One Park Drive, Suite 200 • PO Box 14409
Research Triangle Park, NC 27709
Tel 919-485-8278 • Fax 919-485-8280

TETRA TECH

Memorandum

To: Teresa Rafi (Task Order Leader)
John O'Donnell (QA Officer)

From: Dr. Jonathan Butcher, P.H.

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Subject: Champlain BATHTUB Model QA

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The BATHTUB model has a long history of application to Lake Champlain. The original version (VTDEC and NYSDEC, 1997; Smeltzer and Quinn, 1996) was developed in cooperation with BATHTUB's developer, Dr. William W. Walker, calibrated to data from 1991, and used in the 1997 TMDL. Tetra Tech's current effort was framed as an update and recalibration of the original model, and for this reason the project QAPP did not specify separate calibration and validation tests of the model.

The Tetra Tech revised model has been previously subjected to several rounds of review, including expert reviews by Dr. Walker in 2011 and 2012. The detailed review of September 6, 2012 evaluated the August 10, 2012 draft of the model calibration memo and offered a series of suggestions on the modeling. I compared these suggestions with the existing model and it appears that the majority (although not all) of them have been incorporated, as discussed further below.

Model input files dated 6/13/2014 were provided for this review. These files incorporate the estimates of load from ungaged tributaries based on SWAT watershed model results and were believed to be final, except for accounting for occasional inputs from Burlington CSOs. These were described as having been updated to BATHTUB version 6.2.0 and I confirmed that the models run without problem in a new install of this latest version of BATHTUB. The Tetra Tech (2013) model calibration main report, however, has a date of May 14, 2013, and so represents the state of the model after responding to Dr. Walker's comments, but not incorporating the latest additions and revisions. On the other hand, Appendix B, which presents the detailed BATHTUB calibration results, has been updated to 6/19/2014 and includes the revised inputs from ungaged areas. (Note, however, that the file still includes a header with a date of May 14, 2013.)

Given the long history of the Lake Champlain BATHTUB model and the previous rounds of review, it is believed that the basic structure of the model it was anticipated that the general structure of the model is in good shape. Therefore, only a cursory review was given to basic model components such as the segment linkages and geometry, all of which appear reasonable and consistent with the original model.

1 Calibration Strategy

As noted above, the BATHTUB modeling for this work was characterized as a recalibration and update of the existing model, with no separate corroboration or validation test. The 2012 model had several substantive differences from the original model; however, many of these differences (such as switching to a different total phosphorus sedimentation representation) were removed after Dr. Walker's review. In my opinion, however, there are still enough changes from the original model setup that a validation or corroboration test should be implied. Indeed, the output that is presented essentially does include separate calibration and validation periods, although they are not characterized that way. That is, the model was calibrated to pooled data for water years 2001-2010 and evaluated against 2-year spans within that range. The model was then also applied to 2-year intervals from 1991-2000, which is essentially a validation test.

Potential calibration and validation statistics are shown in Table 1 (note that these are summaries over the 2-year results for all individual segments, not the whole-lake statistics). As would be expected, the quality of fit declines somewhat when the model is extended to a different time period, as shown by the decrease in R^2. For total chloride and chlorophyll *a* the error magnitudes remain small during the validation period; however, for total phosphorus there is a strong increase in the total phosphorus error. The QAPP says "Tt error targets for this lake modeling exercise are specified as 15% mean error for TP and 5% mean error for chlorides, on a total lake basis." As the total phosphorus error criterion appears to be exceeded this should be addressed in more detail.

