EC Espey Consultants, Inc.
Environmental & Engineering Services

M E M O R A N D U M……

DATE: Aug 14, 2008

TO: North Central Texas Water Quality Project

FROM: Margrethe Berge, Mark Ernst, and Jennifer Owens

RE: Cedar Creek WASP Model Development and Calibration Results

EXECUTIVE SUMMARY

The USEPA Water Analysis Simulation Program (WASP) model was calibrated for an 11-year period (1991 – 2001) for Cedar Creek Reservoir. Nutrient loads to Cedar Creek came from four (4) sources:

- SWAT was used to estimate the watershed loading to WASP including both nonpoint source (NPS) loading and point source (PS) loading from 7 wastewater treatment plants (WWTPs).
- Point source loading from two plants that directly discharge to the reservoir were input directly to WASP. All WWTP loadings were based on one year of self-reported nutrient data from the plants.
- Benthic flux of nutrients was based upon changes in Hypolimnetic concentrations during stratified periods.
- Atmospheric loading was based upon rainfall analysis at Richland Chambers Reservoir.

Comparison of observed and predicted data of important system variables (TN, TP, TN:TP ratio, N-limitation, P-limitation and Chl'a') revealed a reasonable “fit” for the model and assurance that the fundamental system response to nutrients was correctly simulated. There appears to be a co-limitation to nitrogen and phosphorus in Cedar Creek, meaning that both parameters are at times limiting to algae growth. However given that the third quarter (July-Sep) algae population is made up of greater than 90% nitrogen fixing blue-green algae, it seems reasonable to focus management on just phosphorus. The overall phosphorus budget for 11-years of modeling has an annual load of 224,000 kg/yr with 86% of the phosphorus coming from NPS (watershed) loading, 7% from the 9 WWTPs, 4% from benthic flux, and 3% from atmospheric loading. Sensitivity analyses show that the reservoir is most sensitive to the watershed loading and benthic flux loading. Systematic reductions from 15% to 65% in watershed loading suggest that loads have to be reduced approximately 25% to have a statistically significant decrease in seasonal Chl'a' concentrations. Similarly, benthic flux has to be reduced approximately 75% for a significant reduction in Chl'a' to occur. A combination of reduced watershed (NPS) loading and hypolimnetic phosphorus (benthic) flux seems like a possible management approach. A simulation with a 15% reduction in NPS loading coupled with a 100% reduction in benthic flux in just the deepest segments of the reservoir (segments 12, 13, 14), significantly reduced Chl'a' in the model. This scenario warrants further modeling with SWAT and research into hypolimnetic phosphorus (benthic) flux reduction as a possible management approach for Cedar Creek Reservoir.

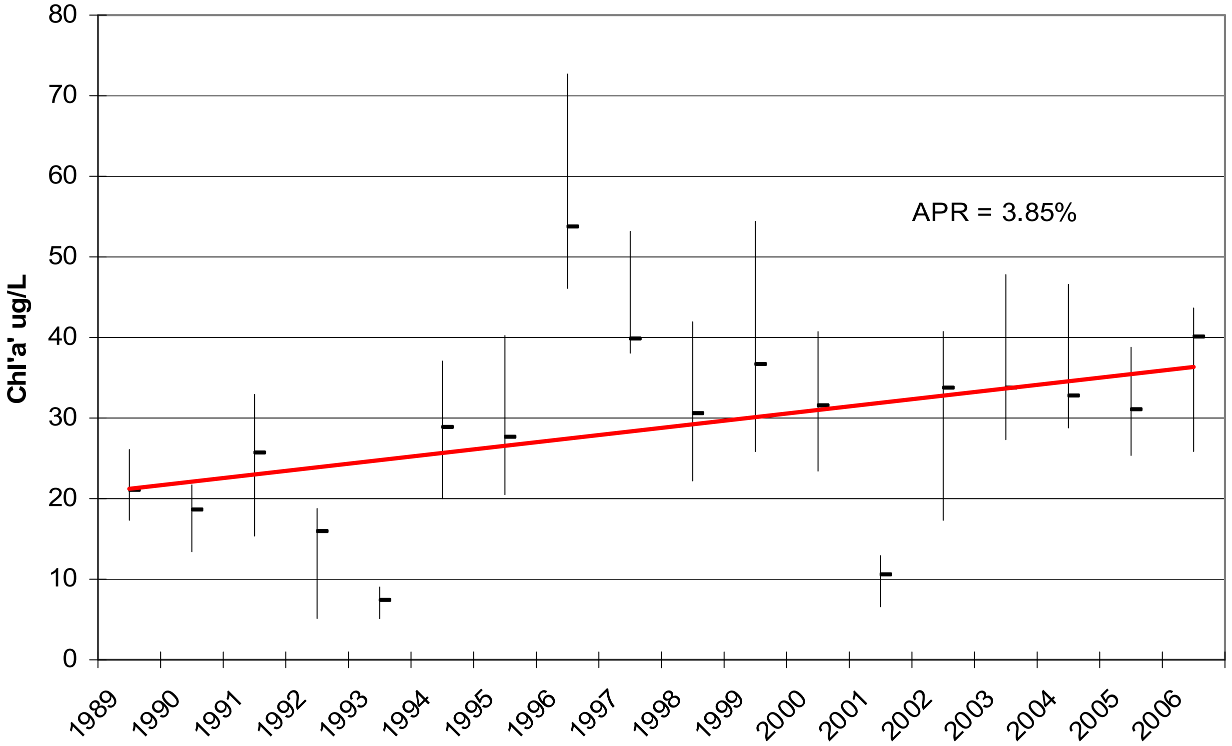
INTRODUCTION

The USEPA Water Analysis Simulation Program (WASP) is a powerful water quality model that can be used to predict and interpret water body responses to various nonpoint source loads and point source pollution. This model was selected by the Tarrant Regional Water District (TRWD) to predict the changes in water-quality over time due to the introduction of PS loadings such as WWTP discharges and NPS loading from the watershed, benthic flux and atmospheric deposition. The Cedar Creek WASP model was calibrated based on an 11-year time period starting January 1, 1991 and ending December 31, 2001.

An 18-year trend of Chlorophyll A (Chl'a') in Cedar Creek reservoir is shown in Figure 1. The trend in Chl'a' in Cedar Creek over the past 18 years has a significant positive slope with an annual rate of increase of 3.85%. TRWD plans to use the calibrated Cedar Creek WASP model to interpret changes in water quality within Cedar Creek that may occur based on the implementation of various nutrient-loading schemes and/or best management practices (BMPs) in order to protect the future water quality of Cedar Creek.

This memo documents the current results of the Cedar Creek WASP model development and calibration. The file name is **CC_91_01_5.wif** with a corresponding postprocessor **High_Low_Close_20.xls**.

Figure 1: 18-Year Trend of Chl'a' in Cedar Creek Reservoir (3.85% APR)



DATA SOURCES

Physical Depiction of Cedar Creek Reservoir in WASP

The WASP model simulates the transformations and transport of water quality variables using mass balance computations for each unique segment defined for the water body. Therefore, the user must segment or discretize the water body according to the physical, chemical and reactive properties of the water body as well as the users modeling goals. For example, if the user is interested in gross lake response to pollution, large segmentation may be appropriate if physical and chemical data allows for such segmentation. An example of such an instance would be for a small, shallow water body that does not exhibit stratification due to temperature or oxygen gradients. For the Cedar Creek segmentation in WASP, temperature stratifications along with physical characteristics of the lake such as depth and incoming tributary flows, were used as a basis for the segmentation. Espey Consultants, Inc (EC) utilized the previous Cedar Creek segmentation provided by TRWD for the main reservoir body of Cedar Creek and in addition, included the 7 additional tributary (cove) segments to the main system that had been simulated separately in past TRWD Cedar Creek modeling efforts.

The Cedar Creek reservoir segmentation consists of 22 segments. Segments are defined either as surface or subsurface segments. Surface segments have unique properties because they serve as contact between the reservoir and the atmosphere (evaporation/precipitation) and they serve as entry points for point source and non point source nutrient loadings from the adjacent watershed areas. In addition, the surface segments define the photic zone in the model to a depth of 6 feet (ft), which represents the approximate depth to which light can penetrate the reservoir. For the Cedar Creek segmentation, the surface segments are defined as the 7 cove/tributary surface segments 15 to 22 and surface segments 1 to 6. The surface segments (horizontal segmentation) in the Cedar Creek WASP model are depicted in Figure 2.

Vertical or subsurface segmentation excluding the cove/tributary segments (15-22) for the Cedar Creek WASP model is depicted in Figure 3. These subsurface segments define the remaining areas of the Cedar Creek reservoir below 2 meters (6 ft). Subsurface segments 7, 8, 9, 10, and 11 characterize the Cedar Creek WASP model to the depth of the typical thermocline of approximately 7 meters. Subsurface segments 12, 13, and 14 define the three hypolimnetic segments in the Cedar Creek WASP model. Each surface and subsurface segment are physically and hydraulically connected to adjacent and adjoining segments where appropriate, by vertical and/or horizontal interfaces.

Dispersion

Due to large segment interfacial areas in the Cedar Creek WASP model, horizontal and vertical dispersion serves as an important transporter of mass in the Cedar Creek WASP model. Horizontal dispersion was estimated from the 4/3 Power Law used routinely in historic TRWD water quality models. Horizontal dispersion ranged from 1 m^2/sec to 10 m^2/sec throughout horizontal segment interfaces in the model. Vertical dispersion between the surface segments and underlying subsurface segments (2 - 7, 3 - 8, 4 - 9, 5 - 10, and 6 - 11) were arbitrarily set at a high rate (0.001 m^2/sec) to ensure uninhibited mixing vertically between segments. Based on Cedar Creek field data and characteristics, TRWD has no information or reason to suspect that the surface segments do not mix freely with subsurface segments below the surface. This segmentation scheme was created to facilitate better algal growth modeling in the model.

Figure 2: Horizontal (Surface) Segmentation of Cedar Creek

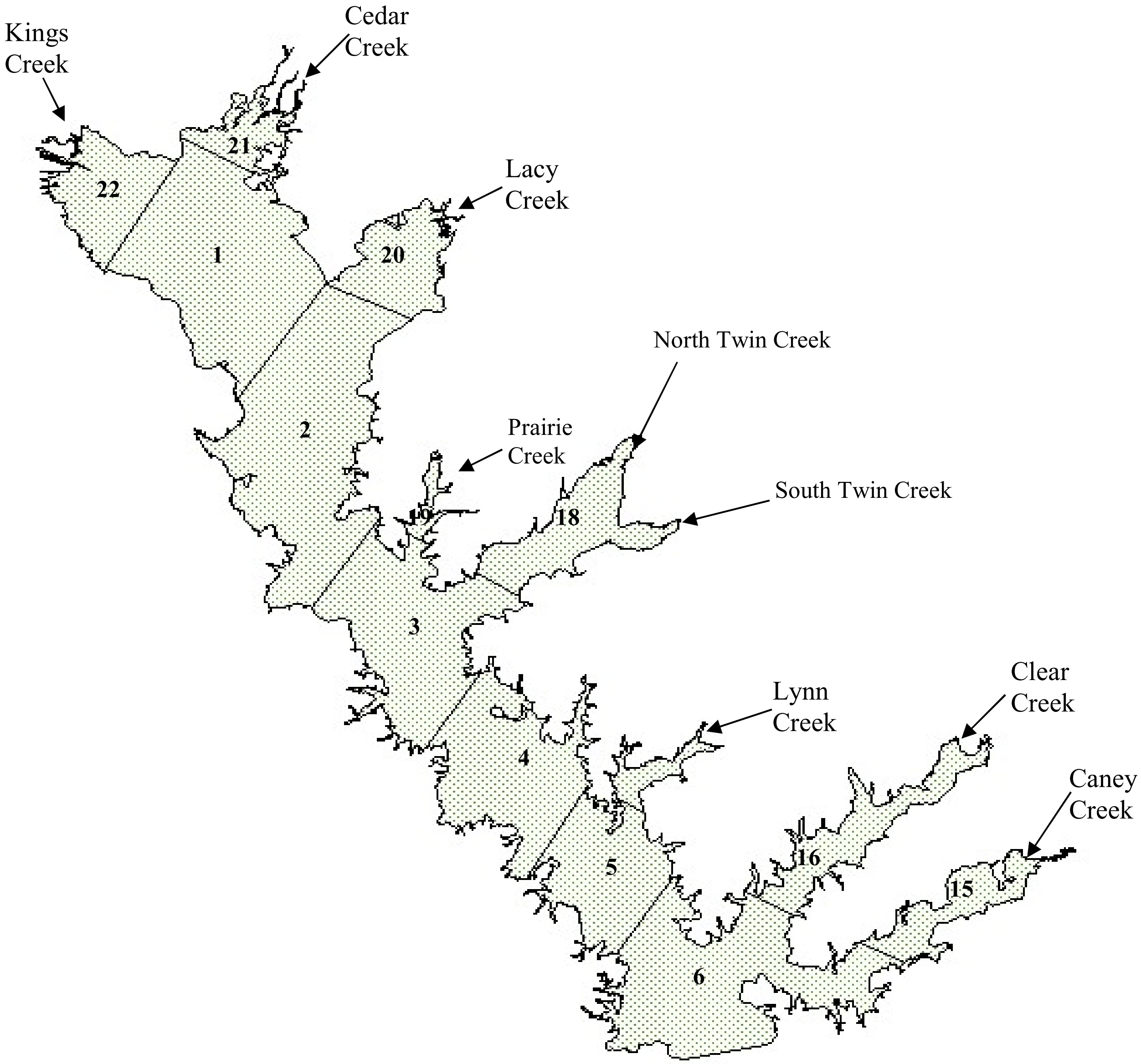
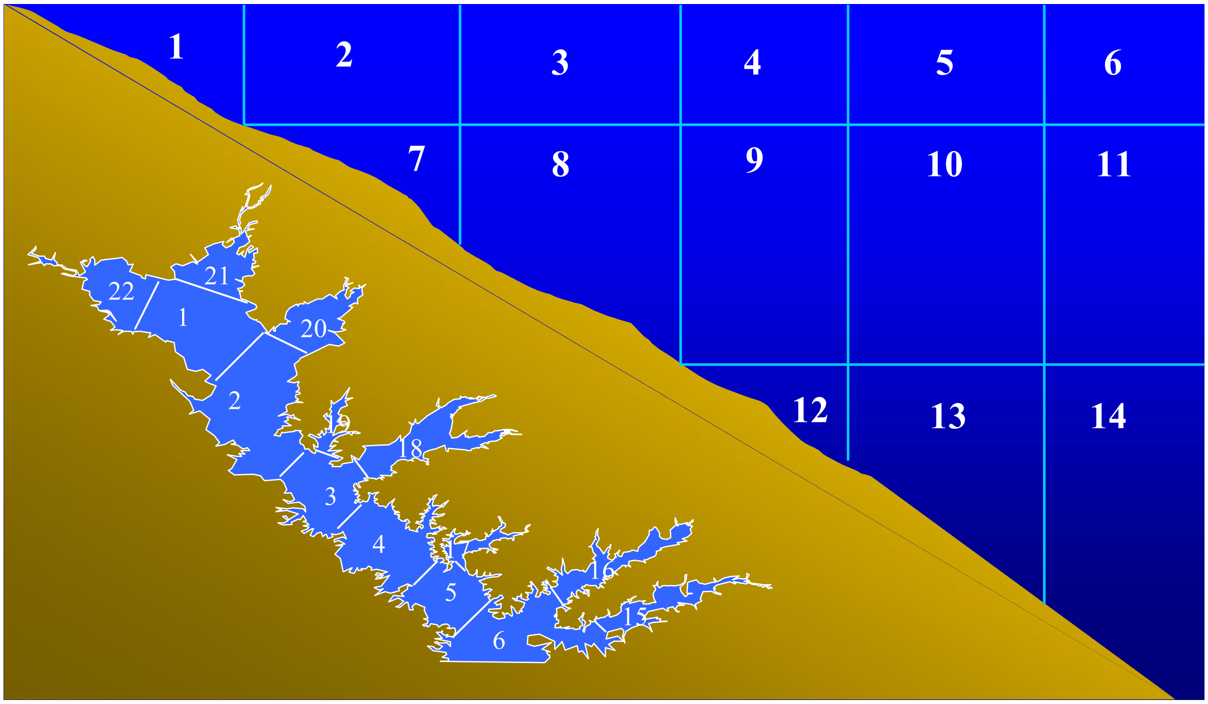
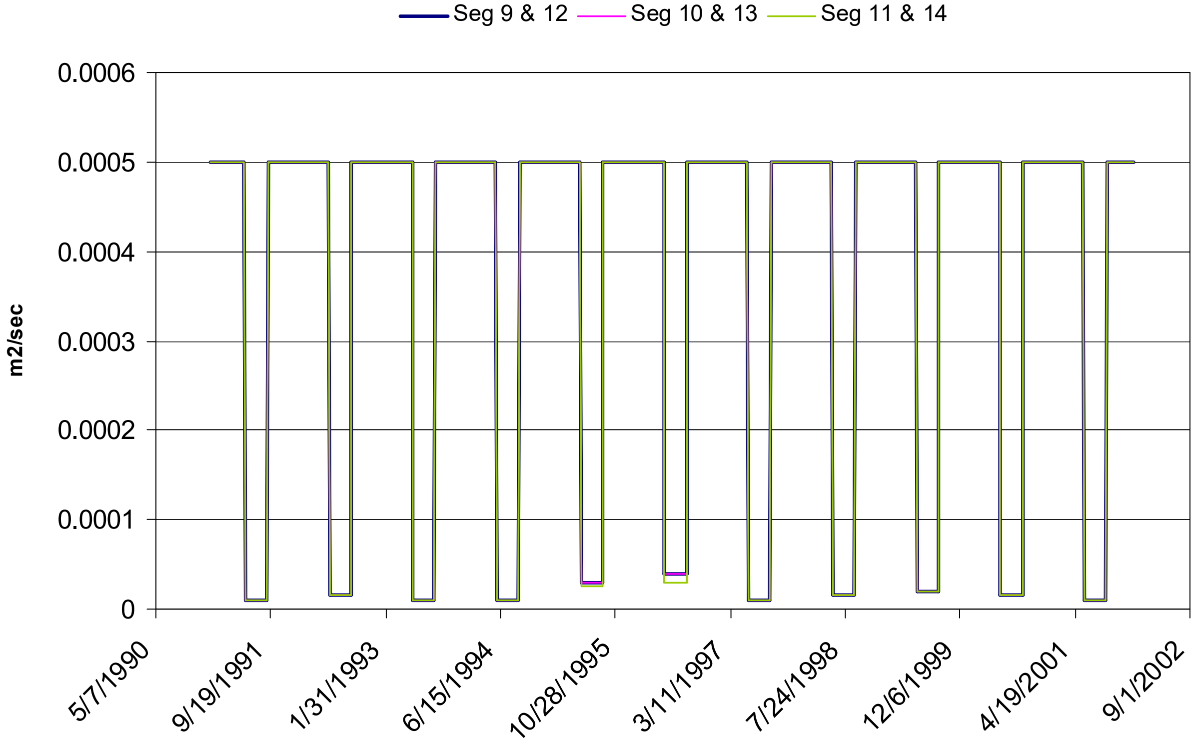


