Lake Champlain TMDL Support

Lake Modeling Approach Recommendation

Prepared for:

U.S. EPA Region 1 – New England
5 Post Office Square
Boston, MA 02109-3912

Prepared by:

Tetra Tech, Inc.
10306 Eaton Place, Suite 340
Fairfax, VA 22030

and

William Walker
Concord, MA

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Introduction

The Lake Champlain Phosphorus TMDL was approved by EPA in 2002. EPA, in collaboration with the Vermont Department of Environmental Conservation (VTDEC), is now revisiting the TMDL and determining if and how to most appropriately update the supporting technical analyses. The purpose of this report is to recommend a technical approach for conducting the in-lake analysis to support TMDL development.

A modified version of the U.S. Army Corps of Engineers (USACE) BATHTUB program was used to develop the 2002 TMDL. The model used an annual steady-state approach with spatial segmentation that accounted for diffusive exchange mixing and advective transport of water and phosphorus among 13 lake segments. It was used to analyze alternative combinations of load reductions from each lake segment watershed in Vermont, Quebec, and New York, and to predict the load reductions required to attain the in-lake phosphorus criteria in each lake segment.

Additional data and studies have become available since development of the original BATHTUB program and TMDL report. This information provides further insight into lake dynamics and is critical to consider when revisiting the TMDL.

The approach taken to provide a recommended path forward involved the following tasks:

1. Data Review: This task involved compiling and evaluating available monitoring data to identify what key processes and factors must be considered when selecting a modeling approach and whether data are sufficient for model calibration purposes.
2. BATHTUB Model Review: Revisiting the existing BATHTUB model, which was successfully implemented to develop the original TMDL, is the most logical place to begin further analysis. The existing BATHTUB model was therefore reviewed, and preliminary updates were made to evaluate its potential for representing more recent conditions.
3. Comparison of Modeling Approaches: Because multiple modeling options are available, it is important to compare BATHTUB's capabilities and limitations to other potential modeling approaches, with a focus on key TMDL development considerations. The objective of this comparison was to identify whether BATHTUB or a different modeling approach is most appropriate to implement given technical, regulatory, and management limitations.

Data Review

A significant amount of data have been collected for Lake Champlain and its contributing watershed over the past decade, and numerous studies have been led by the Lake Champlain Basin Program (LCBP), VTDEC, New York Department of Environmental Conservation (NYDEC), universities, and other agencies. Rather than conducting an exhaustive review of all available information, the data review to aid model selection focused primarily on in-lake and tributary data collected by VTDEC.

A review of the available tributary and lake water quality monitoring data was first conducted. Files containing daily tributary flows and corresponding tributary water quality concentrations (Total Phosphorus-TP, Dissolved Phosphorus-DP and Total Chlorides-TCl) collected on numerous dates at 18 tributary locations, between 1990 and 2009, were obtained from VTDEC. A file containing lake water quality data (Chlorophyll-a, TP, DP, TCl and Secchi Depth) collected on numerous dates at 52 monitoring stations, between 1990 and 2009, were also obtained from VTDEC.

The major objectives of the data review were to: 1) identify if trends are apparent in the data, 2) determine the variability and gaps in both the lake and tributary monitoring data and their adequacy for model calibration, 2) determine the adequacy of the tributary flow and water quality data for use in generating short-term (daily) and long-term (annual, 2-year and greater) tributary water volume and TP and DP loads discharged to each lake segment, for input to a model, and 4) identify key factors that must be considered during modeling.

Tributary Data

Figures 1 through 3 show annual geometric means of log transformed TP, DP and TCl concentrations measured at each of the 18 long-term tributary monitoring stations, between 1990 and 2009. These plots also include standard error bars and highlighted best fit trend lines. Annual geomean values were calculated by taking the monthly geomean first for each site and parameter, and then taking the geomean of the monthly geomean (as opposed to taking the geomean of all the days in each year). Although the values in these plots have not been adjusted for flow, it is important to note that they will be adjusted for flow during subsequent analyses, using updated concentration versus flow relationships established at each tributary monitoring location.