Table 1. Potential Calibration and Validation Statistics (Average and Median over All Individual Segments)

Analyte	Statistic	Calibration (2001-2010)	Validation (1991-2000)
Total Chloride	average error	1.36%	-5.26%
	median error	-0.40%	-4.00%
	median R^2	0.83	0.748
Total Phosphorus	average error	3.89%	23.41%
	median error	4.20%	20.00%
	median R^2	0.946	0.766
Chlorophyll *a*	average error	9.81%	9.53%
	median error	6.10%	2.40%
	median R^2	0.786	0.544

The model report briefly discusses errors in total phosphorus: "The updated BATHTUB model for the 2-year period between water year 1997 and 1998 gave predicted TP levels within some lake segments that were significantly higher than observed. This discrepancy is likely due to the fact that during 1998, which was a very wet year, much of the TP entering the lake from its tributaries was in particulate form. Following discharge to each lake segment, much of this particulate phosphorus was thus likely lost to benthic sediments, resulting in an attenuation of the response of observed lake TP levels to tributary TP loads." It is important to note that the validation error statistics for total phosphorus are over 15 percent when evaluated both as an average and a median. The high median demonstrates that this result is not due only to a single year, and indeed at least one segment has TP errors greater than 20% in each of the validation years. An expanded discussion of the validation period results needs to be supplied.

One phenomenon that can lead to declining quality of fit in validation is over-calibration of the model. Dr. Walker previously raised this issue:

> Alternative calibrations should be explored with the updated datasets. The draft force-fits the lake TP data by adjusting the sedimentation rate separately in model segment. This requires estimation of 13 coefficients. Adjustment of the default values for the coefficients is generally recommended only if the observed and predicted TP values in a given segment are significantly different…The original model made only a few adjustments to the default sedimentation coefficients and obtained a satisfactory, but not exact fit. BATHTUB allows grouping of segments by region for purposes of calibration; that would require estimation of fewer coefficients. The segment groups could be consistent with the allocation framework.

The revised model does indeed have four segment groups specified; however, on inspection and testing, the phosphorus sedimentation rates are still calibrated on a segment-by-segment basis, with a constraint to be between 1 and 4. Ten of the 13 segments are optimized to the constraints (mostly to 1, with two going to 4), which is often a sign of over-calibration.

Dispersion rates were also optimized on a segment-by-segment basis, with a constraint to be between 0.01 and 10 – a three order of magnitude range. Several segments converge to both boundaries. For the narrow, linearly arranged segments 1 through 4 the optimized dispersion rate coefficients are 10, 0.9, 10, and 2.05, which again looks to be over-calibration to limited data.

It should be remembered that the FLUX estimates of loads are themselves subject to high levels of uncertainty. Too much fine-tuning of the model may be fruitless if what is being done is really just forcing a fit to the noise in the data. It is also the case that the quality of information varies between tributaries and lake sites. There is only limited recent monitoring for the inflows to some segments, such as St. Albans Bay, and comparatively much more intensive monitoring for certain other tributaries, which is another argument for not forcing the calibration to adjust on a segment-by-segment basis.

2 Kinetic Models

The original 1996 BATHTUB model used phosphorus sedimentation model 3. The 2012 model switched to sedimentation model 2. Dr. Walker noted that model 3 is better suited to lakes with complex morphometry, and the current revised model is shifted back to model 3.

The chlorophyll *a* simulation uses model 4, in which summer average chlorophyll *a* concentration is a linear function of total phosphorus concentration. This is likely appropriate for Lake Champlain due to high clarity and low nitrogen concentrations. (The principal component 2 and other diagnostics produced by the model confirm that growth is nutrient limited and light is not significantly limiting.) The method does, however, have stated applicability criteria based on nitrogen-phosphorus ratios. No nitrogen data are presented, nor is this issue mentioned. A discussion should be provided to justify the use of model 4.

Calibration factors used in the model are generally within the ranges of variability suggested in the BATHTUB guidance. The one exception is the phosphorus calibration factor of 2.2 in segment 6, which is just above the recommended range of 0.5 – 2.0; however, I believe there were more factors out of the recommended range in the 2012 model.