Figure 3: Vertical (Subsurface) Segmentation of Cedar Creek Reservoir



Hypolimnetic dispersion coefficients for subsurface segments 9 -12, 10 - 13, and 11 - 14 were initially estimated using Thomann and Mueller's (1987) temperature differential technique. However, due to the paucity of data for several locations, a consistent time function for each subsurface and hypolimnetic subsurface segment (9 -12, 10 - 13, and 11 - 14) proved difficult. Observation of temperature plots from Cedar Creek field data comparing one (1) meter below the surface to one (1) meter above the reservoir floor illustrated that there are distinct temperature differentials each summer and minimal mixing between these subsurface segments (9 -12, 10 - 13, and 11 - 14). Based on these temperature plots, TRWD determined the time frame of the temperature differentials for each year at Cedar Creek Sampling Station 4 (CC-04) and applied typical lake vertical dispersion rates listed by Chapra (1997) for each time frame of each respective year. These rates varied from 0.0005 m^2/sec for well-mixed time periods to 0.00001 m^2/sec for summer stratification time periods. Figure 4 presents the step function where dispersion is maximum in the winter and minimum in the summer. Dissolved oxygen and temperature profile data was used to calibrate summer time vertical dispersion rates. For example, 1996 data showed weak stratification and limited hypolimnetic anoxia, hence we increase the vertical dispersion in this summer period to allow more mixing and better simulate the observed data. These rates and duration simulate the stratification period well.

Figure 4: Vertical Dispersion for Hypolimnetic Segments in WASP Model



Hydrodynamics

In order to accurately model the transport and transformation of the nutrients in a water body, it is crucial that the hydrodynamics be represented within the model accurately. For this effort, an external hydrodynamic flow model developed by Alan Plummer and Associates, Inc. (APAI) was utilized. This program utilizes the external flows to the system (precipitation, evaporation, pumpage, discharge, and tributary inflows) as recorded by TRWD and the corresponding geometry of each segment to solve for the advective flows between adjacent segments. The program specifies a matrix solution employing the criteria of minimum kinetic energy and the solution is input into the appropriate flow field for each segment in WASP.

Figure 5 presents the hydrology in Cedar Creek from 1980 to 2005. Note the low inflow and corresponding low water levels in Cedar Creek during 1996 and 2000 for the WASP simulation time-period. This decrease in water surface elevation in 1996 and 2000 is consistent with a higher period of nutrient retention in the reservoir because of the decrease of spillage from the reservoir. This is also presented later in this memorandum in the results discussion.

During the start of the WASP simulation time-period, Cedar Creek Reservoir was not at capacity. At conservation pool the reservoir holds approximately 637,109 ac-ft of water, but in January of 1991 it was at 92% of conservation pool volume. Since the initial volume is crucial in the expression of nutrient mass as a concentration, the initial volumes for the five delta volume (DV) segments (7, 8, 12, 13 and 14) were adjusted to account for the difference in starting pool elevations. Per the APAI flow balance solution, the DV segments are those capable of volume changes in order to force the flow exchange between respective segments, while the remaining segments maintain a constant volume. The matrix flow balance solution developed by APAI uses this initial volume and is capable of changing the capacity of the reservoir to mimic that found during the actual time period modeled. Table 1 provides a comparison of the starting volumes of the 22 reservoir segments used during the model simulation time-period. DV segments (7, 8, 12, 13, and 14) are highlighted in blue.

Figure 5: Cedar Creek Hydrology (1980-2005)

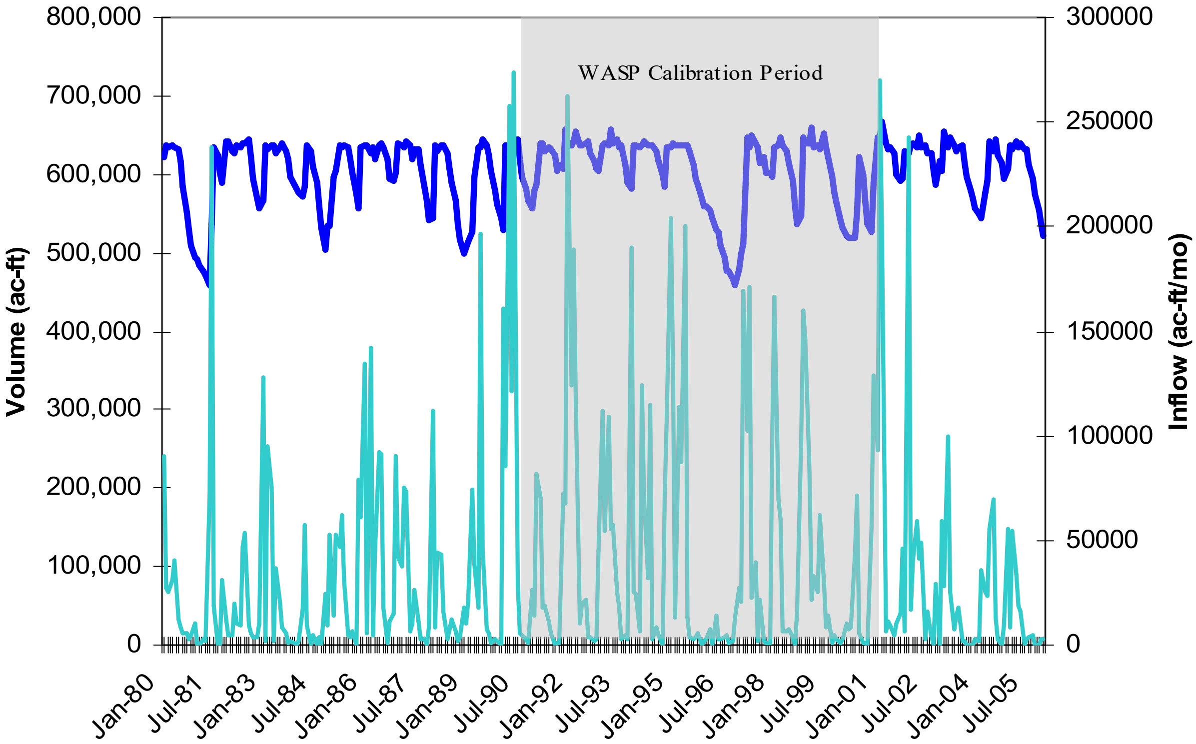


Table 1: Cedar Creek Initial Segment Volumes for WASP Model

Wasp Segment	Total Volume (M^3)	Actual Starting Volume (1991) (M^3)
1	5.99E+07	5.99E+07
2	3.91E+07	3.91E+07
3	2.64E+07	2.64E+07
4	2.28E+07	2.28E+07
5	1.63E+07	1.63E+07
6	3.20E+07	3.20E+07
7	7.57E+07	6.07E+07
8	9.18E+07	7.36E+07
9	6.05E+07	6.05E+07
10	4.07E+07	4.07E+07
11	8.14E+07	8.14E+07
12	3.88E+07	3.11E+07
13	3.22E+07	2.58E+07
14	6.83E+07	5.48E+07
15	1.52E+07	1.52E+07
16	3.15E+07	3.15E+07
17	7.42E+06	7.42E+06
18	2.41E+07	2.41E+07
19	1.69E+06	1.69E+06
20	1.25E+07	1.25E+07
21	8.06E+05	8.06E+05
22	6.66E+06	6.66E+06
Total	7.86E+08	7.25E+08
Ac-ft	637109	587907
Fraction of Actual		0.92

DESCRIPTION: Actual segment volumes at conservation pool and modeled segment volume for model simulations. Shaded cells reflect the delta volume cells that are allowed to change in volume in the matrix solution.

Settling Rates

The physical settling of particulate matter in any reservoir is an important transport phenomenon of nondissolved nutrients and often leads to a distinct longitudinal gradient or slope in concentration. Only 3 of the 8 state variables were assigned settling velocities. Table 2 presents the average fraction dissolved for both organic nitrogen and organic phosphorus in each segment. This data was estimated from limited laboratory measurements of total and filtered samples. We found it necessary to manipulate this term in boundary Segments 20-22. We set both organic N and P to 100% dissolved in these segments so that they would be routed to the reservoir. In reality these segments are shallow and often circuited, but in the model they are a set volume with tremendous settling potential. We also had to increase the percent dissolved in Segment 1, from limited measure data suggesting 0.58 for organic N and 0.15 for organic P to 0.65 for both nutrient species, to allow this segment to conform more closely with the observed data. As a side note, we have found organic N to have a greater fraction in the dissolved state than organic P.

The fraction of organic nitrogen that was determined to be in the undissolved phase (varied from segment to segment based on field data) was given a settling velocity of 8.0×10^{-7} m/sec (0.07 m/day). Algae were given a rate of 5.0×10^{-7} (0.04 m/day) and the fraction of organic phosphorus that was in the undissolved phase were given a settling velocity of 1.6×10^{-6} m/sec (0.14 m/day). Organic phosphorus was given a higher settling velocity because it binds with inorganic clay readily, while organic nitrogen is more often associated with organic matter. The longitudinal profiles of observed data support this position.

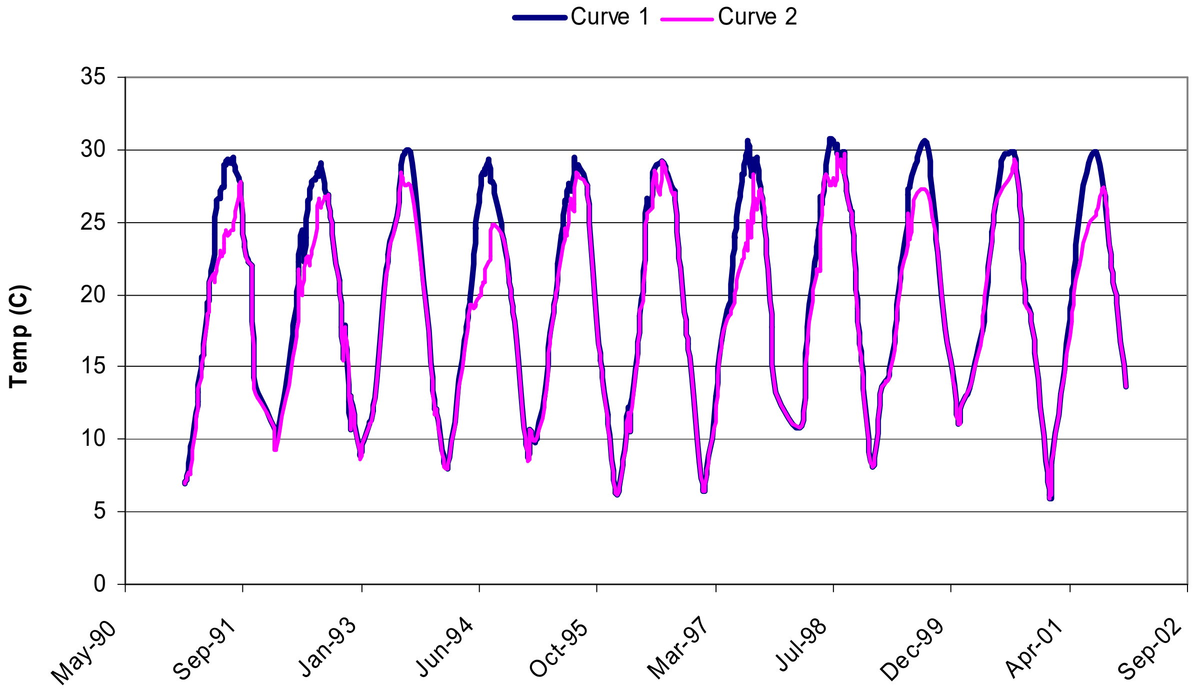
Table 2: Percent Organic Nitrogen and Phosphorus Dissolved
Shaded cells were adjusted, see text

WASP Segment	Organic Nitrogen	Organic Phosphorus
1	0.65	0.65
2	0.70	0.50
3	0.67	0.37
4	0.68	0.36
5	0.70	0.32
6	0.74	0.31
7	0.75	0.18
8	0.66	0.30
9	0.69	0.57
10	0.58	0.22
11	0.59	0.34
12	0.66	0.24
13	0.72	0.28
14	0.64	0.41
15	0.60	0.15
16	0.51	0.28
17	0.55	0.45
18	0.57	0.24
19	0.49	0.11
20	1.00	1.00
21	1.00	1.00
22	1.00	1.00
Average (seg 2-19)	**0.64**	**0.31**

Environmental Time Functions

WASP requires the input of time functions for important environmental functions such as temperature, incident light, light extinction, photoperiod and wind. For this type of water-quality modeling, water temperature, light extinction and incident light are critical components of the nutrient cycle. Three graphs have been created below to demonstrate how the temperature and light functions were determined for the WASP calibration effort. The first graph, Figure 6 presents the two of the three temperature curves that were used to determine temperature time functions for the Cedar Creek WASP model. As shown in Figure 6, Curve 1 represents the main body of the reservoir and Curve 2 represents the deeper portions of the reservoir.

Figure 6: Selected WASP Temperature Curves 1 and 2



Light extinction due to non-algal turbidity is an important time function because the waters of Cedar Creek are relatively turbid and this greatly affects algae modeling in WASP. Four (4) light curves were used to represent the longitudinal gradient from the turbid north end of Cedar Creek to the relatively clearer waters in the southern end near the dam. Figure 7 presents two (2) of these selected light extinction curves. Curve 2 represents the north end area of Cedar Creek, while Curve 4 represents the southern end of Cedar Creek near the dam. For this effort, the light extinction coefficient (Ke') was calculated using the following formula (Ernst 1995):

$$Ke' = 0.9020/z - 0.0045(Chl'a')$$

Where z is the secchi depth in meters and Chl'a' is in ug/L.

