Quantifying Uncertainty in Phosphorus TMDL's for Lakes

prepared for

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by

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March 8, 2001

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Introduction

This report demonstrates the use of probabilistic methods to quantify uncertainty in the development of phosphorus Total Maximum Daily Loads (TMDL's) for lakes. "Uncertainty" refers to prediction error resulting from limitations in the data and models used to formulate the lake phosphorus balance. Consideration of uncertainty is necessary in order to develop reliable TMDL's, i.e. ones with reasonably high probabilities of success. Methods for incorporating uncertainty into the MOS (Margin of Safety) term of the TMDL equation are demonstrated. Because it is a difficult (and sometimes painful) concept, the MOS term is often vaguely defined. As compared with soft-shoe approaches to estimating the MOS term, formal consideration of uncertainty can:

1. Provide a clear definition & objective estimate for the MOS term based upon the degree of uncertainty in the lake mass balance and the maximum acceptable risk of failing to meet the lake objective;

2. Help to clarify the lake goal; and

3. Provide incentive for collecting data to refine TMDL analyses, which may reduce the MOS term, increasing the loads that can be allocated while providing the same degree of certainty in meeting lake objectives.

Downsides are that risk tolerance must be explicitly defined beforehand as part of setting the TMDL (something else to ponder and argue about) and that estimates of uncertainty are themselves uncertain. While somewhat painful, formal consideration of uncertainty enables healthy decision-making.

The probabilistic framework is based upon assessment methodologies developed previously for Vermont (Walker, 1982ab,1983), Minnesota (Wilson & Walker, 1989) & Corps of Engineer reservoirs (Walker, 1996). It also incorporates experience in applying similar models to lake and reservoir eutrophication problems (Walker, 1980-2000). The derivation is somewhat technical and probably not suitable for public consumption, but the techniques can be applied and described without excessive complexity.

The primary intent of this report is to show how probabilistic concepts can be incorporated into lake TMDL's. The example employs specific models and parameter estimates to predict phosphorus loads as a function of watershed land use, phosphorus retention within the lake, and algal response. These models and parameter estimates are used for demonstration purposes. Other models and estimates may be appropriate for specific applications in New England. The probabilistic framework is structured so that it can be applied to TMDL's, regardless of model formulation and calibration.

TMDL Equation – Side One

The popular version of the TMDL equation is written as follows (USEPA, 1999):

$$\text{TMDL} = \Sigma\,\text{LAs} + \Sigma\,\text{WLAs} + \text{Background} + \text{MOS} \qquad (1)$$

TMDL = Total Maximum Daily Load (kg/yr)

Σ LAs = Sum of Load Allocations (~Non-Point Sources)

Σ WLAs = Sum of Waste Load Allocations (~Point Sources)

Background = Background Load (~Natural Sources)

MOS = Margin of Safety

There are a variety of ways to interpret each term of the equation in generating a valid TMDL analysis. In the framework demonstrated below, the LA's are assumed to reflect non-point sources in excess of the Background load, i.e. the anthropogenic portion of the total nonpoint load. For example, a 100 kg/yr total P load from an urban watershed would be reflected in two terms of the equation (say, 10 kg/yr in the Background term representing the expected load with an undeveloped watershed and 90 kg/yr in the LA term representing the increase in load above background resulting from development of the watershed).

The Background load would equal the total load to the lake if the entire watershed were undeveloped. Consideration of the Background load as a separate term in the equation is useful for characterizing anthropogenic impacts and settling realistic goals. For example, it is generally not practical to implement a TMDL that is below the Background load. Reaching this conclusion may indicate that the assumed lake goal is unrealistic.

For the purposes of this analysis, it is assumed that the load allocation terms (LA's and WLA's) represent expected average loads that will occur under the TMDL. Discharge permit limits would be set to be consistent with meeting average loads represented by the WLA's while taking typical variability in effluent quantity and quality into account. In order to operate in compliance with its discharge permit, the average load from a given facility would generally be below the permit level. If discharge permit levels were equated directly to the WLA's (without considering effluent variability), it would be appropriate to consider the difference between the expected average and permitted maximum loads as part of the MOS.

One unfortunate characteristic of the TMDL equation is that, when it is applied with MOS > 0 (as apparently intended), the TMDL does not equal the expected load to the lake (sum of the non-MOS terms). This can lead to confusion. The MOS term is apparently intended to ensure that the load allocation has more than a 50% chance of meeting the lake objective (or less than a 50% risk of failing to meet the objective). This is especially necessary when the lake objective is defined as a lake phosphorus concentration (or other trophic state indicator) not to be exceeded, as compared with a concentration to be achieved.

A Margin of Safety can be provided by making conservative assumptions at various steps in the process (e.g., by selecting a conservative lake target or over-designing BMP's to meet the load allocation, USEPA, 1999). Making conservative assumptions in formulating the mass balance (e.g., in selecting export or retention coefficients) can lead to serious errors in projecting the benefits of BMP's and in projecting lake responses. The author's preference is to formulate the mass balance using the best scientific estimates of the model input values and keep the margin of safety in the MOS term.

In some situations, the MOS is buried in other terms of the TMDL equation and is not explicitly quantified, either in terms of load or the corresponding risk that the lake objective will not be achieved. If the MOS is truly intended to provide a margin of safety, it seems appropriate to quantify it based upon the degree of uncertainty in the mass balance and the maximum acceptable risk of failing to meet the objective. Formulating TMDL's and management plans with MOS terms that are buried and un-quantified amounts to making decisions in the dark. It can generate TMDL's that err seriously in either direction.

TMDL Equation – Side Two

The other side of the TMDL equation estimates the load that can be discharged to the lake without exceeding water-quality standards. This is often described as the lake's "assimilative capacity". The TMDL can be computed using a lake model and a defined lake criterion. For a given lake, most empirical phosphorus models can be reduced to a form where the TMDL is proportional to lake P concentration:

$$\mathrm{TMDL} = K \; P_C \tag{2}$$

where,

K = lake-specific constant (kg/yr/ppb)

P_C = lake P criterion or maximum allowable concentration, averaged over an appropriate time scale (e.g., summer mean) (ppb)

USEPA (2000) provides guidance for selecting an appropriate P criterion. The K factor can be estimated using a mass-balance model that simulates lake response to variations in external phosphorus load and other controlling factors. It is assumed that the model and load allocations are formulated to reflect long-term-average, steady-state conditions. Stochastic terms can be added to the steady-state model to account for uncertainty and temporal variations in the lake response. More complex deterministic models can be used to simulate seasonal and/or year-to-year variations. Such efforts are usually impractical, however, given their extensive data requirements and limitations in time, funding, and the state-of-the-art.