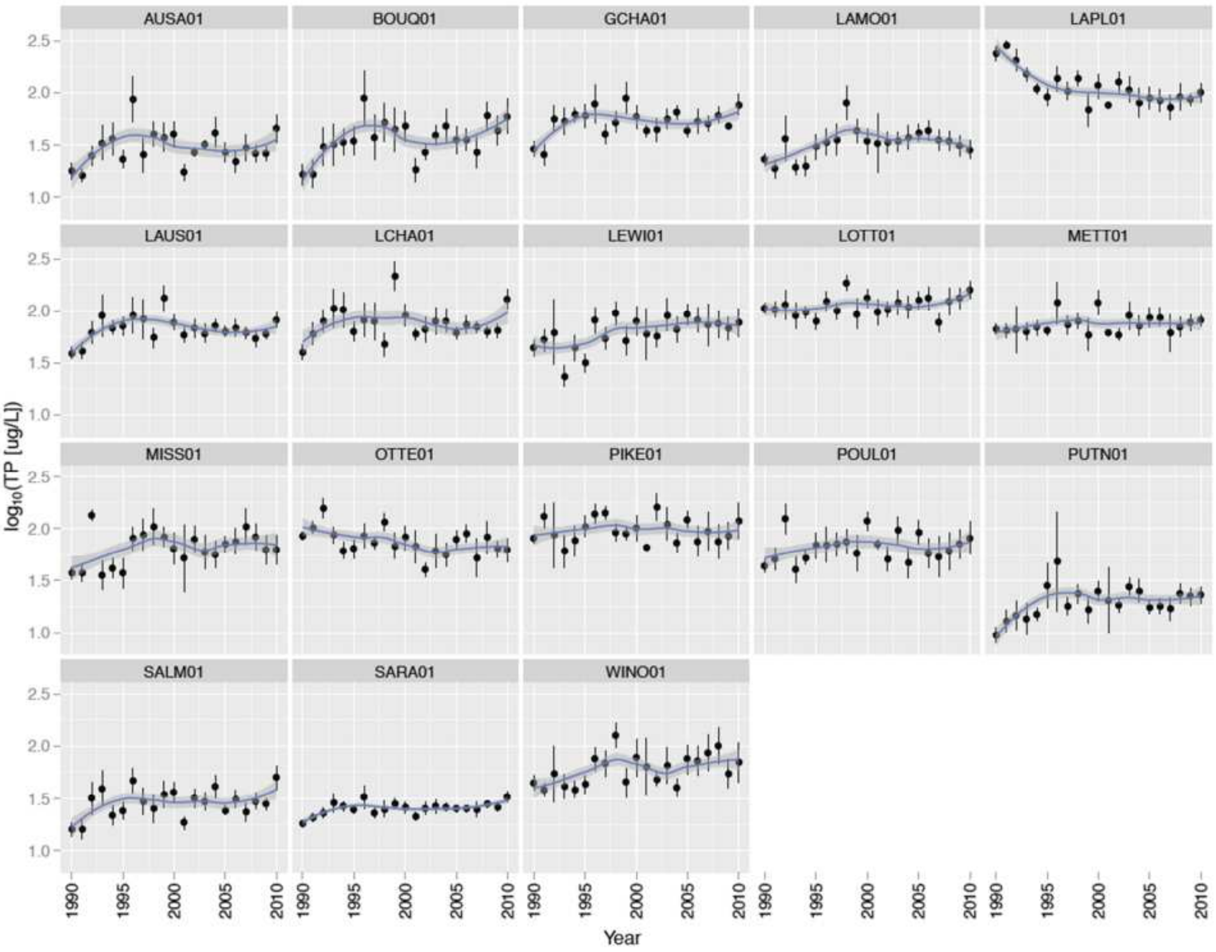

Figure 1: Annual Geomean TP Concentrations at All Tributary Monitoring Locations

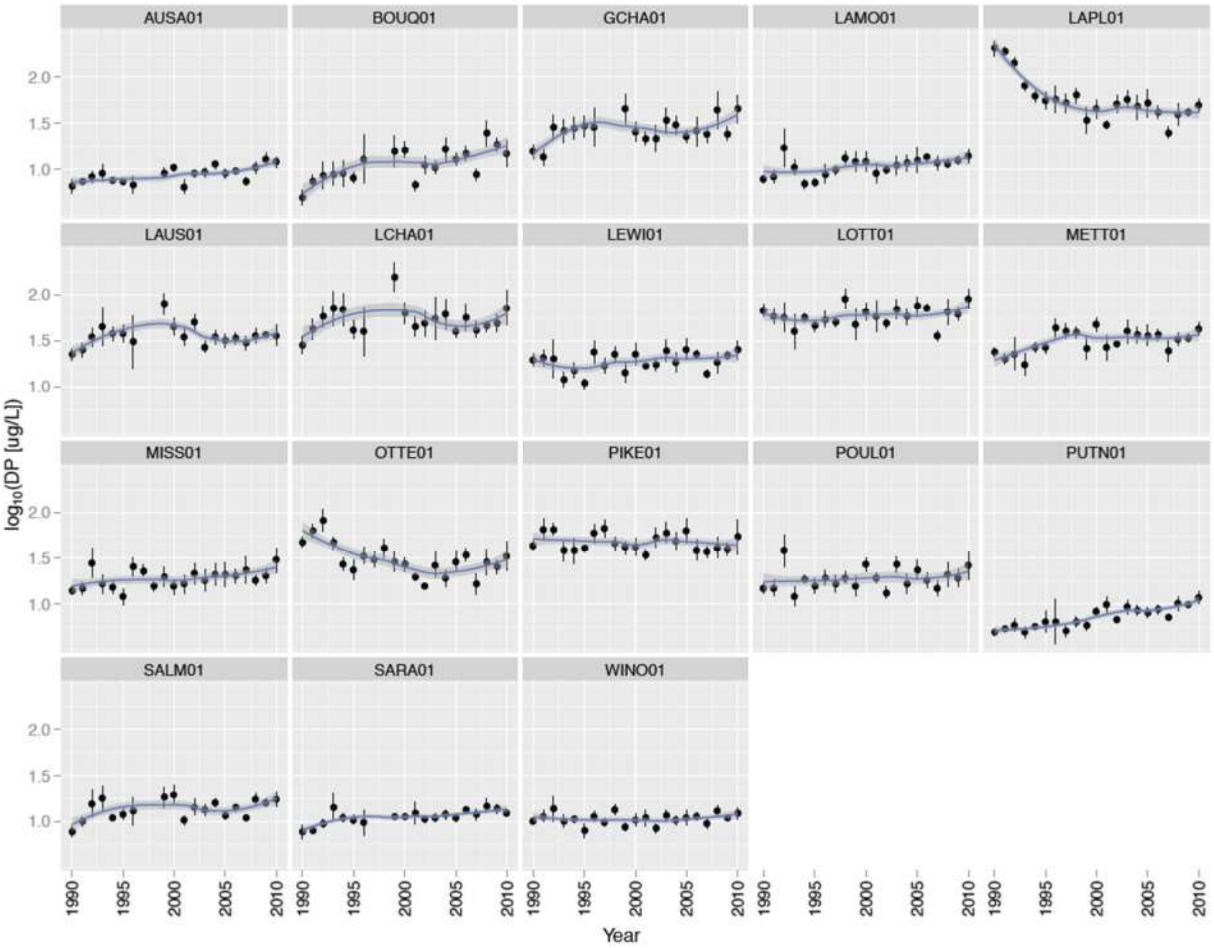

Figure 2: Annual Geomean DP Concentrations at All Tributary Monitoring Locations

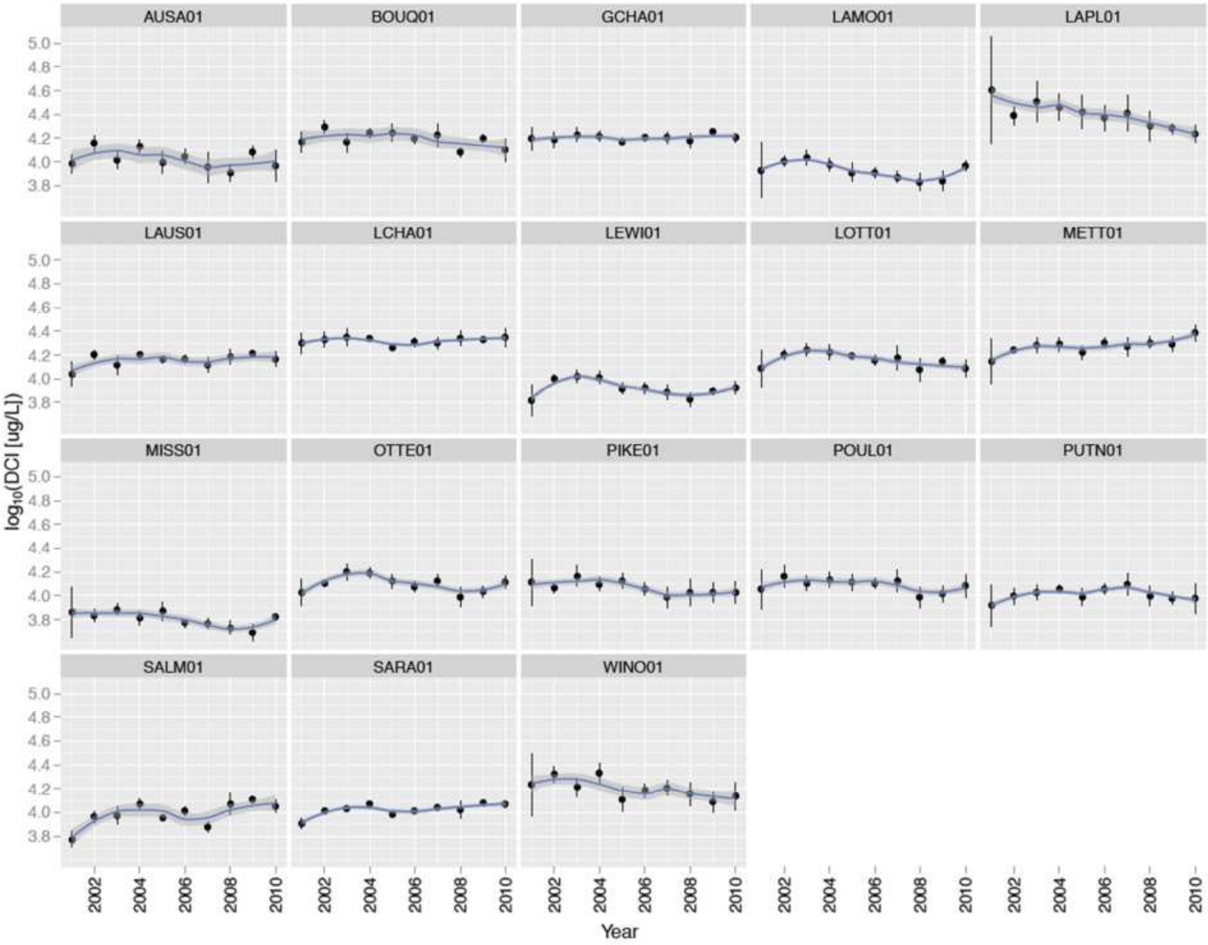

Figure 3: Annual Geomean TCl Concentrations at All Tributary Monitoring Locations

Figure 4 shows the individual tributary TP data points connected by straight lines, for the 18 monitored tributaries, during Water Years 1997 and 1998. TP data points lie at changes in the line segment slopes. The connecting lines are included merely to highlight the extent of periods when no monitoring data are available. It is seen that monitoring during the warm weather growing season (April through October) was typically once or twice per month, whereas during the winter months monitoring occurred only about every 2 months. It is also seen that the highest TP concentrations measured on the Missisquoi River and Winooski River during this 2-year period occurred during early January of 1998. This period corresponded to a very large rainfall event, which resulted in extreme flood flows and TP loads being discharged to the lake from these rivers. Based on plots similar to Figure 4, for the full period between 1990 and 2009, this same pattern of high river flows and sparse and highly variable monitored TP concentration data was found to occur during the winter months in many other years. This characteristic of the monitoring data will likely contribute to levels of uncertainty in calculated daily and long term (seasonal, annual, etc…) tributary TP, DP and TCl loading rates and trends, regardless of calculation method. Accordingly, the sensitivity of tributary loading rates and resulting lake model predictions will be investigated, for alternative load calculation methodologies, following selection of the lake modeling approach.

Figure 5 shows daily TP loading rates found using a simple linear interpolation of TP monitoring data, for the January 1998 rainfall event. The area under the TP load curve for the Missisquoi River during this event amounts to approximately 35% of the predicted annual total TP load discharged into Missisquoi Bay in 1998. Using this very simplified method, similarly high percentages of their annual TP loads were calculated for this rainfall event, for the Winooski River and the Lamoille River. These 3 rivers together dominate the annual TP loadings to the lake as a whole.

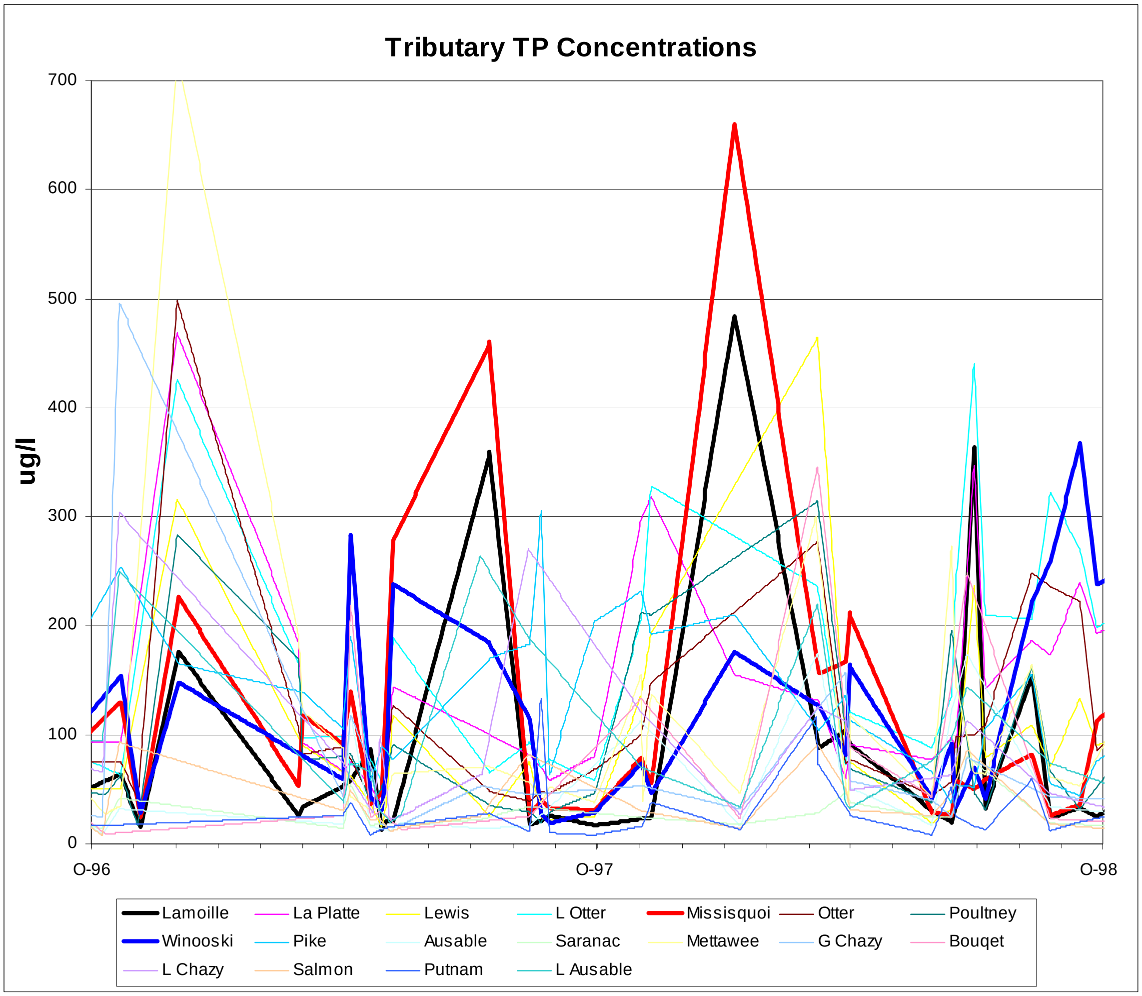

Figure 4: Measured Tributary TP Concentrations, WY 1997-1998

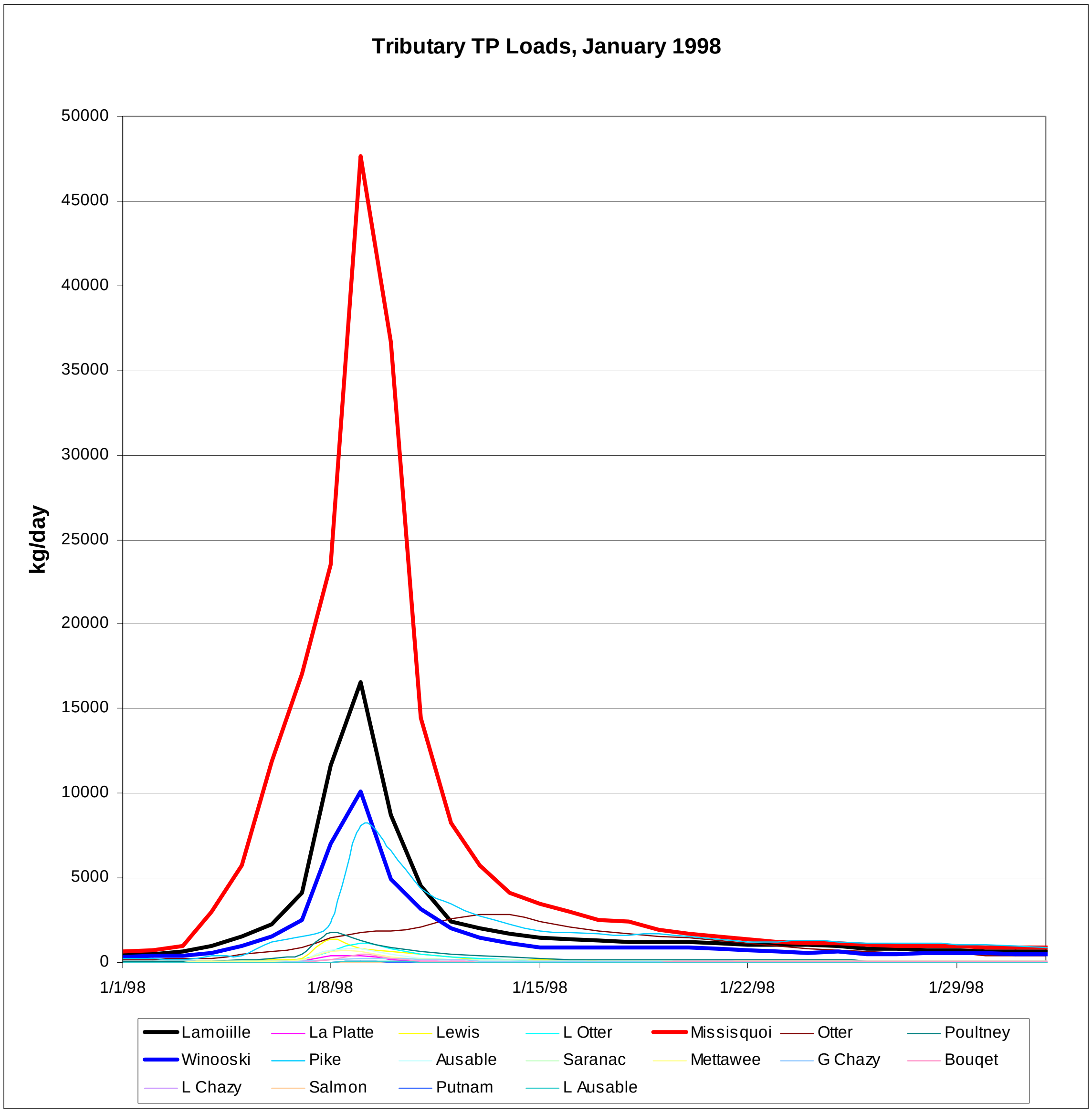

Figure 5: TP Loading Rates for the Missisquoi, Lamoille and Winooski Rivers (Jan 98)

In order to get an idea of potential uncertainties associated with predicting loads based on limited monitoring data, scatter plots of tributary flow on days when tributary TP levels were measured are given in Figures 6 through 8, for the above 3 major tributaries. A large amount of scatter is evident. It will be important to take this into account when developing tributary loading rates for input to the selected lake model.

