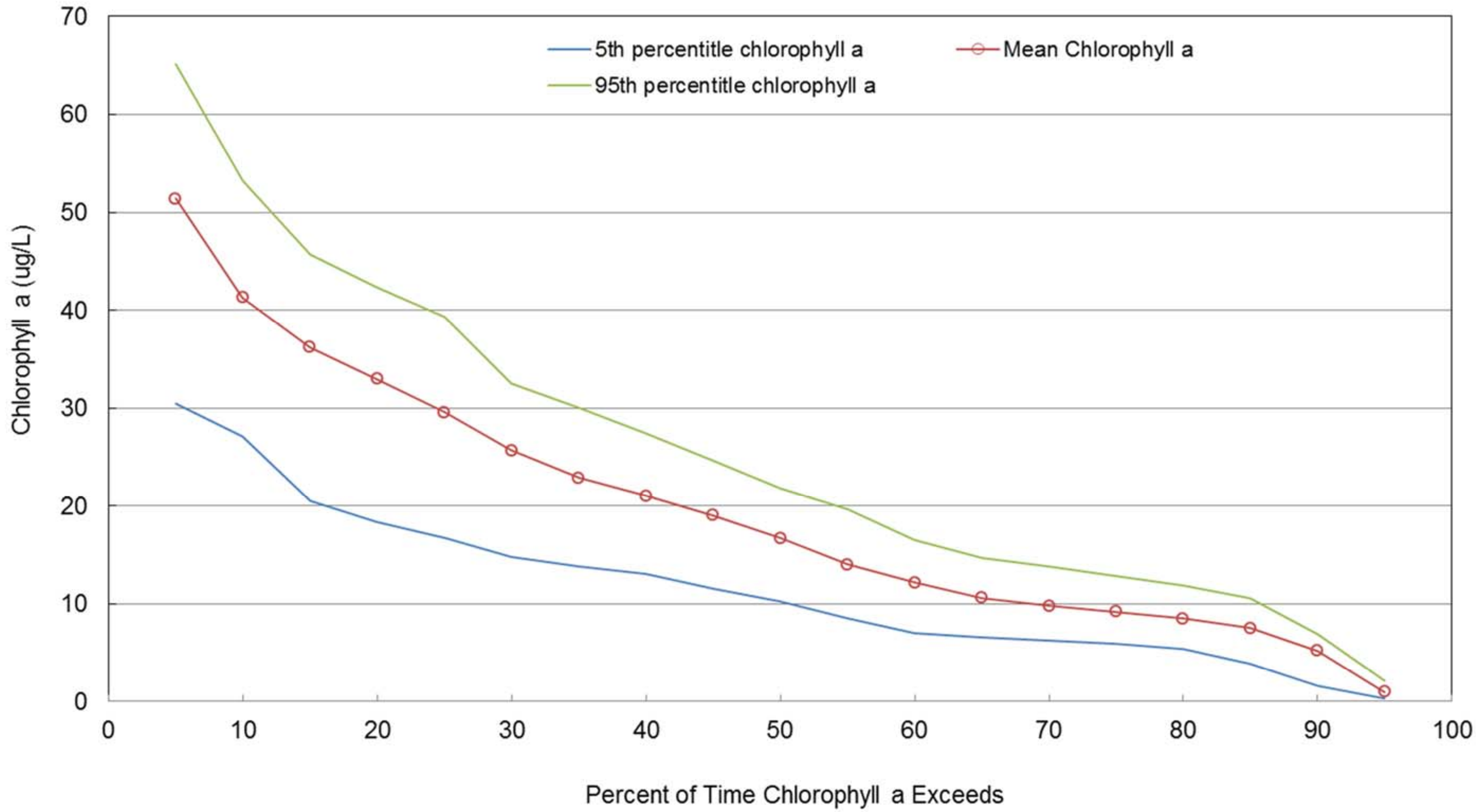


Figure 72 Chlorophyll a Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

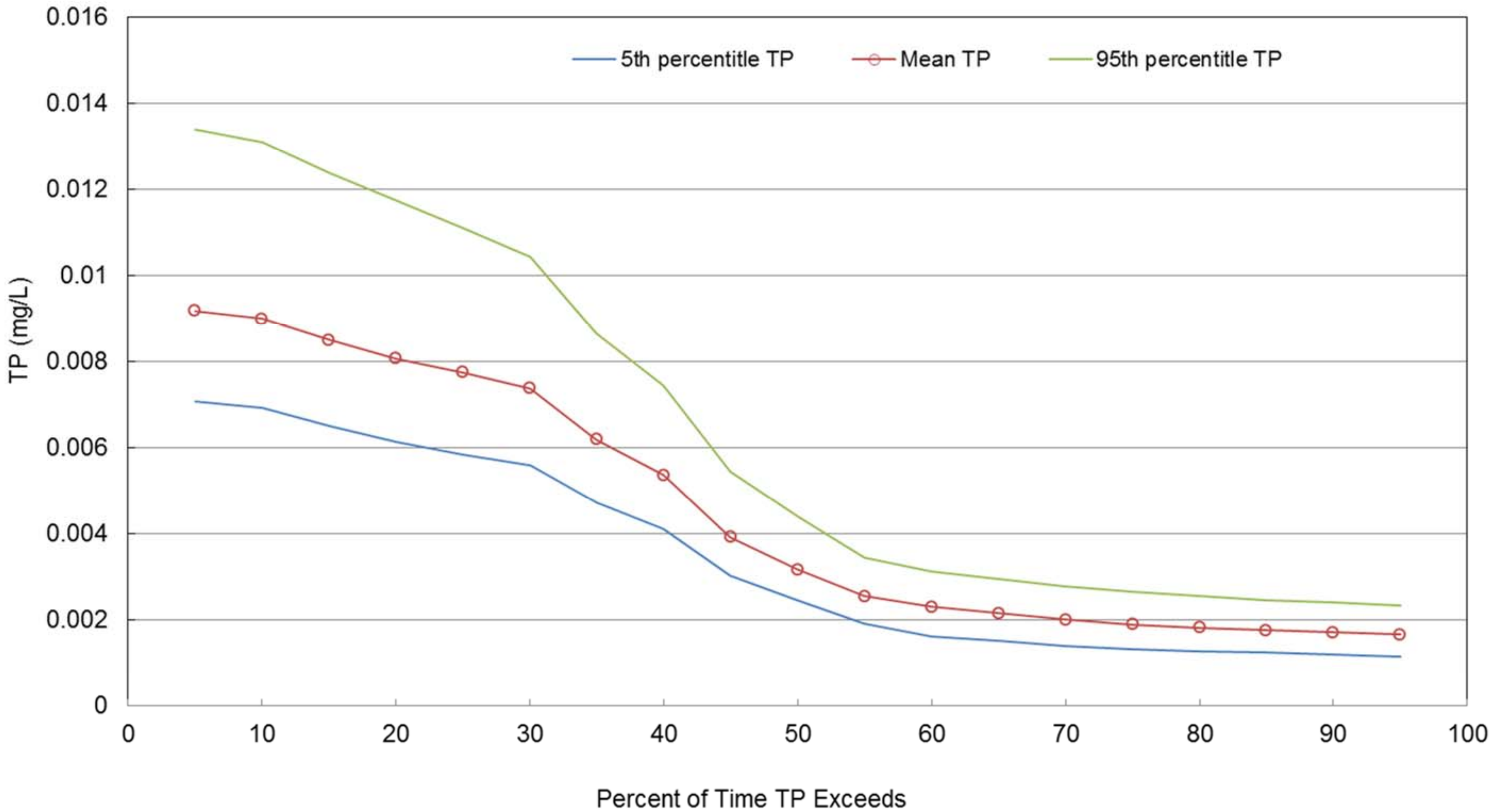


Figure 73 TP Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

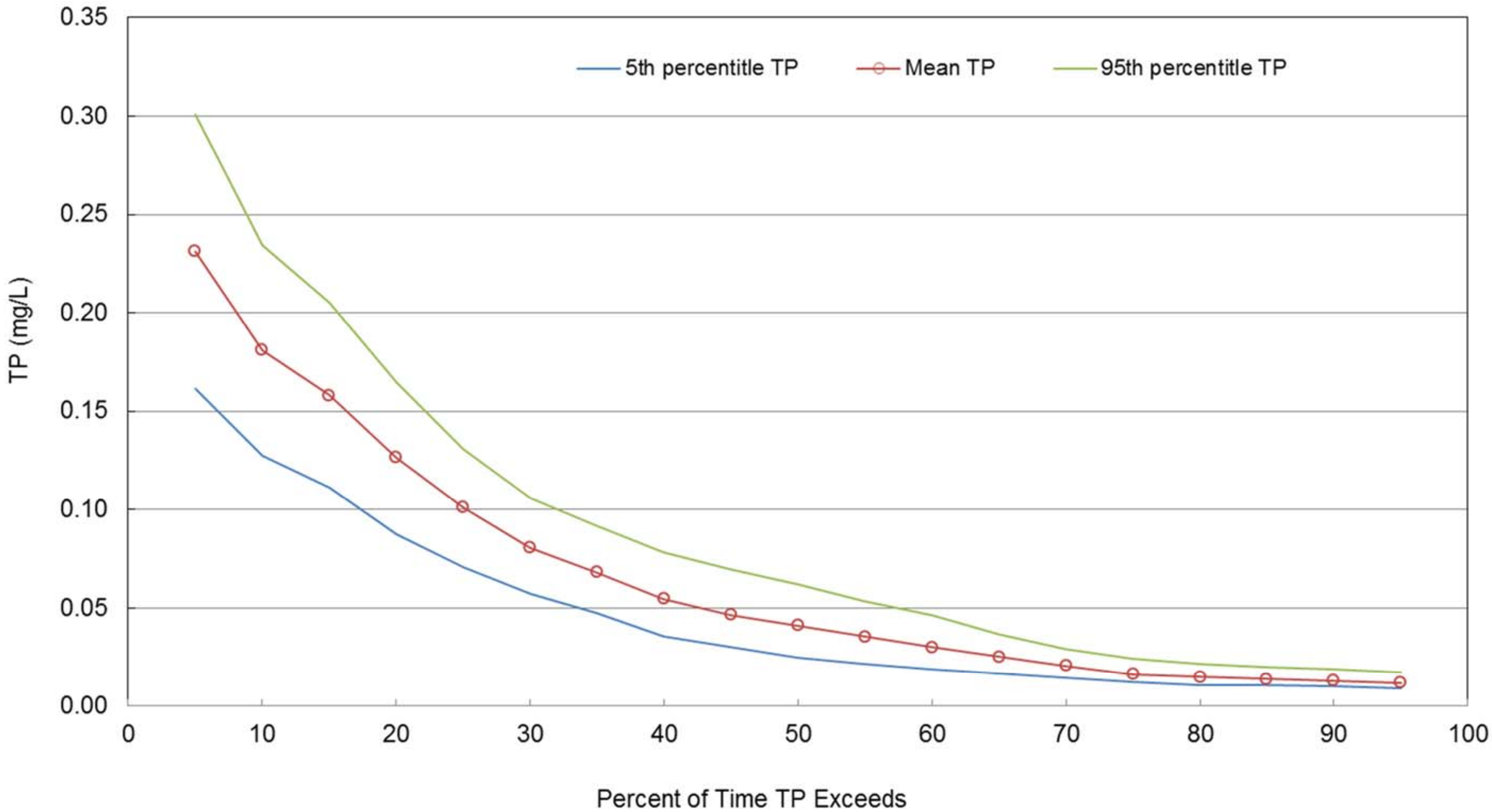


Figure 74 TP Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

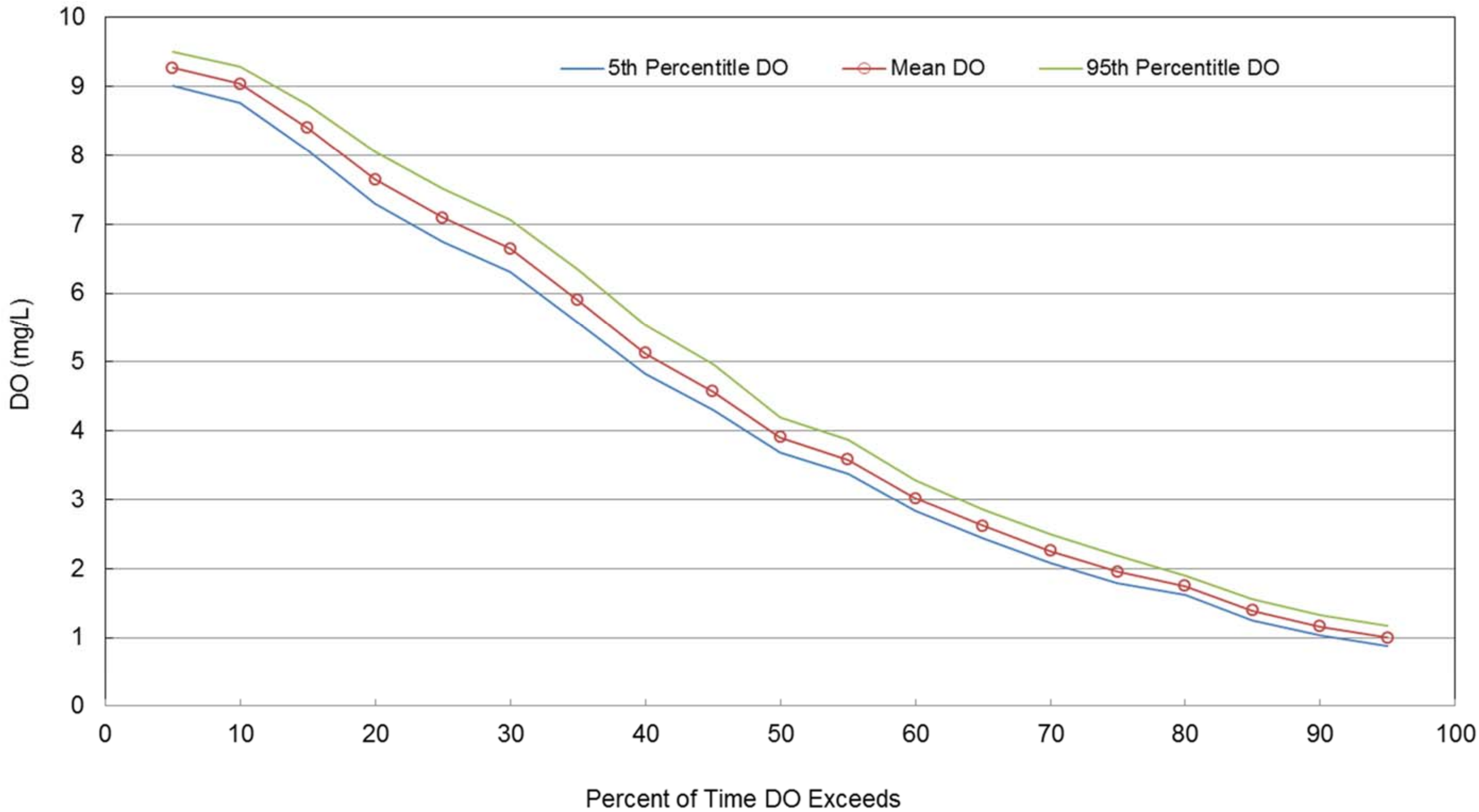


Figure 75 DO Exceedance Curves at LK-01 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

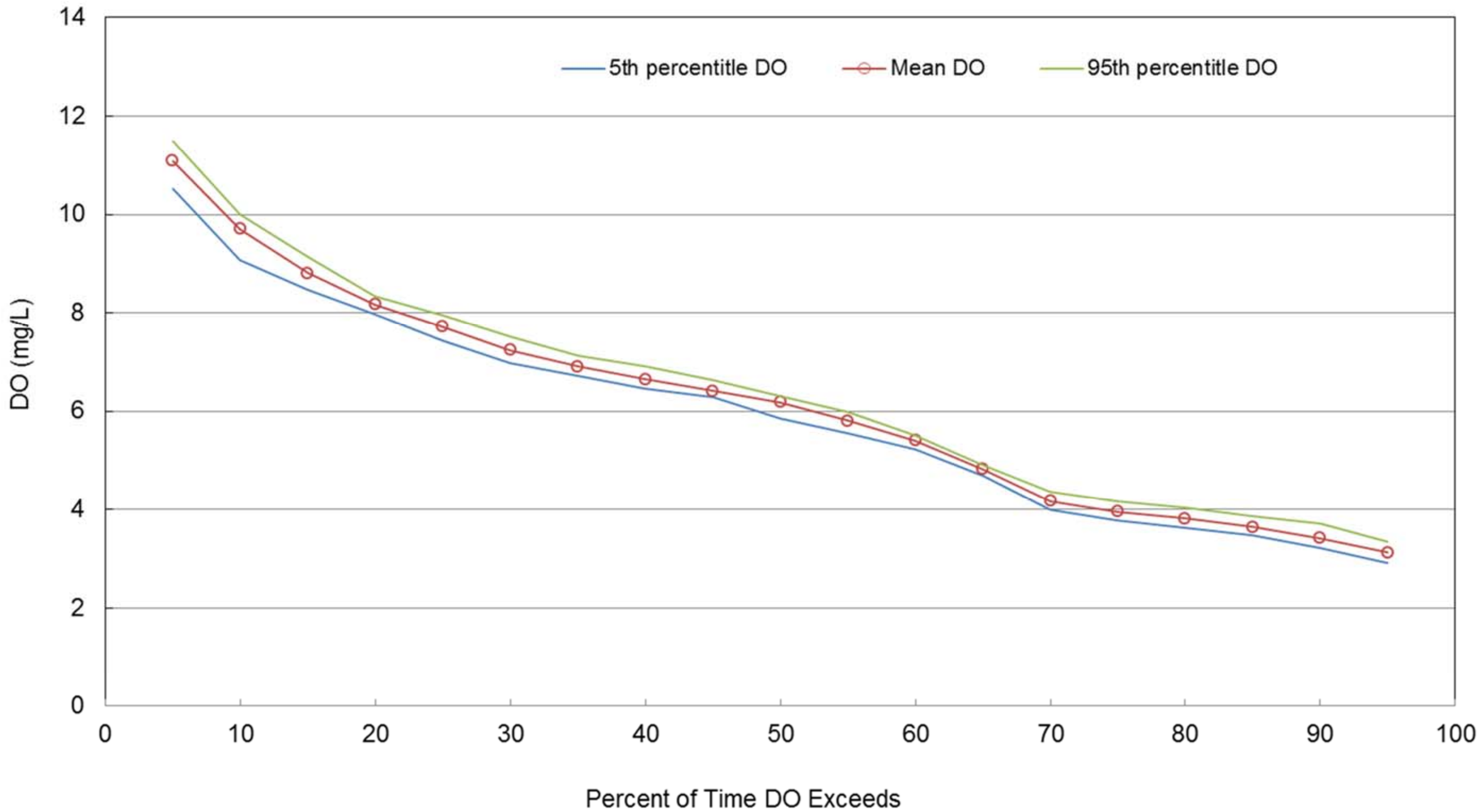


Figure 76 DO Exceedance Curves at LK-03 Showing Mean, 5th, and 95th Percentile Values for the Stratified Period (April 1 – October 31)