The lake model used to estimate the TMDL represents the steady-state phosphorus mass balance:

$$\text{Inputs} = \text{Outputs} + \text{Retention} \tag{3}$$

Empirical models initially calibrated to regional lake datasets can be used to predict the retention or net sedimentation term. The mass balance equation can be solved to predict lake P concentration as a function of external load, hydrologic factors, and morphometric factors. The retention model in the example below uses the "settling velocity" concept to predict net sedimentation (Vollenweider,1969; Chapra,1975):

$$\text{Inputs} = L \tag{4}$$

$$\text{Outputs} = Q \;\; P \tag{5}$$

$$\text{Retention} = U \;\; A \;\; P \tag{6}$$

The mass balance equation can be solved for lake P concentration:

$$P = L / (Q + U A) \tag{7}$$

P = lake P concentration (ppb)
L = average external phosphorus load (kg/yr)
Q = average annual lake outflow (million cubic meters/yr)
A = lake surface area (km^2)
U = phosphorus settling velocity (m/yr)

The literature and experience with other regional lakes generally provide initial estimates of settling rate ($U \sim 10$ m/yr). Depending upon regional experience, other empirical models are sometimes used to provide initial estimates of settling rate as a function of depth and water load (e.g., $U = (Z Q / A)^{0.5}$, Vollenweider, 1976).

These estimates can be refined by calibrating the model to lake-specific data. For a given lake, the terms Q, U, and A are fixed, so that the equation can be solved for the external load corresponding to a given lake concentration:

$$L = P (Q + U A) = K P \tag{8}$$

$$K = (Q + U A) \tag{9}$$

For some retention models (e.g., Canfield & Bachman, 1982), the sedimentation rate is load-dependent, so that lake P concentration is not a linear function of load. These cases require numerical solution of the equation for the load corresponding to a given lake P concentration.

According to equation (2), the TMDL is proportional to a specified phosphorus criterion (P_C) that represents the maximum lake phosphorus concentration consistent with achieving water quality standards. Depending upon the basis for the criterion, lake P concentration would be averaged over an appropriate time scale (long-term-average vs. year), season (annual, spring overturn, or summer) and depth interval (epilimnetic, volume-weighted-mean). Spring-overturn or summer-average epilimnetic concentrations are typically used because they are most directly correlated with critical conditions (algal blooms) that impact water uses or lead to direct violations of water quality standards. The selection of averaging period would influence the calibration of the phosphorus retention model (e.g., settling velocity).

The Margin of Safety

The left-hand(1) and right-hand(2) sides of the TMDL equation can be combined as follows:

$$\text{TMDL} = K P_C = L + \text{MOS} \tag{10}$$

$$L = \Sigma\, LAs + \Sigma\, WLAs + Background \tag{11}$$

Given values for K and P_C, the split between L (the expected load to the lake) and MOS (margin of safety) must be specified in order to solve the equation. The relative magnitude of these terms should reflect the degree of uncertainty in the estimates of K, P_C, and the individual load components.

If the MOS = 0 and the load estimates and model parameters represent best scientific estimates (no inherent safety factors), there would be a 50% risk that the lake concentration would exceed P_C. Whether or not this is acceptable could depend upon how the lake criterion P_C is defined. For example, if P_C corresponds to a summer-average concentration that is likely result in a fish kill, then 50% risk of exceeding P_C would not be acceptable. If, on the other hand, P_C represents to a desired average condition for the lake (target), then a 50% risk might be acceptable.

It is useful to define the factor 'f' which represents the fraction of the TMDL that is allocated to the MOS:

$$MOS = f\ TMDL = f\ K\ P_C \tag{12}$$

$$L = (1 - f)\ TMDL = (1-f)\ K\ P_C \tag{13}$$

The appropriate value of f would tend to be larger in cases with little site-specific data and smaller in cases with extensive monitoring data. Investing in lake studies to reduce uncertainty could result in higher allocated loads. An approach to estimating f is described below.

To estimate f using probabilistic methods, it is necessary to amplify the definition of the TMDL objective to include both a maximum concentration (P_C) and a maximum risk of exceeding this concentration (α). The value $1-\alpha$ can be described as a "confidence level". The TMDL would be the load corresponding to 50% risk of exceeding P_C. The total allocated load (L, without the MOS) would be the load corresponding to the specified risk level α. The MOS would then equal the difference between the TMDL and L.

Risk can be estimated by attaching a random error term to the lake mass balance model. Errors are assumed to be multiplicative and log-normally distributed (Walker, 1982b):

$$\ln(L) = \ln(K\ P_C) + \delta \tag{14}$$

Where,

P = actual lake concentration (ppb)
δ = normally-distributed random variable with mean = 0 and standard deviation = S

The allocated load would be set at the lower end of the predicted confidence interval:

$$L = K P_C \exp(-Z_\alpha S) \qquad (15)$$

where,

Z_α = standard normal deviate with exceedence probability α

Combining with equations 12 & 15, the margin of safety factor (f) can be computed from:

$$f = 1 - \exp(-Z_\alpha S) \qquad (16)$$

The magnitude of S would be estimated on a case-by-case basis, depending upon the amount of information available to support the TMDL assessment. Based upon residual standard errors derived from various lake modeling efforts (Walker,1980-2000; Wilson & Walker, 1989), typical values for S would range from ~0.1 when data are plentiful (model is calibrated to loads and lake concentrations measured over 3 or more years) to ~0.3 when the data are limited (loads estimated from land use, regionally-calibrated export coefficients, and regionally calibrated P retention models). This range refers to predictions of long-term-average P concentrations. It would be higher for predictions of yearly values. The following table summarizes values of the MOS factor for various values of S and α:

Typical Values for the MOS Factor "f"				
α = Risk	0.50	0.25	0.10	0.05
Confidence Level	0.50	0.75	0.90	0.95
Z_α	0.00	0.67	1.28	1.64
Model Standard Error = S				
0.1 data-rich	0.00	0.07	0.12	0.15
0.2	0.00	0.13	0.23	0.28
0.3 data-poor	0.00	0.18	0.32	0.39

More detailed error analysis techniques (Walker, 1982) can be used to estimate appropriate values of S on a case-by-case basis.

The MOS can be described as an "uncertainty cost" associated with the TMDL. This can be high, relative to the actual load reduction required to achieve the lake goal. For example, suppose that the phosphorus balance model indicates that a load reduction of 20% is needed to exactly meet the lake phosphorus goal. With an MOS factor of "f" of 0.2, a load reduction of 40% would be needed to provide the "certainty" required under a TMDL. Accomplishing a 40% vs. 20% reduction would require more than twice as much effort and cost because measures applied to accomplish the first 20% reduction would tend to be more cost-effective (kg P reduced per unit effort or cost), as compared with those applied to accomplish the second 20% (increase 20 to 40%). The second 20% reduction may require technologies that are very costly and less predictable.

Much of the uncertainty results from the TMDL requirement to comply with a fixed concentration objective. If the management objective were expressed in relative terms (i.e. reduction of at least 20% vs. a concentration below 20 ppb), the MOS would be much lower. Regardless of the actual lake concentrations, the confidence that a 20% reduction will be beneficial would be much greater than the confidence that it will result in a concentration below 20 ppb.

High uncertainty costs may hinder the actual progress of lake restoration by reducing credibility and forcing stakeholders to dig in their heals. For this reason, caution is recommended in setting an unrealistically high confidence level (low α levels) as a TMDL goal. An incremental or “adaptive” approach to achieving a high confidence level through successive TMDL’s may be appropriate. Both incremental load reductions and acquisition of new data can increase the probability of meeting the lake objective with each iteration of the process.

Example

A hypothetical example illustrates application of the above concepts. Algal blooms in Bailey Lake are thought to interfere with recreational uses. The Lake has a surface area of 4.5 km^2 and a watershed area of 95 km^2 (5 km^2 urban, 30 km^2 agricultural, and 60 km^2 undeveloped). A single point source in the watershed has an average volume of 0.2 hm^3/yr and average phosphorus concentration of 2.7 ppm, 10% below its permitted level of 3.0 ppm. Based upon the perceived algae problem, water quality is considered impaired by nutrients and a TMDL analysis is undertaken. Initially, there are no site-specific monitoring data from the lake or its watershed, other than a few transparency measurements. Other lakes in the region have been studied and provide approximate estimates of export coefficients, phosphorus settling rate, and algal response parameters for use in the TMDL analysis.

A phosphorus criterion (20 ppb as a long-term, summer-average, epilimnetic concentration) is developed for Bailey Lake based upon the relationship between summer epilimnetic P concentration and algal bloom frequency observed in other regional lakes. This relationship (Figure 1) is quantified based upon a linkage of empirical models relating summer mean P to summer mean chlorophyll-a (Carlson, 1997) and summer mean chlorophyll-a to algal bloom frequency (Walker, 1984; Heiskary & Walker, 1988). An algal bloom is assumed to occur with the daily chlorophyll-a concentration exceeds 20 ppb. This is supported by correlations between chlorophyll-a measurements and user perceptions of water quality found the literature (Walmsley, 1984), as well as in surveys of other regional lakes. As shown in Figure 1, the frequencies of algal blooms increase sharply as lake P concentrations increase above 20 ppb. This criterion is also supported by the fact that other regional lakes with long-term-average P concentrations less than 20 ppb generally comply with water quality standards and are not considered impaired by nutrients, at least for recreational uses. Although no specific requirements or general guidelines are available on this topic, a confidence level of 90% is initially selected for the TMDL development (i.e., with the allocated loads, there would be less than a 10% risk that the long-term-average summer P concentration in Bailey Lake would exceed 20 ppb). This amounts to a policy decision; other confidence levels (e.g., 80%, 95%, 99%) could have been selected.

Relevant data and models are assembled in a spreadsheet that computes phosphorus balances and lake trophic state indicators (lake total P, chlorophyll-a, algal bloom frequency, and Secchi depth). Monte Carlo simulations are preformed to estimate the probability distributions of predicted lake phosphorus concentrations of alternative loading scenarios using methods similar to those described by Walker (1982). The analysis of conducted for five load allocation scenarios:

1. **Existing**. Best estimate of current loads to the lake.

2. **Background**. Estimated loads with a totally undeveloped watershed.

3. **Plan.** Projected future conditions with point & non point source control strategies developed under the TMDL process.

4. **Base**. Future load allocation providing a 50% probability of achieving the lake objective (TP < 20 ppb)

5. **TMDL.** Future load allocation providing a 90% probability of achieving the lake objective

Scenarios 3-5 also consider the anticipated conversion of 1 km^2 of existing agricultural land to urban uses and a 20% increase in wastewater flow. The general objective is to find a plan (suite of practical control measures) that approaches the TMDL (i.e., has a 90% chance of success). The base load and TMDL are computed by adjusting the non-point-source portions of the Plan load to provide 50% and 90% probabilities of meeting the objective, respectively.

Initial TMDL calculations are shown in Table 1 (summary), Table 2 (model inputs and mass-balance calculations), and Figure 2 (display of load components and confidence intervals for lake phosphorus concentration and algal bloom frequency). The assumed model error coefficients of variation (CV's) for export coefficients (30%), setting rate (40%), chlorophyll-a (25%), and Secchi depth (20%) are thought to be appropriate in situations where the models are calibrated to other regional lakes, but no lake-specific data are available (Table 3). The model predicts an existing lake P concentration of 25 ppb (80% confidence interval = 19 to 33 ppb) and an algal bloom frequency of 4% (80% CI = 0.2 to 24 %). The estimated existing lake load of 2530 kg/yr exceeds the estimated Background load (886 kg/yr) and Base load (2005 kg/yr). To provide 90% certainty of meeting the objective, the lake load under the TMDL allocation would be 1506 kg/yr.