3 Watershed Loads

The 2012 model specified watershed loads from monitored tributaries using a continuous FLUX32 analysis, and the original plan called for driving the BATHTUB model directly with output from the

SWAT watershed model. Dr. Walker pointed out that application of FLUX in this way was inappropriate because of trends in concentration reflecting implementation of point-source controls or other factors. Direct use of SWAT output is also inadvisable due to uncertainties in the watershed simulation and the fact that the model is calibrated to loads based on FLUX analyses. Following Dr. Walker's advice, the model was switched to use the two-year FLUX estimates calculated by VT DEC based on tributary monitoring data. I agree that this is the correct approach. Further, review of simulated residence times confirms that the averaging period is appropriate: The hydraulic residence time is 2.23 years and the nutrient turnover ratio is 1.9. (Note, the nutrient turnover ratio is "ideally" greater than 2 for BATHTUB applications, according to the documentation.)

The FLUX loads are determined at points somewhat upstream from the lake. The VT DEC estimates are apparently adjusted on an area basis to represent the nonpoint load at the mouth of the appropriate river (Smeltzer et al., 2009), although this is not documented in the BATHTUB modeling report. It is still necessary to account for additional loading from the downstream segments and from small direct drainages to the lake. This was originally done by application of area-adjusted loading rates from the nearest FLUX station. The revised model uses load estimates taken from the SWAT model of the direct drainage area. This appears appropriate despite the uncertainties in the SWAT model, as much of the nearshore area has characteristics (e.g., low slope, D soils) that are rather different than the upstream watershed area at most of the FLUX stations. There is, however, a small inconsistency in the way that areas directly downstream of a FLUX station and adjacent areas that drain directly to the lake are treated.

One important issue for this approach is that it is necessary to carefully determine where point sources are represented. This is discussed in the next section.

4 Point Sources

The current version of the BATHTUB model has as inputs FLUX estimates of tributary load (prorated to the mouth of the river) and SWAT estimates of direct drainage load. The FLUX estimates implicitly include all point sources upstream of the monitoring station, but not those downstream. The SWAT model of the direct drainage area intentionally does not include point sources as these are specified as direct inputs to the BATHTUB model. To ensure correct representation I cross-checked the point sources between the watershed models and the BATHTUB model. There are a few issues and minor corrections.

1. First, I should note that some of the point sources were previously identified as being omitted from the SWAT watershed models because the poor locations in the PCS shapefile showed them upstream, whereas the discharges are actually direct to the lake and they are (correctly) included in BATHTUB. No model changes are required for these sites:

- Burlington North
- S. Burlington Bart. Bay
- Swanton Village
- Shelburne # 2

2. The following point sources ***are*** included in the watershed models and are ***also*** included in the BATHTUB model as point sources. They are within the boundaries of the watershed models, which could lead to some double-counting. However, this does not result in double representation of their load if they are downstream of the point used for the FLUX analyses. Probably they should be eliminated from the watershed models if they are upstream of all model calibration sites:

- Burlington Main (Winooski)
- Shelburne #1 (Winooski)

3. The following point sources ***are not*** in the watershed models and ***are*** in the BATHTUB model. The corrected location information shows that they could be included in the watershed models; however, it is appropriate to keep them where they are, in BATHTUB, if they are downstream of the water quality stations used by FLUX:

- St. Albans City (Missisquoi)
- Swanton (MIssisquoi; formerly incorrectly located in Lamoille)
- Vergennes (Otter; this station is very near the FLUX gage)

4. The following direct drainage point sources are not in the BATHTUB model. They should be added (or removed from our lists if they are not to be used):

- Burlington Electric-Moran Plant (VT0000531)
- Burlington Electric-McNeill (VT0020401)
- Essex SD (NY0256471 – no discharge file provided)

It appears that only item 4 is likely to have any impact on the BATHTUB calibration, and any such impact would likely be very small.

5 References

Smeltzer, E. and S. Quinn. 1996. "A Phosphorus Budget, Model, and Load Reduction Strategy for Lake Champlain", Lake and Reservoir Management, Vol 12., No. 3, pp 381-393, http://www.anr.state.vt.us/dec/waterq/lakes/docs/lp_lcmphosphorusbudget1996.pdf.

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