The incident radiation curve that was used in his effort is based on National Oceanic and Atmospheric Administration (NOAA) data and has been used in numerous District models. Figure 8 presents the incident radiation curve that was used for the WASP calibration model.

Figure 7: Selected WASP Light Curves 2 and 4

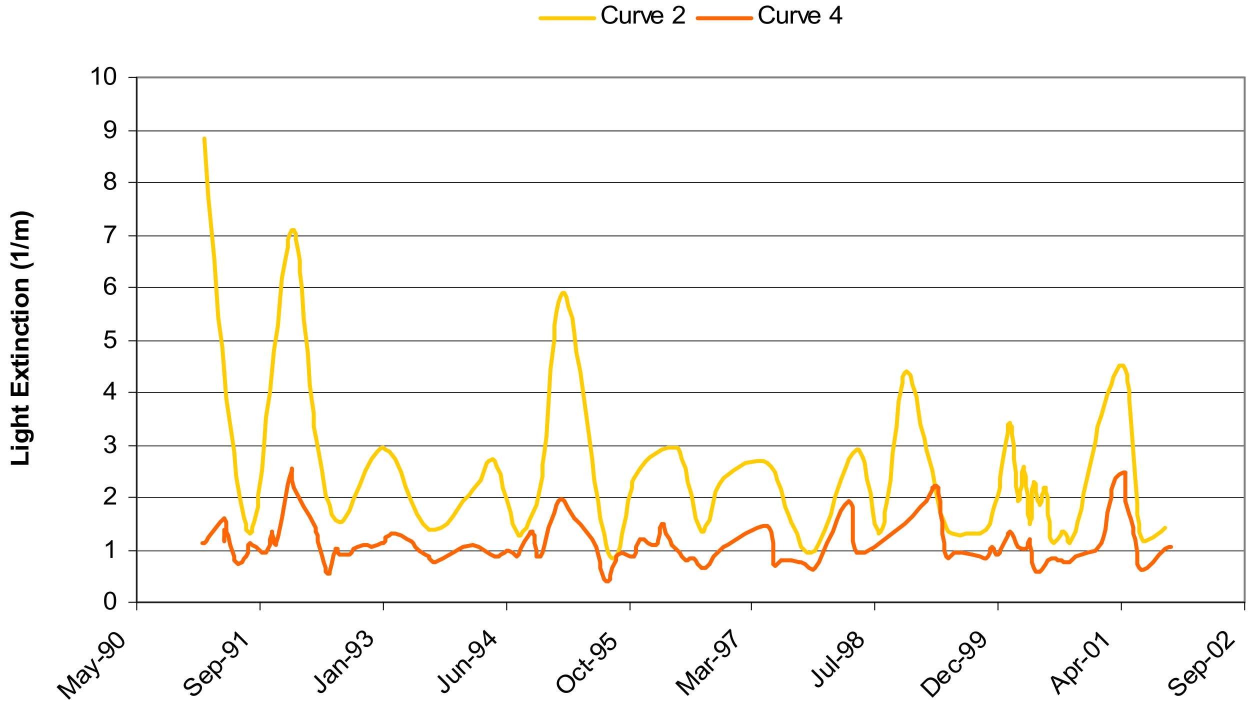
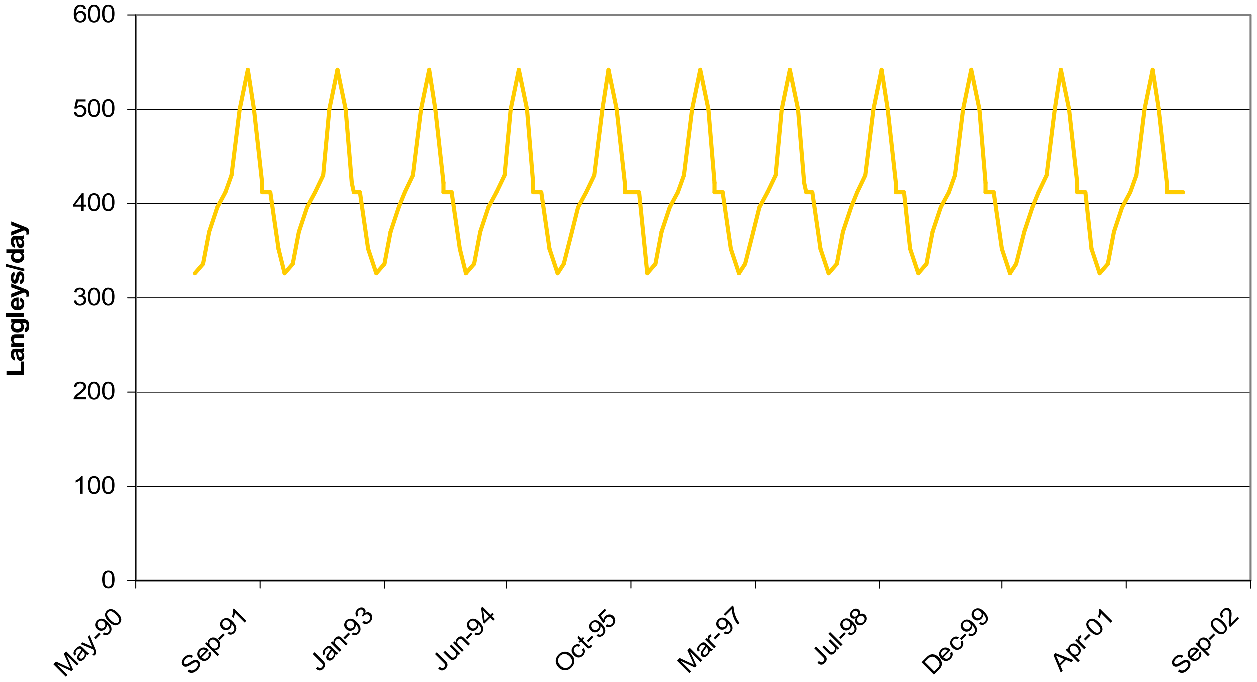


Figure 8: Solar Radiation Curve

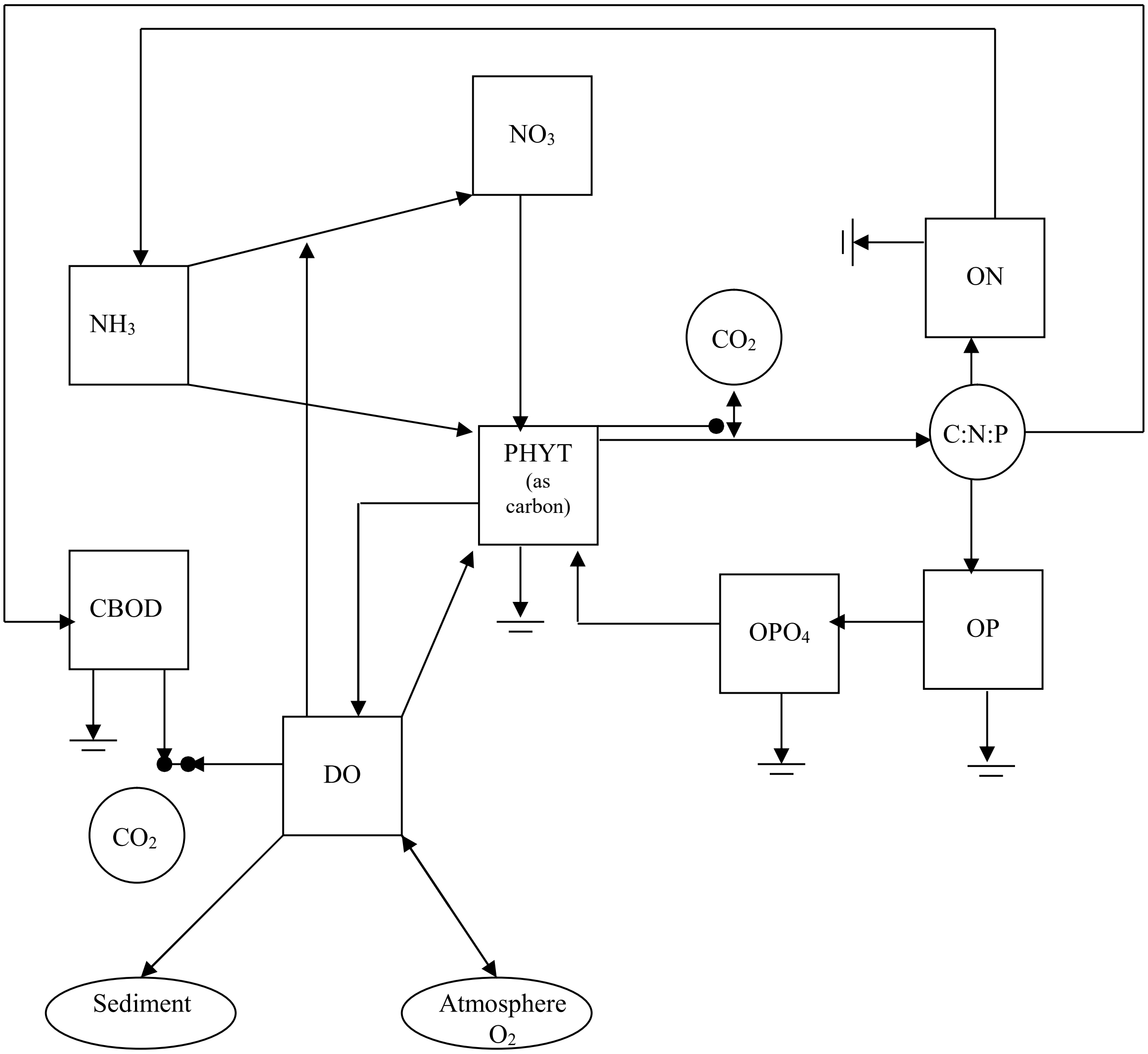


WATER-QUALITY MODELING WITH WASP

WASP 6.2 consists of two stand-alone programs that include a hydrodynamic version and a water quality program. These two programs can be used alone or in conjunction with each other. The hydrodynamic program simulates the movement of water, while the water quality program simulates the movement and interaction of pollutants within the water. For the purposes of this effort, WASP 6.2 was used only for the water quality component of the modeling. As discussed in the previous section, EC utilized a hydrodynamic program developed by APAI for the District.

The principal of the WASP model is the conservation of mass. This applies to both the water quality and the hydrodynamic programs in WASP. In WASP, the nutrient enrichment, eutrophication, and dissolved oxygen (DO) depletion processes are simulated using the EUTRO sub-routine program. Several physical-chemical processes can affect the transport and interaction among the nutrients, phytoplankton, carbonaceous material, and DO in the aquatic environment. The principal kinetic reactions for the nutrient cycles (state variables) in WASP are presented in Figure 9.

Figure 9: EUTRO State Variable Interactions in WASP



Nutrient Loading

The Cedar Creek WASP model includes four (4) types of nutrient loading systems:

1. Lakeside Point Source Loading
2. Atmospheric Deposition
3. Benthic Flux Loading
4. Watershed Loading (Point and Non-Point Sources)

Lakeside Point Source Discharges

This nutrient loading system includes two WWTPs that discharge treated effluent directly to Cedar Creek: East Cedar Creek Fresh Water Supply District (ECCFWSD) and Cherokee Shores (TECON). ECCFWSD weekly nutrient discharge data was available for May 2001 through April 2002 and was used to calculate the annual load of nutrients to Cedar Creek in kilograms/day (kg/d). Since only one year of nutrient discharge data was available, this yearly data was recycled for the 11-year simulation time-period for the calibration model. TECON discharge data was available for October 2001 through September 2002 and was recycled for the 11-year simulation period for the respective months. WASP requires the load to be expressed as kg/day. No flow data is associated with the WWTP load data input to the model. Parameters used to calculate loads that were input into WASP includes NH_3, NO_X, ON, OPO_4 and OP. Referring back to Figures 2 and 3, ECCFWSD point source nutrient data was applied to segment 19 and TECON data was applied to Segment 4 in the Cedar Creek WASP model. Table 3 presents the one-year of nutrient loading data for ECCFWSD and TECON.

Table 3: Lakeside Point Source Loading

Date	**ECCFWSD Segment 19 (kg/d)**					**TECON Segment 4 (kg/d)**				
	NH_3	**NO_x**	**OPO_4**	**Org N**	**Org P**	**NH_3**	**NO_x**	**OPO_4**	**Org N**	**Org P**
January	28.14	1.516	1.535	21.04	0.307	8.904	0.308	0.9037	1.974	0.2048
February	23.94	2.867	1.920	10.67	0.472	11.29	0.036	1.596	1.178	0.3918
March	19.61	7.143	5.222	5.265	0.865	7.963	1.24	1.551	1.786	0.4903
April	26.42	3.291	5.293	12.43	0.644	9.613	0.1817	0.873	1.989	0.2685
May	41.95	2.581	4.341	23.08	1.167	8.658	0.155	1.495	0.4702	0.338
June	48.95	2.685	5.98	0.00	5.599	6.603	0.581	0.7434	1.707	0.1872
July	54.12	2.966	4.719	1.967	1.096	5.836	0.2163	0.7972	4.326	0.1682
August	37.14	3.441	1.940	6.405	0.808	9.283	0.8414	1.131	0.7928	0.3104
September	41.28	2.65	2.68	4.018	0.683	8.875	0.4638	0.8394	1.609	0.1745
October	27.21	2.336	2.00	8.985	0.252	14.02	0.3133	0.545	0.2398	0.1973
November	13.77	1.909	1.12	5.931	0.266	10.66	0.2559	0.4169	0.437	0.1277
December	15.45	3.616	0.952	7.129	0.410	6.16	0.528	0.2036	1.857	0.12

Atmospheric Loads

Nutrient loading from the atmosphere was calculated using precipitation and nutrient data (NH_3, NO_X, ON, and OP) provided by the District from rainwater analysis. This data was compared to literature estimates and found to be very similar. The loads where then converted to a constant daily rate and applied to the model (all surface segments). The calculated rates are presented in Table 4.

Table 4: Global Atmospheric Deposition Rates for Cedar Creek WASP Model

Variable	Rate (mg-m^2/day)
Atmospheric Deposition of Nitrate	0.826
Atmospheric Deposition of Ammonia	0.75
Atmospheric Deposition of Orthophosphate	0.092
Atmospheric Deposition of BOD	0.0
Atmospheric Deposition of Organic Nitrogen	1.396
Atmospheric Deposition of Organic Phosphorus	0.06

Benthic Flux

Benthic flux in the form of ammonia (NH_4) and orthophosphate (OPO_4) was added to the three Hypolimnetic segments (12, 13, 14). Initially the rates were based on sediment sampling and Nurnburg's (1988) regression equation and literature (Erickson and Auer, 1998), but analysis of intensive survey data from two summers allowed estimation of release rates from Hypolimnetic increase in concentration. These rates of increase and the duration of the phenomena were used in the model. However, the way WASP calculates the mass of nutrient released makes the actual flux rate a bit obscure. WASP calculates the surface area of the bottom segment at the beginning of the simulation from the bottom segment volume divided by its depth. WASP does not recalculated this area again, hence since we start the model with actual reservoir volume these surface areas may be very misleading. Scalers were used in the time functions to make sure the area WASP initially calculates is the area represented by the bottom segment volume divided by its depth at conservation pool. The scaler used was 1.25 for the model simulation period. WASP allows the user to apply benthic flux as a time-variable phenomenon and in the Cedar Creek system, flux was applied from June 20th until August 1st when observed data showed increases in both ammonia and dissolved phosphorus in the hypolimnion. Table 5 presents the constant flux rates that were used for the Cedar Creek WASP calibration model.

Table 5: Benthic Ammonia and Phosphate Flux Loading in Cedar Creek WASP Model

WASP Segment	Benthic Ammonia Flux (mg-m^2/day) 1991-2001	Benthic Phosphorus Flux (mg-m^2/day) 1991-2001
12	65	7
13	65	7
14	65	7

Watershed loads

Nutrient loading from the watershed include both PS discharges from 7 WWTPs located in the Cedar Creek watershed, and overland flow from approximately 1000 square miles. These combined nutrient loads from the watershed were estimated using the SWAT model and supplied to WASP via an external NPS file. The nutrient loads for all 8 state variables were entered as kg/d.