Management methods available to develop the plan include BMP's for existing urban, future urban, and agricultural land uses, as well as reductions in point-source phosphorus loads. The formulated plan calls for BMP load reductions (20% for existing urban areas, 60% reduction for new urban developments, and 20% for existing agricultural areas) and a reduction in the average point source discharge concentration from 2.7 to 0.9 ppm. With this reduction, the revised permit levels for the discharge would be 1 ppm. The difference between 0.9 ppm target concentration and 1.0 ppm permit limit allows for typical effluent variability (averaged over an appropriate time frame). This is a technology-based derived from watershed reconnaissance and selection of cost-effective control methods that can be applied in this context within reasonable funding constraints.

With the proposed plan, the expected lake load would be 1931 kg/yr, which is below the Base load (2005 kg/yr) but above TMDL allocation (1506 kg/yr). The MOS associated with the current plan is 74 kg/yr and the probability of achieving the 20-ppb lake goal is 53%. To achieve the lake target with 90% confidence, the MOS would be 500 kg/yr, or 49% of the total load reduction required to achieve the TMDL. This relatively large MOS reflects uncertainty in the projections arising from lack of site-specific data for the lake. Given the level of uncertainty, the ~5-year time frame for implementing control measures, and the high marginal cost of modifying the plan to provide further load reductions, it is decided to undertake a 3 year monitoring study to develop site-specific data for calibrating the TMDL analysis. Because of the lack of site-specific data and high MOS, regulatory agencies and other stakeholders agree that it would be unwise at this point to require immediate design and implementation of a Plan that would have a 90% probability of achieving the lake goal. In fact, this would seem to be an impossible task at this point. The current analysis indicates a low probability (15%) that P concentrations in the lake are below 20 ppb. This is sufficient to justify design and implementation of phosphorus load controls using existing technology during the period of data collection to refine the TMDL analysis.

After a 3-year monitoring period, the models are re-calibrated and TMDL calculations are repeated. Table 3 provides approximate estimates of how model error terms would be expected to decrease as site-specific data are collected for model calibration; these are rough estimates for illustrative purposes. Results of the updated TMDL analysis are contained in Tables 4 & 5 and Figure 3. Based upon 3 years of data, model error CV's are reduced from 30 to 12% for export coefficients, from 40% to 17% for setting rate, from 25% to 12% for chlorophyll-a, and from 20 to 9% for Secchi depth. Other model coefficients are changed during calibration. For example, the urban export concentration increases from 140 to 160 ppb, the undeveloped concentration decreases from 15 to 12 ppb, the settling rate decreases from 10 to 8 m/yr, and the intercept of the chlorophyll-a vs. phosphorus regression increases by 20%.

The calibrated model predicts an existing lake P concentration of 25 ppb (80% CI = 23 to 28 ppb) and an algal bloom frequency of 8.4% (80% CI = 3 to 17 %). The revised estimate of the existing lake load (2318 kg/yr) still exceeds the Base load (1825 kg/yr) and TMDL (1631 kg/yr). As a consequence of additional data collection, the MOS required to achieve a 90% confidence level is reduced from 500 to 194 kg/yr, or 28% of the required total load reduction (686 kg/yr). Based upon initial results from demonstration projects being conducted in the watershed and recent literature, the load reduction assumed for agricultural BMP's is increased from 20% to 25%. With this change to the plan and the reduced uncertainty in the model projections, the revised plan has a 116 kg/yr MOS and a 76% probability of meeting the objective.

While it falls short of the 90% confidence-level objective, the Plan has a reasonable chance of success and there are no established regulations or guidelines regarding the required confidence level for a TMDL. The Plan is adopted, subject to provisions that the monitoring program continue and that the Plan (including the specified phosphorus criterion) be reviewed and revised, as appropriate, after five years in light of new information on the watershed, lake, and evolving control technologies. The next iteration of the Plan will work towards achieving the 90% confidence-level objective.

Late in the process, a savy lakeshore resident asks whether a long-term average goal of 20 ppb is sufficient to avoid nuisance algal blooms in every year. This is a valid point, since recreational users and lake biota sensitive to algal blooms will be impacted by blooms occurring in a given day or week, as opposed to their long-term average frequency. Based upon year-to-year variability observed in other regional lakes, it is expected that if the long-term average summer-mean phosphorus concentrations were equal to 20 ppb, phosphorus concentrations would exceed 25 ppb in extreme years (say, 1 year out of 5). In such years, the expected frequency of nuisance blooms (>20 ppb chlorophyll-a) could exceed 5% and the frequency of severe nuisance blooms (> 30 ppb chlorophyll-a) could exceed 1% (Figure 1). If extreme-year conditions violate water quality standards or are otherwise considered unacceptable, the simplest approach to modifying the TMDL would be to reduce the long-term-average phosphorus criterion from 20 ppb to, say, 15 ppb. This would provide a "Margin of Variability" (MOV) that would be analogous to the MOS. A data set longer than 3 years and possibly a more detailed model are needed to characterize year-to-year variations in lake P concentrations and algal bloom frequencies likely to result from a given long-term-average load and thus to derive an appropriate MOV. The possibility of adopting a more ambitious goal that explicitly accounts for year-to-year variations will be considered in the next iteration of the TMDL process.

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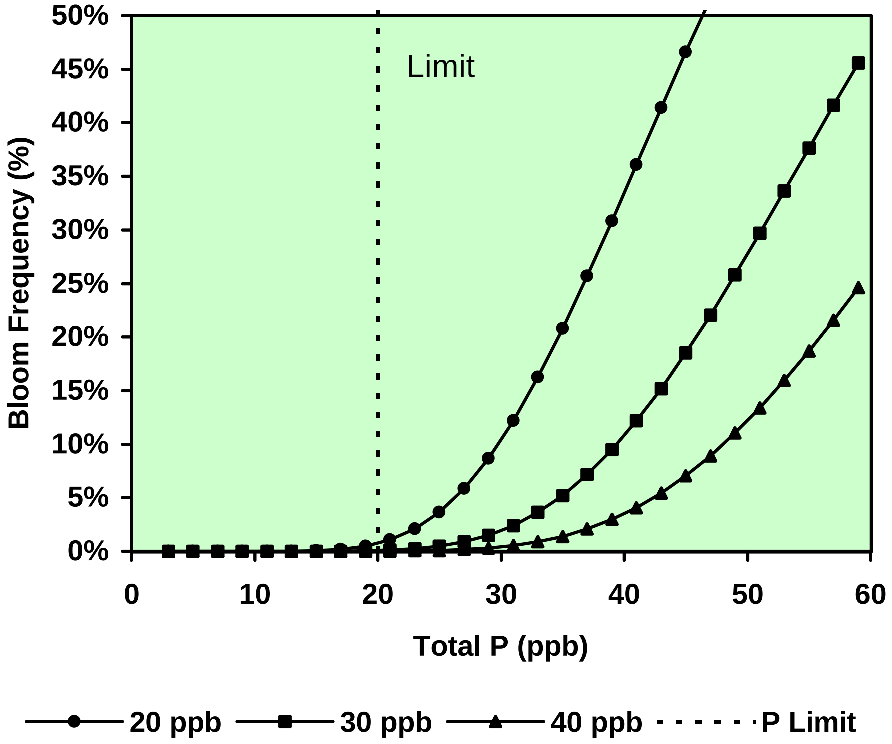
List of Figures