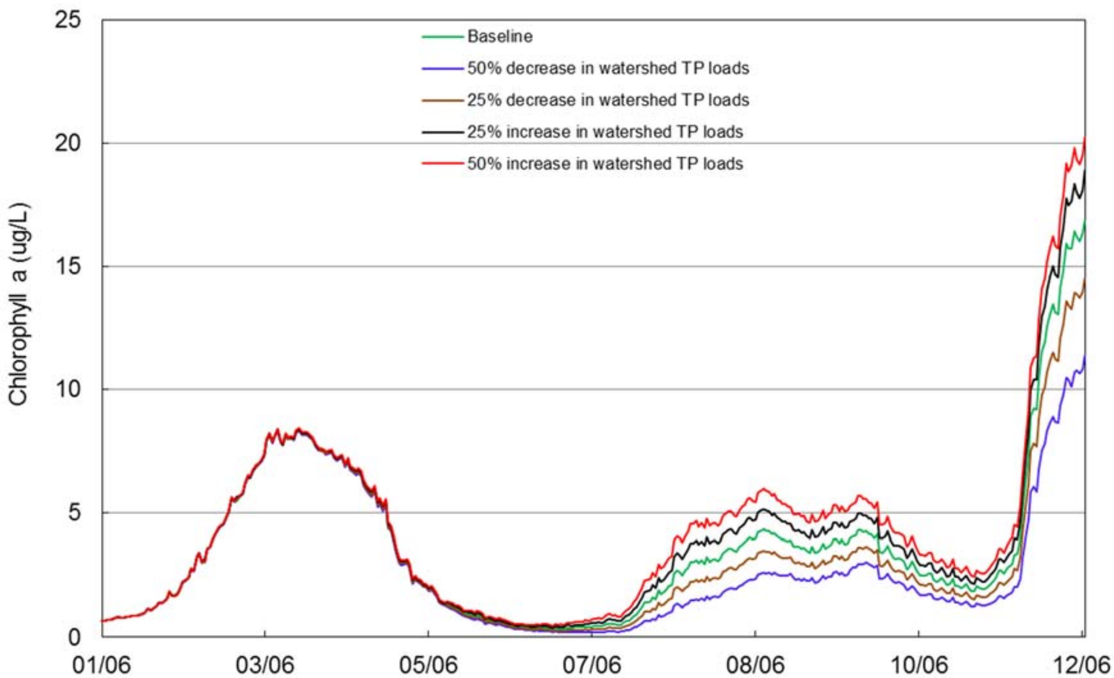


Figure 77 Modeled Chlorophyll a at LK-01 under Perturbation Levels of Watershed TP Loads

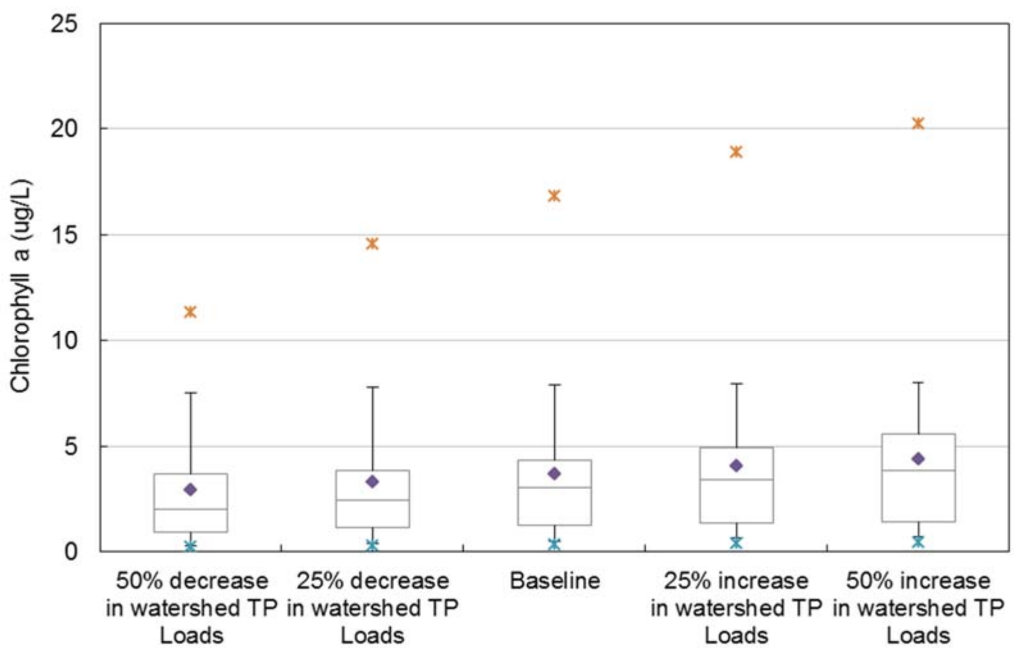


Figure 78 Box-Whisker-Plot of Chlorophyll a at LK-01 under Watershed TP Loads Perturbation

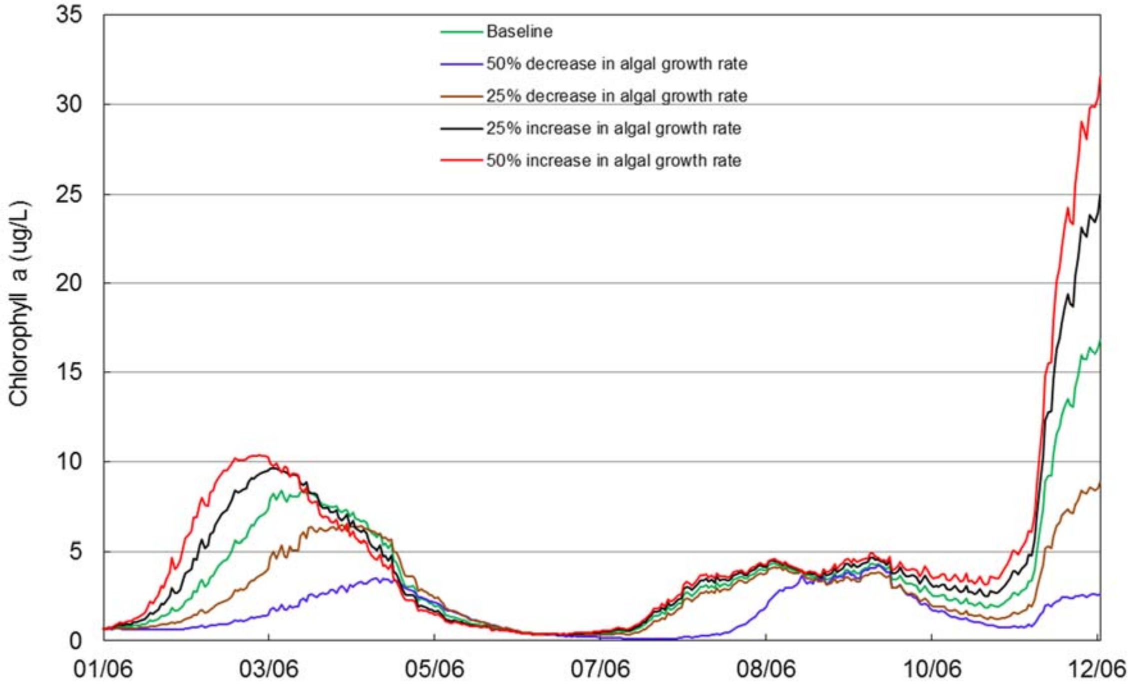


Figure 79 Modeled Chlorophyll a at LK-01 under Perturbation Levels of Algal Growth Rate

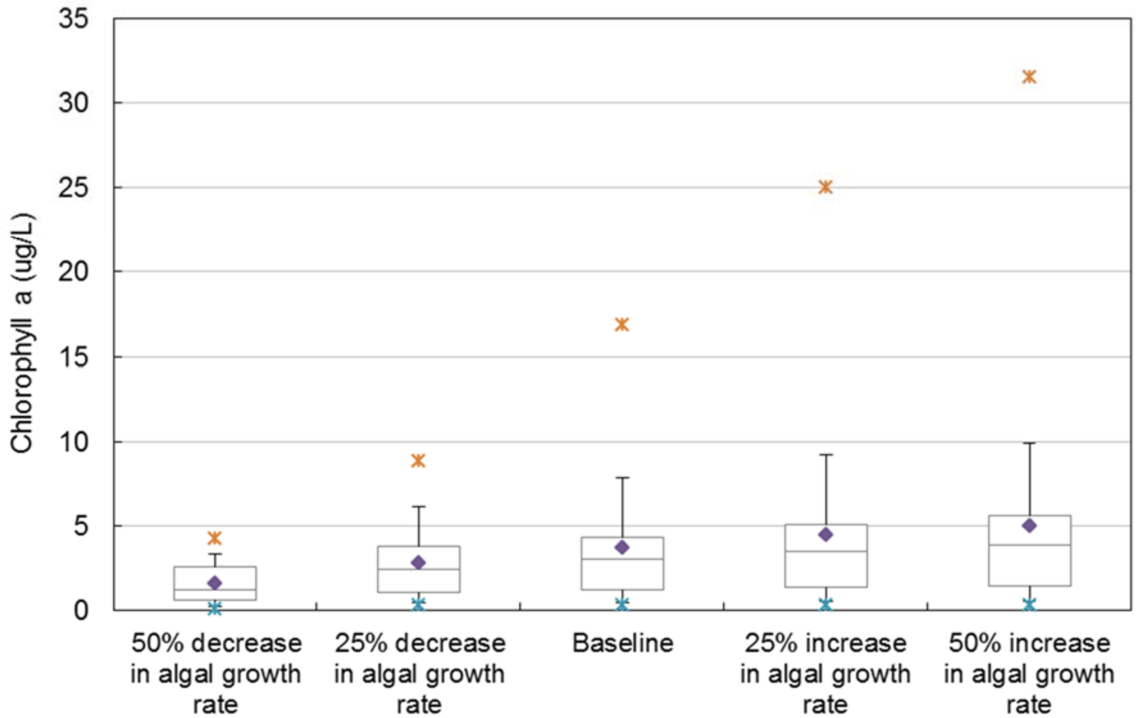


Figure 80 Box-Whisker-Plot of Chlorophyll a at LK-01 under Algal Growth Rate Perturbation

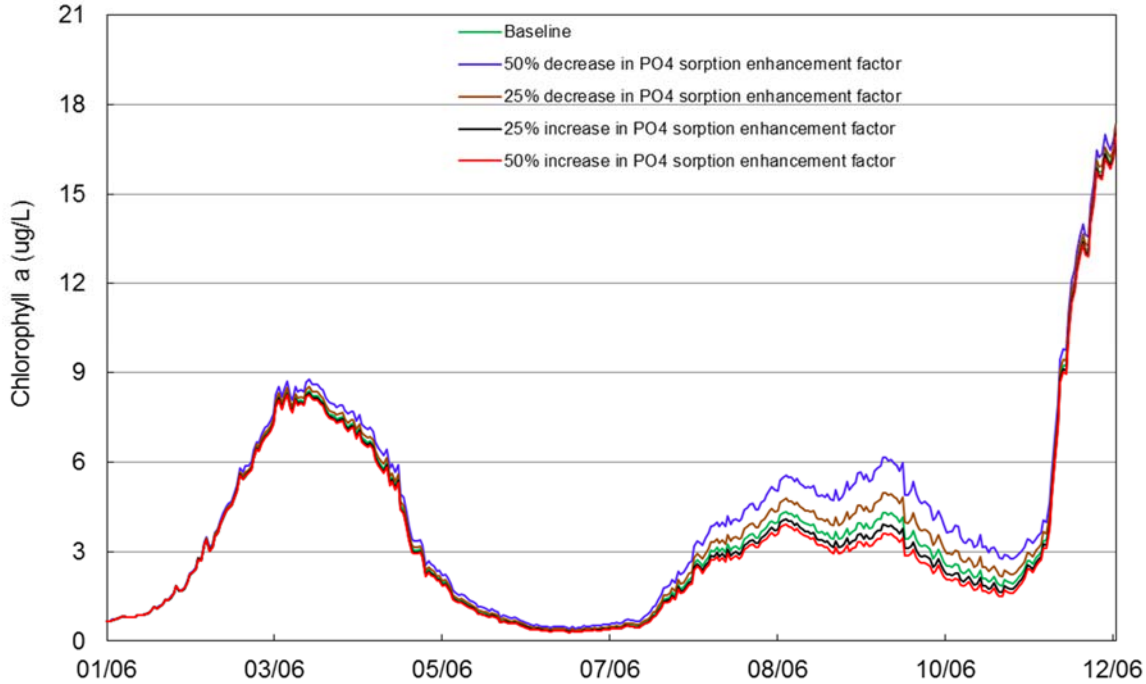


Figure 81 Modeled Chlorophyll a at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

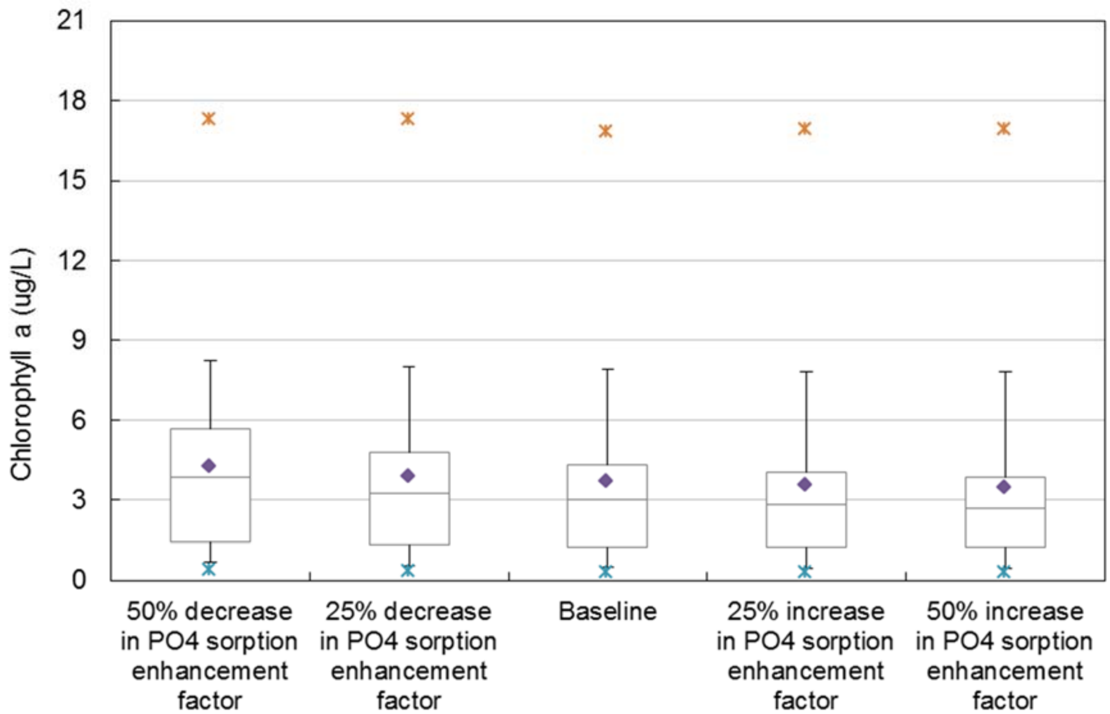


Figure 82 Box-Whisker-Plot of Chlorophyll a at LK-01 under PO4 Sorption Enhancement Factor Perturbation