Kinetics

Presented in Table 6 are the kinetic rates used in the Cedar Creek WASP calibration model. All values are within the suggested literature ranges. Important kinetic parameters are the Michaelis-Menton half saturation constants and the nutrient to carbon ratios. These directly affect algal modeling and growth in WASP. The nitrogen half saturation constant of 0.0485 mg/L was based on Cedar Creek bioassays performed by Sterner and Grover (1998). The phosphorus half saturation constant of 0.007 mg/L P was calibrated in the model. The nitrogen to carbon ratio of 0.15 and a phosphorus to carbon ratio of .022 was fit to the Cedar Creek model during calibration and is within the range of commonly used values in the literature. These ratios suggest a stoichiometry of 6.82 N: P, which is biased toward less nitrogen-limitation. This was determined to be appropriate because it best represents Cedar Creek and its large proportion of nitrogen fixing blue-green algae. Kinetics that favor a 10 to 1 or higher N: P ratio are most representative of green algae growth requirements and underestimate the late summer Chl'a' in Cedar Creek and similar TRWD reservoirs. Ideally, a WASP model that allows simulation of two algal groups would circumvent this problem, but this technology for WASP is not available at this time.

Table 6: Kinetic Constants for Cedar Creek Calibration and Validation Model

WASP Kinetic Constant Type	Avg. Range	Cedar Creek	Units
Nitrification Rate @ 20º C	0.001 – 0.2	0.15	day $^{-1}$
Nitrification Temp Coeff.	1.02 – 1.08	1.04	NA
Half Saturation: Nitrification Oxygen Limit	0.5 – 2.0	1.0	mg O_2/L
Denitrification Rate @ 20º C	0 – 0.09	0.06	day $^{-1}$
Denitrification Temp Coeff.	1.02 – 1.09	1.06	NA
Half Saturation: Denitrification Oxygen Limit	0 – 2.0	2	mg O_2/L
Phytoplankton Growth Rate @ 20º C	1.0 – 3.0	2.0	day $^{-1}$
Phytoplankton Growth Temp Coeff.	0 – 1.07	1.06	NA
Phytoplankton Light Formulation Switch (1 = DiToro)	NA	1 = DiToro	NA
Phytoplankton Max Quantum Yield Constant	NA	NA	NA
Phytoplankton Self Shading Extinction	NA	NA	NA
Phytoplankton Carbon::Chlorophyll Ratio	0 – 200	50	mg carbon/mg chla
Phytoplankton Optimal Light Saturation	0 – 350	200	Ly/day
Phytoplankton Half Saturation Constant: Nitrogen	0.01 – 0.06	0.0485	mg-N/L
Phytoplankton Half Saturation Constant: Phosphorus	0.0005 – 0.05	0.007	PO_4-P/L
Phytoplankton Endogenous Respiration Rate @ 20º C	0 – 0.5	0.05	day $^{-1}$
Phytoplankton Respiration Temp Coeff.	1.0 – 1.08	1.045	NA
Phytoplankton Death Rate Non-Zooplankton Predation	0 – 0.25	0.05	day $^{-1}$
Phytoplankton Zooplankton Grazing Rate	0 – 5	NA	L/cell-day
Nutrient Limitation Option (0 = Min; 1 = Multiplicative)	0, 1	0	NA
Phytoplankton Decay Rate in Sediments @ 20º C	0 – 0.02	0.02	day $^{-1}$
Phytoplankton Decay Rate Temp Coeff.	1.0 – 1.08	1.08	NA
Phytoplankton Phosphorus::Carbon Ratio	0 – 0.24	0.022	mg P/mg C
Phytoplankton Nitrogen::Carbon Ratio	0 – 0.43	0.15	mg N/mg C
Phytoplankton Half Saturation for N and P	0 – 1.0	0	NA
BOD Decay Rate @ 20º C	0.05 – 0.4	0.1	day $^{-1}$
BOD Decay Rate Temp Correction	1.0 – 1.07	1.04	NA
BOD Decay Rate in Sediments @ 20º C	0.0004 – 1.0	1.0	day $^{-1}$
BOD Decay Rate in Sediments Temp Coeff.	1.0 – 1.08	1.08	NA
BOD Half Saturation Oxygen Limit	0.5 – 1.0	1.0	NA
Waterbody Type for Wind Driven Aeration	1.0 – 3.0	NA	NA
Oxygen::Carbon Stoichiometeric Ratio	0 – 2.67	2.67	mg O_2/mg C
Reaeration Rate Constant @ 20º C	0.5 – 3.0	1	day $^{-1}$
Reaeration Rate Option (sums Wind and Hydraulic Ka)	0 – 1.0	NA	NA
Dissolved Organic N Mineralization Rate @ 20º C	0.02 – 0.075	0.02	day $^{-1}$
Dissolved Organic N Mineralization Temp Coeff.	1.0 – 1.08	1.045	NA
Organic N Decay in Sediments @ 20º C	0.0004 – 0.01	0	day $^{-1}$
Organic N Decay in Sediments Temp Coeff.	1.0 – 1.08	1.045	NA
Fraction of Phytoplankton Death Recycled to ON	0 – 1.0	1.0	NA
Dissolved Organic P Mineralization Rate @ 20º C	0 – 0.22	0.045	day $^{-1}$
Dissolved Organic P Mineralization Temp Coeff.	1.0 – 1.08	1.045	NA
Organic P Decay in Sediments @ 20º C	0.0004 – 0.01	0	day $^{-1}$
Organic P Decay in Sediments Temp Coeff.	1.0 – 1.08	1.08	NA
Fraction of Phytoplankton Death Recycled to OP	0 – 1.0	1.0	NA

RESULTS – CEDAR CREEK WASP MODEL CALIBRATION

This section presents the results of the Cedar Creek 11-year WASP model calibration.

Figures 10 through 20 present and compare the median results of the WASP calibration model to observed Cedar Creek water quality data for variables NH_3, NO_X, ON, TN, OPO_4, OP, TP, TN/TP ratio, nitrogen limitation, phosphorus limitation and Chl'a' in segments 1, 2, 3, 4, 9, 5, and 6, respectively for the 11-year simulation time-period. Calibration concentrated on achieving overlapping observed and predicted data percentiles for each segment and mimicking the longitudinal trends (gradients) of each parameter. We feel this model does an adequate job at both.

Table 7 provides statistics for each of the annual calibration figures and for seasonal (April – September) calibration (figures not included here). R-square results were significant for TNa dn TP, both annually and seasonally, demonstrating a good basis for the model. R-square values were not significant for Chl'a' but the Relative Percent Difference calculation suggest that the error in observed and predicted data was similar to the difference we have seen in duplicates sent in for laboratory analysis. We feel this is as good as we can expect with a single algae group model. The excellent fit for P implies that this may be a good parameter for BMP evaluation.

Table 7: Statistical Analysis of CC WASP Model Results

Comparison of Observed and Predicted Medians

	R-square Values		**Relative Percent Difference**		
Parameter	**Annual**	**Seasonal**	**Annual**	**Seasonal**	**Lab QC**
NH3	0.1622	0.3372	15.2%	42.4%	
NOX	0.5637	0.0121	63.3%	67.2%	
Org N	0.2976	**0.9340**	15.5%	31.4%	
TN	**0.9050**	**0.9361**	12.9%	20.9%	17.2%
OPO4	**0.9209**	**0.7601**	13.1%	37.4%	
Org P	**0.8455**	**0.9430**	22.7%	17.6%	
TP	**0.9345**	**0.9200**	10.0%	15.2%	16.8%
TN:TP	0.6721	0.3183	18.2%	21.4%	28.3%
Chl'a'	0.2332	0.0130	17.7%	26.4%	21.0%
N-limit	0.3315	0.0841	9.0%	11.6%	
P-limit	**0.9704**	**0.8739**	4.1%	14.1%	

Highlighted r-square values significant at p =0.05
RPD = ABS (O-P)/avg(O+P) * 100
Lab QC is the RPD of 32 duplicate samples for these parameters from 2000-05 on CC