List of Tables

Figure 1
Algal Bloom Frequency vs. Lake Total P



Model:

Mean Chlorophyll-a vs. Mean Total P: Carlson (1977)

$$B = 0.087 \quad P^{1.45}$$

Bloom Frequency: Walker (1984)

$$F^* = 1 - \mathrm{CUM\_NORMAL}(Z^*)$$

$$Z^* = (\ln (B^* / B) + 0.5\, C^2) / C)$$

CUM_NORMAL = cumulative normal distribution

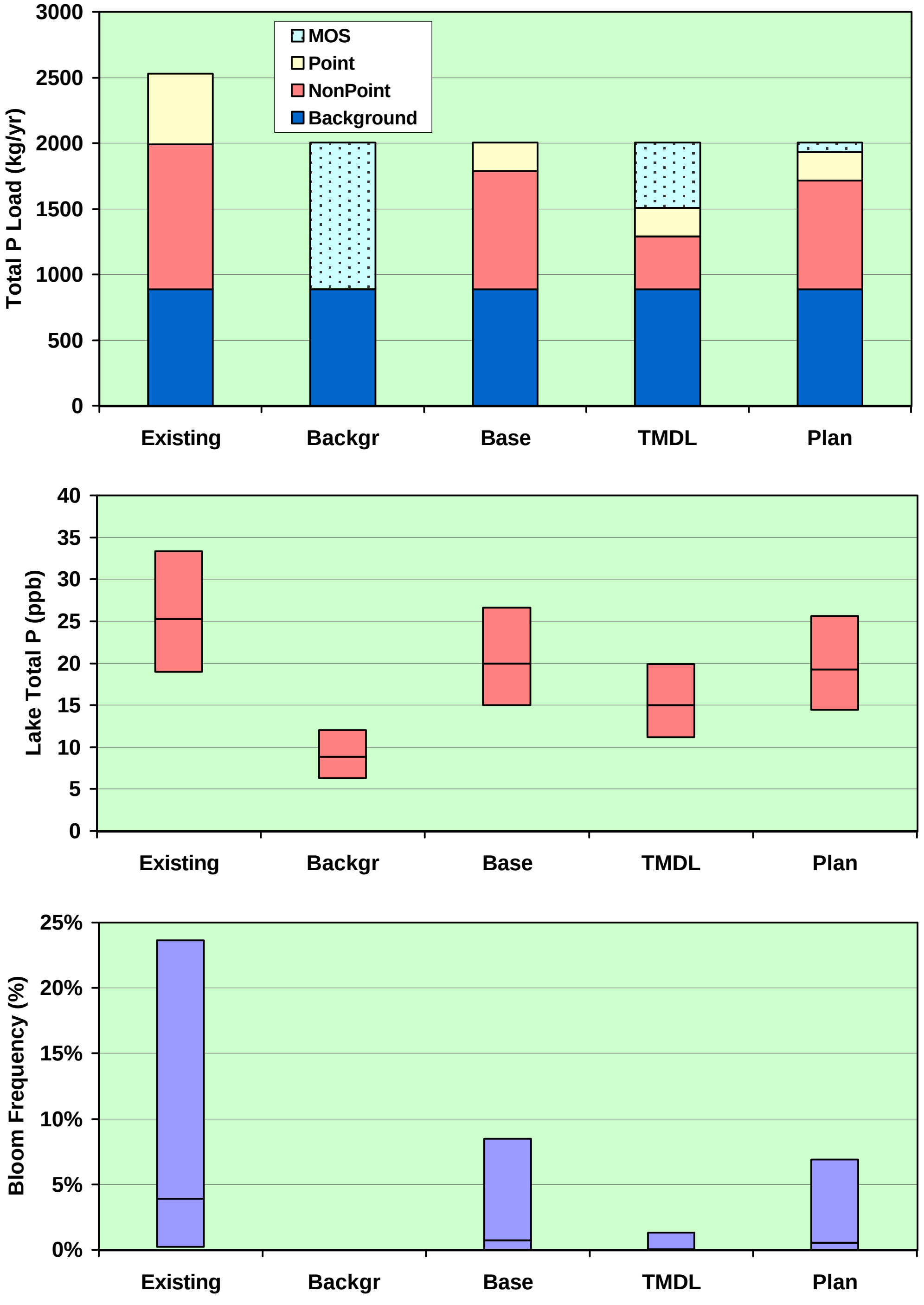
C = within-year standard deviation of ln(chl-a) = 0.5

B* = algal bloom criterion (20, 30, or 40 ppb)

Proposed P Limit	20	ppb	
Bloom Criterion	20 ppb	30 ppb	40 ppb
Bloom Frequency	0.7%	0.1%	0.0%

Figure 2

TMDL Results **Bailey Lake** **Case 1**

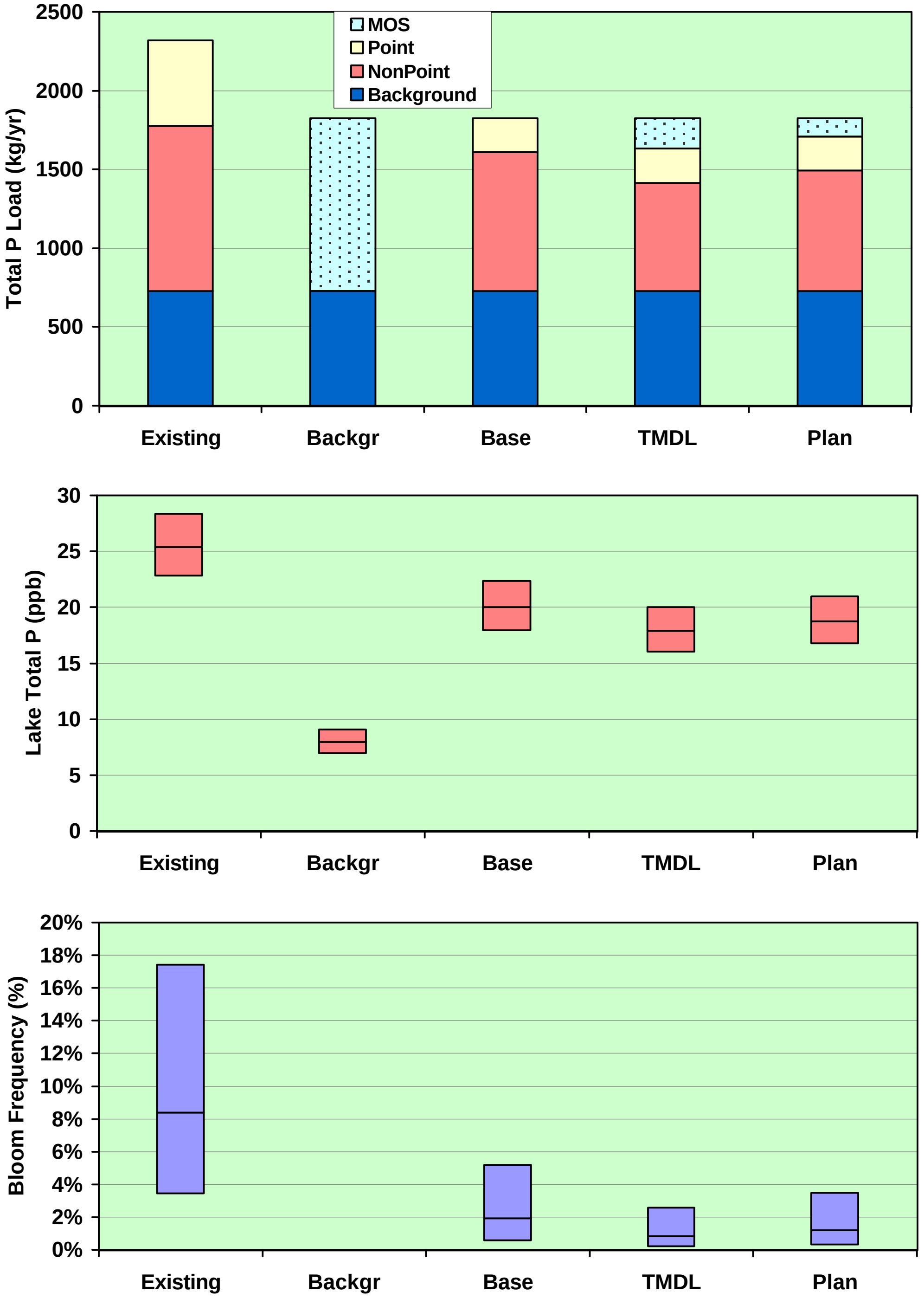


Predicted Confidence Intervals: 10% 50% 90%

TMDL	Backgr	NonPoint	Point	MOS	Total
Load (kg/yr)	886	403	216	500	2005
Percent of Total	44%	20%	11%	25%	100%

Figure 3

TMDL Results **Bailey Lake** **Case 2**



Predicted Confidence Intervals: 10% 50% 90%

TMDL	Backgr	NonPoint	Point	MOS	Total
Load (kg/yr)	727	688	216	194	1825
Percent of Total	40%	38%	12%	11%	100%

Table 1

TMDL Summary **Bailey Lake** **Case 1**

Years of Monitoring Data-------> 0 No Lake Data; Uses Regionally Calibrated Models

	Objectives	
Lake TP Criterion (ppb)	20	<-------Base Load Computed to Match This
Confidence Level	90%	<-------TMDL (Base - MOS) Computed to Match This

Load Allocation	Description
Existing	Existing Watershed & Point-Sources
Background	Background Conditions, No Anthropogenic Impacts
Plan	Proposed Watershed Plan
Base	Allocation with ~50% Probability of Meeting TP Objective
TMDL	Allocation with ~90% Probability of Meeting TP Objective

Control Program		Existing	Backgr	Plan	Base	TMDL
BMP Load Reduc - Existing Urban	%	0.0%	0.0%	20.0%		
BMP Load Reduc - Future Urban	%	0.0%	0.0%	60.0%		
BMP Load Reduc - Agric	%	0.0%	0.0%	20.0%		
Max. Point Source Conc	ppb	9999	0	900		
Results						
Total Load Reduction	kg/yr	0	1644	599	525	1024
Reduction in Anthropogenic Load	%	33%	100%	50%	45%	75%
Reduction in Total Load	%	0%	65%	24%	21%	40%
Total Load to Lake	kg/yr	2530	886	1931	2005	1506
Background Load	kg/yr	886	886	886	886	886
NonPoint Load (above Backgr.)	kg/yr	1104	0	829	903	403
Point Load	kg/yr	540	0	216	216	216
Margin of Safety	kg/yr	0	1119	74	0	500
Lake Load + MOS	kg/yr	2530	2005	2005	2005	2005
Probability [Lake P < 20 ppb]	%	15%	100%	53%	50%	90%
Objective	%			90%	50%	90%
Total P Load						
Predicted Value	kg/yr	2530	886	1931	2005	1506
10th Percentile	kg/yr	2158	698	1631	1693	1267
90th Percentile	kg/yr	3097	1127	2387	2479	1854
Lake Total P						
Predicted Value	ppb	25.2	8.9	19.3	20.0	15.0
10th Percentile	ppb	19.0	6.3	14.4	15.0	11.2
90th Percentile	ppb	33.4	12.1	25.6	26.6	19.9
Mean Chl-a						
Predicted Value	ppb	9.4	2.1	6.3	6.7	4.4
10th Percentile	ppb	5.5	1.1	3.7	3.9	2.5
90th Percentile	ppb	15.8	3.5	10.8	11.4	7.5
Algal Bloom Frequency						
Predicted Value	%	3.9%	0.0%	0.5%	0.7%	0.1%
10th Percentile	%	0.2%	0.0%	0.0%	0.0%	0.0%
90th Percentile	%	23.7%	0.0%	6.9%	8.5%	1.3%
Mean Secchi						
Predicted Value	m	1.9	5.4	2.5	2.4	3.2
10th Percentile	m	1.3	3.6	1.7	1.6	2.2
90th Percentile	m	2.8	8.4	3.7	3.5	4.7

Table 2

TMDL Calculations **Bailey Lake** **Case 1**

Scenario	Units	Existing	Backgr	Plan	Base	TMDL	Error CV
Model Input Values							
Existing Urban	km2	5.00	0.00	5.00	5.00	5.00	
New Urban Development	km2	0.00	0.00	1.00	1.00	1.00	
Agric Area	km2	30.00	0.00	29.00	29.00	29.00	
Undeveloped Area	km2	60.00	95.00	60.00	60.00	60.00	
Precipitation	m/yr	1.09	1.09	1.09	1.09	1.09	0.05
Evaporation	m/yr	0.66	0.66	0.66	0.66	0.66	0.05
Unit Runoff	m/yr	0.56	0.56	0.56	0.56	0.56	0.05
Exist. Urban P Conc (pre-BMP)	ppb	140	140	140	140	140	0.30
Future Urban P Conc (pre-BMP)	ppb	140	140	140	140	140	0.30
Agric P Conc (pre-BMP)	ppb	60	60	60	60	60	0.30
Undeveloped P Conc	ppb	15	15	15	15	15	0.20
Point Source Flow	hm3/yr	0.20	0.00	0.24	0.24	0.24	0.00
Point Source TP (pre-Control)	ppb	2700	0	2700	2700	2700	0.00
Atmos P Load	kg/km2-yr	20	20	20	20	20	0.20
Lake Surface Area	km2	4.50	4.50	4.50	4.50	4.50	
Algal Bloom Criterion (Chla)	ppb	20	20	20	20	20	
Chla Temporal Coef. of Var.	-	0.50	0.50	0.50	0.50	0.50	
P Settling Rate	m/yr	10.0	10.0	10.0	10.0	10.0	0.40
Mean Chl-a Model Error	-	1.00	1.00	1.00	1.00	1.00	0.25
Mean Secchi Model Error	-	1.00	1.00	1.00	1.00	1.00	0.20
Water Balance							
Existing Urban	hm3/yr	2.79	0.00	2.79	2.79	2.79	
New Urban	hm3/yr	0.00	0.00	0.56	0.56	0.56	
Agricultural	hm3/yr	16.76	0.00	16.21	16.21	16.21	
Undeveloped	hm3/yr	33.53	53.09	33.53	33.53	33.53	
Total Watershed	hm3/yr	53.09	53.09	53.09	53.09	53.09	
Point Sources	hm3/yr	0.20	0.00	0.24	0.24	0.24	
Precipitation	hm3/yr	4.91	4.91	4.91	4.91	4.91	
Total Inflow	hm3/yr	58.20	58.00	58.24	58.24	58.24	
Evaporation	hm3/yr	2.97	2.97	2.97	2.97	2.97	
Outflow	hm3/yr	55.23	55.03	55.27	55.27	55.27	
Total P Concentrations							
Existing Urban	ppb	140	140	112	119	70	
New Urban	ppb	140	140	56	60	35	
Agricultural	ppb	60	60	48	51	30	
Undeveloped	ppb	15	15	15	15	15	
Total Watershed	ppb	36	15	31	32	23	
Point Sources	ppb	2700	0	900	900	900	
Precipitation	ppb	18	18	18	18	18	
Total Inflow	ppb	43	15	33	34	26	
Outflow	ppb	25	9	19	20	15	
Total P Balance							
Existing Urban	kg/yr	391	0	313	334	194	
New Urban	kg/yr	0	0	31	33	19	
Agricultural	kg/yr	1006	0	778	829	483	
Undeveloped	kg/yr	503	796	503	503	503	
Total Watershed	kg/yr	1900	796	1625	1699	1200	
Point Sources	kg/yr	540	0	216	216	216	
Precipitation	kg/yr	90	90	90	90	90	
Total Inflow	kg/yr	2530	886	1931	2005	1506	
Sedimentation	kg/yr	1136	399	867	900	676	
Outflow	kg/yr	1394	488	1064	1105	830	

Table 3
Estimated Model Error Terms vs. Years of Monitoring to Support TMDL Development

Years of Monitoring	Export Coef	Settling Veloc	Chla vs. TP	Secchi vs. TP	Notes
0	0.30	0.40	0.25	0.20	a
1	0.20	0.30	0.20	0.15	b
2	0.14	0.21	0.14	0.11	c
3	0.12	0.17	0.12	0.09	c
4	0.10	0.15	0.10	0.08	c
5	0.09	0.13	0.09	0.07	c
10	0.06	0.09	0.06	0.05	c

Values in Table = CV's of Predicted Long-Term Means

a	For zero years of monitoring, the TMDL is assumed to be based upon regionally-calibrated export coefficients & lake response models. No lake-specific data are available for calibration. Typical CV's derived from various modeling efforts (Walker, 1978;1982;1983; 1996)
b	Export coefficients & lake response models are calibrated to data from one year. Values represent standard errors of calibrations, based upon typical year-to-year variability in measured values from various lake datasets. (Smeltzer et al, 1989;Walker,1999,2000)
c	Export coefficients & lake response models are calibrated to data from N years. Values computed using formula for standard error of the mean; $CV(N) = CV(1) / N^{.5}$

Table 4

TMDL Summary **Bailey Lake** **Case 2**

Years of Monitoring Data-------> 3 Used for Model Calibration

	Objectives	
Lake TP Criterion (ppb)	20	<-------Base Load Computed to Match This
Confidence Level	90%	<-------TMDL (Base - MOS) Computed to Match This

Load Allocation	**Description**
Existing	Existing Watershed & Point-Sources
Background	Background Conditions, No Anthropogenic Impacts
Plan	Proposed Watershed Plan
Base	Allocation with ~50% Probability of Meeting TP Objective
TMDL	Allocation with ~90% Probability of Meeting TP Objective