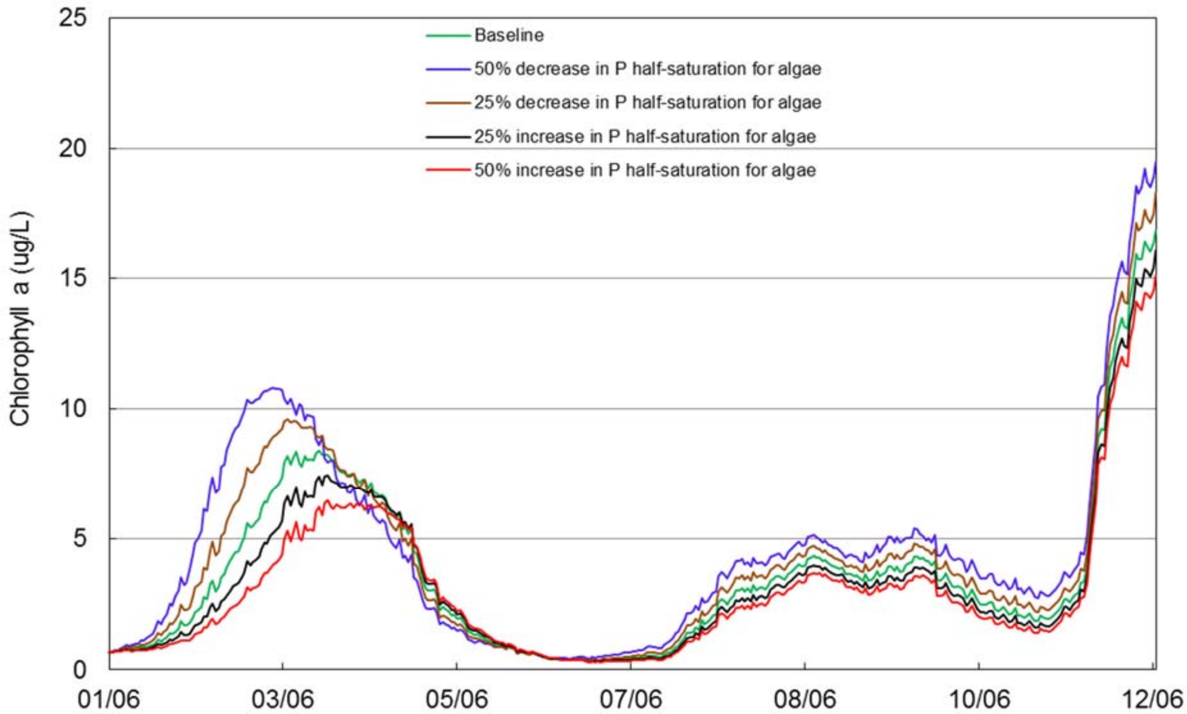


Figure 83 Modeled Chlorophyll a at LK-01 under Perturbation of P Half-saturation for Algae

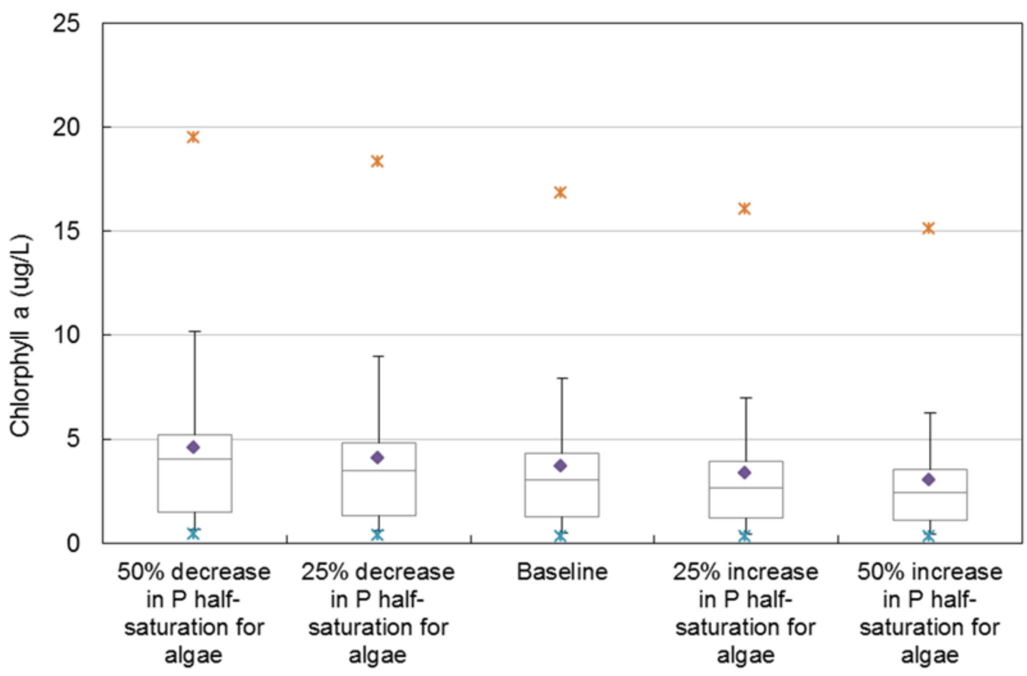


Figure 84 Box-Whisker-Plot of Chlorophyll a at LK-01 under P Half-saturation for Algae Perturbation

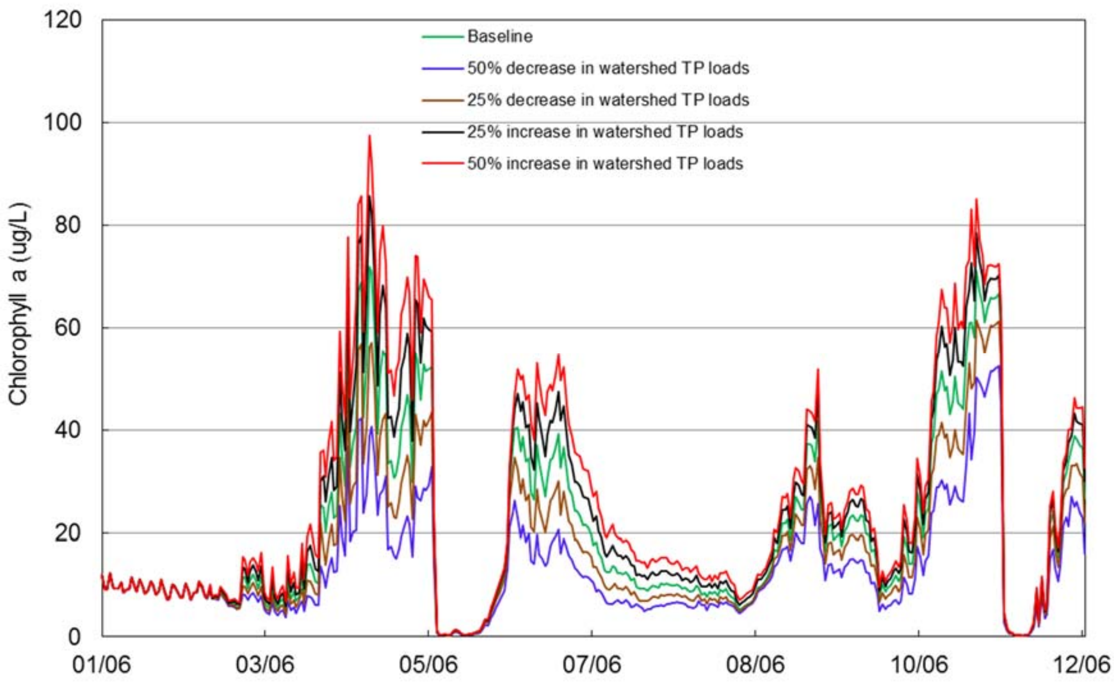


Figure 85 Modeled Chlorophyll a at LK-03 under Perturbation Levels of Watershed TP Loads

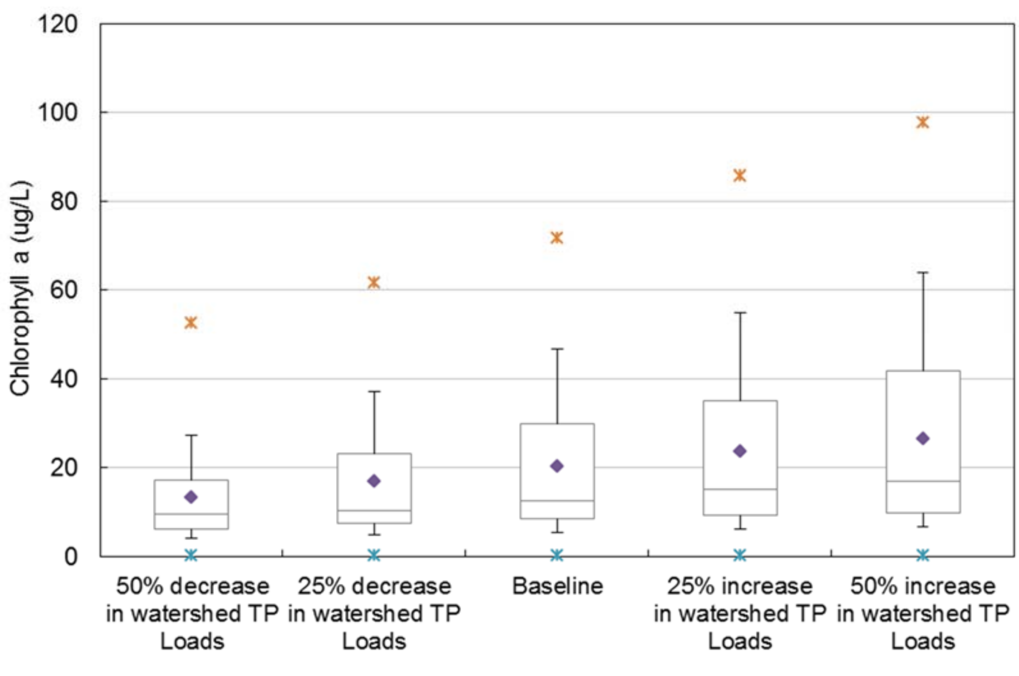


Figure 86 Box-Whisker-Plot of Chlorophyll a at LK-03 under Watershed TP Loads Perturbation

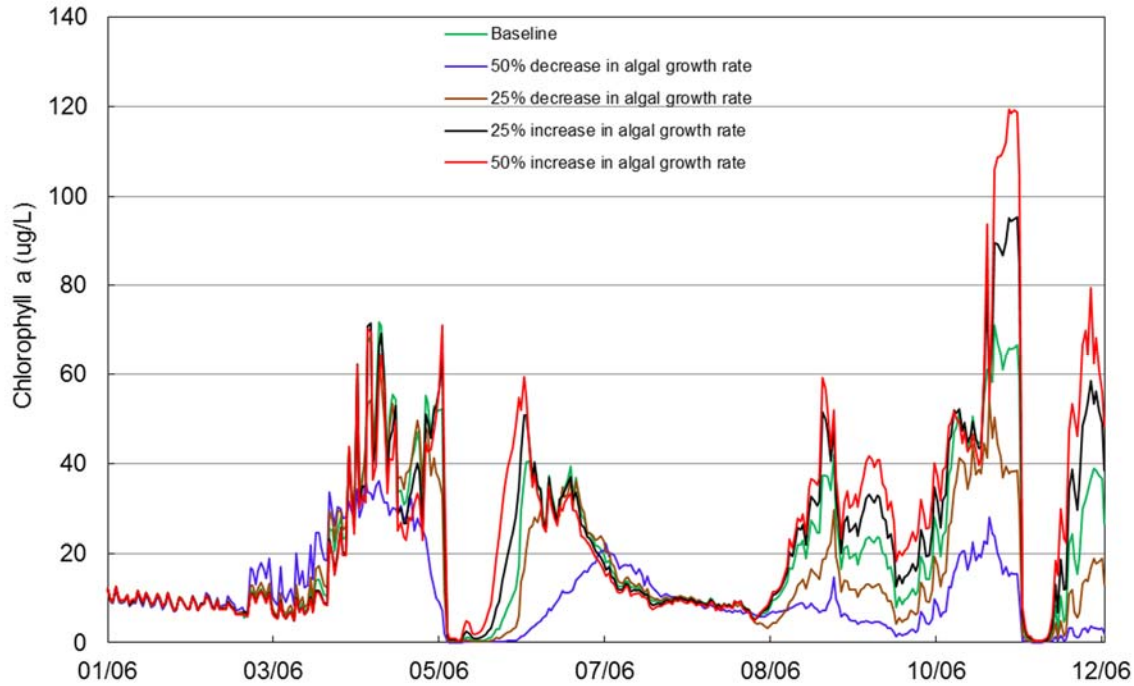


Figure 87 Modeled Chlorophyll a at LK-03 under Perturbation Levels of Algal Growth Rate

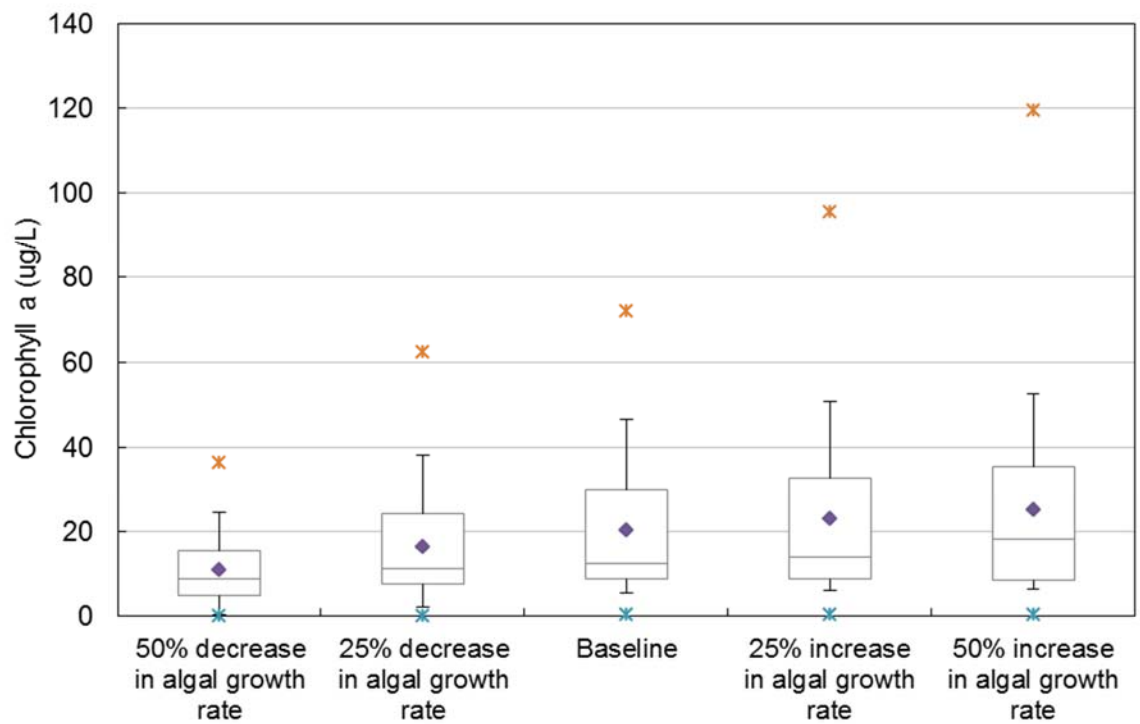


Figure 88 Box-Whisker-Plot of Chlorophyll a at LK-03 under Algal Growth Rate Perturbation

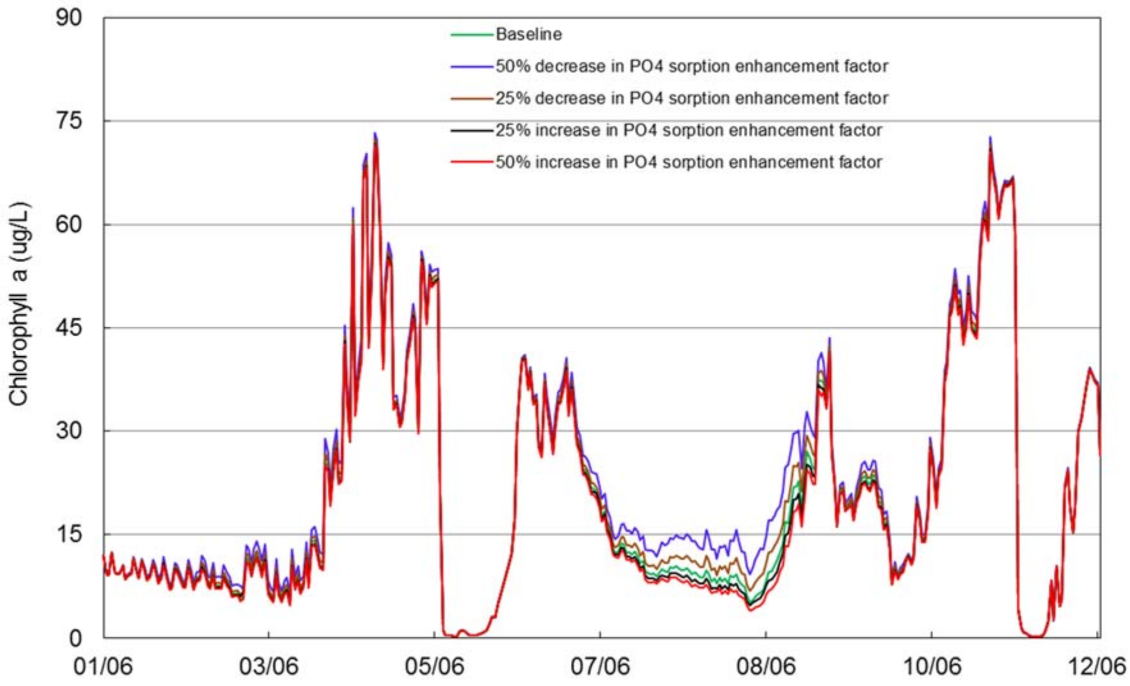


Figure 89 Modeled Chlorophyll a at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