Figure 10: Cedar Creek NH3 (1991 – 2001)
Median + 25th Percentiles

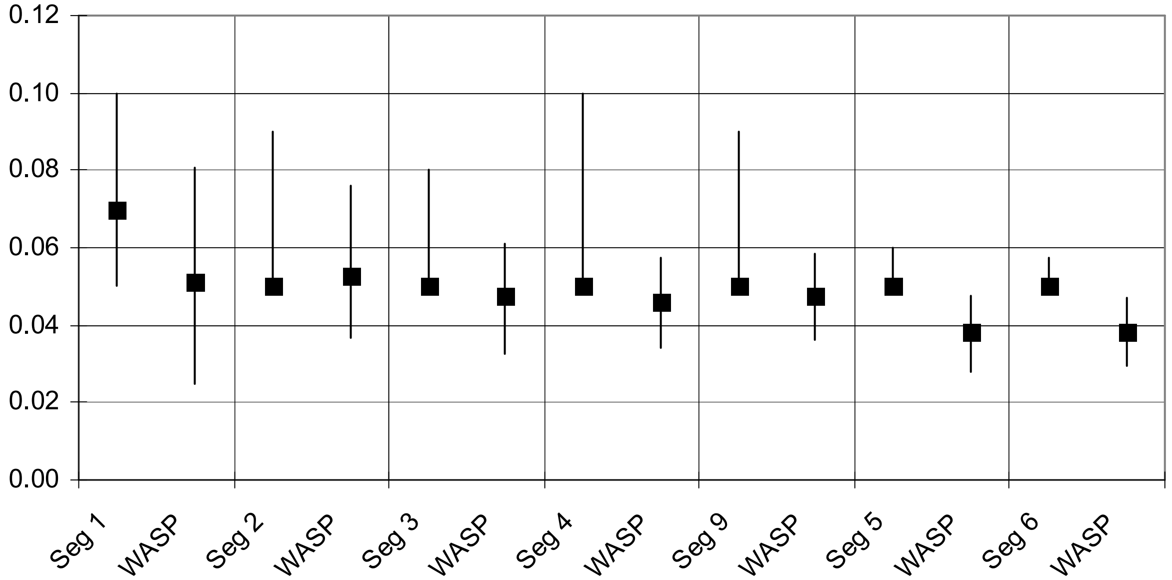


Figure 11: Cedar Creek NOx (1991 – 2001)
Median + 25th Percentiles

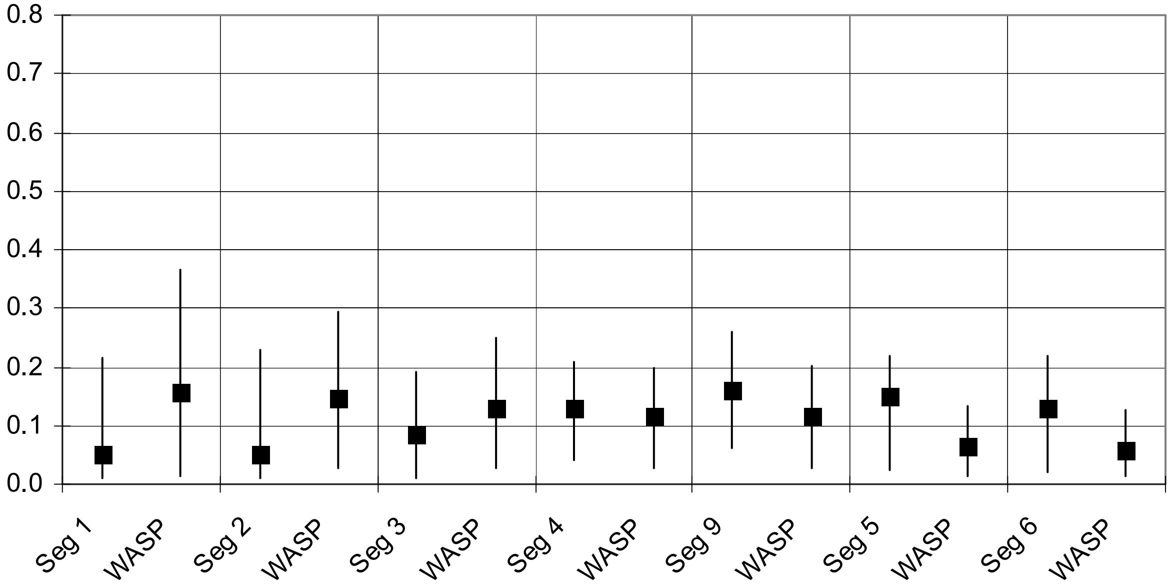


Figure 12: Cedar Creek Organic Nitrogen (1991 – 2001)
Median + 25th Percentiles

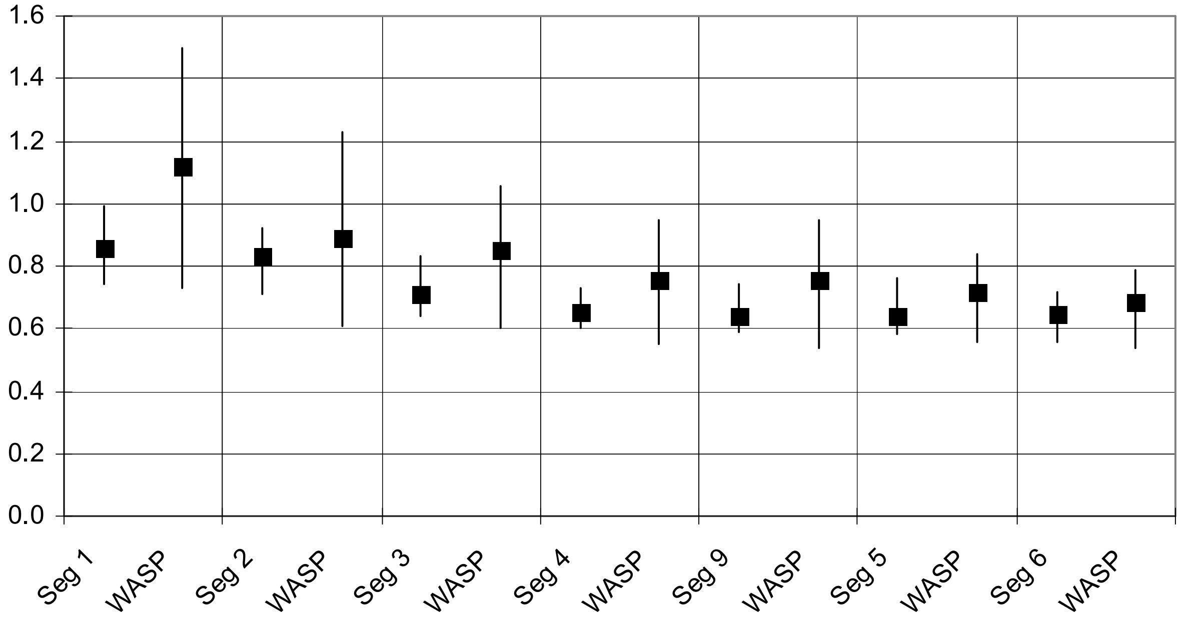


Figure 13: Cedar Creek Total Nitrogen (1991 – 2001)
Median + 25th Percentiles

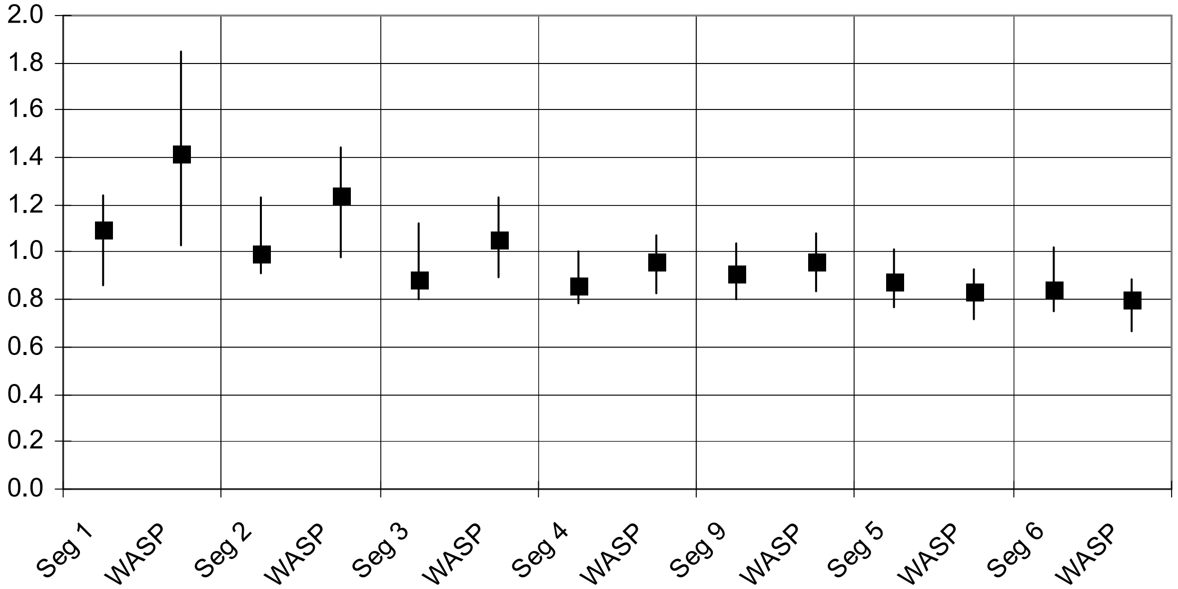


Figure 14: Cedar Creek OPO4 (1991 – 2001)
Median + 25th Percentiles

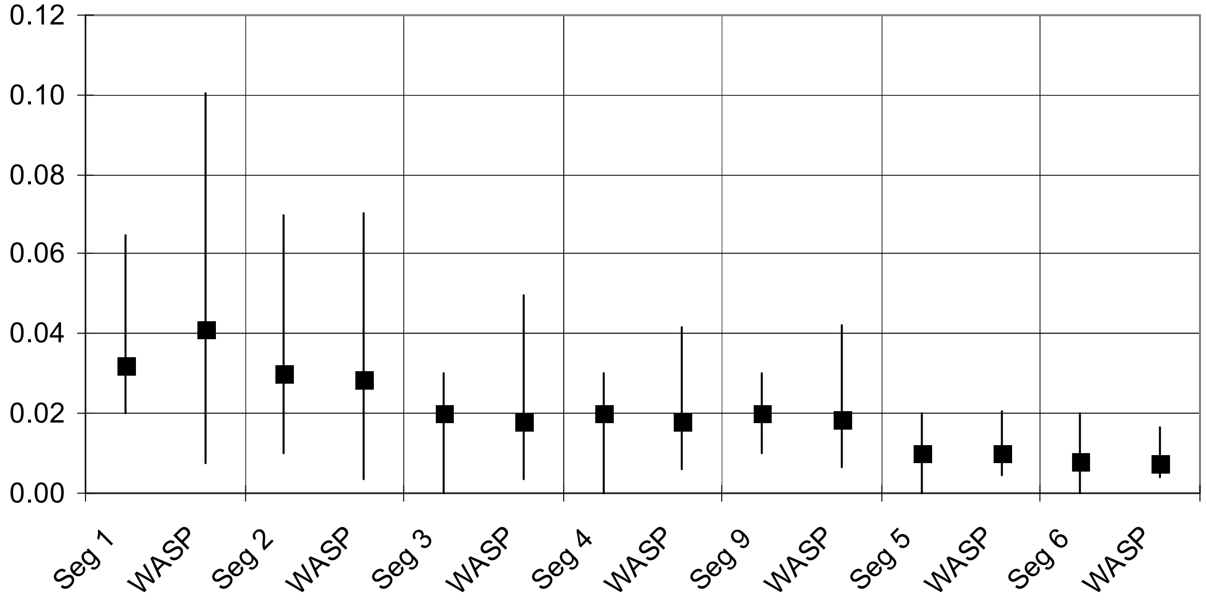


Figure 15: Cedar Creek Organic Phosphorus (1991 – 2001)
Median + 25th Percentiles

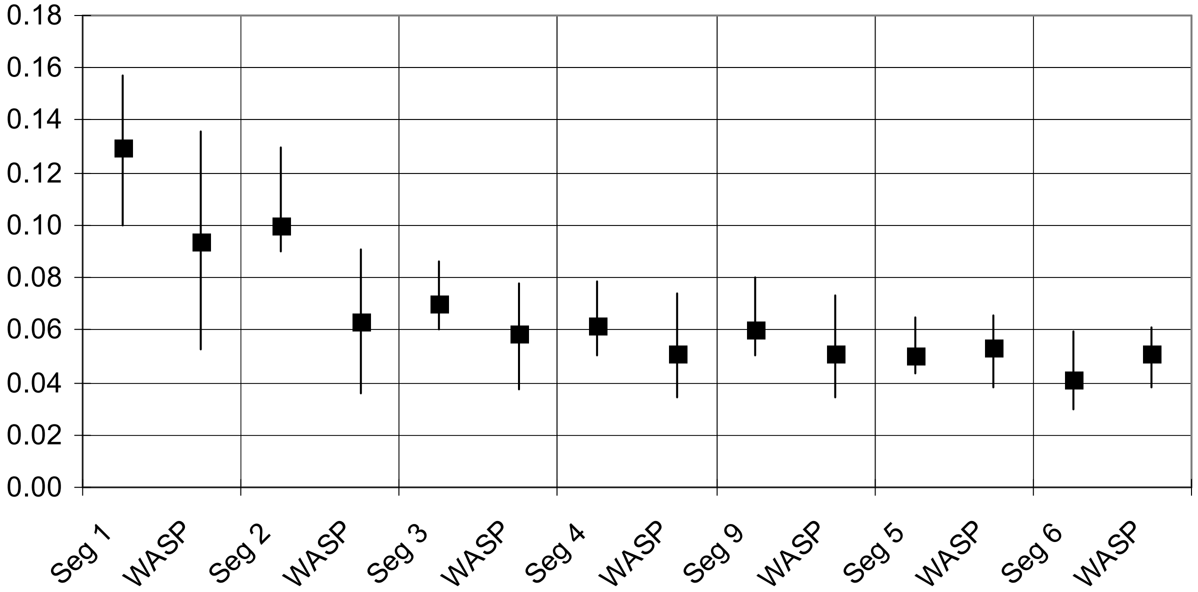


Figure 16: Cedar Creek Total Phosphorus (1991 – 2001)
Median + 25th Percentiles

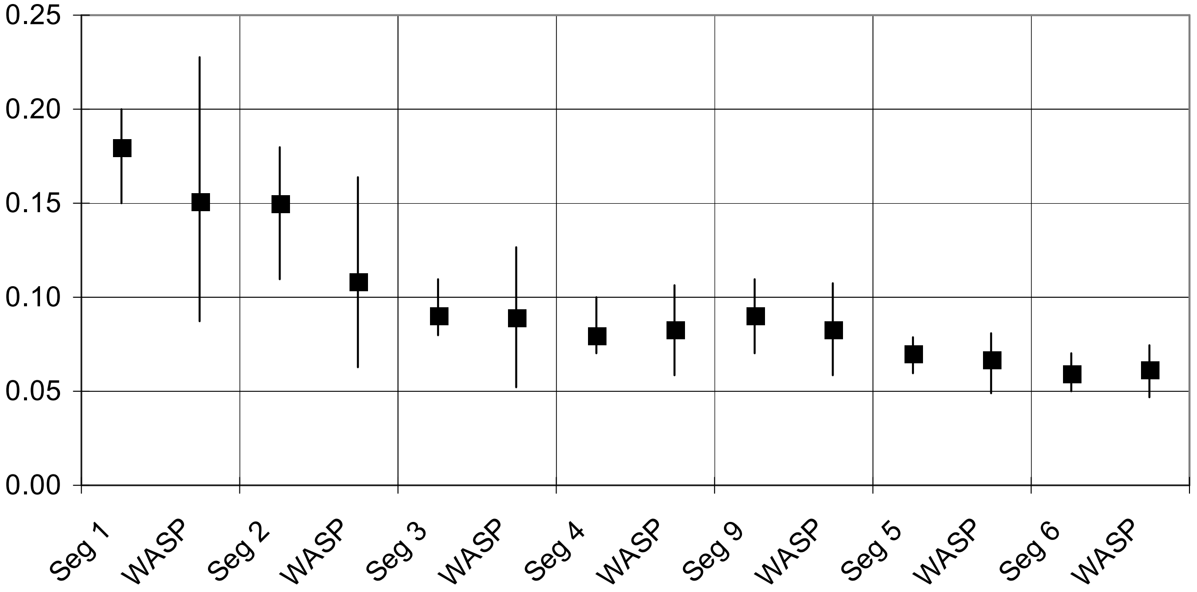


Figure 17: Cedar Creek Chl'a' (1991 – 2001)
Median + 25th Percentile

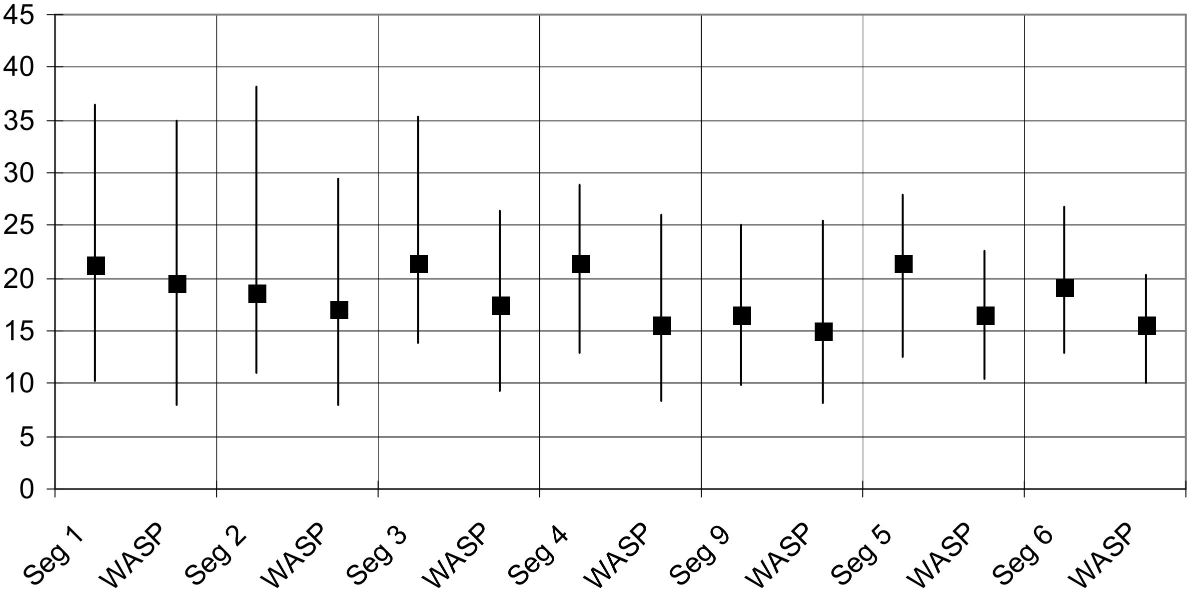


Figure 18: Cedar Creek TN/TP Ratio (1991 – 2001)
Median + 25th Percentile

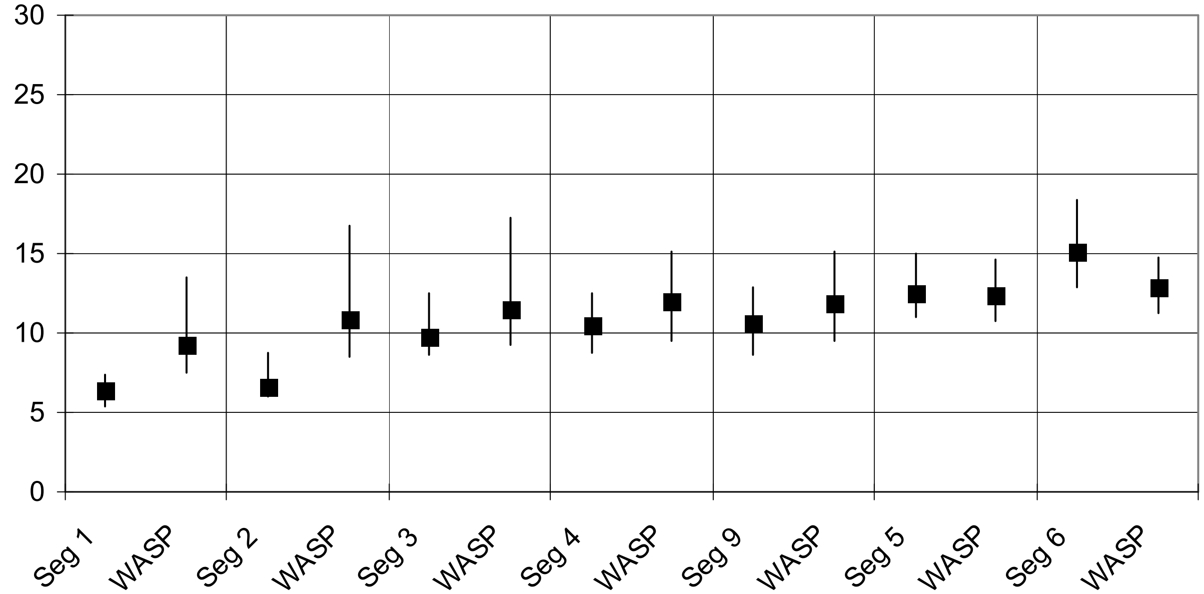


Figure 19: Cedar Creek Nitrogen Limitation (1991 – 2001)
Median + 25th Percentile

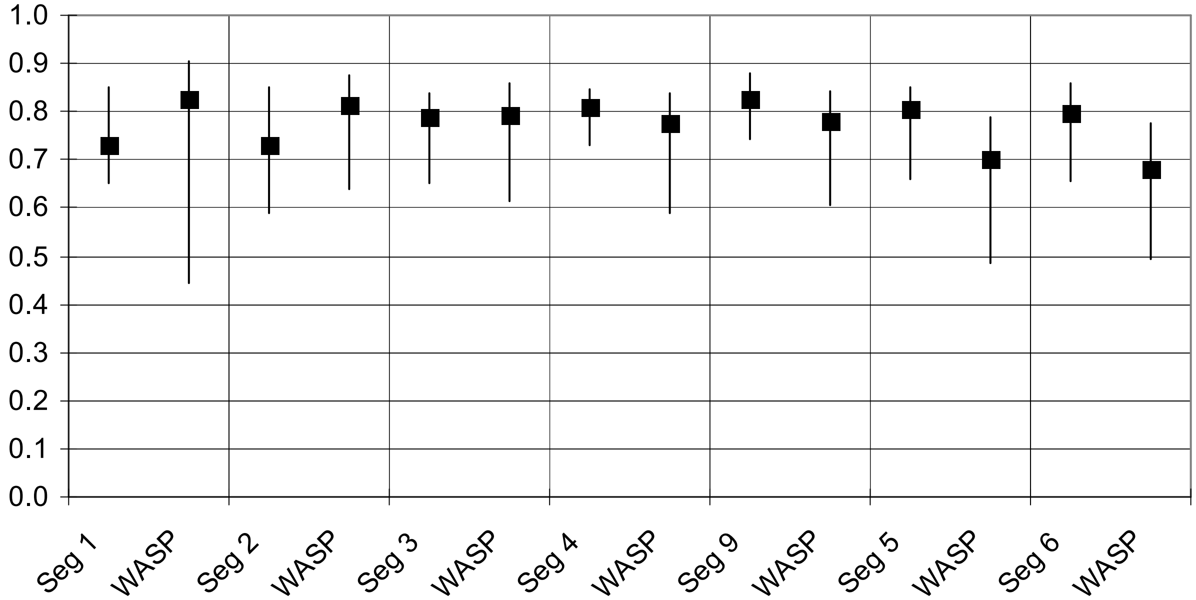
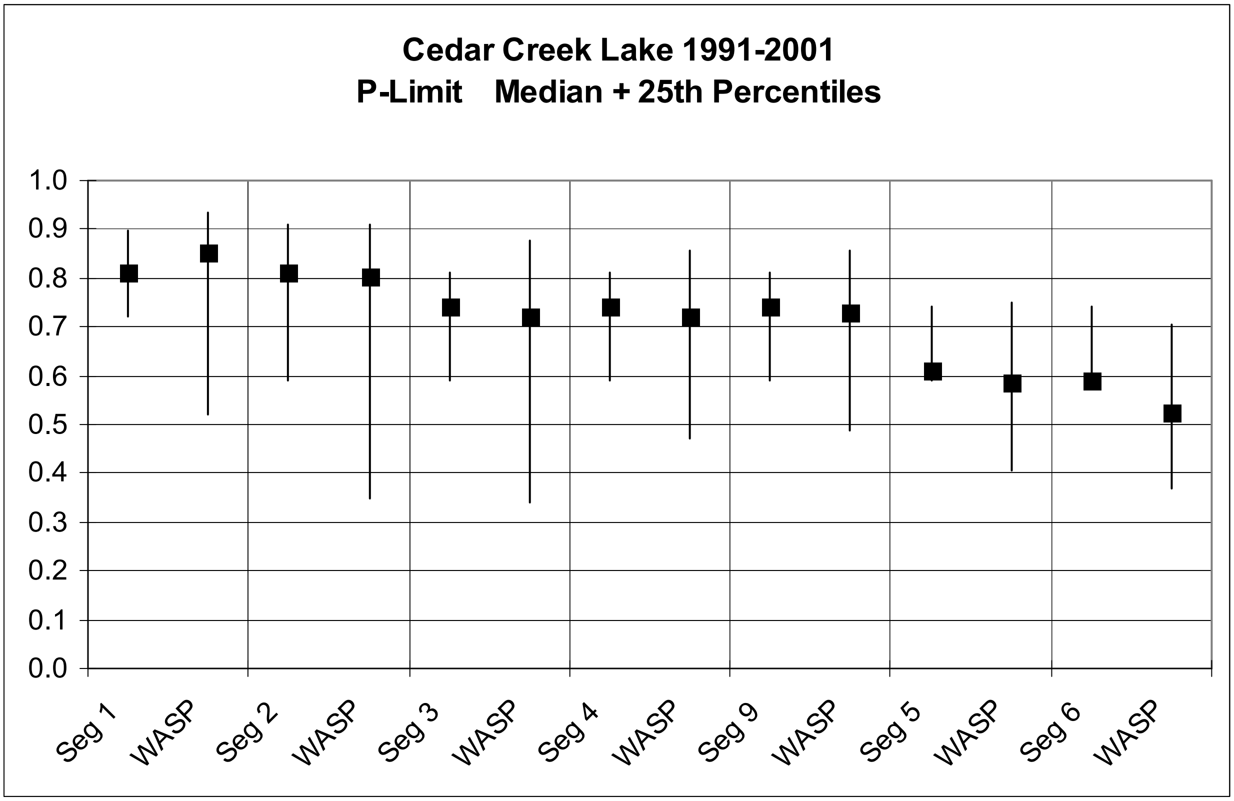