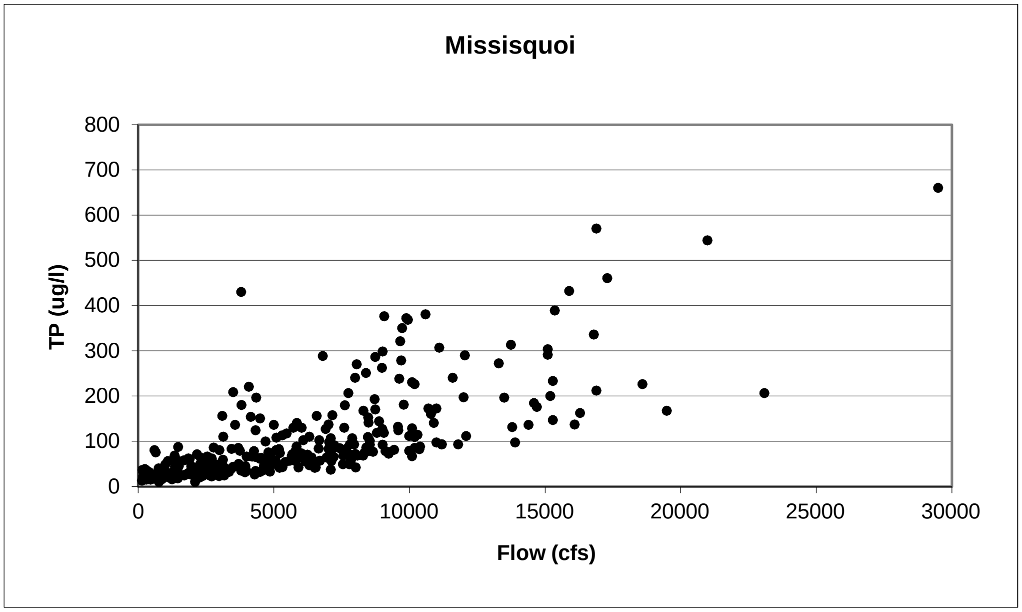

Figure 6: TP versus flow for the Missisquoi River (1990-2008)

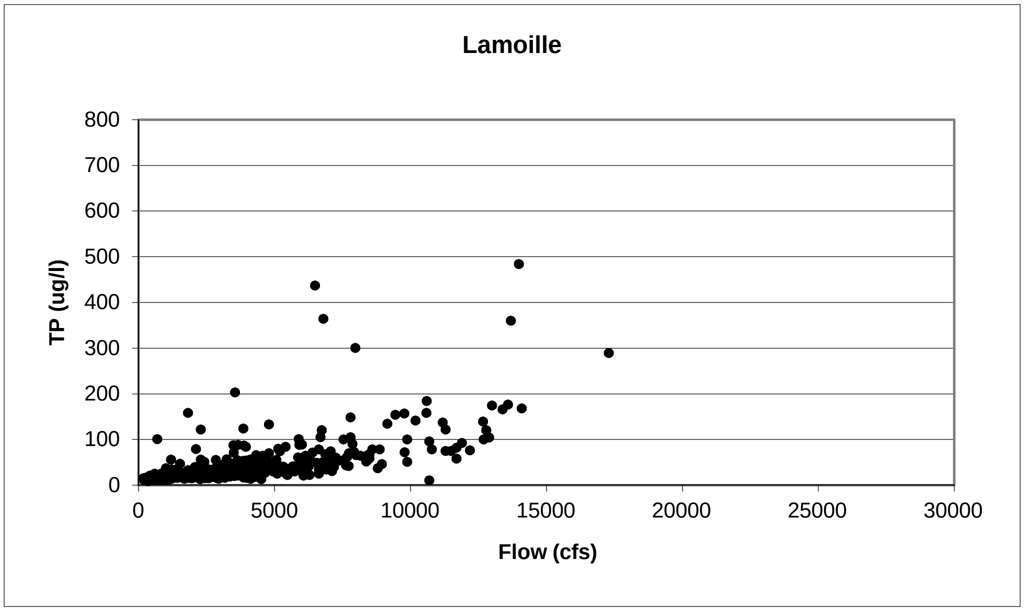

Figure 7: TP versus flow for the Lamoille River (1990-2009)

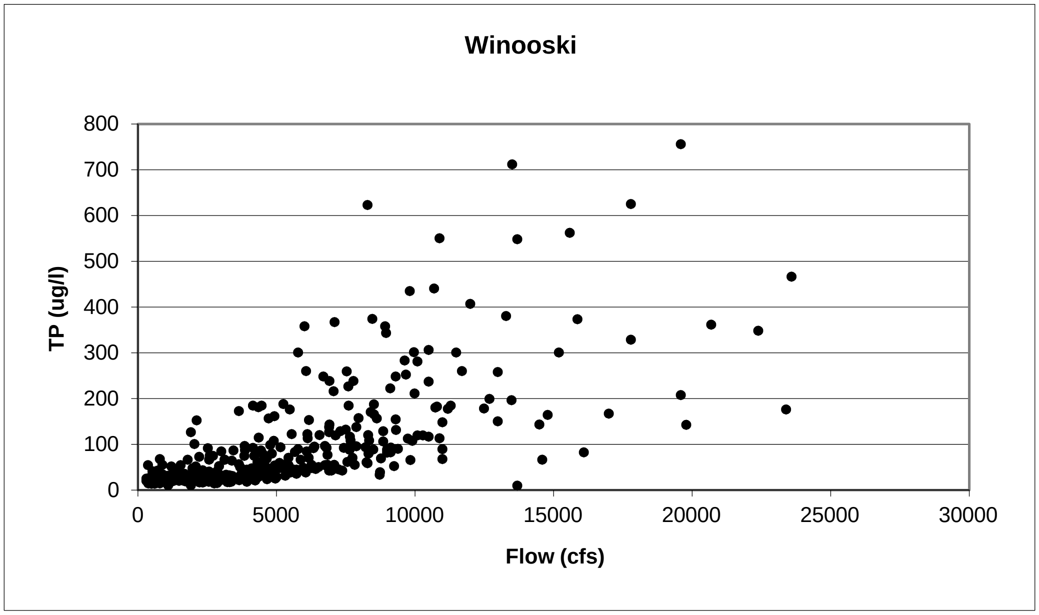

Figure 8: TP versus flow for the Winooski River (1990-2009)

Of particular importance in the selection of an appropriate modeling approach is the importance of partitioning of the tributary phosphorus loads between dissolved and particulate forms. The BATHTUB modeling of TP captured this partitioning in an approximate manner via specification of TP settling and/or bottom sediment (internal) source rates within each lake segment. Accordingly, the tributary monitoring data was next analyzed to determine the importance of this partitioning.

Figures 9 through 11 show the fraction of tributary TP that is in the dissolved form (DP), at monitoring stations on the Missisquoi, Lamoille and Winooski Rivers, respectively. Also shown on these plots are calculated daily TP loads for each tributary, normalized to the maximum daily TP load for the entire 20-year monitoring period. The spikes seen in tributary TP loads represent wet weather periods when river flows were high. For the Missisquoi (Figure 9) it is seen that the fraction of TP that was dissolved was less than 10%, during most of the highest TP loading periods. In particular, during the January 1998 rainfall event the fraction of TP that was dissolved was less than 2%, indicating that essentially all the TP load discharged from the Missisquoi River during this event was in particulate form. In contrast, during dry weather periods the dissolved fraction generally ranged between 10% and 60%, due to the increased importance of point sources during periods of low river flow. The BATHTUB model assumed that the dissolved fraction of the tributary TP loading was constant over time. The data suggest that the distribution between particulate and dissolved forms may be important to consider in this phase of work. The observations made above for the Missisquoi are also valid for the Lamoille and Winooski Rivers.