Control Program		**Existing**	**Backgr**	**Plan**	**Base**	**TMDL**
BMP Load Reduc - Existing Urban	%	0.0%	0.0%	20.0%		
BMP Load Reduc - Future Urban	%	0.0%	0.0%	60.0%		
BMP Load Reduc - Agric	%	0.0%	0.0%	25.0%		
Max. Point Source Conc	ppb	9999	0	900		
Results						
Total Load Reduction	kg/yr	0	1591	608	492	686
Reduction in Anthropogenic Load	%	34%	100%	52%	45%	57%
Reduction in Total Load	%	0%	69%	26%	21%	30%
Total Load to Lake	kg/yr	2318	727	1709	1825	1631
Background Load	kg/yr	727	727	727	727	727
NonPoint Load (above Backgr.)	kg/yr	1051	0	766	882	688
Point Load	kg/yr	540	0	216	216	216
Margin of Safety	kg/yr	0	1098	116	0	194
Lake Load + MOS	kg/yr	2318	1825	1825	1825	1825
Probability [Lake P < 20 ppb]	%	0%	100%	76%	50%	90%
Objective	%			90%	50%	90%
Total P Load						
Predicted Value	kg/yr	2318	727	1709	1825	1631
10th Percentile	kg/yr	2145	649	1573	1680	1503
90th Percentile	kg/yr	2524	813	1872	1999	1789
Lake Total P						
Predicted Value	ppb	25.4	8.0	18.7	20.0	17.9
10th Percentile	ppb	22.8	7.0	16.8	17.9	16.0
90th Percentile	ppb	28.4	9.1	21.0	22.4	20.0
Mean Chl-a						
Predicted Value	ppb	11.4	2.1	7.3	8.0	6.8
10th Percentile	ppb	9.1	1.7	5.8	6.4	5.5
90th Percentile	ppb	14.2	2.7	9.1	10.1	8.6
Algal Bloom Frequency						
Predicted Value	%	8.4%	0.0%	1.2%	1.9%	0.8%
10th Percentile	%	3.5%	0.0%	0.3%	0.6%	0.2%
90th Percentile	%	17.4%	0.0%	3.5%	5.2%	2.6%
Mean Secchi						
Predicted Value	m	1.7	5.4	2.3	2.2	2.4
10th Percentile	m	1.4	4.5	2.0	1.8	2.1
90th Percentile	m	2.0	6.4	2.7	2.5	2.8

Table 5

TMDL Calculations **Bailey Lake** **Case 2**

Scenario	Units	Existing	Backgr	Plan	Base	TMDL	Error CV
Model Input Values							
Existing Urban	km2	5.00	0.00	5.00	5.00	5.00	
New Urban Development	km2	0.00	0.00	1.00	1.00	1.00	
Agric Area	km2	30.00	0.00	29.00	29.00	29.00	
Undeveloped Area	km2	60.00	95.00	60.00	60.00	60.00	
Precipitation	m/yr	1.09	1.09	1.09	1.09	1.09	0.05
Evaporation	m/yr	0.66	0.66	0.66	0.66	0.66	0.05
Unit Runoff	m/yr	0.56	0.56	0.56	0.56	0.56	0.05
Exist. Urban P Conc (pre-BMP)	ppb	160	160	160	160	160	0.12
Future Urban P Conc (pre-BMP)	ppb	160	160	160	160	160	0.12
Agric P Conc (pre-BMP)	ppb	50	50	50	50	50	0.12
Undeveloped P Conc	ppb	12	12	12	12	12	0.08
Point Source Flow	hm3/yr	0.20	0.00	0.24	0.24	0.24	0.00
Point Source TP (pre-Control)	ppb	2700	0	2700	2700	2700	0.00
Atmos P Load	kg/km2-yr	20	20	20	20	20	0.20
Lake Surface Area	km2	4.50	4.50	4.50	4.50	4.50	
Algal Bloom Criterion (Chla)	ppb	20	20	20	20	20	
Chla Temporal Coef. of Var.	-	0.50	0.50	0.50	0.50	0.50	
P Settling Rate	m/yr	8.0	8.0	8.0	8.0	8.0	0.17
Mean Chl-a Model Error	-	1.20	1.20	1.20	1.20	1.20	0.12
Mean Secchi Model Error	-	0.90	0.90	0.90	0.90	0.90	0.09
Water Balance							
Existing Urban	hm3/yr	2.79	0.00	2.79	2.79	2.79	
New Urban	hm3/yr	0.00	0.00	0.56	0.56	0.56	
Agricultural	hm3/yr	16.76	0.00	16.21	16.21	16.21	
Undeveloped	hm3/yr	33.53	53.09	33.53	33.53	33.53	
Total Watershed	hm3/yr	53.09	53.09	53.09	53.09	53.09	
Point Sources	hm3/yr	0.20	0.00	0.24	0.24	0.24	
Precipitation	hm3/yr	4.91	4.91	4.91	4.91	4.91	
Total Inflow	hm3/yr	58.20	58.00	58.24	58.24	58.24	
Evaporation	hm3/yr	2.97	2.97	2.97	2.97	2.97	
Outflow	hm3/yr	55.23	55.03	55.27	55.27	55.27	
Total P Concentrations							
Existing Urban	ppb	160	160	128	143	118	
New Urban	ppb	160	160	64	71	59	
Agricultural	ppb	50	50	38	42	35	
Undeveloped	ppb	12	12	12	12	12	
Total Watershed	ppb	32	12	26	29	25	
Point Sources	ppb	2700	0	900	900	900	
Precipitation	ppb	18	18	18	18	18	
Total Inflow	ppb	40	13	29	31	28	
Outflow	ppb	25	8	19	20	18	
Total P Balance							
Existing Urban	kg/yr	447	0	358	399	330	
New Urban	kg/yr	0	0	36	40	33	
Agricultural	kg/yr	838	0	608	678	560	
Undeveloped	kg/yr	402	637	402	402	402	
Total Watershed	kg/yr	1688	637	1403	1519	1325	
Point Sources	kg/yr	540	0	216	216	216	
Precipitation	kg/yr	90	90	90	90	90	
Total Inflow	kg/yr	2318	727	1709	1825	1631	
Sedimentation	kg/yr	915	288	674	720	644	
Outflow	kg/yr	1403	440	1035	1105	988	