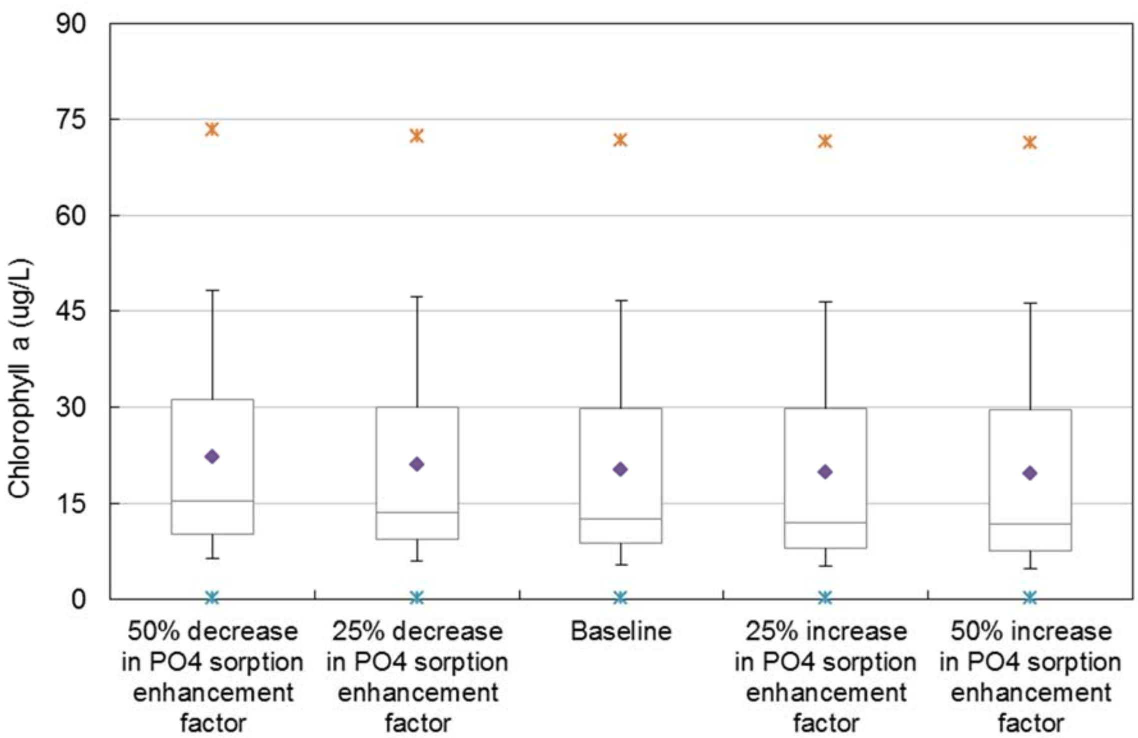


Figure 90 Box-Whisker-Plot of Chlorophyll a at LK-03 under PO4 Sorption Enhancement Factor Perturbation

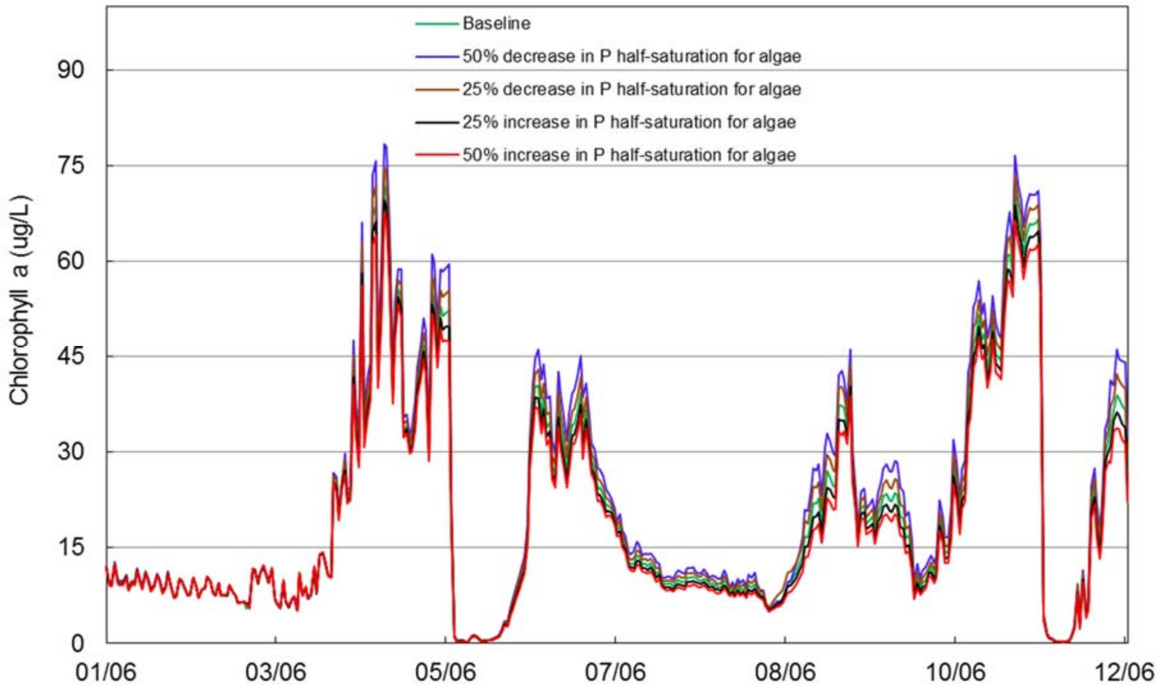


Figure 91 Modeled Chlorophyll a at LK-03 under Perturbation of P Half-saturation for Algae

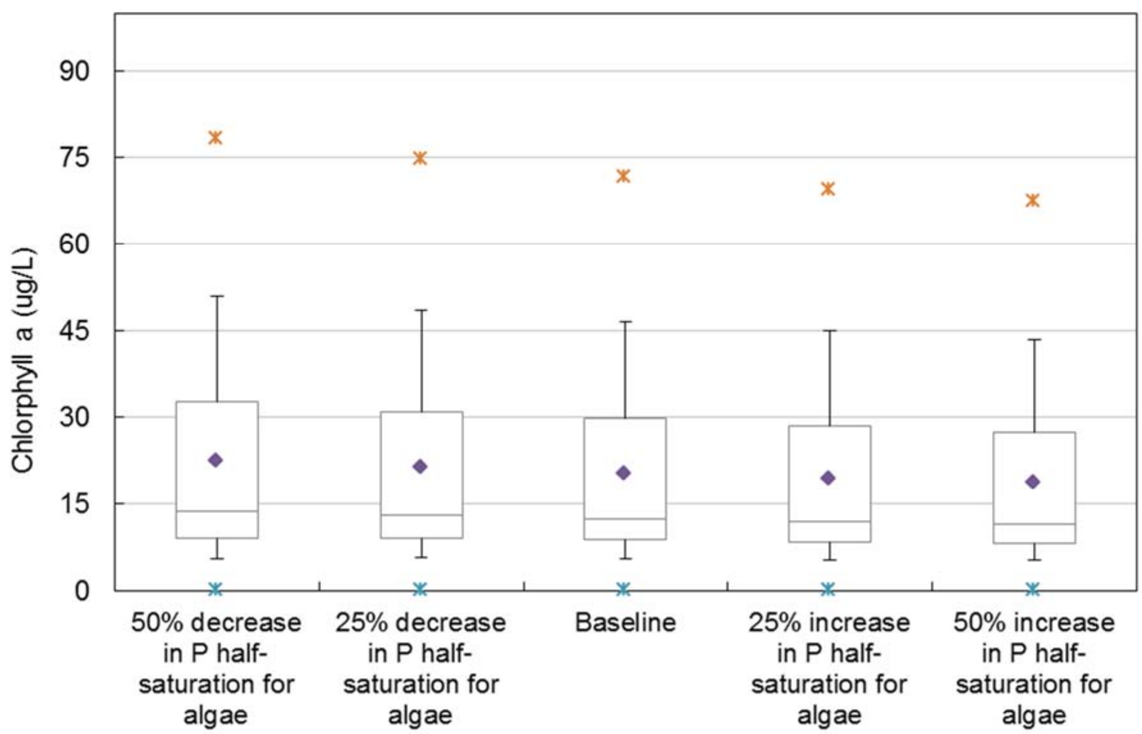


Figure 92 Box-Whisker-Plot of Chlorophyll a at LK-03 under P Half-saturation for Algae Perturbation

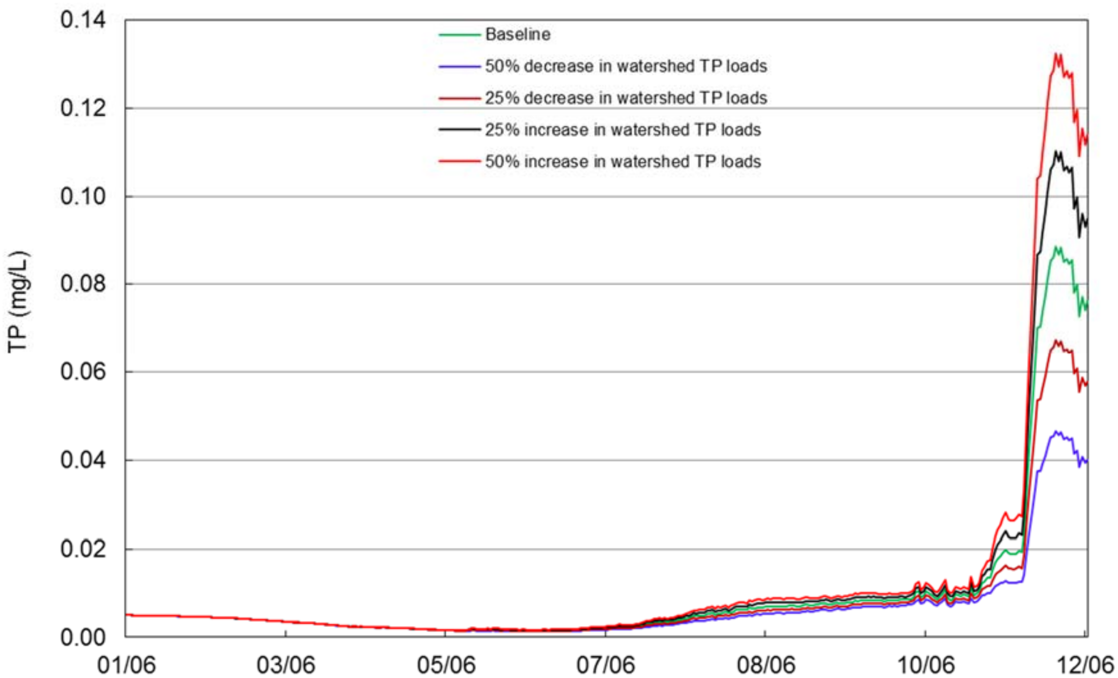


Figure 93 Modeled TP at LK-01 under Different Perturbation Levels of Watershed TP Loads

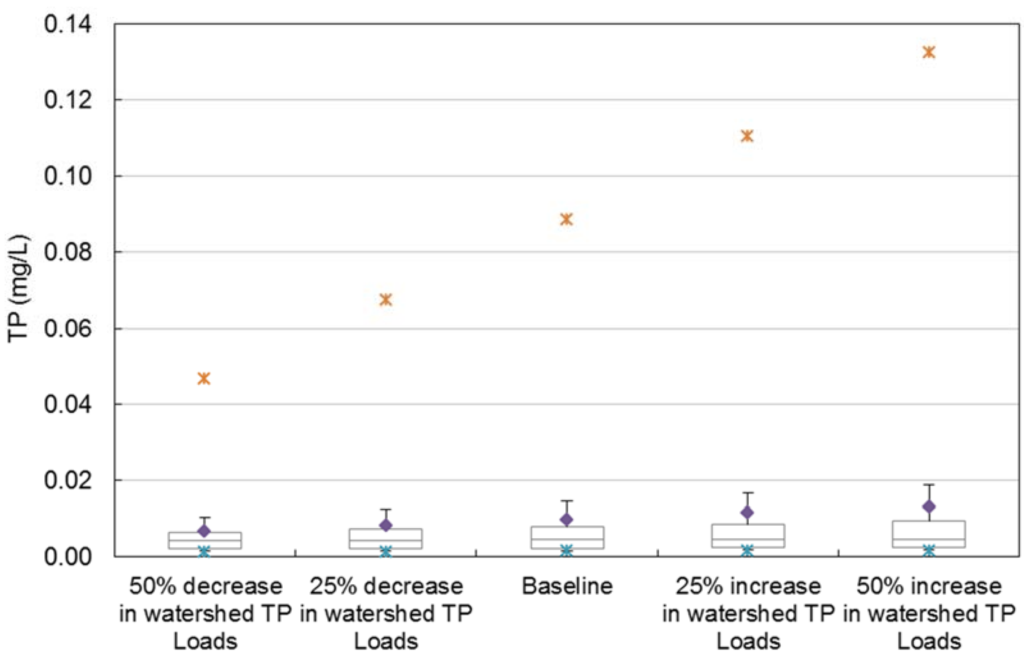


Figure 94 Box-Whisker-Plot of TP at LK-01 under Watershed TP Loads Perturbation

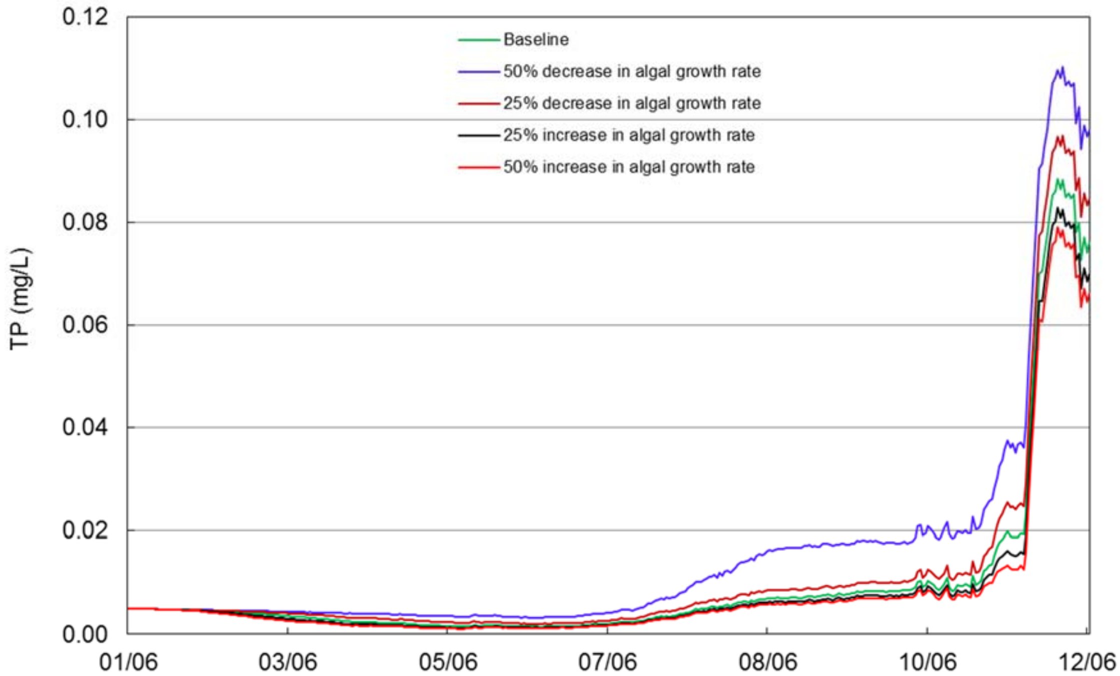


Figure 95 Modeled TP at LK-01 under Different Perturbation Levels of Algal Growth Rate

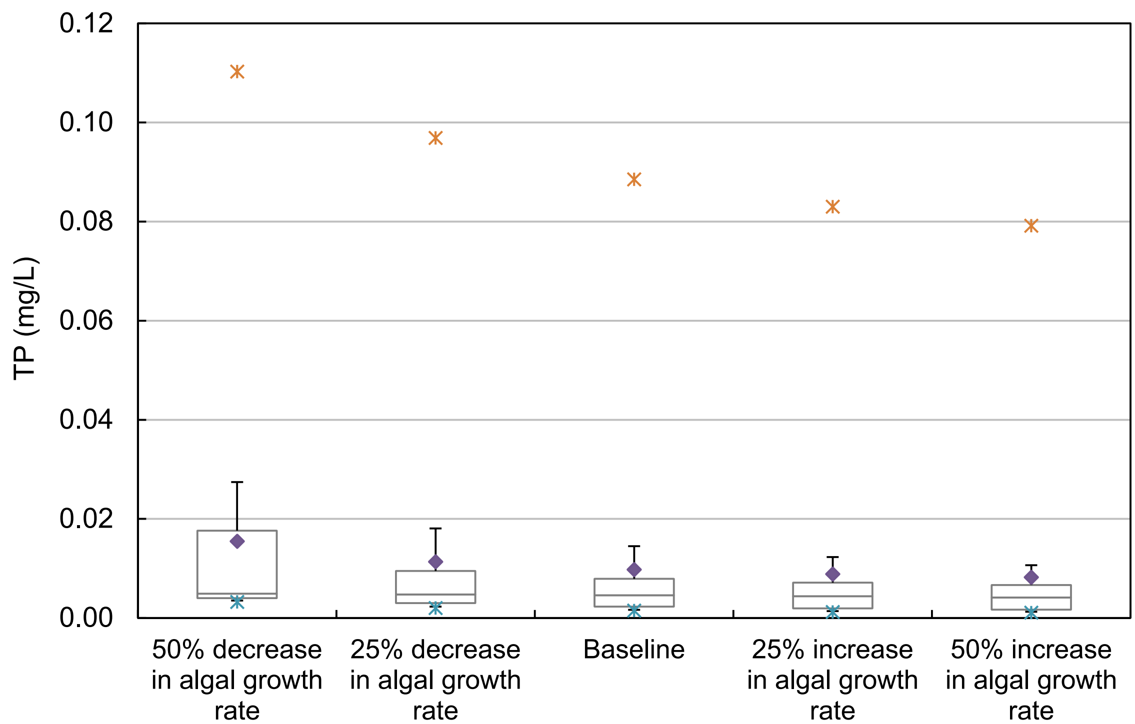


Figure 96 Box-Whisker-Plot of TP at LK-01 under Algal Growth Rate Perturbation

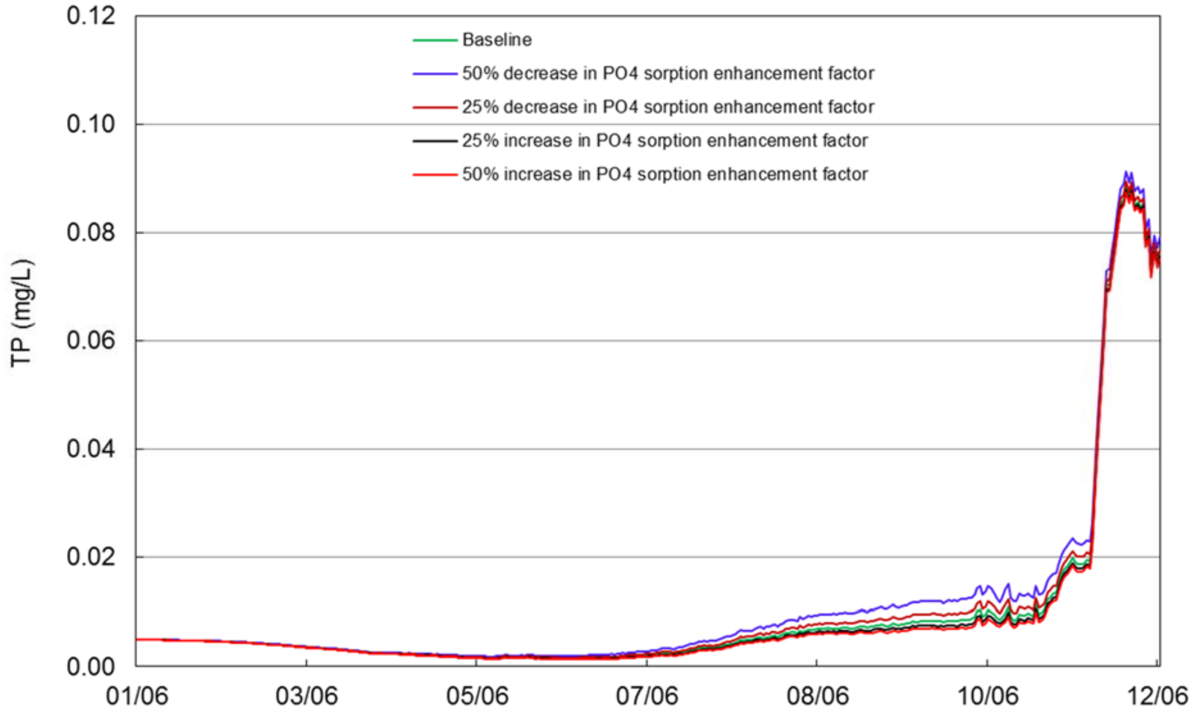


Figure 97 Modeled TP at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

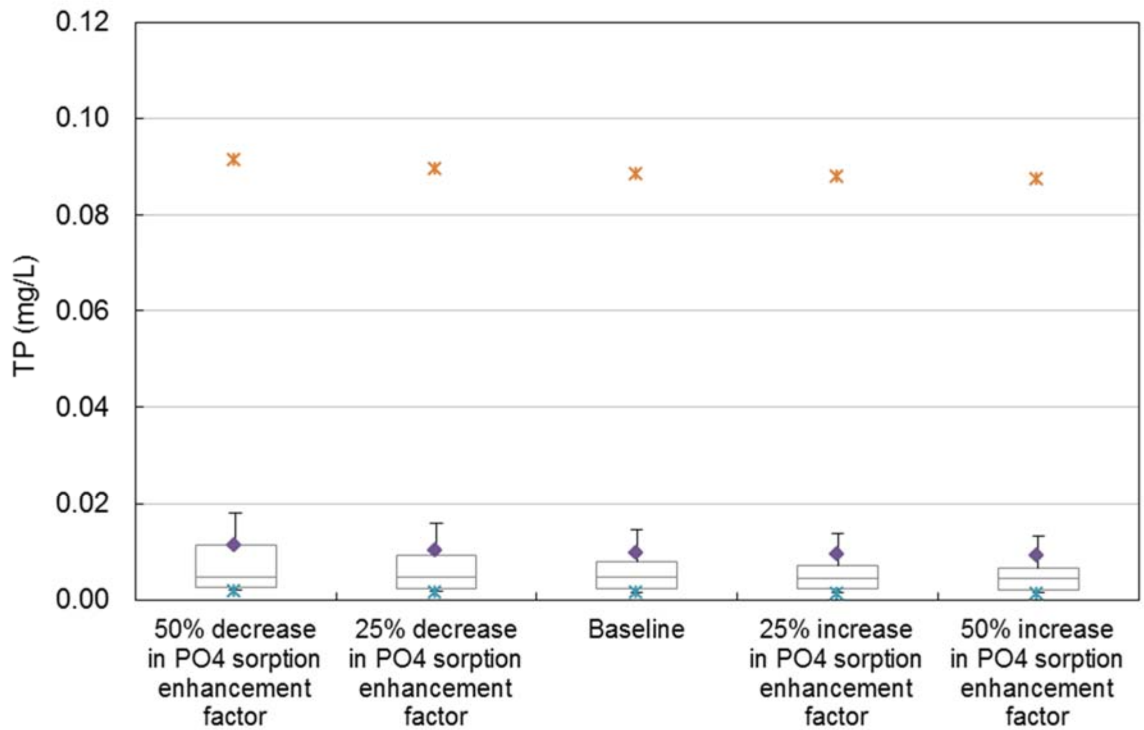


Figure 98 Box-Whisker-Plot of TP at LK-01 under PO4 Sorption Enhancement Factor Perturbation

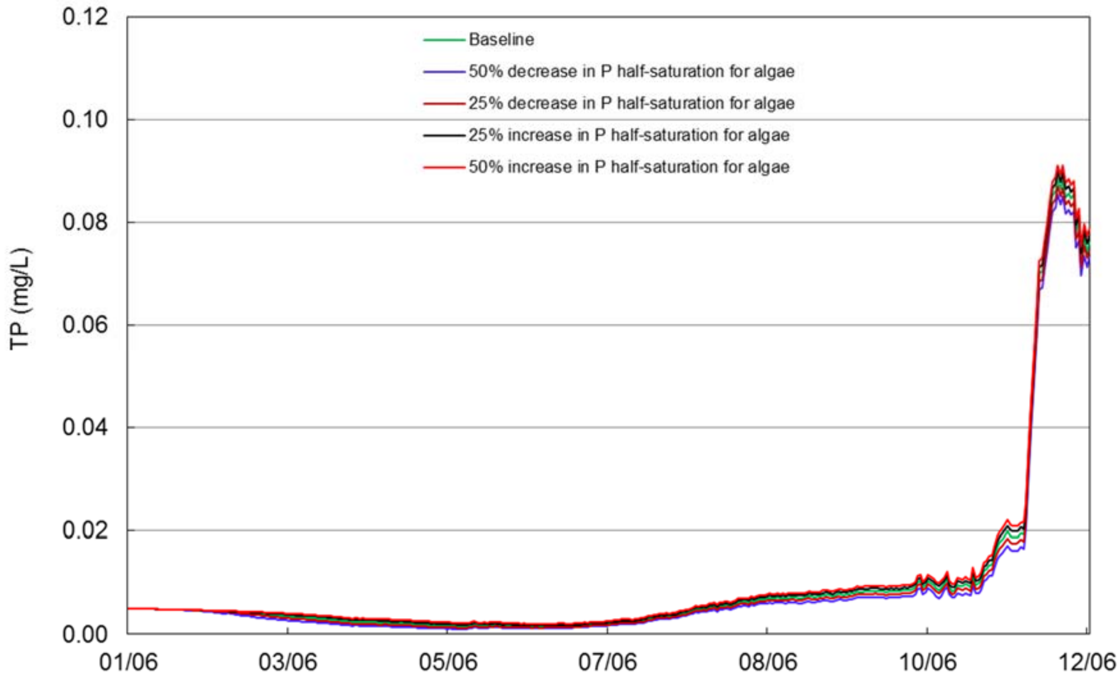


Figure 99 Modeled TP at LK-01 under Different Perturbation of P Half-saturation for Algae

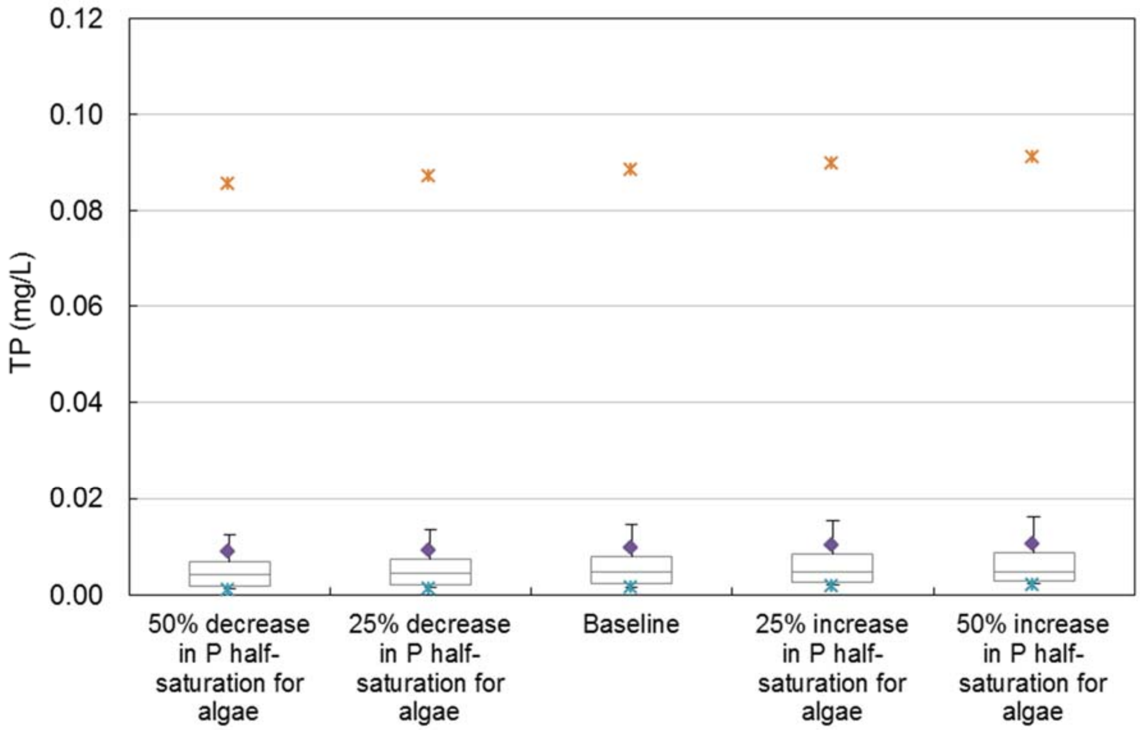


Figure 100 Box-Whisker-Plot of TP at LK-01 under P Half-saturation for Algae Perturbation

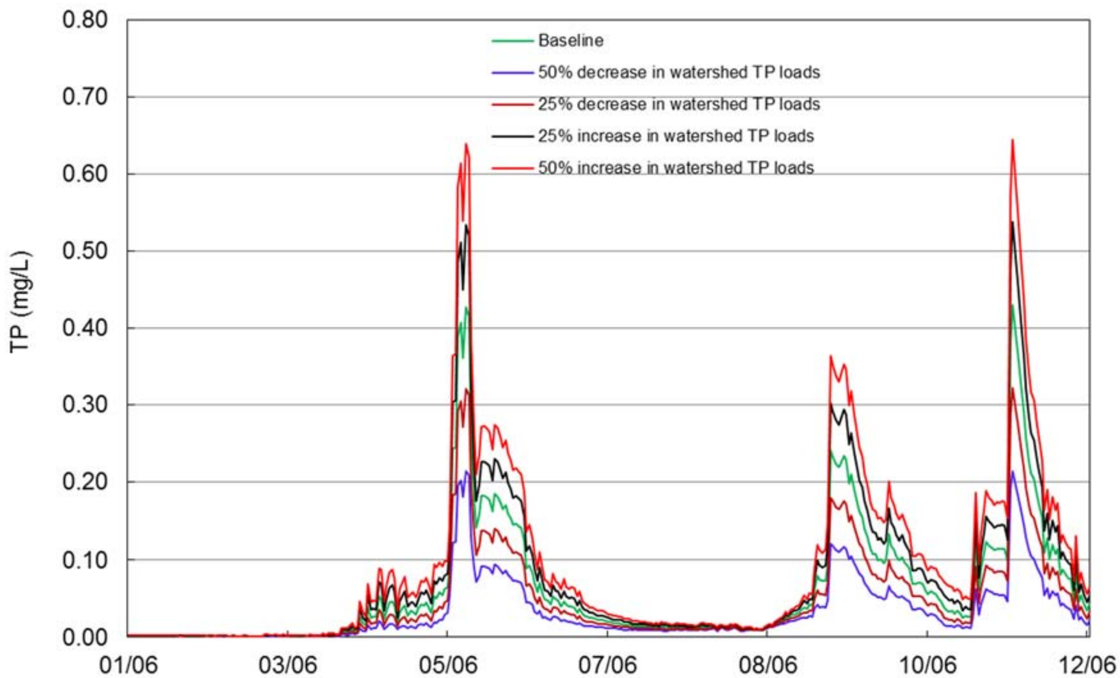


Figure 101 Modeled TP at LK-03 under Different Perturbation Levels of Watershed TP Loads

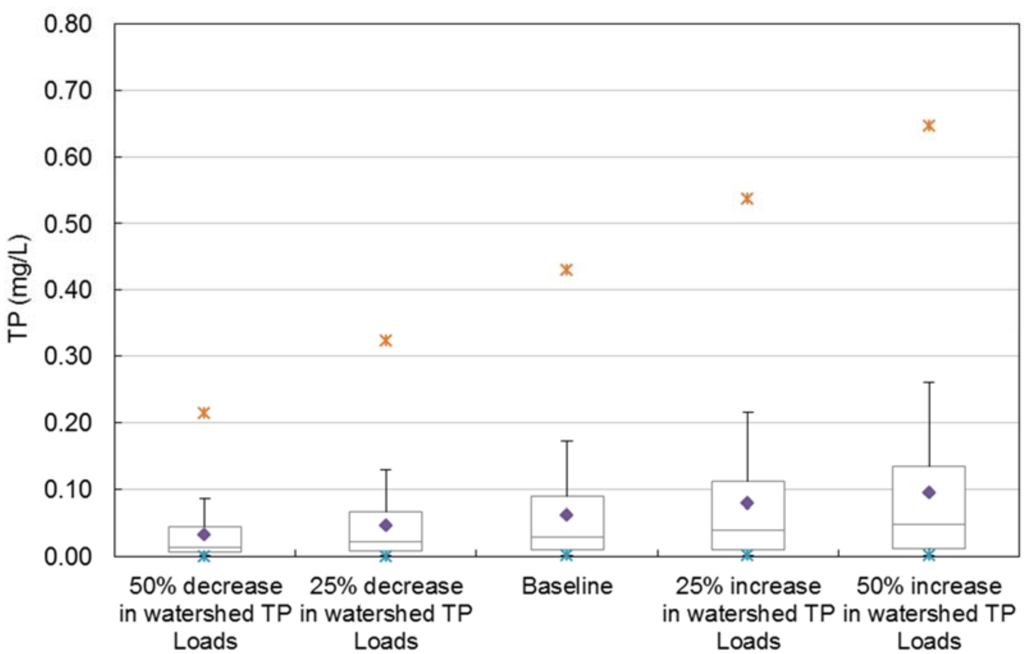


Figure 102 Box-Whisker-Plot of TP at LK-03 under Different Watershed TP Loads Perturbation

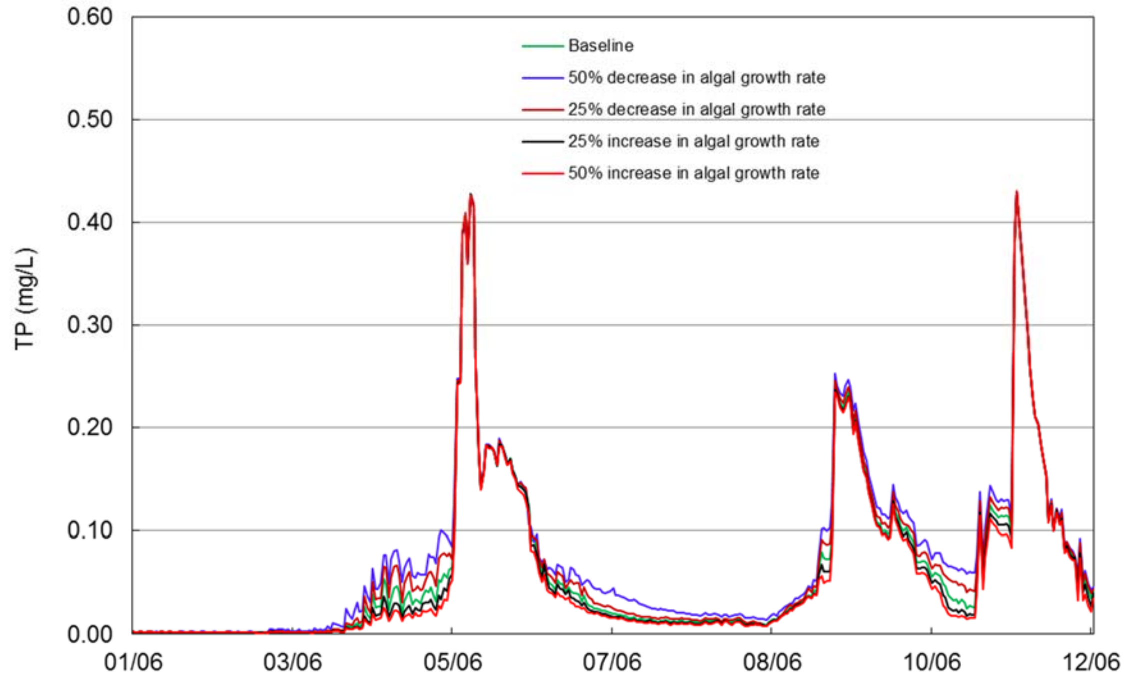


Figure 103 Modeled TP at LK-03 under Different Perturbation Levels of Algal Growth Rate