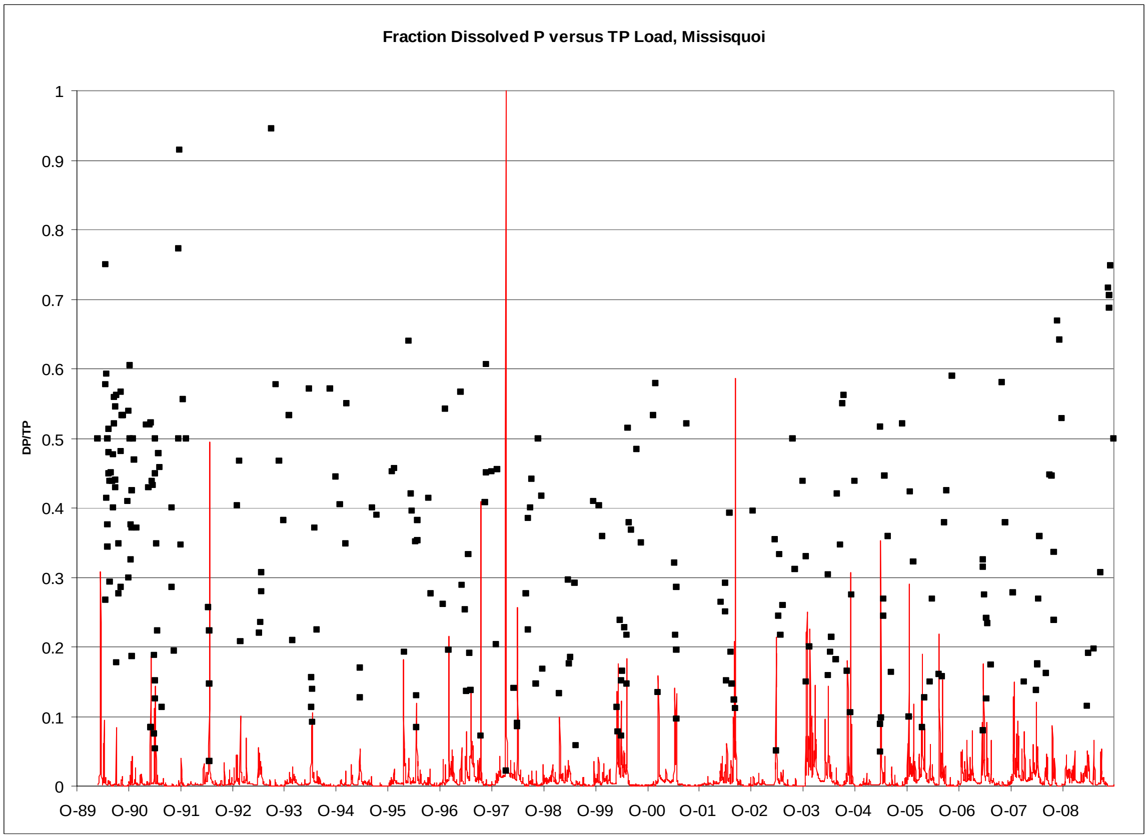

Figure 9: Fraction of TP in Dissolved Form for Missisquoi River

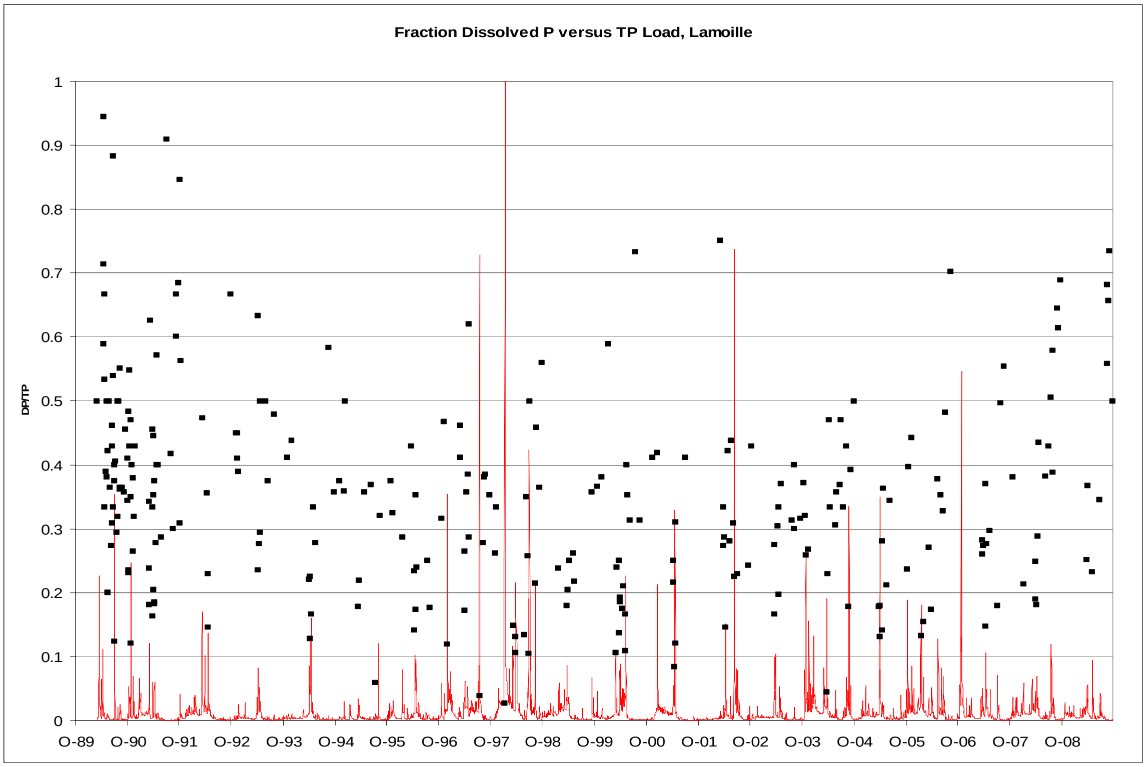

Figure 10: Fraction of TP in Dissolved Form for Lamoille River

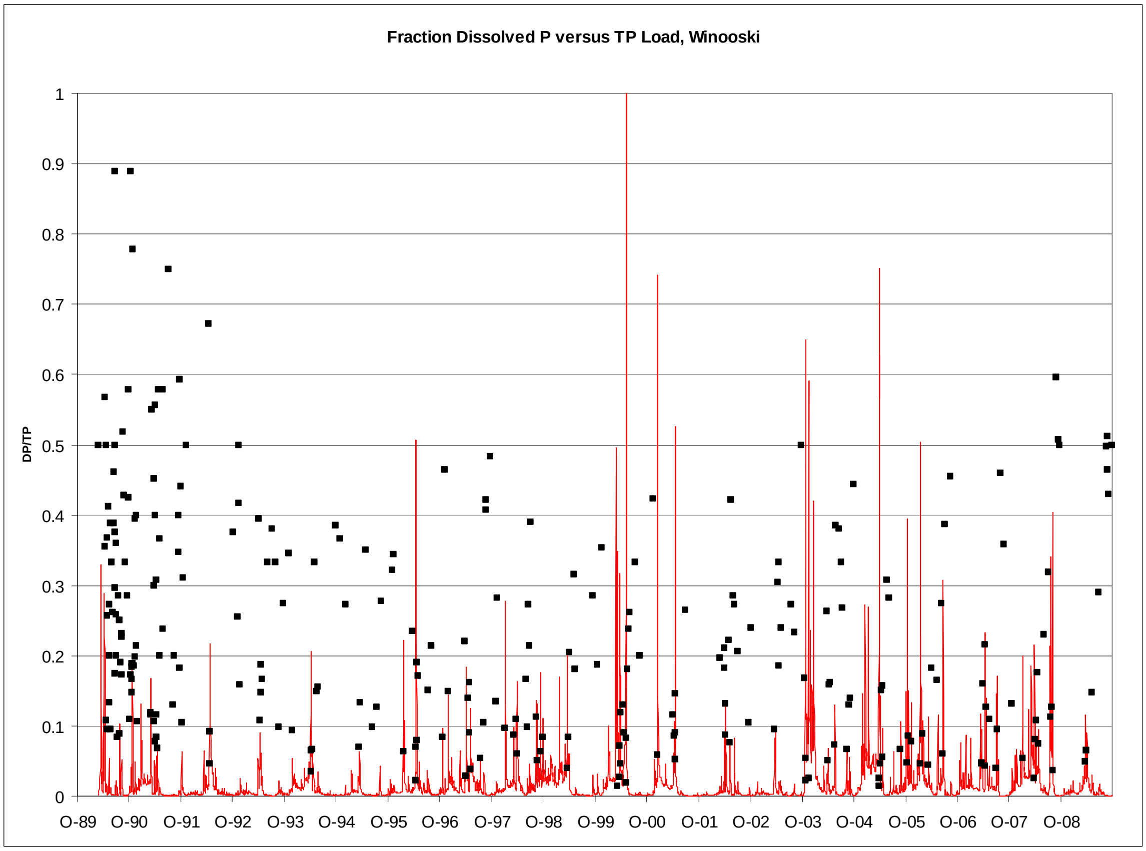

Figure 11: Fraction of TP in Dissolved Form for Winooski River

Scatter plots were made of the calculated fraction of the TP that is DP versus river flow on monitoring days. Results are presented on Figures 12 through 14, for the Missisquoi, Lamoille and Winooski rivers, respectively. These plots demonstrate the data observations made earlier - that high river flow phosphorus loads are mostly particulate.

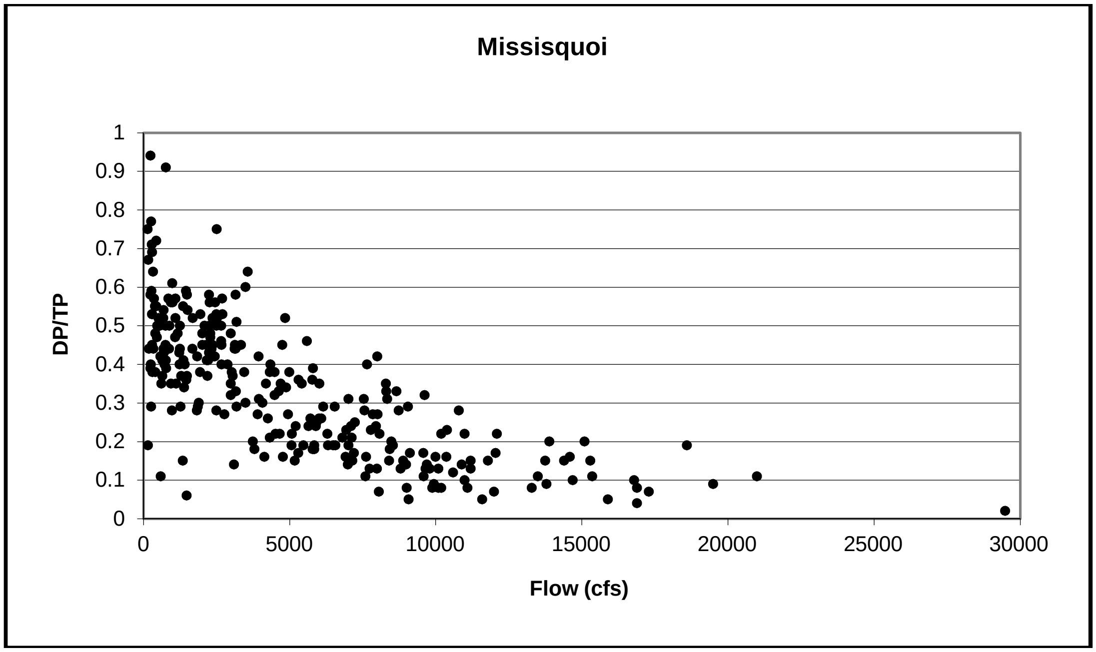

Figure 12: Missisquoi River – Fraction DP versus flow (1990-2009)

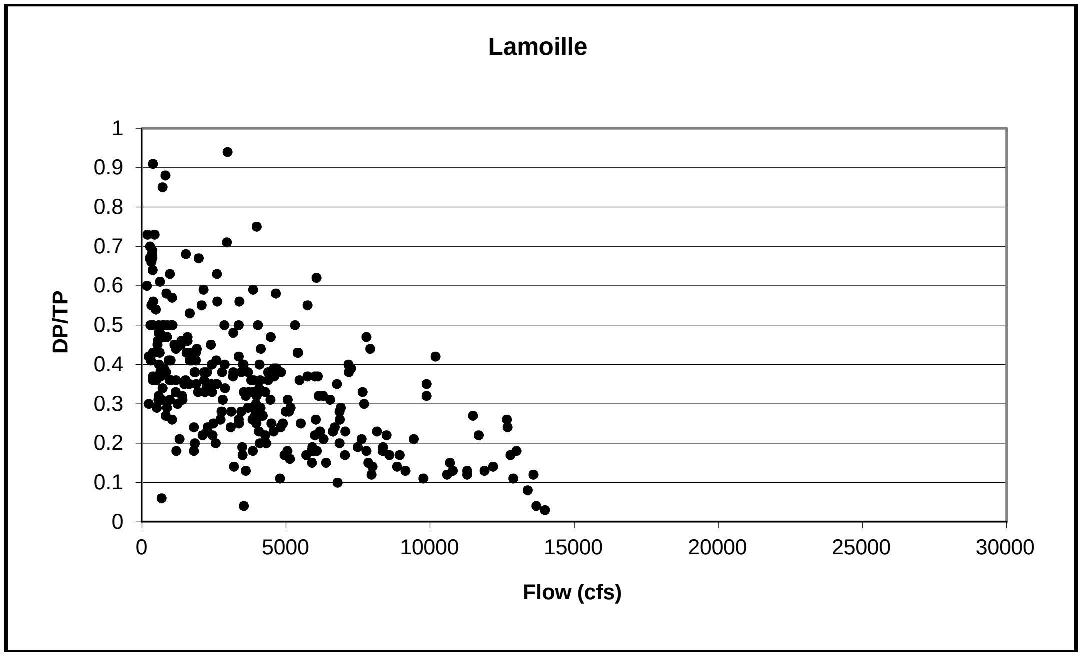

Figure 13: Lamoille River - Fraction DP versus flow (1990-2009)