Figure 20: Cedar Creek Phosphorus Limitation (1991 – 2001)
Median + 25th Percentile



Cedar Creek Nutrient Balance

An annual and 11-year mass balance of the nutrients coming into Cedar Creek, leaving Cedar Creek and the percent retained by the lake was calculated using all sources of incoming nutrients for the calibration period (1991-2001). Using the incoming nutrient data along with the inflows and outflows from the reservoir, the percent of nutrients retained by Cedar Creek was calculated as:

Retention = Benthic Flux + ATM Load + Lakeside PS Load + Watershed Load - Outflow

Figures 21 and 22 present the nutrient budget for TN and TP, respectively. The red line across the graphs represents the percent of nutrients retained. As can be seen from Figures 23 and 24, the highest periods of retention in Cedar Creek occurred during the low flow period in 1996 and 2000. This is also evident from the incoming flow in the Cedar Creek hydrology data presented in Figure 5, that clearly shows low flow throughout most of 1996 and 2000 and hence, little outflow from the reservoir. The average 11-year nutrient budgets for TN and TP for Cedar Creek are presented in Figures 26 and 27 respectively. For Total Phosphorus the average annual loading is 224, 000 kg/day, broken down as follows: NPS 194,000 kg/day, WWTP 15,400 kg/day, Atm 6,850 kg/day and benthic flux 6,990 kg/day.

Figure 21: Cedar Creek Nutrient Budget – Total Nitrogen (1991-2001)

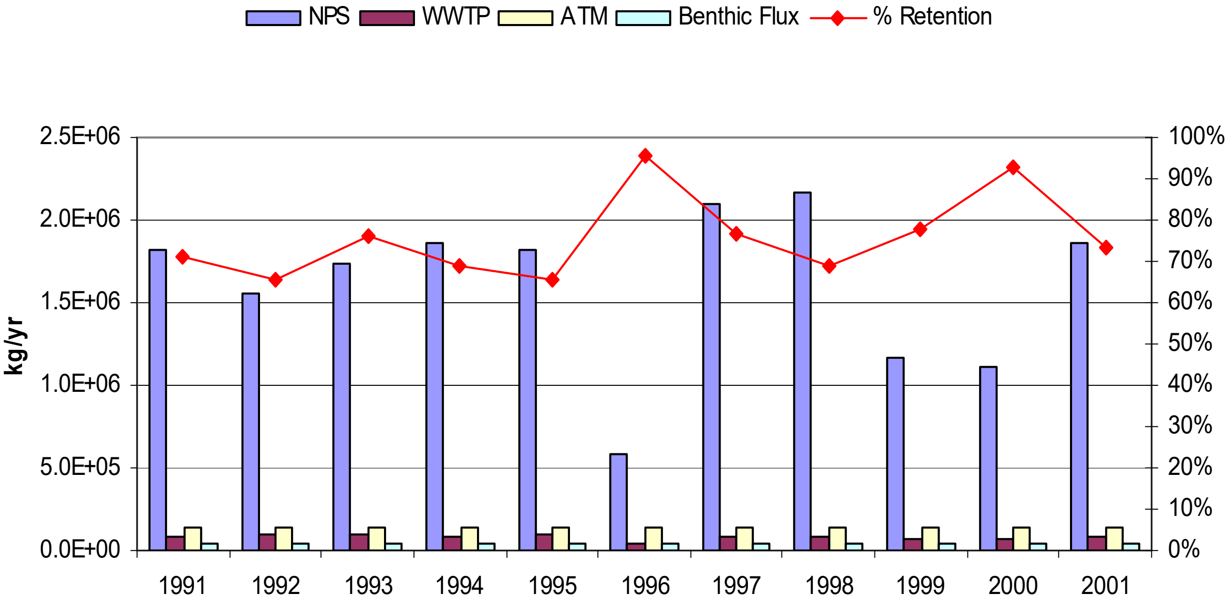


Figure 22: Cedar Creek Nutrient Budget – Total Phosphorus (1991-2001)

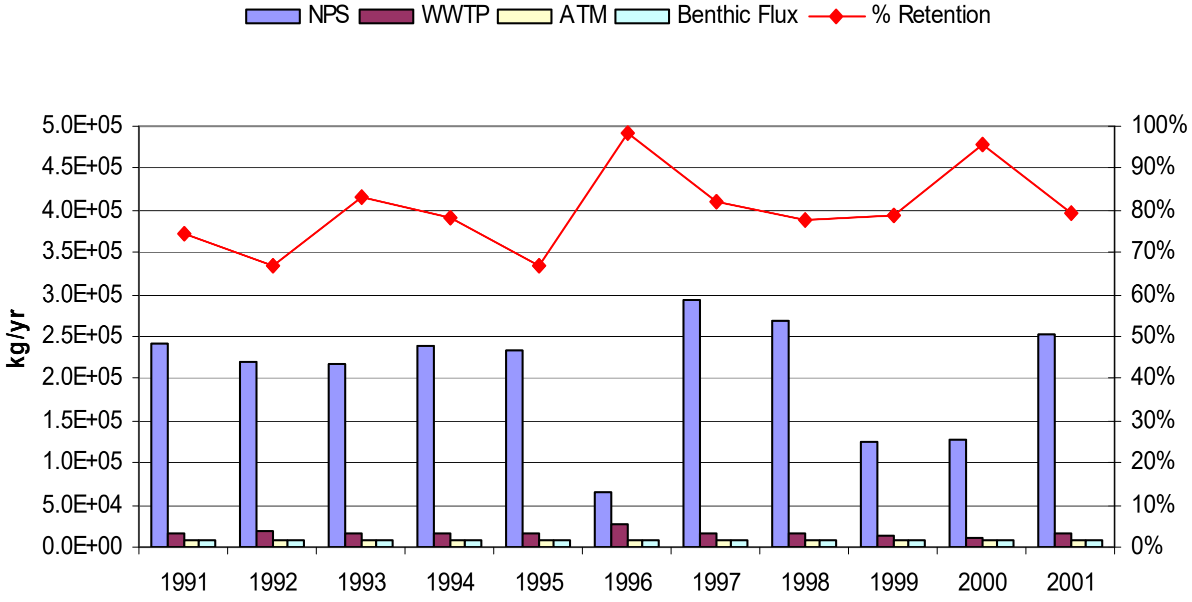


Figure 23: Cedar Creek Average 11-Year Total Nitrogen Budget

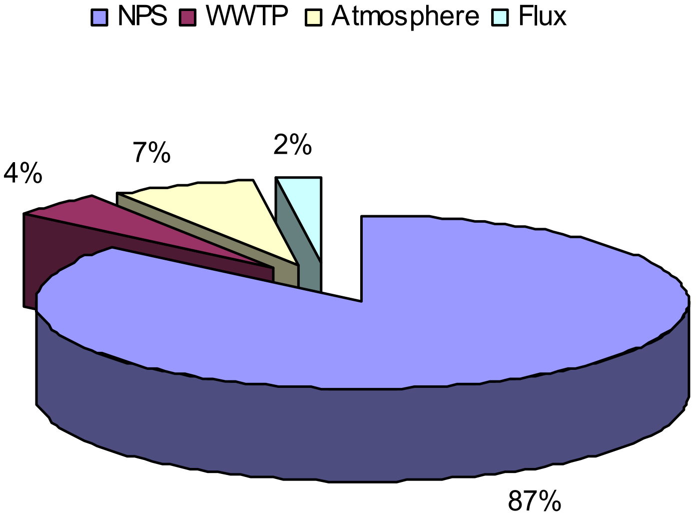
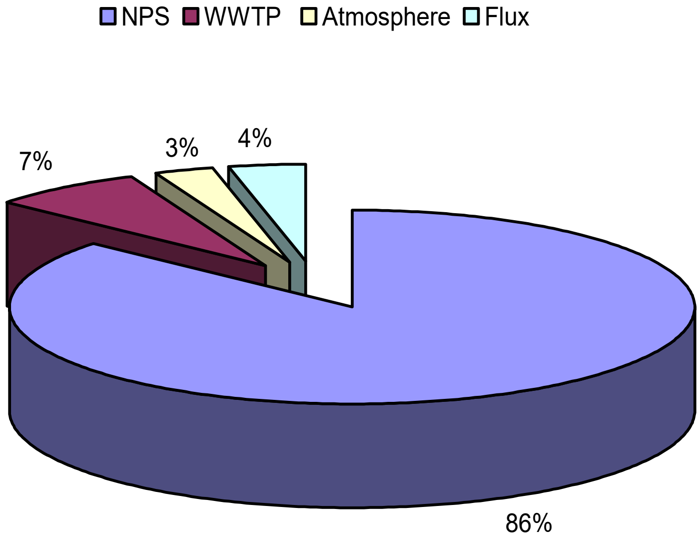


Figure 24: Cedar Creek Average 11-Year Total Phosphorus Budget
Annual load of 224,000 kg/yr



Sensitivity Analysis

The response of the calibrated WASP model to five (5) nutrient loading scenarios was evaluated independently by systematically shutting each off. The response of algae (Chl'a') growth during the calibration period for segments 4 and 6 are presented in Figures 25 and 26 respectively. The first bar on the graph represents the calibrated WASP model; the second bar represents the response of Chl'a' if the SWAT external watershed load is shut off; the third bar represents the response of Chl'a' if the seven (7) WWTPs in the external SWAT watershed file and the two (2) WWTPs with direct input to the reservoir are shut off; the fourth bar represents the response of Chl'a' if benthic flux is switched off; and the fifth bar represents the response of Chl'a' if atmospheric deposition of nitrogen and phosphorus are switched off. Likewise, the same sensitivity analyses were conducted for segments 4 and 6 to test the sensitivity of TP concentrations in the calibrated model as presented in Figures 27 and 28 respectively. Statistical testing with a Kruskal-Wallis Multiple Comparison test (alpha = 0.05) shows all simulations that are not significantly different from the calibration as having the same letter designation (i.e. A). These results, suggest that watershed loading is the most important contributors to Chl'a' growth. Watershed loading is the most significant forcing function but its impact is relatively less in Seg 6 than in Seg 4, probably as a result of the Cedar Creek hydrology routing much of the flow out through Seg 9 rather than the more conventional location of the dam.

Figure 25: Cedar Creek Reservoir Annual Chl'a' Segment 4 Median and Percentiles (1991-2001)

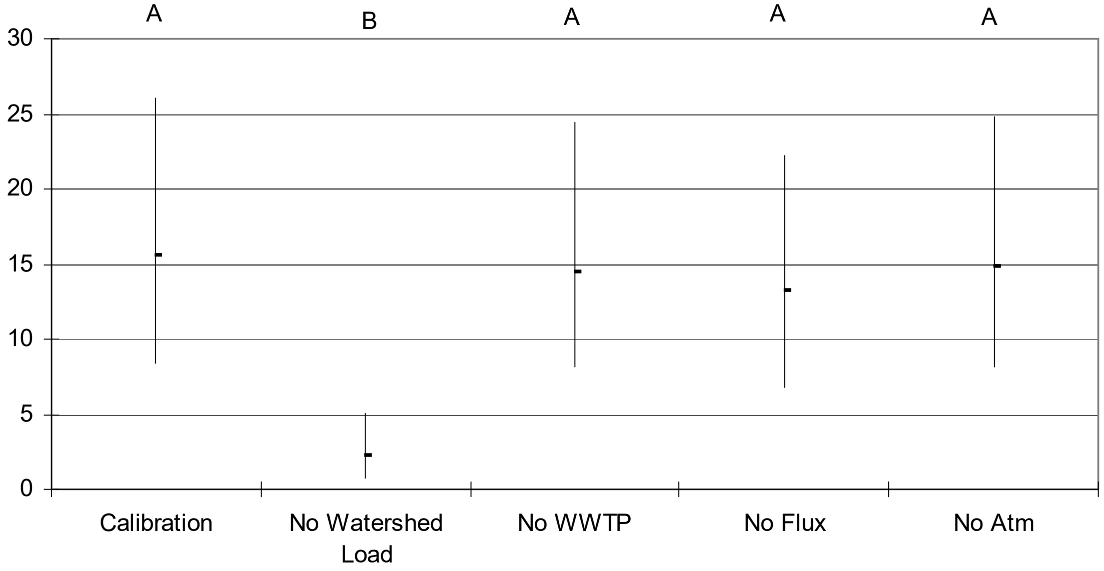


Figure 26: Cedar Creek Reservoir Annual Chl'a' Segment 6 Median and Percentiles (1991-2001)

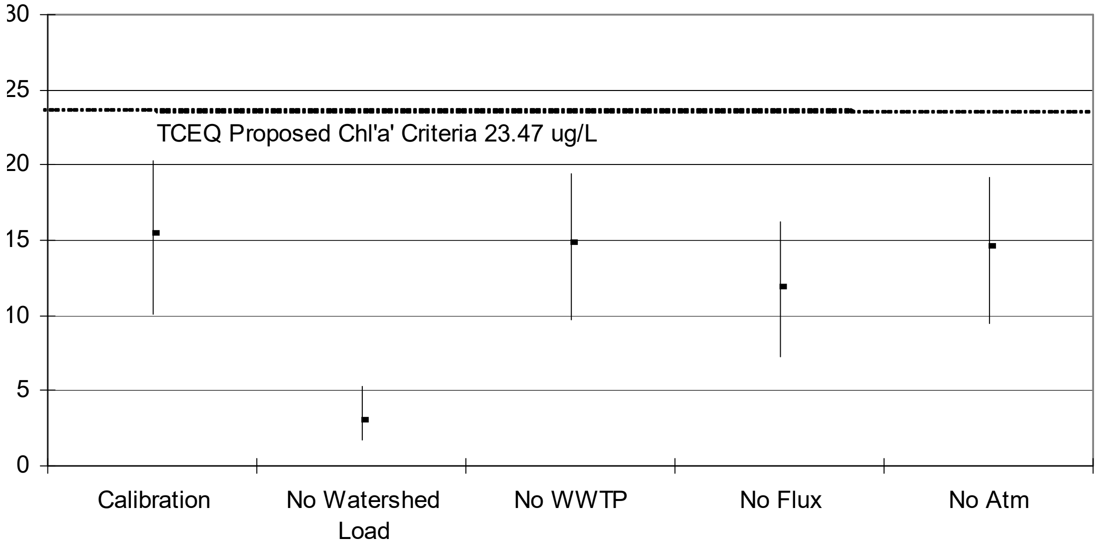


Figure 27: Cedar Creek Reservoir Annual TP Segment 4 Median and Percentiles (1991-2001)

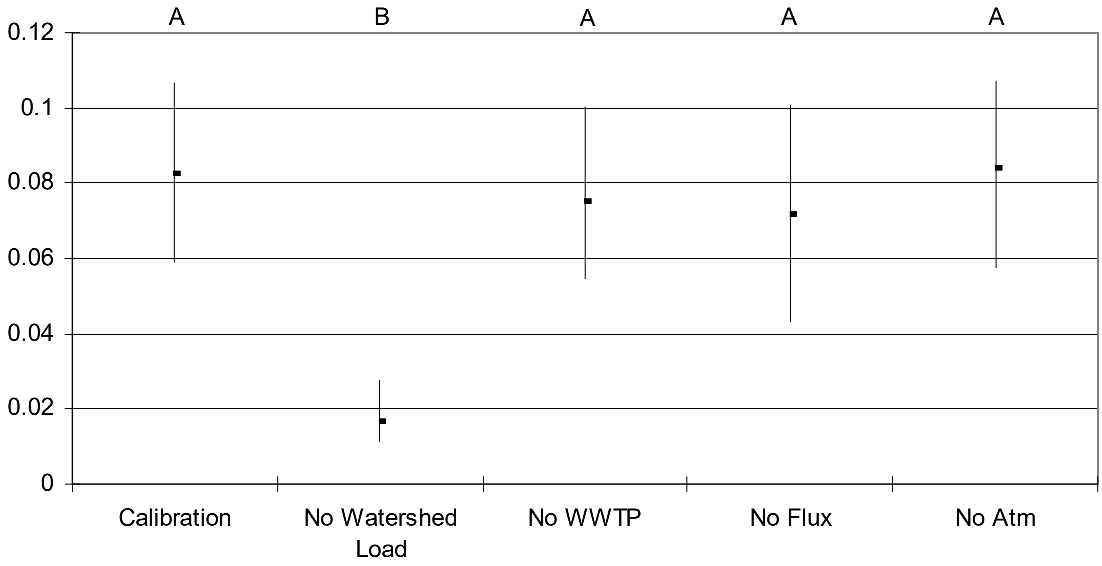
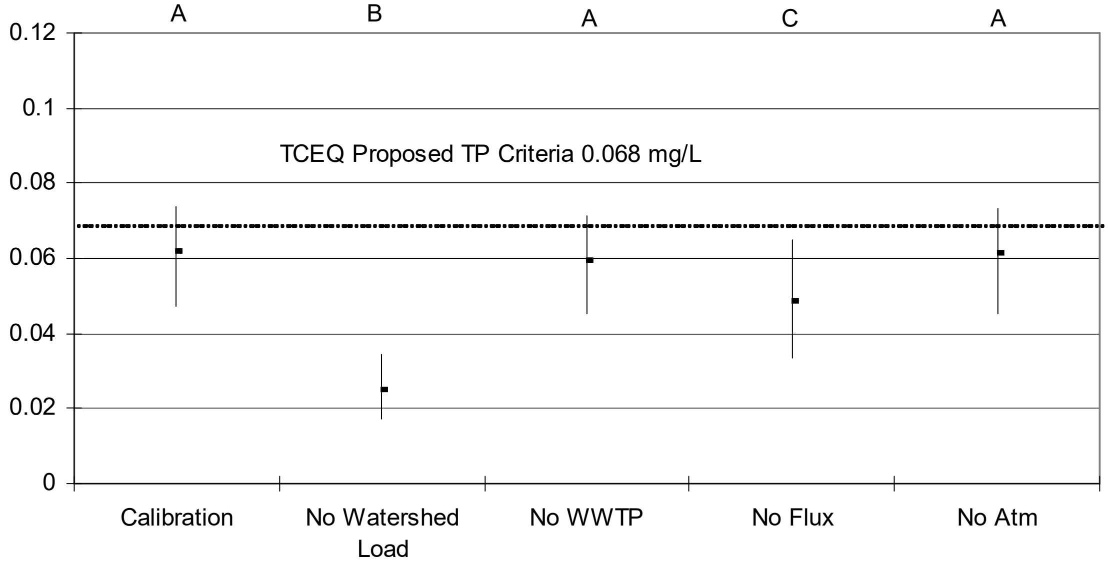


Figure 28: Cedar Creek Reservoir Annual TP Segment 6 Median and Percentiles (1991-2001)



Load Reduction Scenarios

Watershed Reductions

Five load reductions were simulated during the calibration years by scaling the NPS file to create reductions ranging from 15% to 65%. As evident from Figures 29 through 30, a significant reduction in Chl'a' and TP concentration is not realized until about a 25% to 35% reduction in the watershed loading.

Figure 29: Cedar Creek Annual Chl'a' in Segment 4: Reduction in SWAT *NPS File Loading – Median and Percentiles (1991 – 2001)

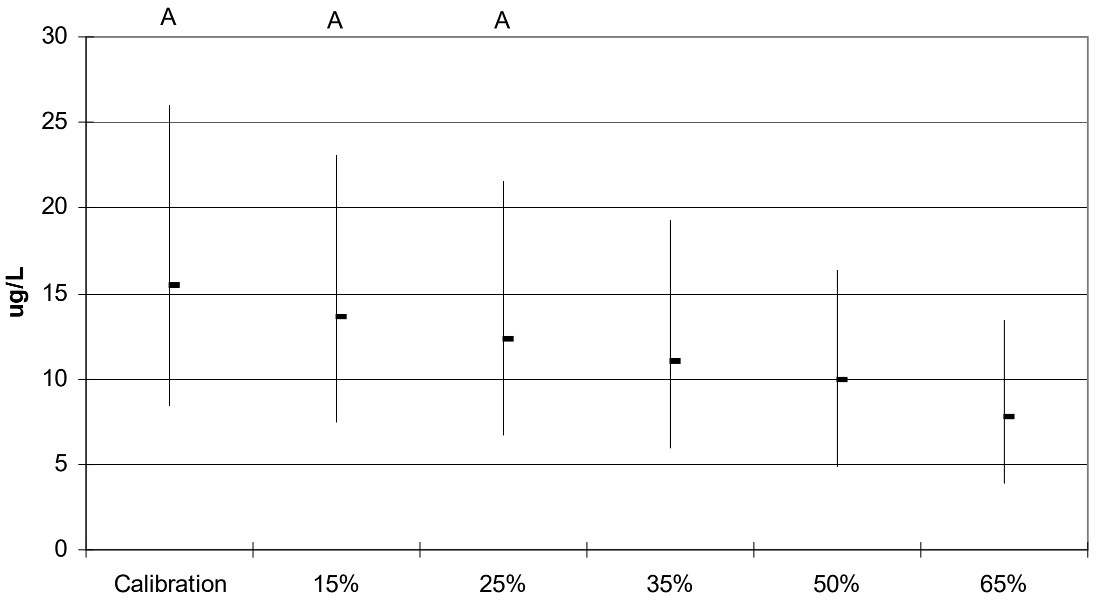


Figure 30: Cedar Creek Annual Chl'a' in Segment 6: Reduction in SWAT *NPS File Loading – Median and Percentiles (1991 – 2001)

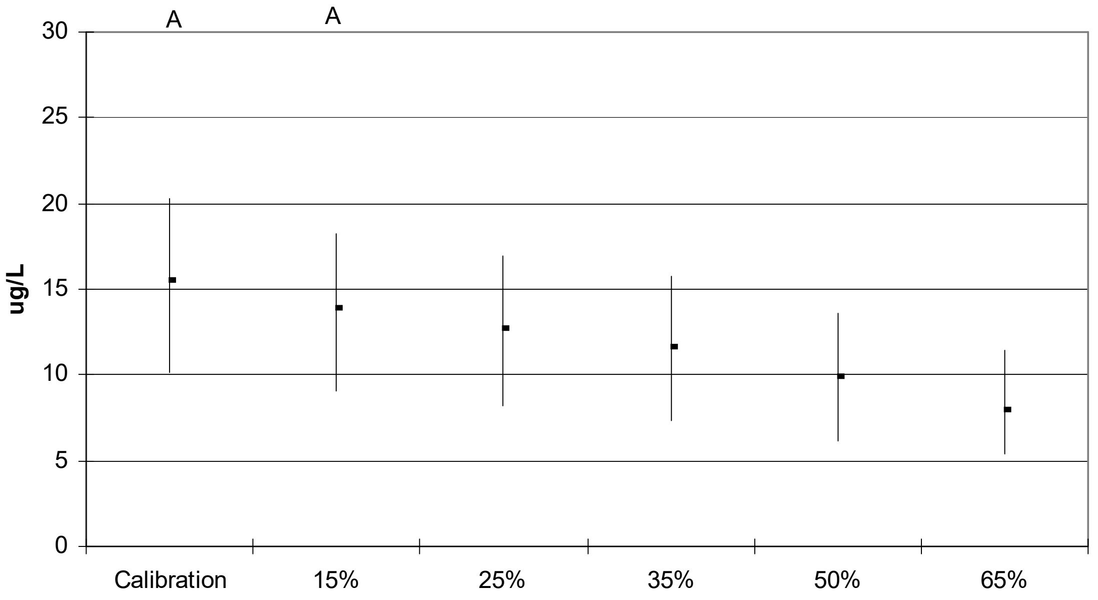


Figure 31: Cedar Creek Annual TP in Segment 4: Reduction in SWAT *NPS File Loading – Median and Percentiles (1991 – 2001)

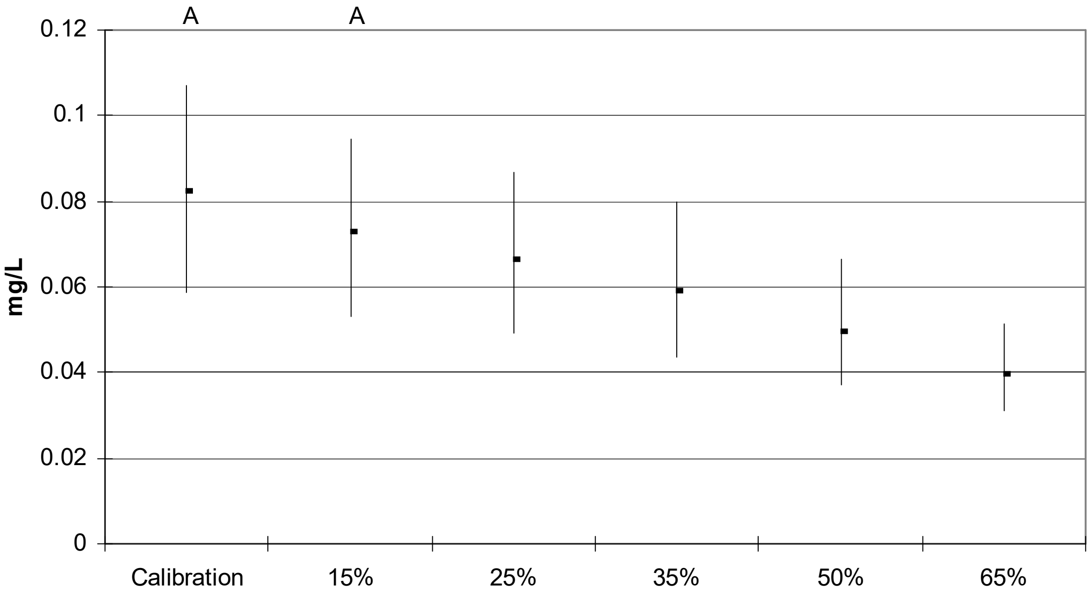
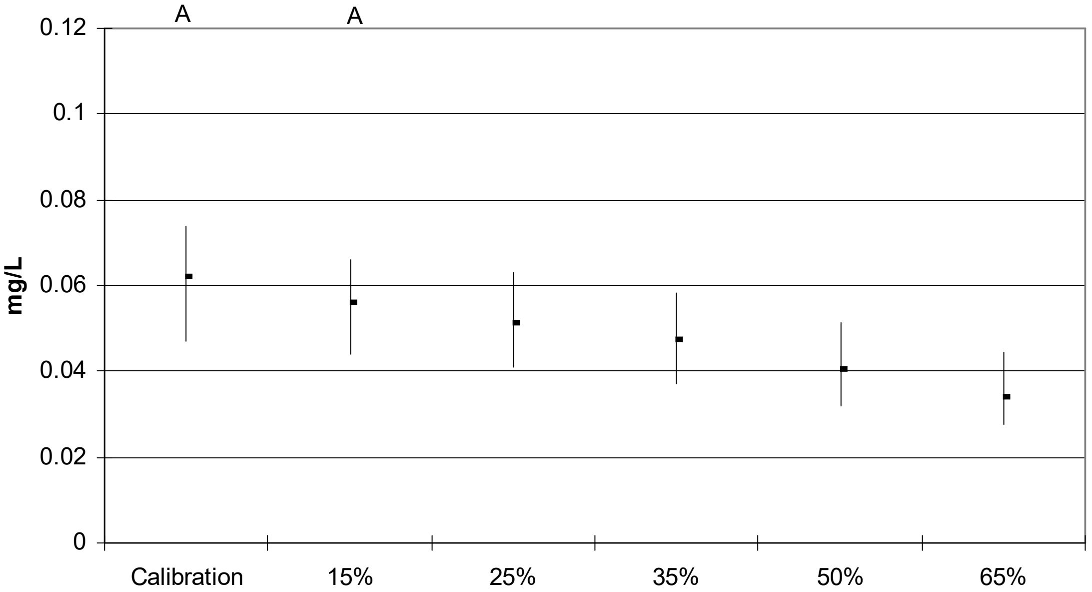


Figure 32: Cedar Creek Annual TP in Segment 6: Reduction in SWAT *NPS File Loading – Median and Percentiles (1991 – 2001)



Benthic Flux Reductions

Benthic flux reduction scenarios were done only with phosphorus since this is the most manageable nutrient (alum treatment). Reductions in phosphorus flux were done in a systematic fashion similar to that for the watershed loads. Phosphorus flux was reduced from 15% to 75%. Figures 33-36 show that flux reductions had to be in the range of 35-75% to predict Chl'a' and TP levels significantly less than the calibrated baseline conditions. Seg 6 was more sensitive to benthic flux reductions than Seg 4.

Figure 33: Cedar Creek Annual Chl'a' in Segment 4: Reduction in Benthic Flux Loading - Median and Percentiles (1991 – 2001)

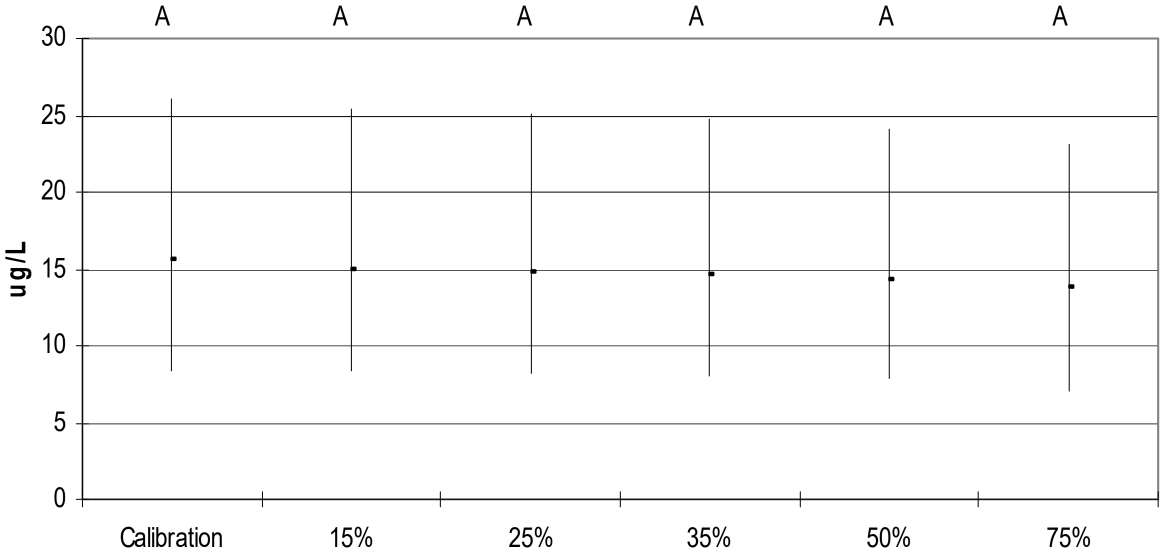


Figure 34: Cedar Creek Annual Chl'a' in Segment 6: Reduction in Benthic Flux Loading - Median and Percentiles (1991 – 2001)

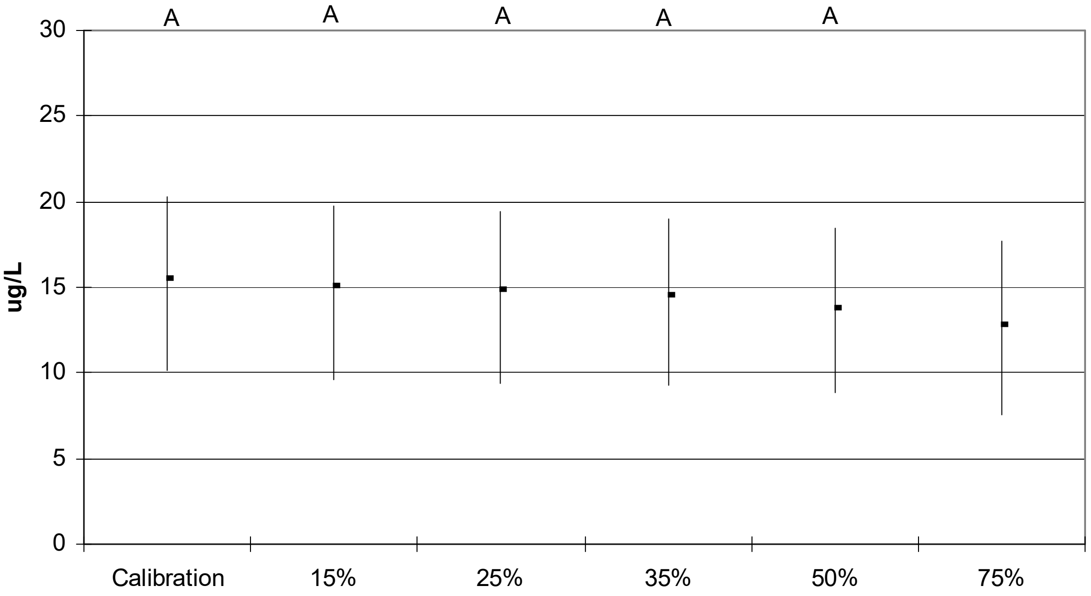


Figure 35: Cedar Creek Annual TP in Segment 4: Reduction in Benthic Flux Loading - Median and Percentiles (1991 – 2001)

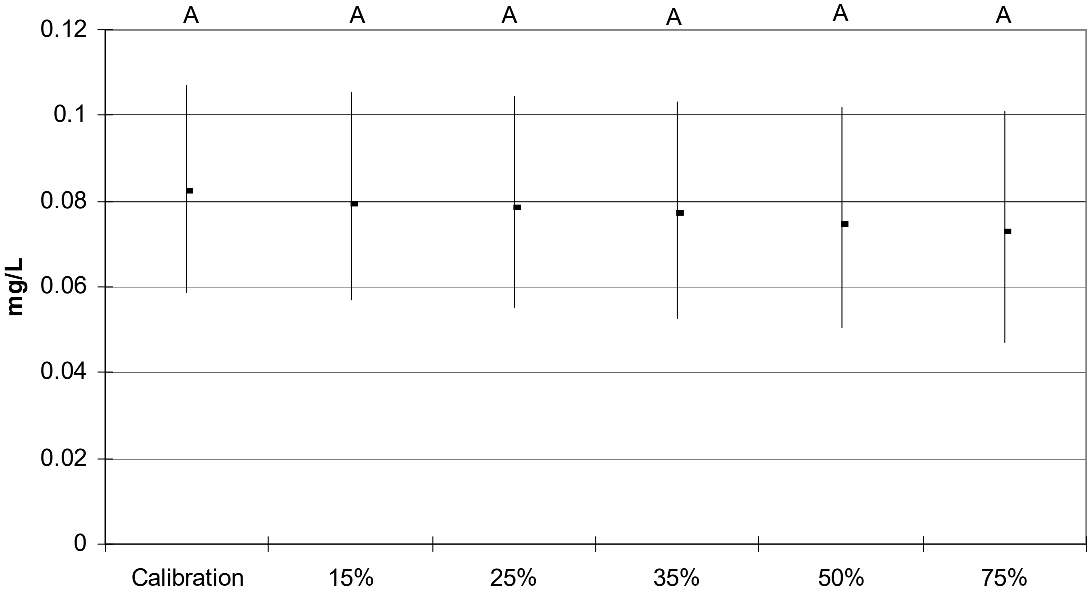
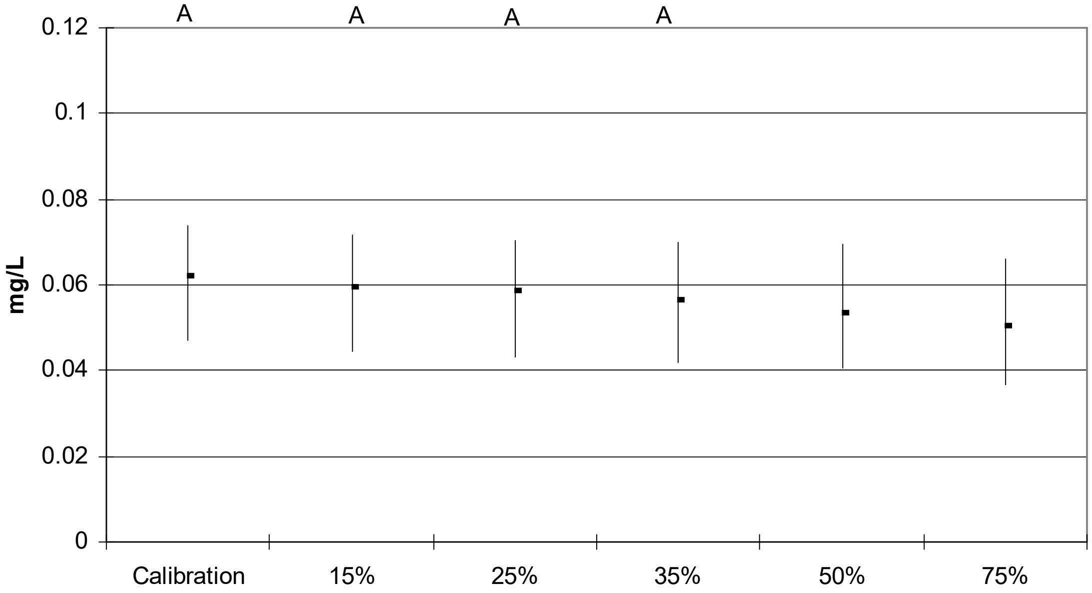


Figure 36: Cedar Creek Annual TP in Segment 6: Reduction in Benthic Flux Loading - Median and Percentiles (1991 – 2001)



Combination Scenarios

Figures 37 to 40 consider some possible combination scenarios for the calibration period (1991-2001) where both NPS (watershed loading) and phosphorus benthic flux are reduced. In-lake reduction of phosphorus flux is possible with alum addition. Results for segment 4 and 6 were similar and indicate that with theoretical reductions in both of these loading mechanisms a statistically significant reduction in Chl'a' is possible. Two of the most attractive scenarios to consider for future efforts are a 50%

reduction in the hypolimnetic phosphorus flux from Segments 12, 13, and 14 and a 25% reduction in NPS (watershed) loading, or a 75% reduction in hypolimnetic phosphorus flux from segments 12, 13, and 14, and a 30% NPS loading reduction from Kings Creek and Cedar Creek tributaries. All combination scenarios must focus on reducing the external loading to maintain the Hypolimnetic treatment of the sediment. The internal flux is not so much a source of P as it is a mechanism for P to become available for algae growth.

Figure 37: Cedar Creek Annual Chl'a' in Segment 4: Reduction in Benthic Flux and NPS Loading - Median and Percentiles (1991 – 2001)

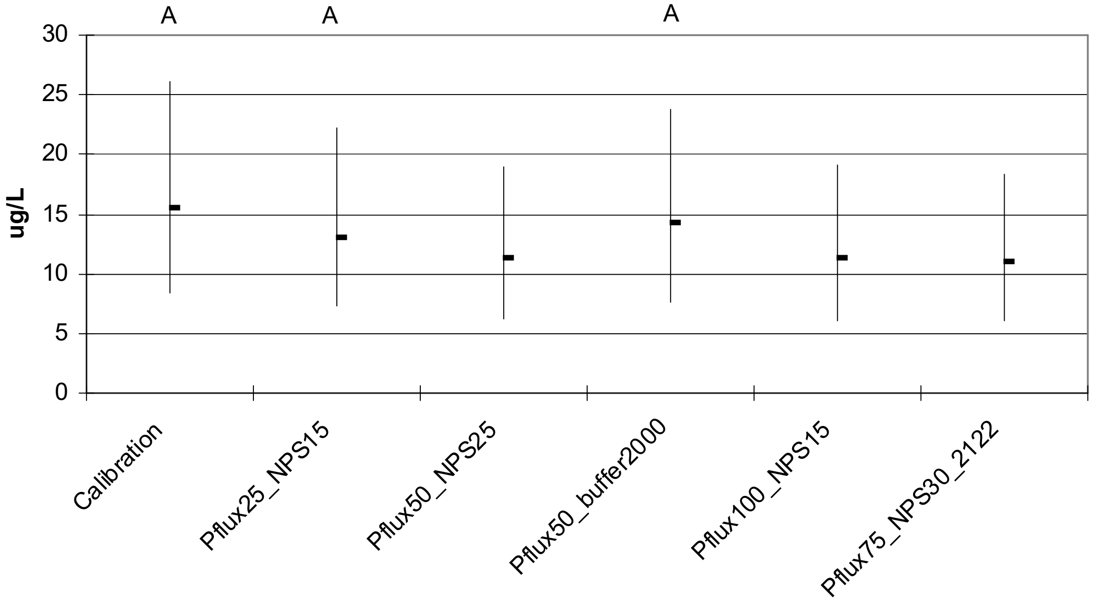


Figure 38: Cedar Creek Annual Chl'a' in Segment 6: Reduction in Benthic Flux and NPS Loading - Median and Percentiles (1991 – 2001)

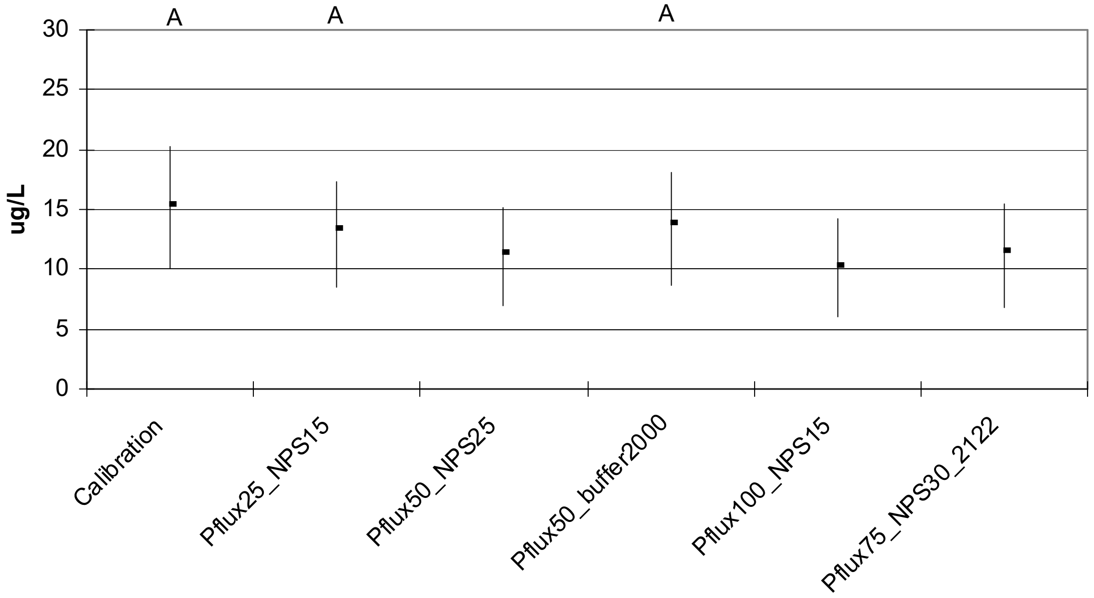


Figure 39: Cedar Creek Annual TP in Segment 4: Reduction in Benthic Flux and NPS Loading - Median and Percentiles (1991 – 2001)

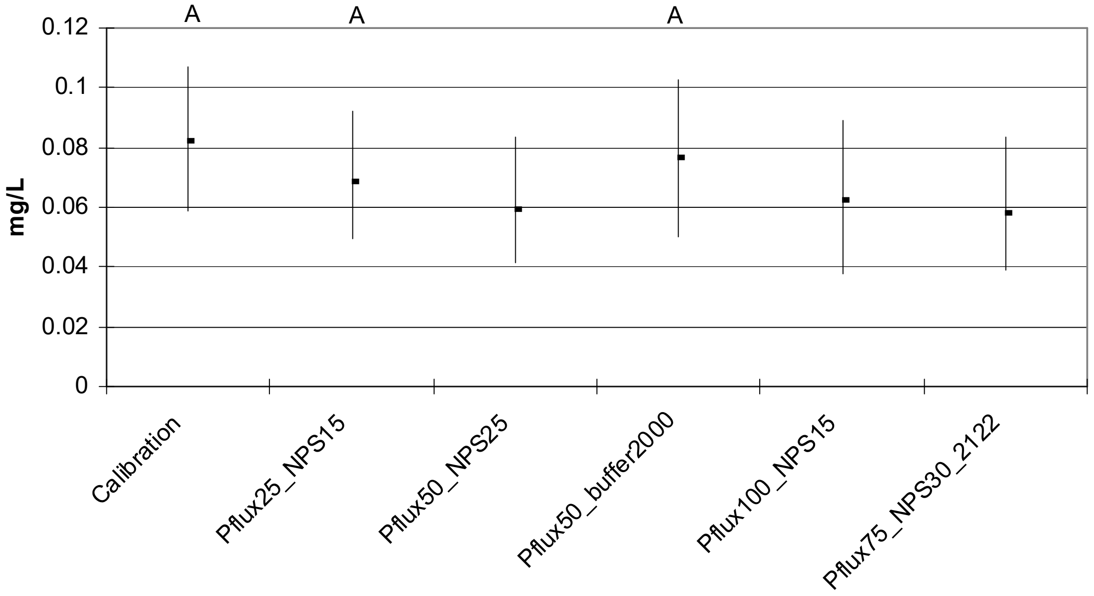
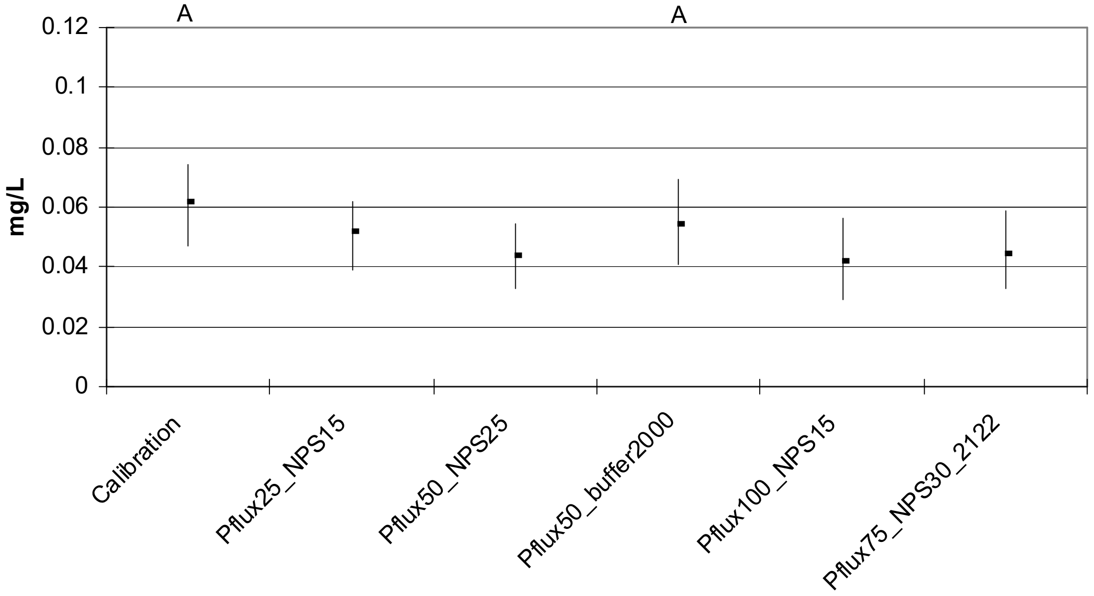


Figure 40: Cedar Creek Annual TP in Segment 6: Reduction in Benthic Flux and NPS Loading - Median and Percentiles (1991 – 2001)



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