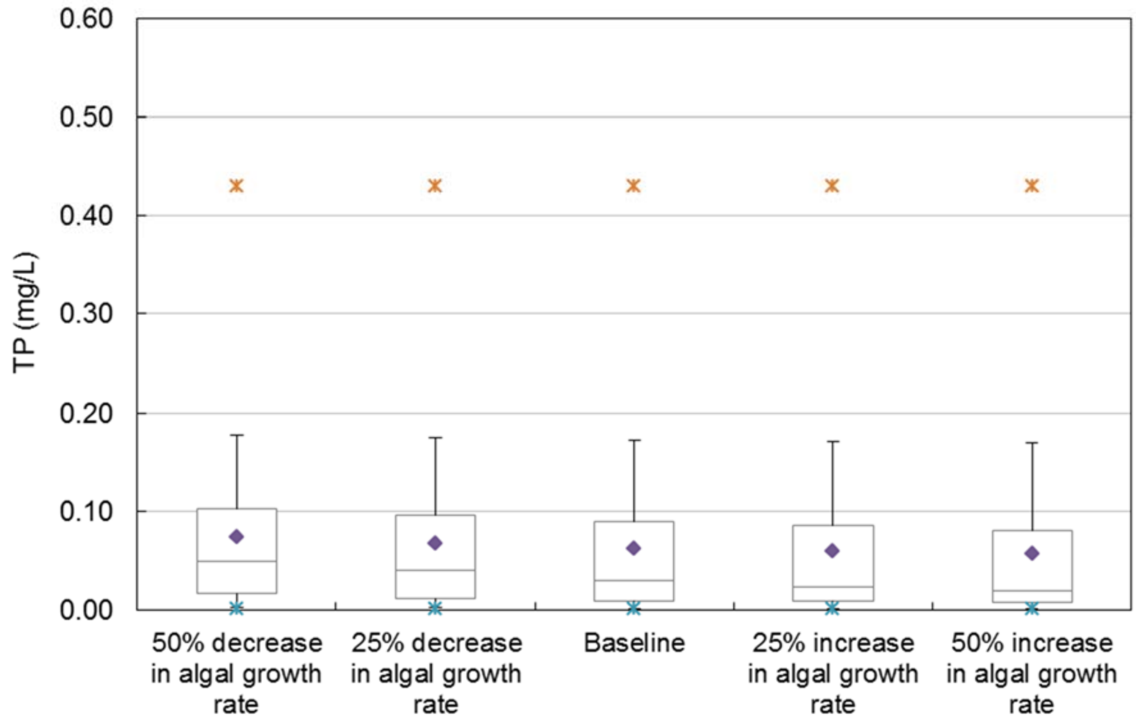


Figure 104 Box-Whisker-Plot of TP at LK-03 under Different Algal Growth Rate Perturbation

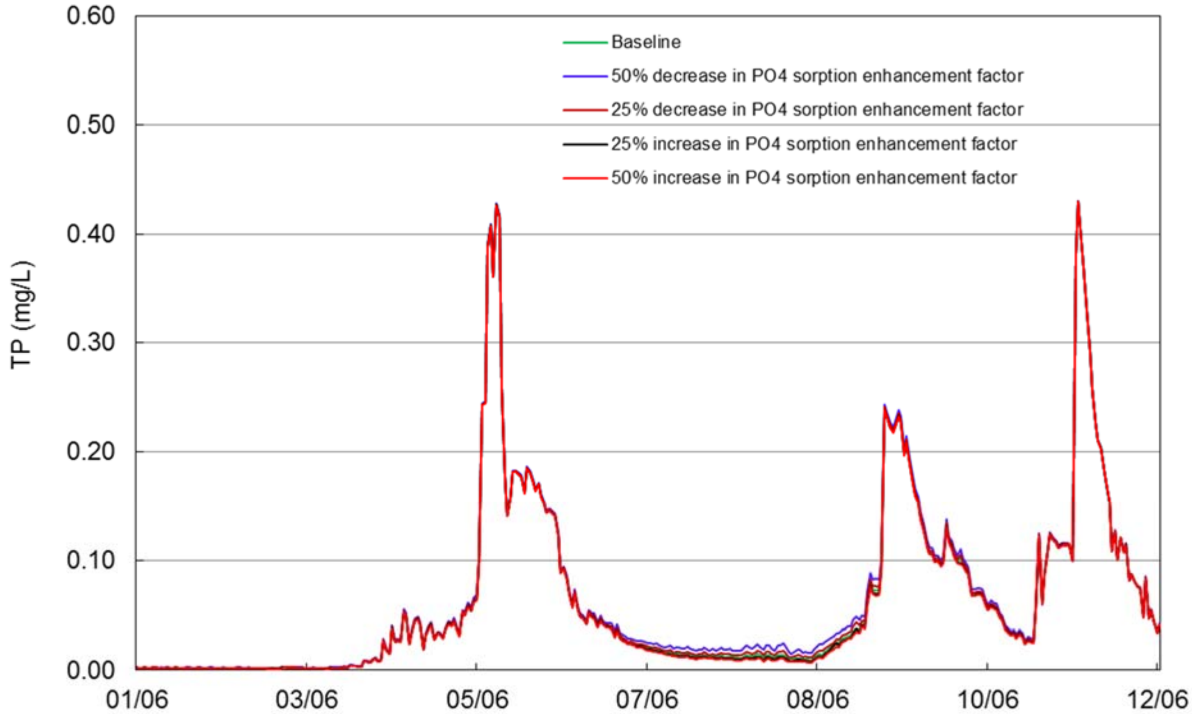


Figure 105 Modeled TP at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

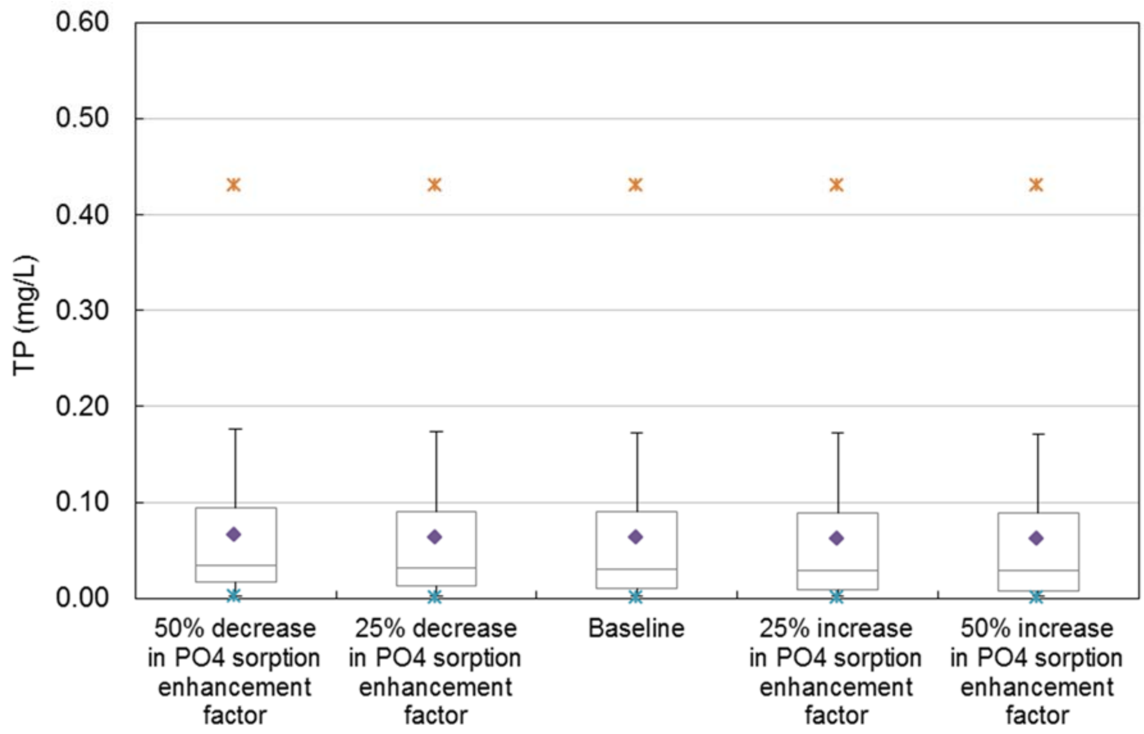


Figure 106 Box-Whisker-Plot of TP at LK-03 under PO4 Sorption Enhancement Factor Perturbation

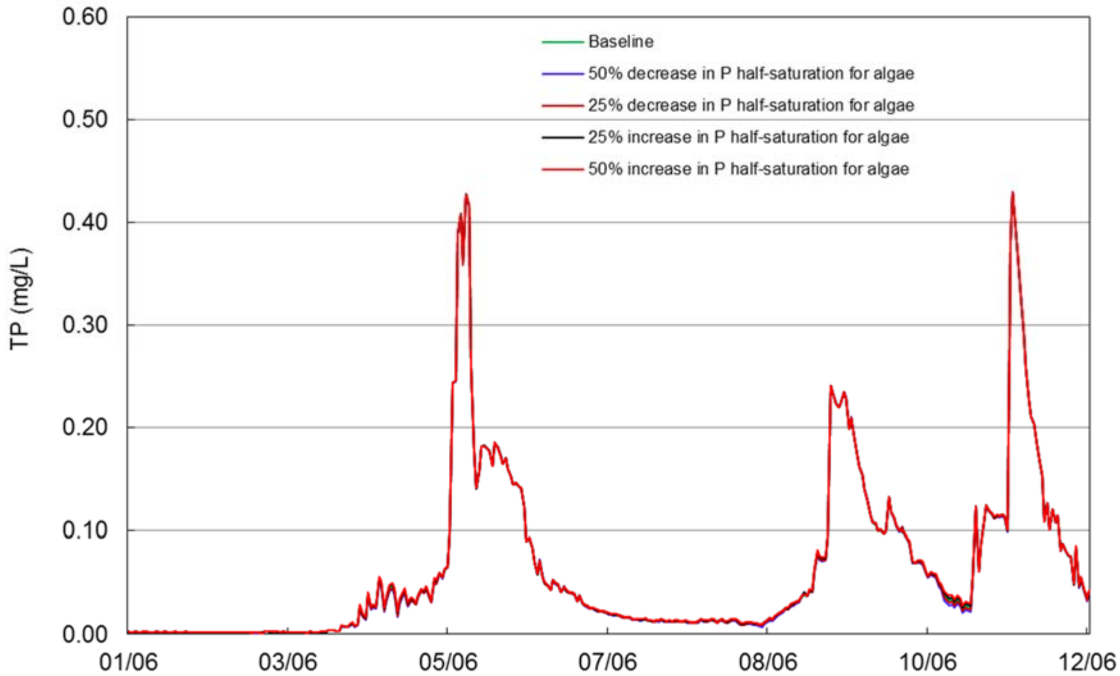


Figure 107 Modeled TP LK-03 under Different Perturbation of P Half-saturation for Algae at

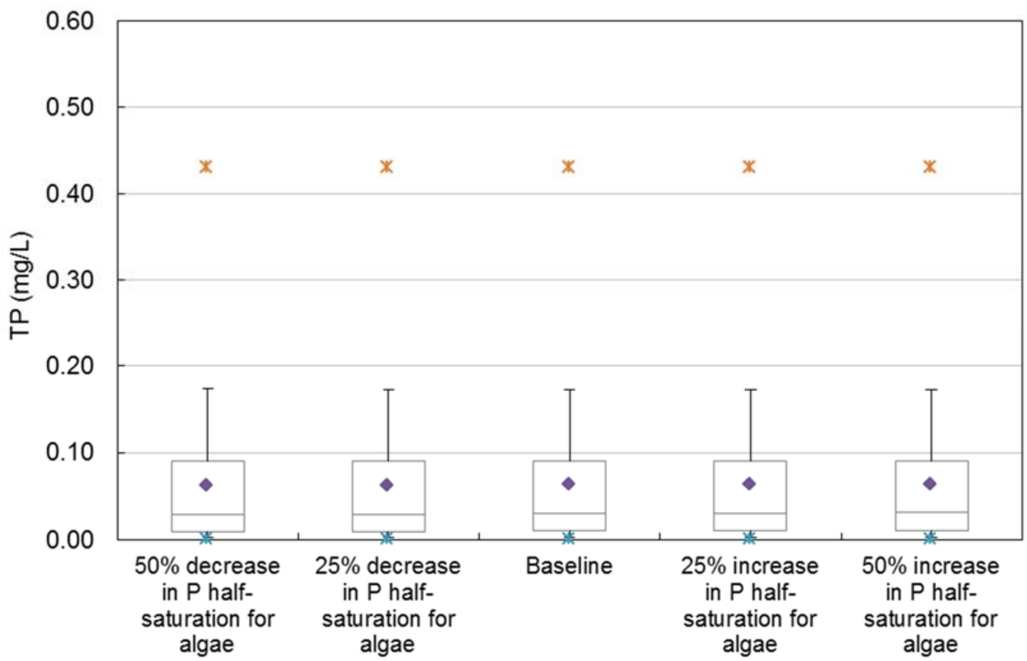


Figure 108 Box-Whisker-Plot of TP at LK-03 under P Half-saturation for Algae Perturbation

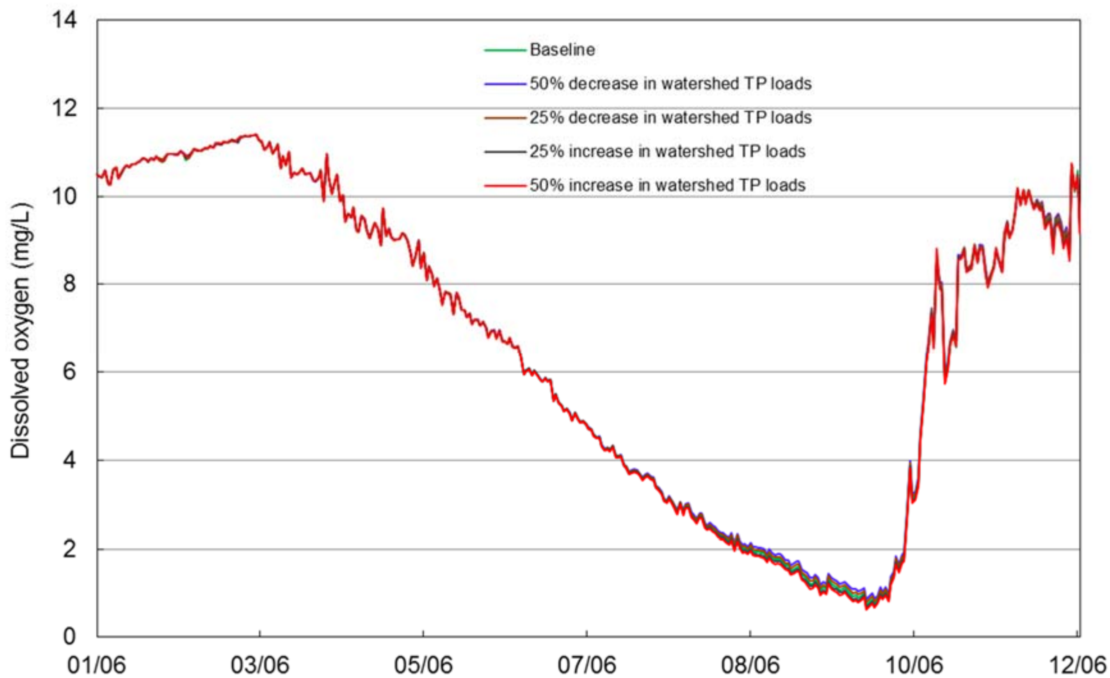


Figure 109 Modeled DO at LK-01 under Different Perturbation Levels of Watershed TP Loads

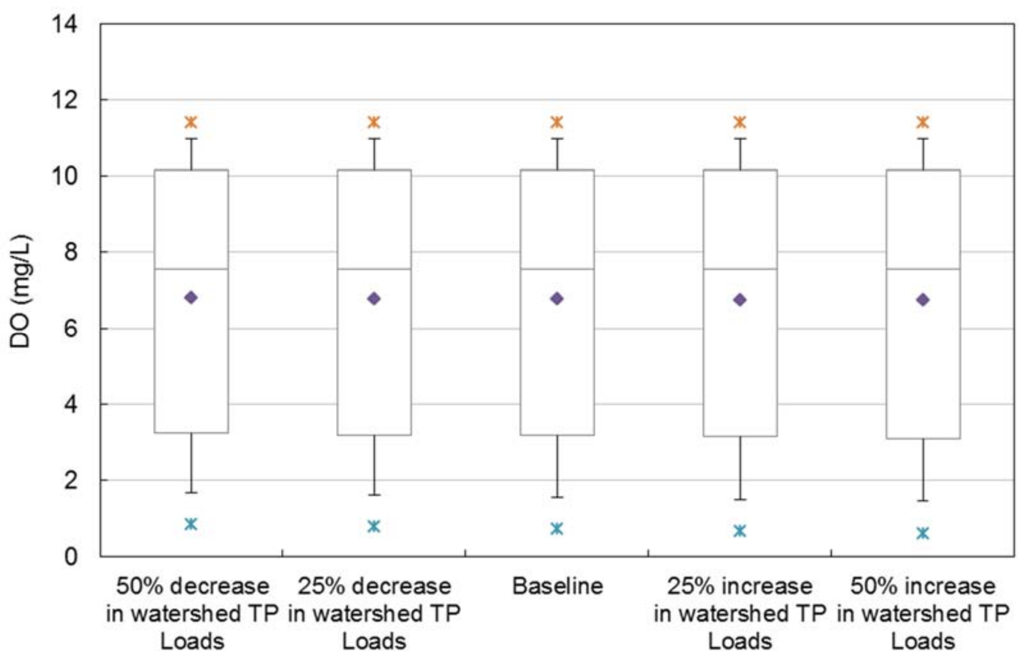


Figure 110 Box-Whisker-Plot of DO at LK-01 under Different Watershed TP Loads Perturbation