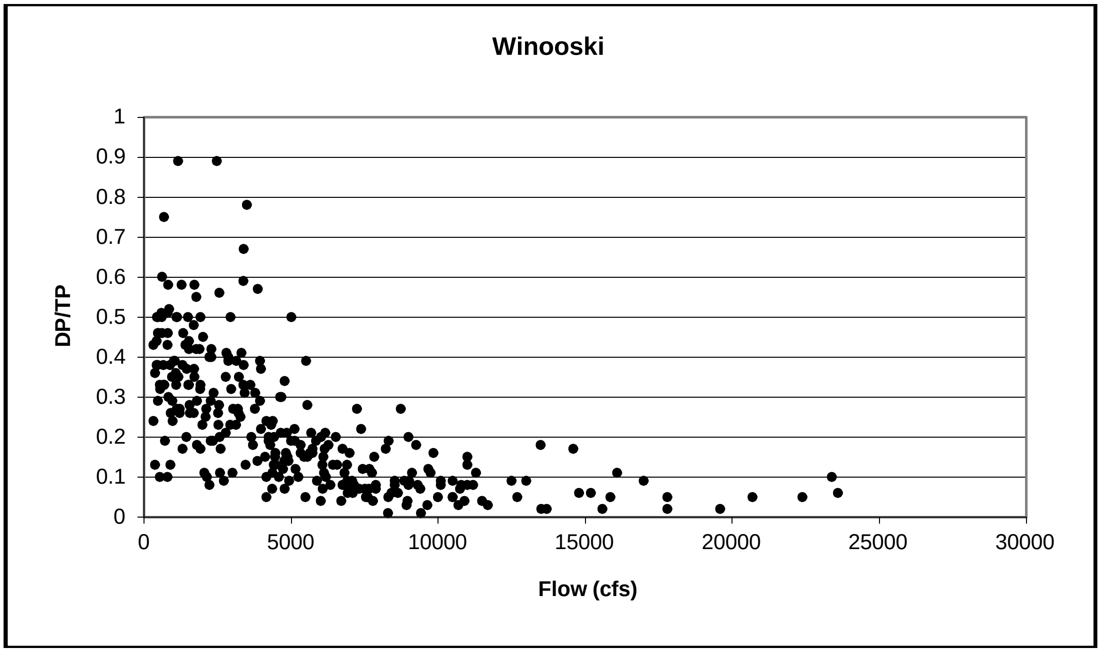

Figure 14: Winooski River - Fraction DP versus flow (1990-2009)

Lake Data

Lake water quality monitoring (chlorophyll-a, TP, DP, TCl and secchi depth) was generally collected during the warm weather growing season, between April and October of each year, at each of the 13 lake segments. Figure 15 shows monitored TP concentrations within each lake segment, during the period between Water Years 1991 and 2008. Highest TP levels were measured in the segment South Lake B (station 2 – black box). Next highest TP levels were generally measured within Missisquoi Bay (stations 50 – red box and 51-green box) and South Lake A (station 4-light blue box). Although station 51 was used in the BATHTUB TMDL modeling to quantify water quality within the center of the bay, data at station 51 (outlet of bay) is much more extensive during the full monitoring period.

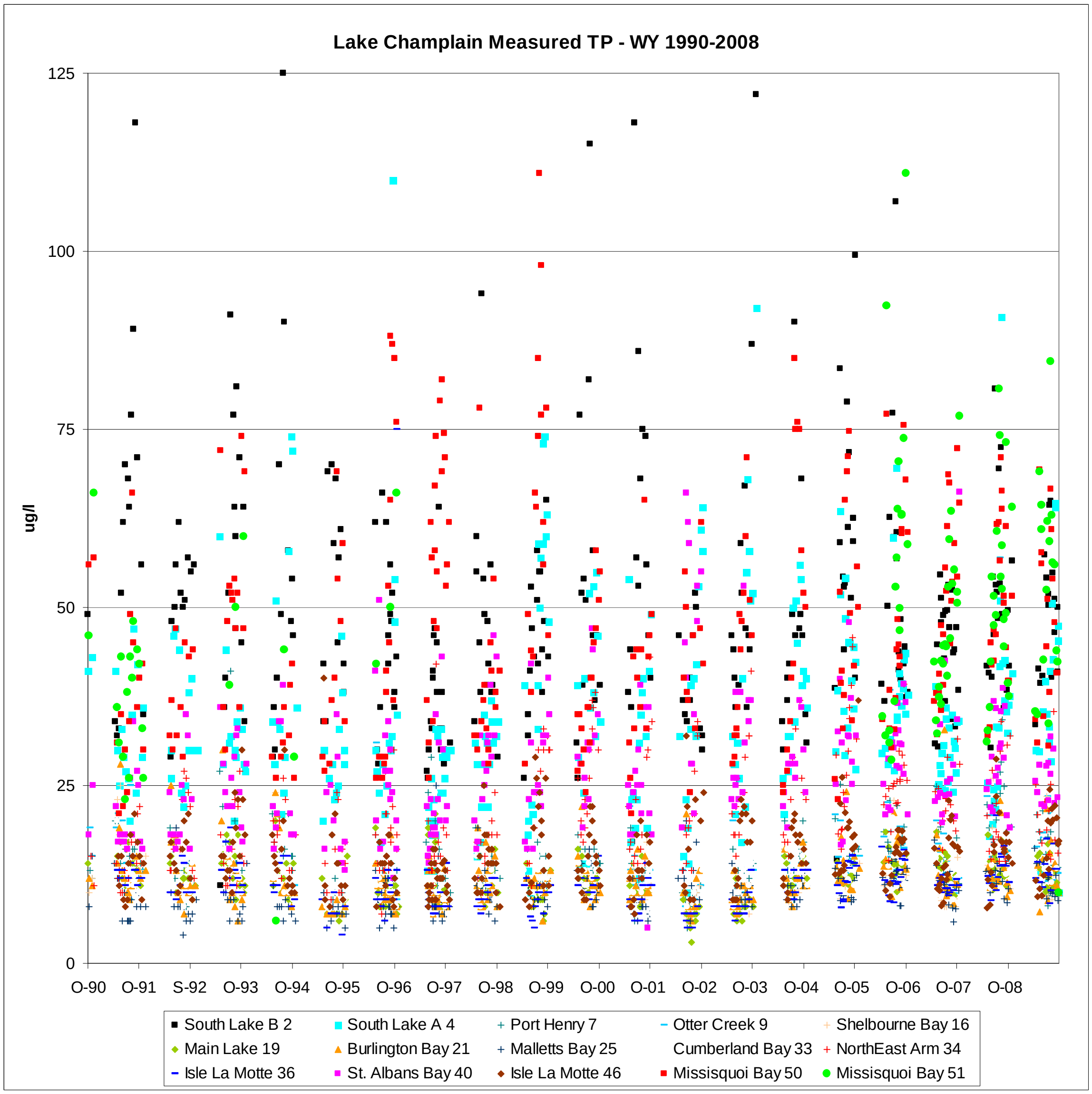

Figure 15: Monitored TP Concentrations within Lake Segments, WY 1991-2009

Figure 16 shows the same data as Figure 15, windowed in to Water Years 1997-2000. TP monitoring data at station 50 in Missisquoi Bay (red box) indicates relatively low TP levels, during WY 1998, when its tributary TP loads (Missisquoi and Pike Rivers) were quite high (see Figure 9). This is likely due to the fact that most of the wet weather tributary TP loading during this year was in particulate form, likely resulting in its rapid loss to bottom sediments. In contrast, the following year (WY 1999) exhibited much lower tributary TP loading yet much higher TP levels at station 50. This suggests that the high tributary particulate TP loads occurring in WY 1998 may have been brought back up into the water column in WY 1999, due to either wave-induced re-suspension or sediment diagenesis and release. The lake TP monitoring data for other lake segments suggest that these internal phosphorus cycling processes may also be important within other lake segments.

A recent Lake Champlain tributary phosphorus trend analyses by USGS indicated that flow-normalized TP concentrations and loads increased during the 1990s and decreased during the 2000's, within most tributaries. This finding suggests that the tributary concentration versus discharge relationships may have shifted over time. Accordingly, the impact of these changes on annual load estimation by alternative methods will be investigated, during the modeling phase.

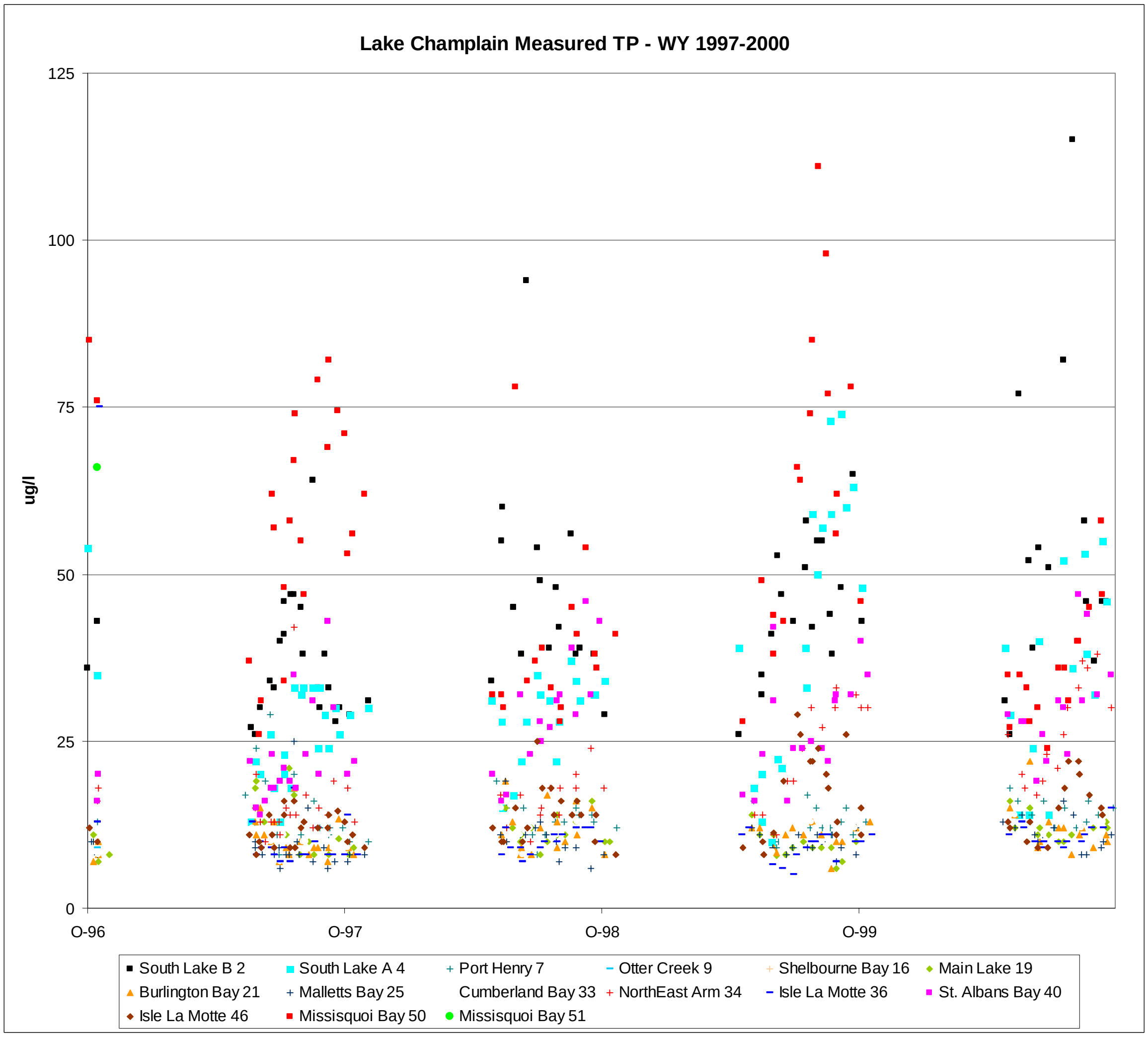

Figure 16: Monitored TP Concentrations within Lake Segments, WY 1997-2000

Observations

Based on the above review of available tributary flow and water quality monitoring data and lake water quality monitoring data, the following conclusions can be made:

1. When calculating daily or longer term (annual or multiple years) tributary loading of phosphorus for input to a model, the method of estimating tributary concentrations on days without monitoring data is crucial. Several different methods, including use of FLUX, average values and linear or higher order interpolation over time, should be investigated and the sensitivity of model predictions to these methods should be included in future modeling analyses.
2. Tributary water volume and phosphorus loading is highly transient (wet weather versus dry weather) over time, such that a large portion of annual water and phosphorus loading to some

lake segments may occur during one or only several rainfall events, during a given year. These features suggest the use of a dynamic modeling approach.

3. Knowledge of the partitioning of phosphorus between dissolved and particulate forms is important, both with regard to determination of tributary loading and in selection of alternative approaches for modeling of in-lake phosphorus loss and internal cycling processes.

BATHTUB Model Review

The existing BATHTUB model of Lake Champlain is perhaps the most obvious candidate model to implement when revisiting the TMDL. While many other models have been developed for Lake Champlain over the past two decades, none have been developed to more directly address TMDL requirements for the lake. The existing model was expressly configured to represent the lake management units defined by VTDEC and NYSDEC, and was constructed to evaluate TP levels for direct comparison to water quality criteria. While it did not fully represent hydrodynamics and all water quality considerations, it proved successful in simulating historical TP conditions and was deemed sufficient for use in deriving load allocations.

The major limitation of the existing BATHTUB model is that it was only calibrated for the calendar year 1991 (VTDEC & NYSDEC, 1997; Smeltzer & Quinn, 1996). With nearly two decades of monitoring data now available, it is clearly important to consider long-term variability and recent conditions when revisiting the TMDL. In order to consider the existing BATHTUB model a candidate for the TMDL revision, it was deemed necessary to evaluate the model's predictive capability for more recent conditions. Rather than fully implementing the model as would be done for the TMDL application, a simplified version of the model was tested.

A detailed summary of the approach, associated analyses, and results are presented in the Appendix of this report.

Water and phosphorus budgets were developed for 2-year intervals between 1991 and 2008 (Smeltzer et al., 2009). Despite simplifications associated with this approach, the period of record provides an excellent basis for testing the model under hydrologic and P loading conditions that are significantly different relative to the 1991 baseline. The model tests were performed using a simplified Excel version of BATHTUB provided by VTDEC.

Results of model testing against the 1991-2008 data demonstrate that the model captures the basic spatial and temporal trends in the lake data collected after 1991, especially considering the expected level of precision for this type of model (~20%), data limitations, wide range of hydrologic conditions, and the short duration of the calibration dataset. Differences between observed and predicted concentrations reflect the net effects of uncertainty in measured flows and loads, measured lake concentrations, and model error. Preliminary results indicate that it will be possible to recalibrate the model to the longer period of record with relatively small changes in the P sedimentation and/or transport terms. Further review and potential refinement of the load computation methods are recommended to improve the accuracy of the model assessment.

Comparison of Modeling Approaches

Two general approaches have been considered for applicability to the Lake Champlain TMDL. The first is implementation of the existing BATHTUB model and may include further customization to address technical considerations highlighted earlier in this report. The second is implementation of a multi-dimensional (hydrodynamic and/or water quality) modeling framework (e.g., the Environmental Fluid Dynamics Code [EFDC] or the Water Quality Analysis Simulation Program [WASP]). Both approaches have their merits and limitations.

Qualitative Comparison of Approaches

Table 1 presents an evaluation of the two approaches' applicability to a range of important technical, regulatory, and management considerations. Technical criteria refer to the ability to simulate the physical system in question, including physical characteristics/processes and constituents of interest. Regulatory criteria make up the constraints imposed by regulations, such as water quality standards or procedural protocol. Management criteria comprise the operational or economical constraints imposed by the end-user and include factors such as financial and technical resources. Although the evaluation is qualitative, it is useful in supporting a model determination based on the factors that are most critical to this project, in particular. The relative importance of each consideration, as it pertains to the Lake Champlain TMDL revision, are presented alongside the models' applicability ratings.

Table 1: Evaluation of Approaches Based on Technical, Regulatory, and Management Criteria

<table>
<tr><td colspan="4">● High applicability ◐ Medium Applicability ○ Low Applicability</td></tr>
<tr><th>Considerations</th><th>Relative Importance</th><th>BATHTUB (including potential updates)</th><th>Multi-Dimensional Model</th></tr>
<tr><td colspan="4">Technical Criteria</td></tr>
<tr><td>Physical Processes:</td><td></td><td></td><td></td></tr>
<tr><td>• advection, dispersion</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>• ability to simulate seiche and currents</td><td>◐</td><td>◐</td><td>●</td></tr>
<tr><td>• momentum</td><td>○</td><td>○</td><td>●</td></tr>
<tr><td>Water Quality:</td><td></td><td></td><td></td></tr>
<tr><td>• total nutrient concentrations</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>• dissolved/particulate partitioning</td><td>◐</td><td>◐</td><td>●</td></tr>
<tr><td>• particle fate</td><td>○</td><td>○</td><td>●</td></tr>
<tr><td>• predictive sediment diagenesis</td><td>○</td><td>○</td><td>●</td></tr>
<tr><td>• sediment transport</td><td>○</td><td>○</td><td>●</td></tr>
<tr><td>• algae</td><td>○</td><td>◐</td><td>●</td></tr>
<tr><td>• dissolved oxygen</td><td>○</td><td>◐</td><td>●</td></tr>
<tr><td>Temporal Scale and Representation:</td><td></td><td></td><td></td></tr>
<tr><td>• long term trends and averages</td><td>●</td><td>●</td><td>●</td></tr>
</table>

● High applicability ◐ Medium Applicability ○ Low Applicability

Considerations	**Relative Importance**	**BATHTUB (including potential updates)**	**Multi-Dimensional Model**
- continuous – ability to predict small time-step variability	◐	◐	●
Spatial Scale and Representation:			
- multi-dimensional representation	◐	◐	●
- grid complexity - allows predictions at numerous locations throughout model domain	◐	○	●
- suitability for local scale analyses, including local discharge evaluation	◐	○	●
- high level of segmentation adjustability	○	◐	◐
Regulatory Criteria			
Enables comparison to VT nutrient criteria	●	●	●
Flexibility for analysis of scenarios, including climate change	●	●	●
Technically defensible (previous use/validation, thoroughly tested, results in peer-reviewed literature, previous TMDL studies)	●	●	●
Management Criteria			
Existing model availability	●	●	○
Data needs	●	◐	○
Public domain	●	●	●
Cost	◐	●	○
Time needed for application	◐	◐	○
Stakeholder community familiarity	◐	◐	○
Level of expertise required	○	◐	○
User interface	○	◐	◐
Model documentation	○	◐	◐

Based on the evaluation, it is apparent that both proposed approaches have distinct advantages and disadvantages. The multi-dimensional modeling approach provides for more detailed representation of physical and water quality processes. It can also provide more detail with respect to temporal and spatial variability. Although the BATHTUB approach does not necessarily provide the same level of detail as the multi-dimensional approach, it scores highly in areas that are of importance to the Lake Champlain application. Notably, it is capable of predicting the constituents of importance at the necessary spatial and temporal scale. The approaches diverge most significantly for management criteria. The BATHTUB approach scores considerably higher than the multi-dimensional approach for nearly all considerations, particularly the considerations deemed most important to the study.

Discussion of Technical Considerations

The following discussion highlights some of the key technical considerations for modeling associated with the Lake Champlain TMDL revision and compares the ability of BATHTUB and a multi-dimensional model to address these considerations. Based on the review of lake and tributary monitoring and the literature, some key factors that will likely be important in the modeling effort include:

1. Speciation of tributary loads and lake TP into separate but interacting dissolved and particulate forms,
2. Consideration of observed short-term variability in tributary TP loading and in lake phosphorus transforming processes,
3. Spatial averaging of in-lake processes over each segment,
4. Ability to capture circulation processes likely to occur within some lake segments, such as: near-shore transport of tributary discharge plumes directly adjacent to downstream lake segments (short-circuiting), internal wave propagation ,and wind-induced seiche.
5. Ability to include several potentially important interactions between lake segment water columns and bottom sediment phosphorus pools, including solids sedimentation, wind and wave-induced sediment re-suspension, bottom sediment diagenesis and possible sediment phosphorus release.

Phosphorus Representation

Tributary data suggest that annual TP loads discharged to some of the lake segments with the highest monitored in-lake TP levels were dominated by wet weather events, when most of the tributary phosphorus was in particulate form. This is particularly evident in Missisquoi Bay, which exhibits an extensive depositional delta surrounding the outlet of the Missisquoi River. Following discharge to the lake segments, particulate phosphorus may rapidly settle to the bottom, resulting in either temporary or long-term removal of these algal nutrients from the water column.

Use of a time-variable, multi-dimensional modeling approach, such as EFDC or WASP, would permit the speciation of TP into dissolved and particulate forms and would include transformation processes controlling the availability of these phosphorus forms for algal uptake and growth. Adequate tributary loading and in-lake water quality data is available for calibration of a more complex model. However, since monitoring data is not available for simulation of other algal nutrients, such as nitrogen forms, these more complex approaches would need to be simplified to include only dissolved and particulate phosphorus forms, water temperature and algae biomass. Both EFDC and WASP are set up to allow this lumped state variable simulation approach. Lake segment water temperature and heat fluxes would be simulated using available hourly or daily meteorological inputs, such as solar radiation, air temperature, relative humidity, wind speed and direction. The hydrodynamic components of these more complex models, in particular the advective and diffusive exchange of water between adjacent lake segments, would be calibrated using total chloride monitoring data collected within the tributaries and individual lake segments. Use of these more complex modeling approaches would also allow the separation of the impacts of tributary dissolved and particulate loads into those due to non-point (land uses) and point sources (wastewater treatment plants) within each tributary. This feature would be advantageous during simulation of future TMDL reduction scenarios, although the reduction of point source TP loadings in recent years suggests it is of reduced importance compared to non-point source loadings.

While the BATHTUB model does not inherently consider detailed speciation of nutrients, it could be run to evaluate consequences of variable speciation regimes. This is further described in the final section of this report.

Temporal and Spatial Scales and Circulation Processes

The available monitoring data suggest that both the tributary loading of phosphorus forms and the response of lake phosphorus and algae levels were highly variable during the 19 year monitoring period, over both space and time scales. The previous BATHTUB modeling assumed that lake phosphorus and algae levels respond relatively quickly to tributary TP loadings, such that the steady-state modeling assumption gave reasonable calibration results for chlorophyll-a, TP, total chlorides and secchi depth, on an annual and 2-year averaged basis. The BATHTUB model subdivided the lake into 13 discrete, fully mixed segments, which is consistent with the fact that lake monitoring data were generally limited to one location within the central portion of each segment.

Use of a time-variable, multi-dimensional modeling approach, such as EFDC or WASP, would permit the simulation of phosphorus transformation and algae growth, death and sedimentation processes over time scales less than a year (daily, monthly and seasonal) and spatial scales smaller than a lake segment (4 to 8 horizontal computational elements per lake segment, with one or more vertical layers). However, since the lake monitoring data generally do not include multiple locations within each segment, their further sub-division would be carried out primarily to study the possible impacts of winds and tributary discharges on circulation patterns and water quality variations within a segment (such as tributary load bypassing of a segment or near-shore transport of a tributary discharge plume). The possibility of lake segment load bypassing and near-shore plume transport have been suggested by high-resolution hydrodynamic modeling studies of Lake Champlain by Manley and Belesky. Due to a lack of calibration data and likely time frame necessary for modeling, the more complex modeling approaches would still not allow for the simulation of complex hydrodynamic processes, such as seiche and internal wave propagation. Alternatively, each lake segment could be simulated with the more complex models as one fully mixed computational element, analogous to the previous BATHTUB modeling. This may not be warranted, however, given the availability of the existing BATHTUB model for the lake.