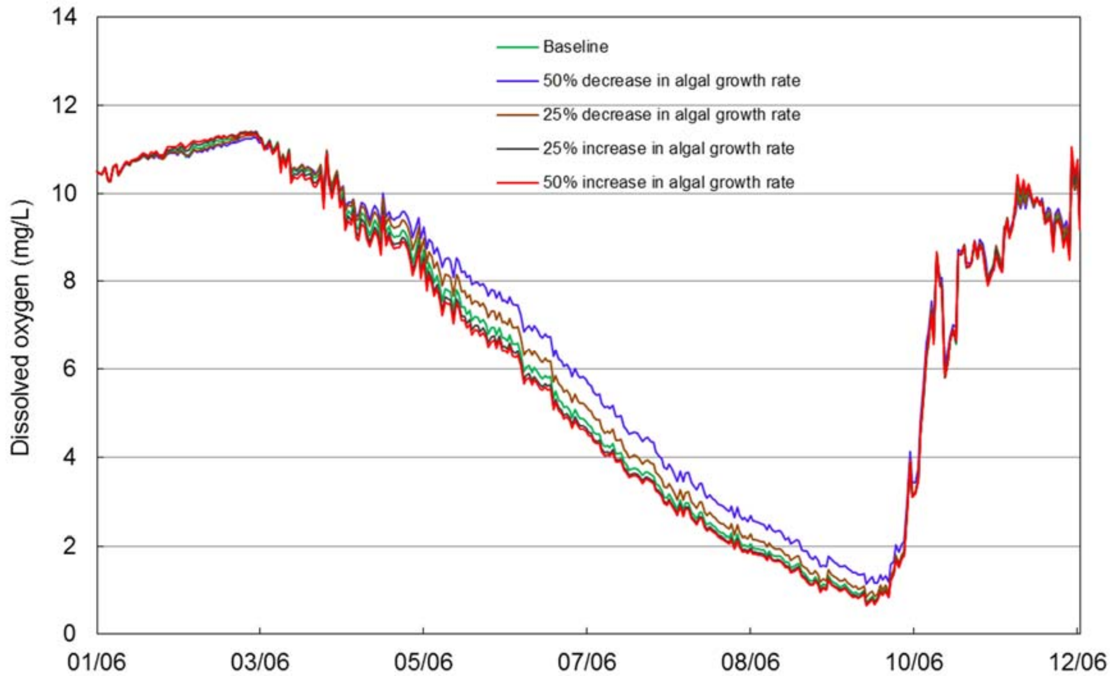


Figure 111 Modeled DO at LK-01 under Different Perturbation Levels of Algal Growth Rate

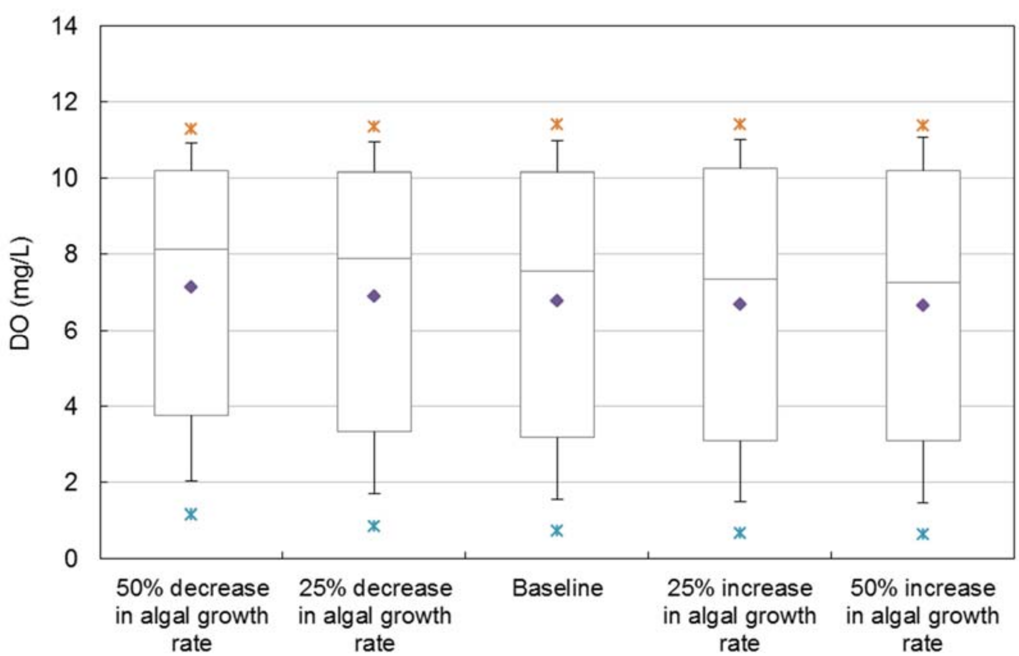


Figure 112 Box-Whisker-Plot of DO at LK-01 under Different Algal Growth Rate Perturbation

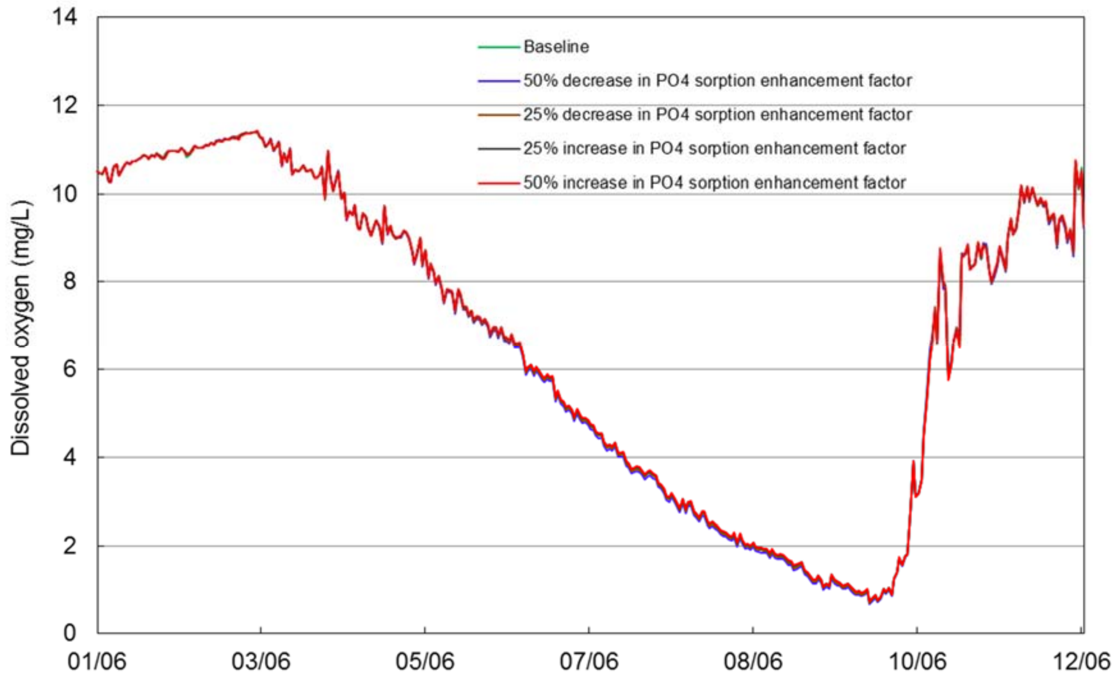


Figure 113 Modeled DO at LK-01 under Perturbation of PO4 Sorption Enhancement Factor

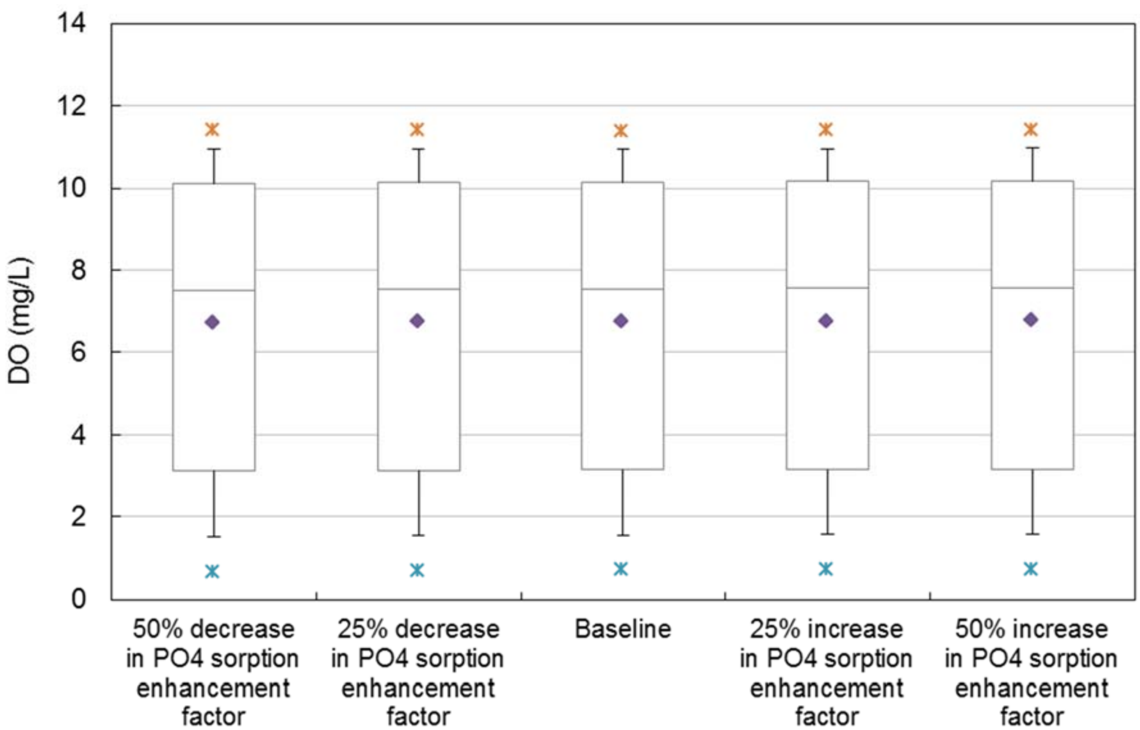


Figure 114 Box-Whisker-Plot of DO at LK-01 under PO4 Sorption Enhancement Factor Perturbation

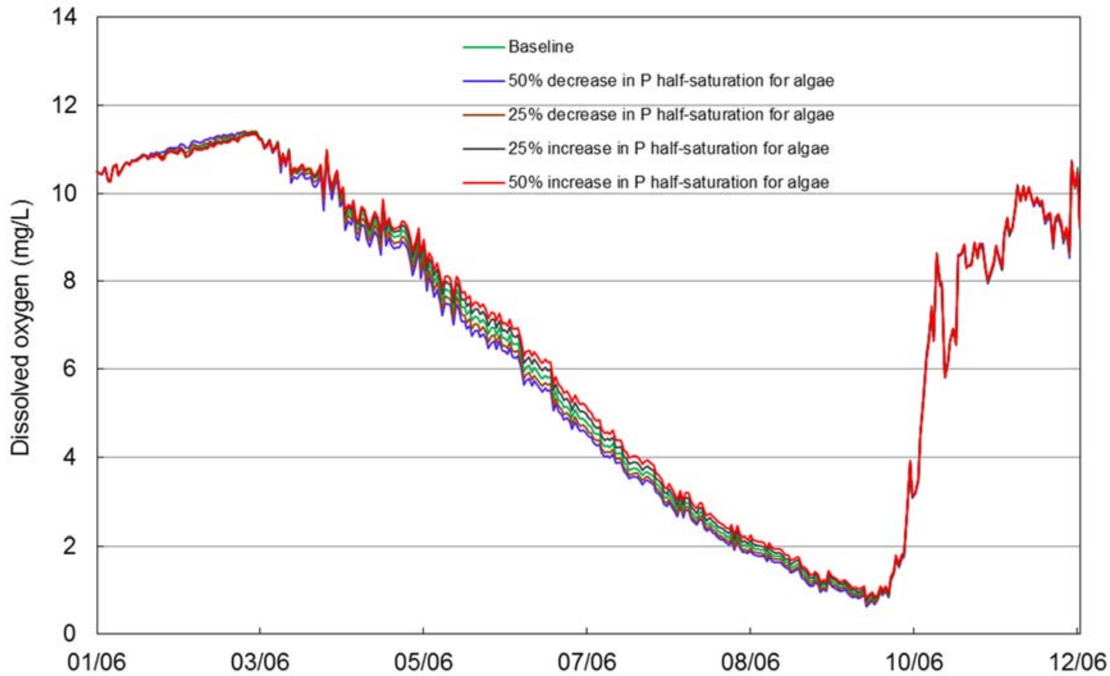


Figure 115 Modeled DO at LK-01 under Different Perturbation of P Half-saturation for Algae

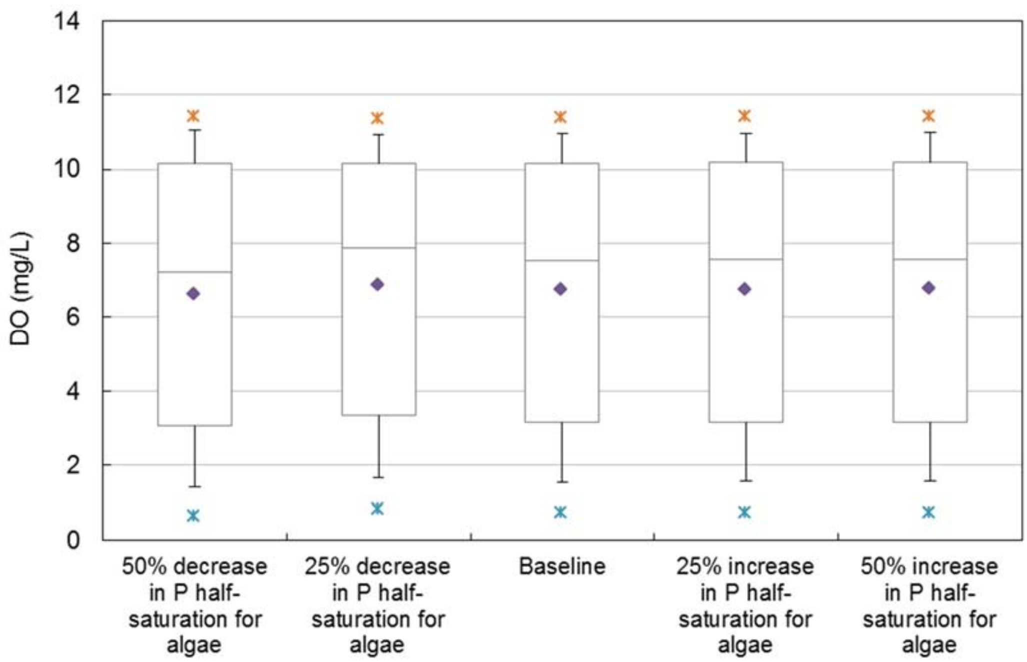


Figure 116 Box-Whisker-Plot of DO at LK-01 under P Half-saturation for Algae Perturbation

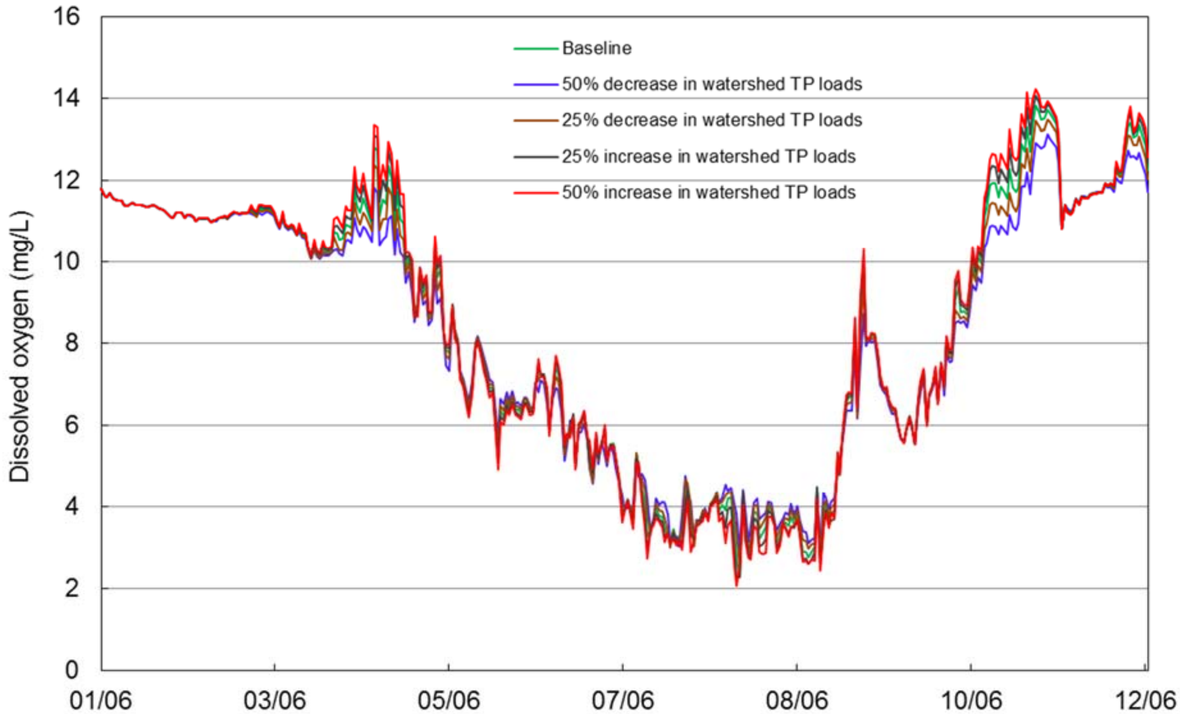


Figure 117 Modeled DO at LK-03 under Different Perturbation Levels of Watershed TP Loads

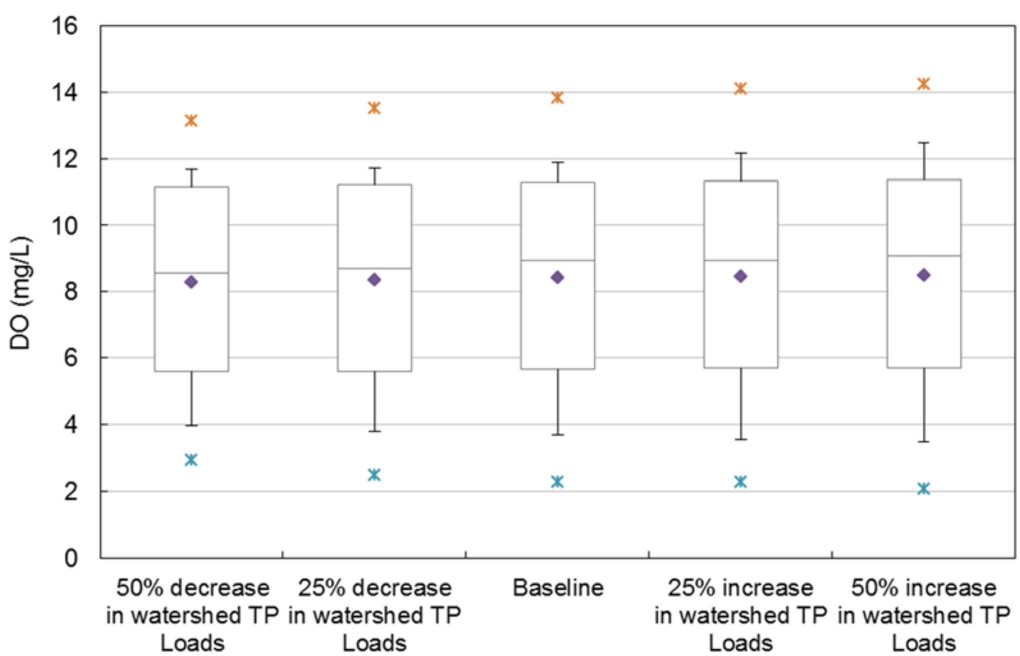


Figure 118 Box-Whisker-Plot of DO at LK-03 under Different Watershed TP Loads Perturbation

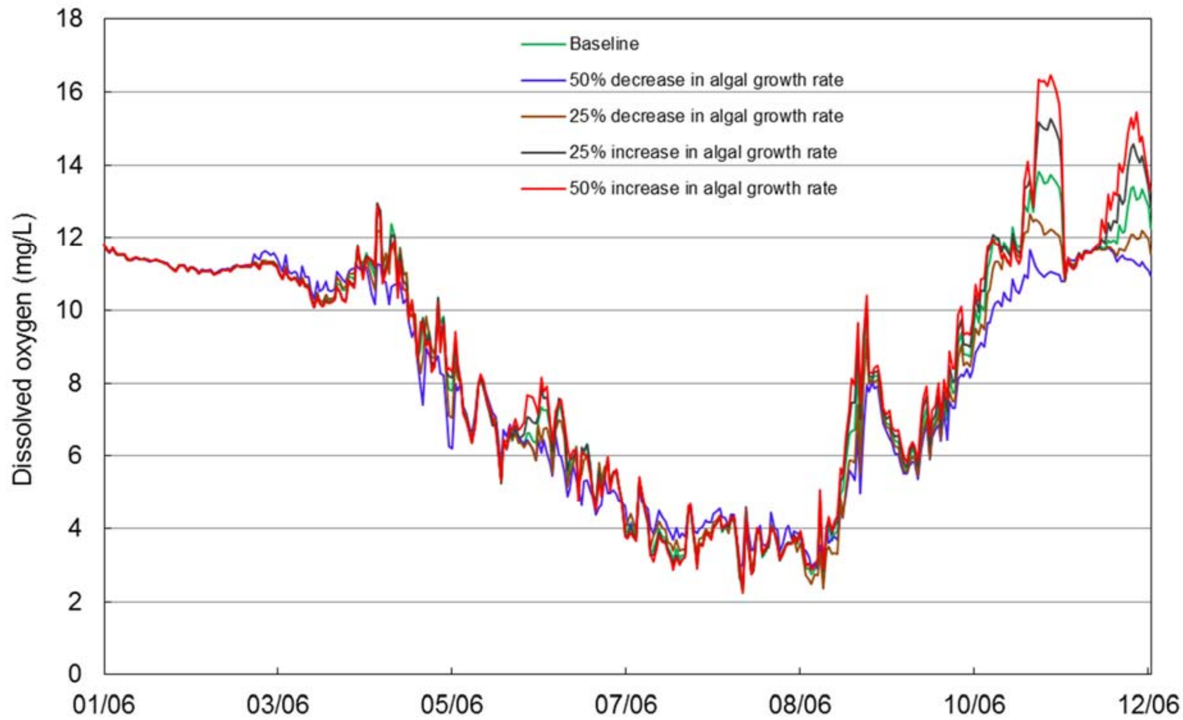


Figure 119 Modeled DO at LK-03 under Different Perturbation Levels of Algal Growth Rate

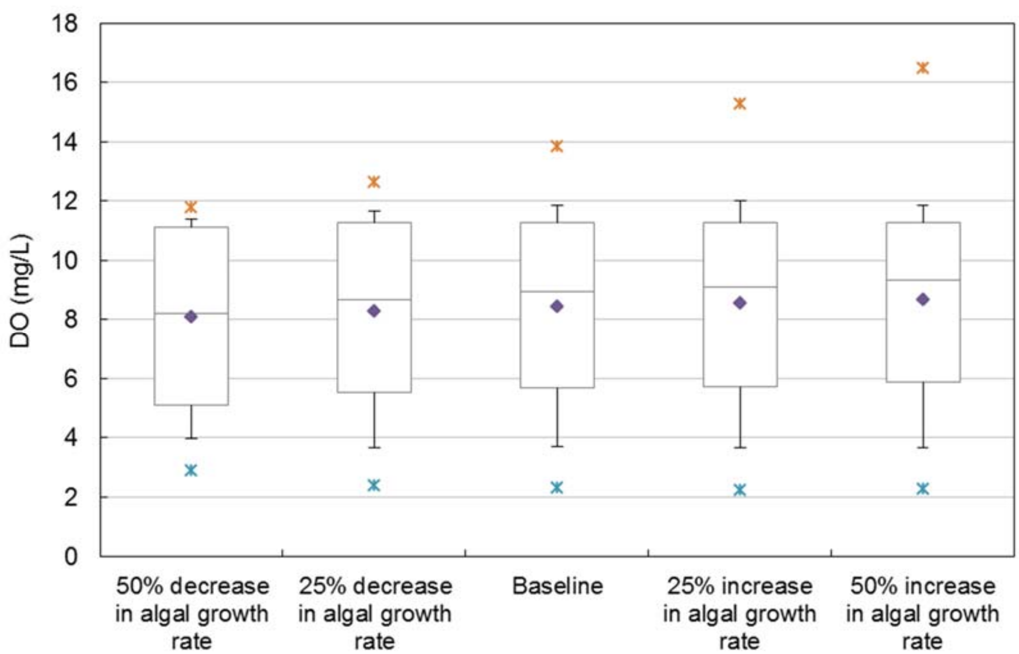


Figure 120. Box-Whisker-Plot of DO at LK-03 under Different Algal Growth Rate Perturbation

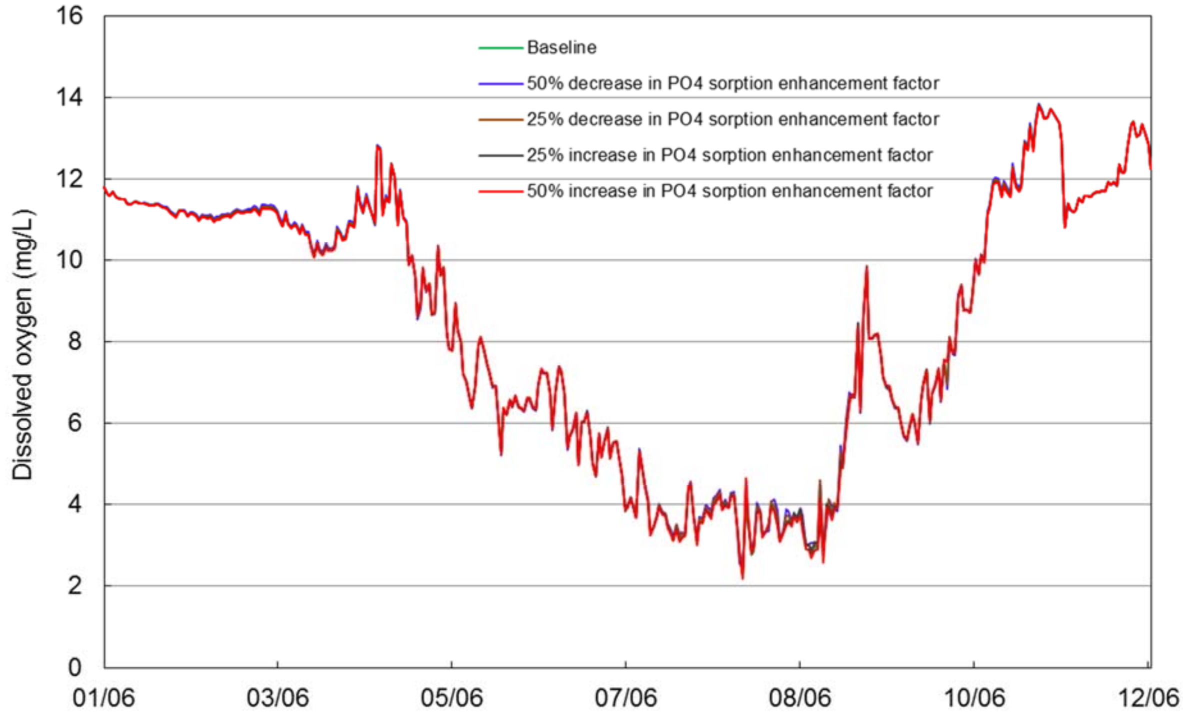


Figure 121 Modeled DO at LK-03 under Perturbation of PO4 Sorption Enhancement Factor

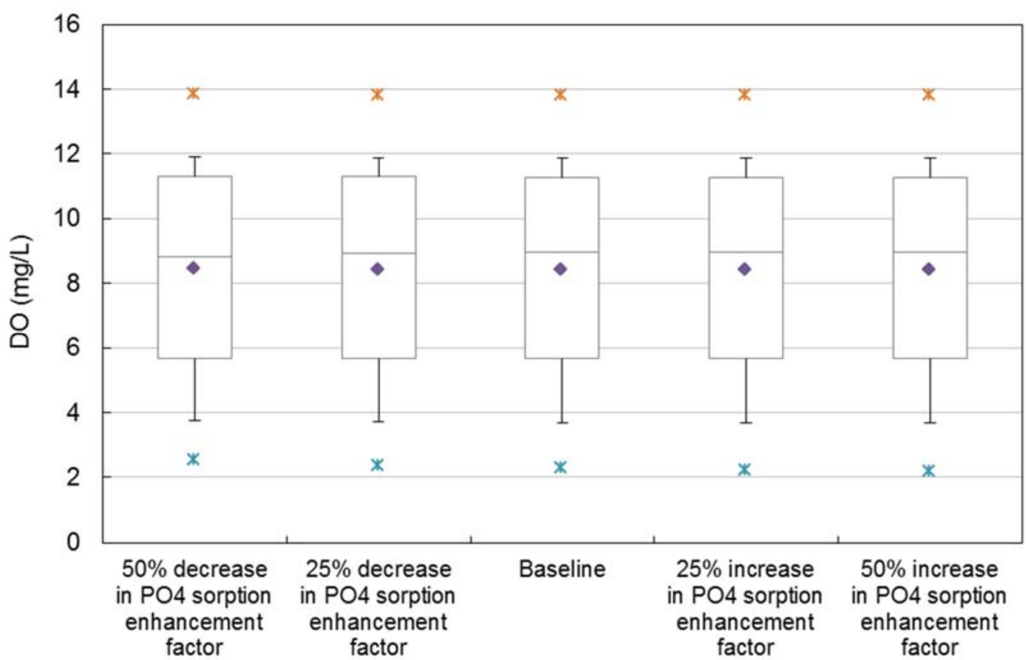


Figure 122 Box-Whisker-Plot of DO at LK-03 under PO4 Sorption Enhancement Factor Perturbation

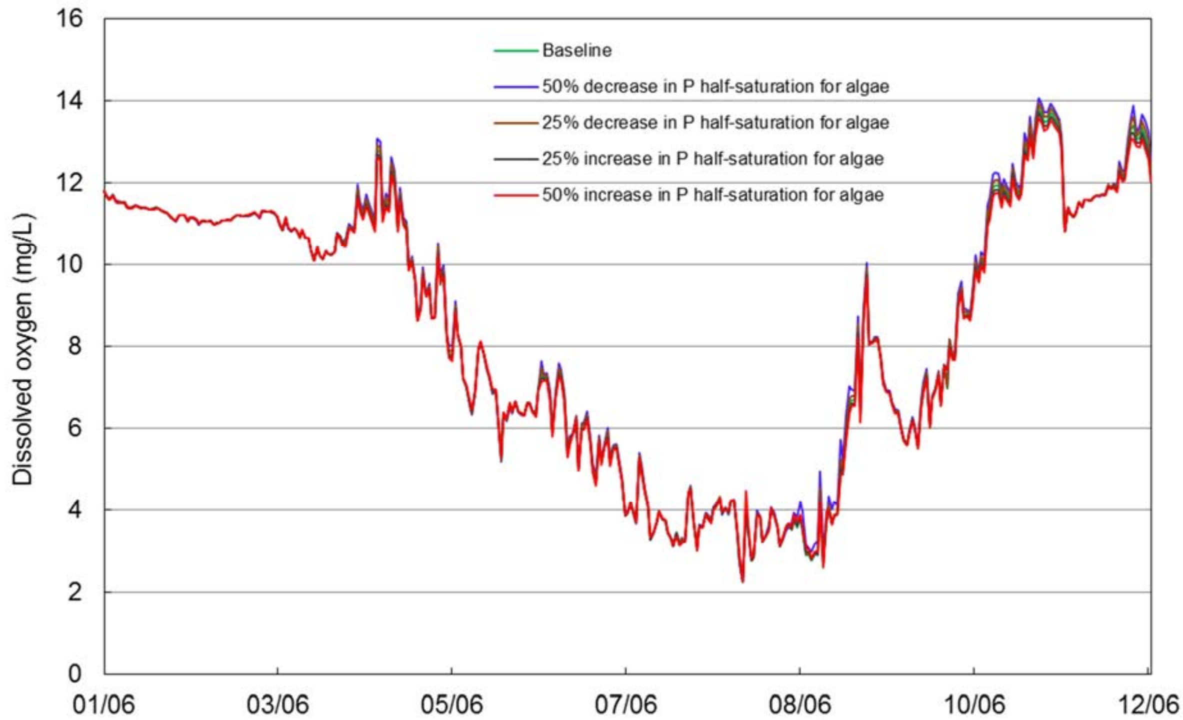


Figure 123 Modeled DO at LK-03 under Different Perturbation of P Half-saturation for Algae

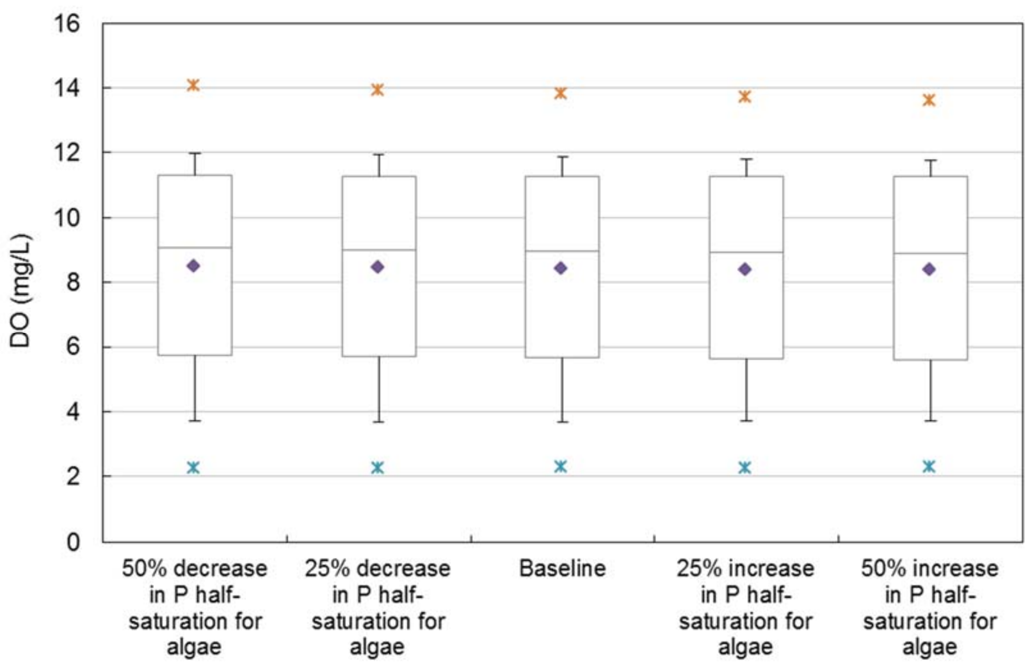


Figure 124 Box-Whisker-Plot of DO at LK-03 under P Half-saturation for Algae Perturbation