Lake water quality monitoring was conducted on a monthly basis, primarily during the warm weather algae growing season. Monitored lake TP and chlorophyll-a levels were found to vary significantly over the growing season of each year and from year to year. Use of a time-variable modeling approach would allow the simulation of the response of algae levels during the growing season to winter and spring tributary available phosphorus loading, lake circulation, water temperature and solar radiation.

Sediment-water column Interactions

The BATHTUB modeling included simplified terms for settling (net loss) of TP to the lake bottom within each segment. It also included a net source of TP from bottom sediments, within St. Albans Bay. The rates of these TP sedimentation losses and internal recycling sources were estimated during model calibration.

Use of a time-variable, multi-dimensional modeling approach, such as EFDC or WASP, would permit the simulation of these internal loss and recycling processes in a more detailed manner than available with BATHTUB. In particular, monitoring and modeling recently conducted in Missisquoi Bay by Limnotech for the LCBP could be used as the basis for the more complex modeling within this lake segment, and by extension it could be used to inform modeling of these processes, within the other lake segments. The above more complex models could be used with various levels of detail, for these water column-bottom sediment interaction processes. These approaches would range from simple sedimentation and constant bottom sources, to full bottom sediment diagenesis and release processes. However, the diagenesis simulation capabilities would not likely be used, as adequate monitoring data is not available and they would require simulation of dissolved oxygen and other water quality parameters outside the project scope.

Recommendations

Based on the data review, preliminary success of the existing BATHTUB model to simulate a longer time period, and apparent advantages of BATHTUB over an alternative approach – particularly with respect to management criteria, it is recommended that the BATHTUB model be implemented for the Lake Champlain TMDL revision. It is recommended that the existing BATHTUB model be further tested and refined to address some of the key issues previously noted.

BATHTUB Updates

Subsequent project tasks to support further testing and refinement of the model should include development of yearly budgets for Total P, Dissolved P, and Chloride. The yearly chloride budgets will be developed to support testing and refinement of the hydraulic exchange terms. The P sedimentation terms will be recalibrated, as appropriate, after updating the hydraulic coefficients and refining the load estimates.

The modeling consequences of variations in the proportions of dissolved and particulate loads will also be evaluated. Flow-dependent variations in P forms generally occur in watersheds and their presence does not necessarily mean that they must be explicitly modeled, especially given the additional layers of complexity and data requirements. Calibrating the model to data after 1994, when most of the major point source reductions had been accomplished, would be one way to reduce the potential impact of variations in DP/TP load ratios on model performance and load allocations without injecting further complexity into the model. Depending on results of model testing, further consideration can be given to using BATHTUB P retention models that explicitly account for variations in P speciation (Walker, 1996).

Model performance during the next phase of updates will be evaluated using different averaging intervals (1, 2-yr, 5-yr, 10-yr). The need to enhance BATHTUB for dynamic simulation will be further evaluated. Another potential modeling consideration is further sub-division of some lake segments horizontally (and possibly vertically), in order to capture any bypassing of tributary loads to adjacent downstream lake segments, such as near to shorelines.

Alternative Analyses

In the event that enhancements to the BATHTUB model prove unsuccessful (though this is not currently anticipated), an alternative approach would be to implement a simplified multi-dimensional model. A coarse-scale (e.g., about 4 horizontal cells for each lake segment, with several vertical layers) linked hydrodynamic-water quality model, such as EFDC, could be used. Use of a simplified EFDC model would permit an assessment of the importance of short-term lake phosphorus loading and response controlling processes, including particulate phosphorus sedimentation, bottom sediment phosphorus re-suspension and possible bottom sediment phosphorus diagenesis and release to the lake water column.

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Appendix

Progress Report – Lake Champlain TMDL Update
Preliminary Testing of BATHTUB Application to Lake Champlain

prepared for Tetra Tech, Inc.

W. Walker & J. Walker

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BATHTUB was originally calibrated using loading data for calendar year 1991 (VTDEC & NYSDEC, 1997; Smeltzer & Quinn, 1996). Water and phosphorus budgets were subsequently developed for 2-year intervals between 1991 and 2008 (Smeltzer et al., 2009). Estimation of total loads to each model segment requires relatively complex calculations and several assumptions in order to estimate loads from major tributaries below gaging stations, unmonitored tributaries, direct runoff to the lake, and point sources. The 1991-2008 dataset provides a good basis for initial testing of the model. Subsequent project tasks to support further testing and refinement of the model will include development of yearly budgets for Total P, Dissolved P, and Chloride for the entire 1990-2010 period of record.

Lake segments and monitoring sites are displayed in the Appendix. Features and limitations in the 1992-2008 data relative to that used in the 1990-1991 data used in the original model calibration include:

- A general decrease in sampling frequency of the 15 major tributaries from weekly-biweekly in 1990-1991 to ~monthly with supplemental samples during high flow periods in 1992- (see data inventory)

- Most of the 12 minor tributaries were not sampled after 1992. Exceptions include Rock (2007-2010), Stevens (2009-2010), Jewett (2009-2010), and Mill (2009-2010). These are particularly important because they impact critical lake segments (Missisquoi Bay, St Albans Bay, and the Northeast Arm), where increasing trends in Lake TP concentrations have been observed. Data from 2009-2010 will provide the most complete basis for testing and refining the model.

- While inflows to St. Albans Bay were not monitored in 1992-2008, flows have been estimated using correlations with measured flows (Lamoille River) and the flow-weighted-mean concentrations measured in 2008-2010 for purposes of initial model testing. The lack of direct inflow data to St. Albans Bay will make it difficult to evaluate model performance in this segment, particularly with respect to the internal P loading assumed in the original calibration.

- Flows and phosphorus loads at the major tributary gauging sites accounted for approximately 80% of the flow and Total P load to the lake over the 1991-2008 period. Corresponding percentages are approximately ~46% for the South Lake, and ~85% for the Main Lake and Northeast segments. The low percentages for the South Lake will limit model testing.

- While the initial calibration was based upon loading data for calendar year 1991, model testing will utilize loads summarized on a Water Year basis (September-October). That is consistent with recommendations for BATHTUB applications and with the fact that the model is calibrated to lake data collected during the growing season (May-September), which would not be influenced by loads occurring in October-December of the same calendar year.

Despite various limitations, the long-term record provides an excellent basis for testing the model under hydrologic and P loading conditions that are significantly different relative to the 1991 baseline. Differences include:

- Increasing trends in precipitation and temperature, based upon the NOAA long-term database and also found by The Nature Conservancy (2010)

- Corresponding increases in lake water levels.

- Increases in tributary runoff (Winooski example), lake inflow volumes and TP loads, primarily associated with the increases in rainfall (Smeltzer et al., 2009).

- Decreases in the percentage of TP load from point sources and decreases in the flow-weighted-mean TP concentrations in some of the gaged tributaries (Smeltzer et al., 2009)

- Decreases in the DP/TP load percentage in the major tributaries from 30-40% in 1990-1994 vs. 20-30% in 1995-2009.

- Increasing trends in chloride concentrations in many of the lake segments and tributary chloride loads. These are potentially related to increases in road salt application and/or long-term accumulation in groundwater. (Smeltzer, Pers. Com. 2011). The chloride trends could impact testing of the water budget and calibration of the transport terms in the model (exchange and channel flows).

Each of the above factors could have significant impacts on model calibration and any updated TMDL calculations. The one-year calibration period for the Lake Champlain TMDL model is very short relative to the 10-20 year periods used in developing TMDLs for other major lake basins.

Preliminary tests utilize a simplified Excel version of BATHTUB provided by VTDEC. Subsequent work will utilize the full version of BATHUB, which supports error analysis and provides additional diagnostic output. Lake phosphorus, chlorophyll-a, and transparency data have been averaged at 2-year intervals to provide a basis for model testing. Chlorophyll-a levels and Secchi depths are predicted from TP concentrations using BATHTUB Sub-Models 4 and 1, respectively, and calibrated to the average observed values in each segment for the 2000-2008 period of record.

Results of model testing against the 1991-2008 data are shown in Figure 1. Additional diagnostic plots provide more detailed comparison of observed and predicted values in each segment and 2-year interval. The original BATHTUB calibration captures the basic spatial and temporal trends in the lake data collected after 1991, especially considering the expected level of precision for this type of model (~20%), data limitations, wide range of hydrologic conditions, and the short duration of the calibration dataset. Differences between observed and predicted concentrations reflect the net effects of uncertainty in measured flows and loads, measured lake concentrations, and model error. Application of the full BATHTUB model will permit a more detailed error analysis.

Basic patterns in the results of preliminary model testing are summarized below:

- TP levels in the South Lake are over-predicted by an average of ~20%. Only ~46% of the TP loads to these segments were directly measured. Model predictions are sensitive to both the sedimentation and hydraulic exchange parameters of the model. This lake region is relatively dynamic, as indicated by large seasonal variations in chloride and TP relative to the main lake segments. Higher lake levels and decreases in water chestnut densities observed in recent years would be expected to enhance mixing with the main lake and decrease south lake TP concentrations. This hypothesis will be tested by simulating chloride gradients.

- TP levels in the main lake segments are over-predicted by ~10%. This is generally consistent with decreases in the percentage of dissolved P vs. total P load during the period as a consequence of reductions in point source loads (Smeltzer et al, 2009).

- TP levels in Missisquoi Bay and Northeast Arm are under-predicted by an average of ~20%. Consideration of recent monitoring data from Rock Creek may improve the fit. Despite the higher TP levels relative to the early 1990's, there is no indication of an uptrend in the residuals over the 1999-2008 period.

- While the TP levels in St. Albans bay are over-predicted by ~20% in the 1990's, there is good agreement in 1999-2008. Direct measurements of flow and TP concentration in the bay tributaries were available only 2008-2009.

- There no indication of bias in the model predictions at the lake outlet (Isle LaMotte). This indicates that the initial model calibration successfully captures the overall P budget, despite possible deviations in the individual lake regions.

- TP and chlorophyll-a levels in many segments are over-predicted by 20-60% in Water Years 1997-1998 (see Figure 1 and diagnostic plots).

- Review of the flow and concentration data indicates that load estimates were heavily influenced by loading spike that occurred following a major rainfall event in January 1998. Preliminary calculations indicate that this event accounted approximately 20% of the total load in Water Years 1997-1998 (percentages are 26%, 18%, and 25% for the South, Main, and Northeast regions). The estimates of flow and load are likely to have low precision because of the extreme flows, potential complications due to ice, and sparse sampling frequency.

- Figure 3 (Smeltzer et al, 2009) shows the extreme magnitudes and uncertainties of load estimates for these years in many of the tributaries (e.g. Missisquoi, Pike, Lamoille, Little Otter, Otter, Mettawee, Putnam, Salmon) that discharge to segments where the model over-predicted lake TP concentrations.

- Despite the bias, diagnostic plots indicate that TP and chlorophyll-gradients in the northeastern and main lake segments were captured, particularly in Missisquoi Bay. Values were over-predicted in the south lake segments, where only ~46% in the loads were directly measured.

- No bias is evident in the Secchi Depth predictions for this period. This is important because water transparency is more directly linked to user perception of recreational potential, as compared with TP and chlorophyll-a, except under extreme nuisance bloom conditions (Smeltzer & Heiskary, 1990).

- Model performance and the water quality significance of the January 1998 loading event can be influenced by the low precision of the flow and load estimates, timing of the event relative to the growing season, and rapid sedimentation of larger particles likely to have been transported into the Lake due to high flow velocities. The load estimates, climatologic conditions, hydrologic conditions associated with this event merit further review before drawing conclusions about model performance.

Preliminary results indicate that it will be possible to recalibrate the model to the longer period of record with relatively small changes in the P sedimentation and/or transport terms. Further review and potential refinement of the load computation methods are recommended to improve the accuracy of the model assessment. The need for more complex dynamic models can be considered after thorough refinement and testing of the BATHTUB application.

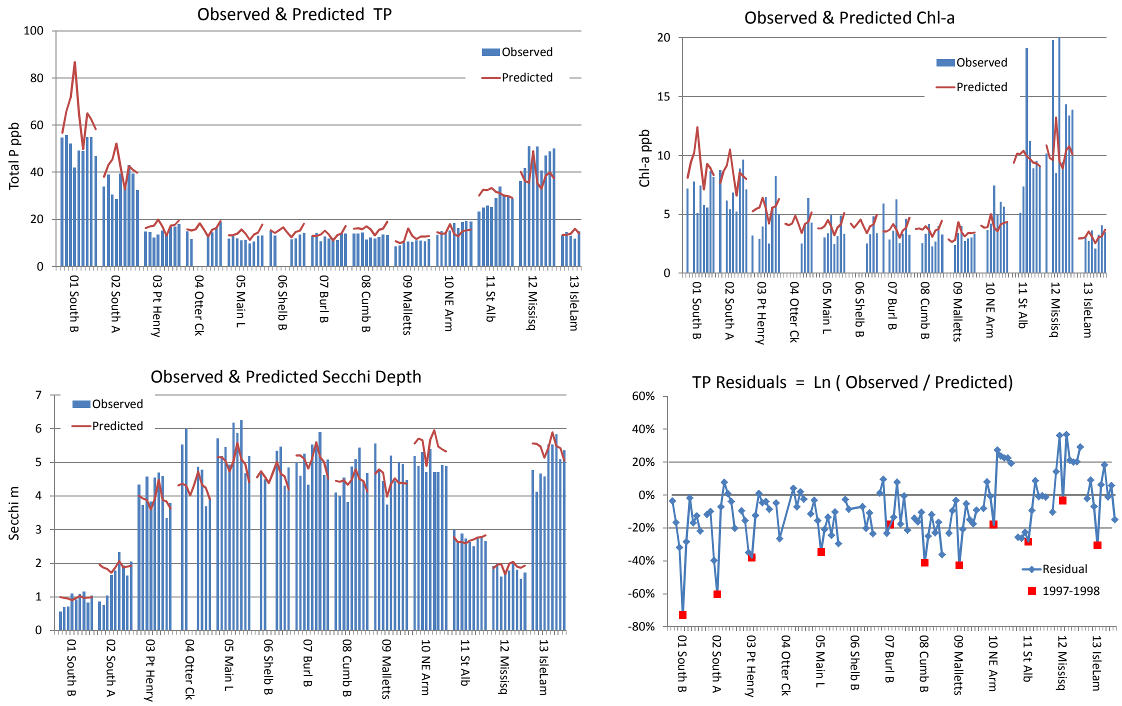
Subsequent project tasks to support further testing and refinement of the model will include development of yearly budgets for Total P, Dissolved P, and Chloride. Databases and software have been assembled to support these calculations. The computation framework is built upon previous work in Onondaga Lake and utilize a several enhanced algorithms for load computations, including FLUX, simple interpolation, and multiple regressions similar to the USGS LOADEST algorithm. Preliminary output has been posted for illustration purposes but has not been reviewed, interpreted, or integrated into the modeling effort (user interface, daily & yearly time series, 30-day time series, trend analysis). The diagnostic output elucidates the flow, concentration, and load dynamics on daily, monthly, and yearly time scales, as well as the importance of the sampling program design and load computation algorithm as a foundation for modeling and the TMDL. This framework will facilitate further refinement in the historical load estimates used for model testing and identification of the best algorithms for automated updating of future load estimates.

The yearly chloride budgets will be developed to support testing and refinement of the hydraulic exchange terms. This task will depend on estimates of un-gauged salt loads from road runoff and/or groundwater, which were necessary to close the chloride budget in the original calibration. The P sedimentation terms will be recalibrated, as appropriate, after updating the updated hydraulic coefficients and refining the load estimates.

The modeling consequences of variations in the proportions of dissolved and particulate loads will be evaluated in the next project phase. A preliminary data analysis indicates that annual average DP/TP load percentage in the major tributaries ranged from 30-40% in 1990-1994 vs. 20-30% in 1995-2009. Flow-dependent variations in P forms generally occur in watersheds and their presence does not necessarily mean that they must be explicitly modeled, especially given the additional layers of complexity and data requirements. Calibrating the model to data after 1994, when most of the major point sources reductions had been accomplished, would be one way to reduce the potential impact of variations in DP/TP load ratios on model performance and load allocations without injecting further complexity into the model. Depending on results of model testing, further consideration can be given to using BATHTUB P retention models that explicitly account for variations in P speciation (Walker, 1996). Those models were initially found to provide a slightly better fit of the Lake Champlain data (VTDEC & NYSDEC, 1997, Table 27, p 88), but were not utilized because of their relative complexity and difficulty in forecasting the impacts of watershed P loading controls on P speciation at the lake inflow points.

Model performance will be evaluated using different averaging intervals (1, 2-yr, 5-yr, 10-yr). One option would be to calibrate the model to the long-term average P balance (e.g., 10 years) and simulate year-to-year variations stochastically (Walker, 2003). The need for more complex dynamic models can be considered after thorough refinement and testing of the BATHTUB application. Alternative model segmentation schemes and load allocations can be evaluated using the updated model.

Figure 1 – Preliminary Model Testing Results



Red line = predicted. Blue bars = observed for each 2-year interval, Water Years 1991-2008. Lower right shows residual TP value expressed as a percentage of predicted values relative to a +/-20% margin of error. The red symbol represents data from Water Years 1997-1998, which were heavily influenced by data from extreme rainfall/runoff event in January 1998.

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http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/vermont/howwework/champlain_climate_report_5_2010.pdf

Useful Hyperlinks

Additional Reports Compiled to Support Model Testing and Future Tasks:
http://www.wwwalker.net/champ/tmdl/references

The Lake Champlain Phosphorus TMDL:
http://www.vtwaterquality.org/lakes/htm/lp_phosphorus.htm

A Phosphorus Budget, Model, and Load Reduction Strategy for Lake Champlain – Article in Journal of Lake and Reservoir Management
http://www.anr.state.vt.us/dec/waterq/lakes/docs/lp_lcmphosphorusbudget1996.pdf

Lake Champlain Phosphorus Diagnostic-Feasibility Study:
http://www.vtwaterquality.org/lakes/docs/lp_lcdfs-finalreport.pdf

Lake Champlain Phosphorus Concentrations and Loading Rates, 1990 – 2008:
http://www.lcbp.org/techreportPDF/57_Phosphorus_Loading_1990-2008.pdf

Lake Champlain Monitoring Data:
http://www.vtwaterquality.org/lakes/htm/lp_longterm.htm

P Issues:
http://www.lcbp.org/ATLAS/HTML/is_pintro.htm

Map Index:
http://www.lcbp.org/ATLAS/HTML/maps.htm

P Status vs. TMDL:
http://www.lcbp.org/phospsum.htm

Load Trends:
http://www.lcbp.org/phospsum3.htm

Atlas – NonPoint Sources:
http://www.lcbp.org/Atlas/HTML/is_pnps.htm

Progress Report - 2000:
http://www.lcbp.org/PDFs/Phos_report2000.pdf

Lake P Trends thru 2003:
http://www.lcbp.org/ATLAS/PDFmaps/is_pconc.pdf

Long-Term Monitoring Plan – Data Portal:
http://www.vtwaterquality.org/lakes/htm/lp_longterm.htm

Long-term Monitoring Plan – Details:
http://www.vtwaterquality.org/lakes/docs/lcmonitoring/lp_lclongtermprogdesc.pdf

WWW Vermont Projects:

http://www.wwwalker.net/champ/vt_projects.htm

http://www.wwwalker.net/champ/index.htm

Onondaga Database & Software:

http://www.wwwalker.net/onondaga/index.htm

http://www.wwwalker.net/onondaga/database_help/onondagaWebMain.html

Lake Regions & Model Segments:

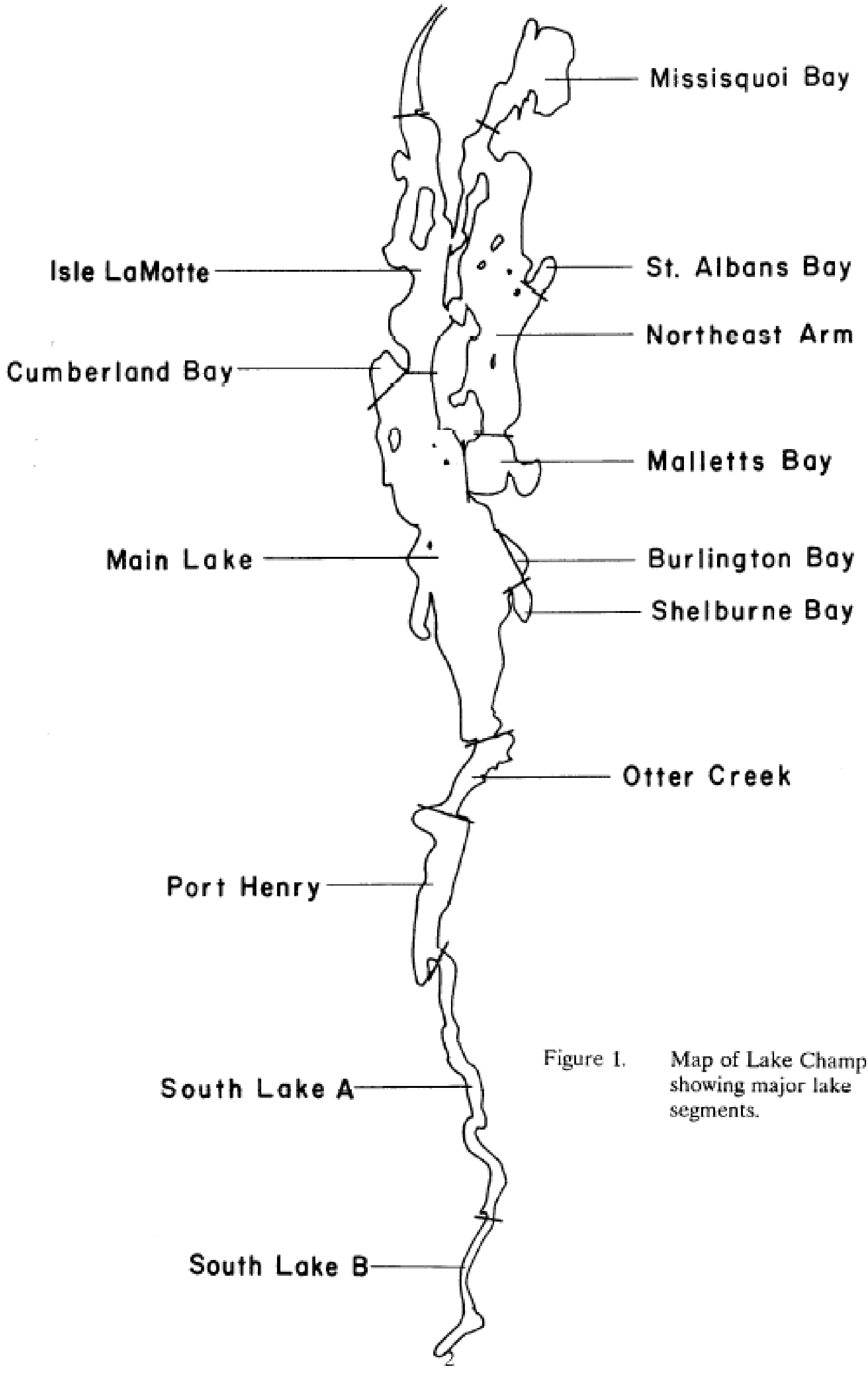

Figure 1. Map of Lake Champlain showing major lake segments.

Tributary & Lake Monitoring Network: