Scientific review of watershed and water quality modeling to support nutrient management in the Falls Lake watershed

Final report (July 2020-Oct 2023)

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Contents

1. Executive Summary

Falls Lake is a critical water supply reservoir for central North Carolina (NC). Water quality in the reservoir is affected by anthropogenic nutrient loading, contributing to high algal levels (chlorophyll concentrations) and other concerns associated with eutrophication (e.g., hypoxia, potential for cyanotoxins). The Upper Neuse River Basin Association (UNRBA) has been developing a suite of models to better understand the feasibility of improving water quality, particularly through watershed nutrient management. These models can assess the benefits of management actions over different spatial and temporal scales. Like all environmental models, the UNRBA models provide an approximate representation of water quality processes and incorporate numerous assumptions related to uncertainties in model structure and biophysical rates. In this study, we provided review and input to the UNRBA modeling effort in the context of related scientific literature, considering model setup, forcing data, biophysical rates, and simulation results. Particular attention was paid to nitrogen (N) and phosphorus (P) dynamics, as nutrients are key drivers of eutrophication in most reservoirs.

Atmospheric nutrient deposition is a major driver of the UNRBA's watershed model (WARMF-watershed) and ultimately the lake response. Understanding reasonable rates and uncertainties in nutrient deposition is important for developing reliable and interpretable results. To this end, we provided a scientific literature review on nutrient deposition, with an emphasis on studies/results relevant to central NC. We were able to characterize spatio-temporal variability in N deposition with a relatively high level of confidence. P deposition was relatively uncertain, though it is also a relatively small source (relative to other P sources in the watershed). This information informed UNRBA model and scenario development. The review also highlights the need to consider how atmospheric deposition will respond to changes in local watershed development/activities.

Internal nutrient fluxes from reservoir bottom sediments are another driver of lake water quality. Internal loading provides a long-term supply of nutrients that can delay the benefits of external (watershed) loading reduction. Thus, we developed a literature review of typical phosphorus and nitrogen internal flux rates, focusing on comparable waterbodies, that informed UNRBA model calibrations. At the same time, the wide range of flux estimates suggest that considerable uncertainties remain. Consistent with principles of adaptive management, additional monitoring and model updating may be advantageous for constraining uncertainties in these fluxes and better anticipating rates of lake water quality improvement/decline in response to changing nutrient loads.

Characterizing nutrient loading rates from various land uses, such as urban, agricultural, and forest, can help inform the development of realistic and effective watershed management strategies. Initial UNRBA watershed modeling results indicated similar loading rates from developed and undeveloped lands, which was unexpected. Thus, we developed a literature review of typical nutrient loading rates from other comparable studies. We found that nutrient loading rates from developed lands are typically several times higher than from undeveloped lands. This information helped motivate an update of the model calibration, but remaining uncertainties should be considered when applying the model to various management scenarios.

In addition to the research items listed above, another substantial component of this project was to provide a more general review of the model development process and address various questions and issues that arose throughout this process. Section 5 of this report describe some of the additional modeling review activities performed throughout this project. Finally, I would like to acknowledge NC State University graduate students, Kimia Karimi and Smitom Borah, who were the primary authors of the literature reviews on atmospheric deposition and internal loading, respectively. They contributed to various other aspects of this project, as well.

2. Atmospheric nutrient deposition

To help support the modeling effort, we provided a review of atmospheric nutrient deposition estimates from various academic and governmental sources. Our complete reports on nitrogen and phosphorus deposition can be found in our year 1 and year 2 project reports, respectively. A summary of key findings is provided below:

Nitrogen deposition:

- The median total annual N deposition for the study area is 12 kg/ha/y.
- Spatially distributed estimates of total N deposition (for 2010-2012) typically range from 9-13 kg/ha/y across the study area, with higher values in urban areas.
- Total N deposition is highest in summer, followed by spring, mainly due to higher precipitation in our study area during these seasons.
- Total annual N deposition is positively correlated with annual precipitation. This is primarily due to precipitation increasing wet deposition.
- Dry N deposition makes up about 60% of total deposition.
- Total N deposition is higher in urban areas, primarily due to higher dry oxidized deposition; and in intensive livestock areas (southeast NC), primarily due to higher dry reduced N deposition.
- Oxidized N accounts for about 40% of wet deposition, 80% of dry deposition, and 65% of total deposition.

Phosphorus deposition:

- There is less reliable monitoring data for P deposition relative to N deposition.
- Estimates of atmospheric TP deposition vary widely across different studies. In the U.S., estimates typically range from 0.05 to 0.5 kg/ha/yr.
- In a recent EPA study, atmospheric TP deposition for the Falls Lake Basin was approximately at 0.08 kg/ha/yr in 2012, but with notable uncertainty.
- In most studies, dry TP deposition exceeds wet TP deposition.
- Temporal variability in P deposition may be driven by precipitation and agricultural activities.
- Higher P deposition is often found in agricultural areas but trends with urbanization are less clear across studies.

These reports informed watershed model calibration and are included in the appendices of the UNRBA watershed modeling report. These reports also demonstrate how a significant portion of deposition (particularly N deposition) is derived from local sources, which should be considered in the modeling of future scenarios.

While P deposition rates are quite small relative to N deposition rates (N:P ~ 100 by mass), the large uncertainty in P deposition rates suggests that additional monitoring of this source may be beneficial.

3. Internal nutrient fluxes

Recycling of nutrients from the reservoir bottom sediments can represent a large fraction of the total nutrient input to a waterbody. Such recycling can delay benefits from external (watershed) mitigation efforts. This source is often referred to as “internal loading”, though it may reflect the accumulation of external loads over long time periods. To inform the modeling effort, we provided a review of internal loading estimates from similar lakes and reservoirs around the country. Our complete reports on phosphorus and nitrogen internal loading can be found in our year 1 and year 2 project reports, respectively. A summary of key findings is provided below:

Nitrogen internal loading:

- Measurements of internal N fluxes are less common than internal P flux measurement.
- Measurement of internal N fluxes under anaerobic conditions typically range from 0.6 to 3.0 g/m^2/month in eutrophic lakes and reservoirs. Anaerobic conditions are most prevalent in summer, when warmer temperatures also increase ammonia flux rates.
- Measurements of internal N fluxes under aerobic conditions typically range from 0 to 2.5 g/m^2/month.
- The above estimates are for ammonia-N, which is the dominant form of N released by sediments.
- Nitrate-N is lost at the sediment layer due to denitrification, and this can offset the ammonia release to varying degrees (literature estimates vary widely).
- These measurements do not include all N release mechanisms, such as resuspension of sediment/benthic material during wind-mixing events.
- Our modeling study of Jordan Lake indicated internal N fluxes of around 10 g/m^2/month in summer and 2 g/m^2/month in winter (averaged across the lake), which are above typical literature values (but not without precedent in warm eutrophic systems).
- N flux estimates (from measurement studies) for Falls Lake generally suggest fluxes of 1-5 g/m^2/month as ammonia in summer. Nitrate-N fluxes were generally small or negative. Ammonia fluxes were typically highest in downstream monitoring locations, where sediments tend to accumulate and hypoxic water conditions are most common.

Phosphorus internal loading:

- Measurements of internal P fluxes under anaerobic conditions typically range from 0 to 1.2 g/m^2/month in eutrophic lakes and reservoirs. Anaerobic conditions are most prevalent in summer.
- Measurements of internal P fluxes under aerobic conditions are typically under 0.2 g/m^2/month.
- These measurements do not include all P release mechanisms, such as resuspension of sediment/benthic material during wind-mixing events.

- Our modeling study of Jordan Lake indicated internal P fluxes of around 0.5 g/m^2/month in summer and 0.1 g/m^2/month in winter (averaged across the lake), generally consistent with the literature review.
- A wide range of internal P flux estimates (from measurement studies) have been reported for Falls Lake. While one study indicated values similar to our estimates for Jordan Lake, another suggests lower values.

Overall, this literature review suggests that internal loading is a substantial nutrient source for Falls Lake. However, preliminary UNRBA model simulations suggested relatively small internal fluxes. As these simulations are dependent on numerous parameters that are imprecisely known, there was room to make adjustments to the model calibration. Based partly on this review, UNRBA modelers were able to increase nutrient fluxes to be more consistent with literature expectations. In addition, UNRBA modelers conducted additional model simulations to test the sensitivity of phosphorus fluxes to various model parameters (12/19/2022 memo from Dynamic Solutions).

While simulated fluxed did increase through model refinement, they remain on the low end of literature ranges. Several possible reasons were discussed, including a very thin sediment layer present throughout much of the upstream half of the reservoir. It is also possible that reservoir sediments may contain high levels of P-binding elements (e.g., aluminum), which appears plausible based on USGS geochemical soil maps. Given the uncertainties associated with internal loading, and consistent with principles of adaptive management, additional monitoring and model updating may be advantageous for constraining uncertainties in these fluxes and better anticipating how the lake will respond to changes in nutrient loading over the long term. If internal loading is higher than the modeled rates, then stakeholders may need to wait longer than expected before they will see water quality improvements (following any watershed loading reductions).

Note that our Jordan Lake modeling results were presented at the Falls Lake Nutrient Management Study Research Symposia, Chapel Hill, NC, in May 2021 and April 2023. The 2021 presentation included a more general discussion of different modeling approaches, while the 2023 presentation included a more detailed discussion of nutrient flux estimates, including a comparison with those in Falls Lake.

4. Nutrient fluxes from urban versus undeveloped lands

Anthropogenic activities, such as urban development and agriculture, are expected to increase watershed nutrient export. This is largely due to increased fertilizer use and erosion in developed or developing areas. Other factors like pet waste and leaking sewage infrastructure may also contribute.

From November 2021 to January 2022, there were a series of meetings and correspondences with UNRBA staff/modelers regarding the nutrient source apportionment of the WARMF-watershed model. Results suggested similar levels of nutrient export (per unit area) from undeveloped (e.g., forest) and urban lands. To explore this issue from a broader perspective, we compared nutrient loading rates from urban and undeveloped lands based on other studies in the region. This review, which is contained in our year 2 report, suggests that urban areas export 4-12 and 2-8 times more TP and TN, respectively, than undeveloped lands. My group's independent modeling of the Falls and Jordan Lake watersheds also suggested that urban nutrient loading rates are several times higher than forest loading rates, and this research was presented at the Falls Lake Nutrient Management Study Research Symposium, Chapel Hill, NC, April 2022.

Motivated in part by this review, the model calibration was updated by extending the model warmup (or spin-up) period so that soil processes and nutrient export could better equilibrate with nutrient inputs, resulting in greater differences between urban and undeveloped land export. The presentation of source apportionment results was also updated to highlight the role of streambank erosion in urban phosphorus export, which is tracked as a separate category in the WARMF-watershed model.

In the finalized model, the urban:forest loading ratio is estimated to be about 1.7 and 1.1 for TN and TP, respectively. If streambank erosion is assumed to occur largely (say 80%) in developed areas, then these ratios increase to around 2:1 for both TN and TP.

To help justify the calibration, UNRBA staff/modelers note that approximately 90 percent of "urban" land in the Falls Lake watershed is low intensity development or developed open space (both have an assumed percent imperviousness of 20 percent). To comply with the Falls Lake Rules, local governments have installed over 350 development retrofit projects. For these reasons, urban export in the Falls Lake watershed may be lower than in historical studies of areas with limited BMPs (or in studies that discount BMPs). Also, the WARMF-watershed model only readily provides nutrient loads to Falls Lake after being subject to removal/retention in upstream water bodies; and the predominantly forested lands around the edge of the reservoir have less opportunity for removal/retention.

At the same time, constraints in the model formulation may also limit the model's ability to fully differentiate the loading rates associated with different land use types. For example, the same hydraulic conductivity is assigned throughout a subwatershed regardless of variations in land use type. Such limitations should probably be addressed when the model is applied to alternative future (or past) land use scenarios. This issue came up in 2023, when the model was applied to an "all-forest" scenario. When we raised these issues, UNRBA modelers adjusted hydraulic conductivities to some extent. However, since hydraulic conductivity was treated as a calibration parameter (rate) in model development (rather than as a function of soil properties), a more rigorous adjustment was not readily available, especially within UNRBA timeline and budget constraints. Other factors, such as the variability in soil denitrification rates used in the model, may also warrant attention when producing and interpreting various model scenarios.

These issues highlight the potential benefits of model parameters and results that are readily comparable to literature values. UNRBA provided this to the extent possible, given project constraints. In future efforts, additional adjustments to the watershed model and/or model development process may be beneficial. Note that some of these issues were addressed in a review of the UNRBA draft watershed modeling report (attached here as Appendix A). This report continues to be updated with feedback from myself and other interested parties.

5. Additional review and recommendations

In addition to the major items described in the previous sections, we also responded to various impromptu questions and technical issues that arose over the last three years. Some particularly notable examples are provided below:

1. In October 2020, we provided a memorandum on the segmentation of the WARMF-Lake model. This memorandum provided a theoretical basis for making segmentation decisions. The recommendations included splitting an existing segment at the Cheek Road causeway, which was adopted. A memorandum on this topic was included in the year 1 report.
2. In early 2021, we provided a memorandum for reconciling flows (in and out of Falls Lake) and thus closing the flow balance. We provided recommendations on how and where to make flow adjustments and what level of smoothing is appropriate for these adjustments. We also provided an illustrative example of how the smoothing algorithm works. Falls Lake modelers have worked to implement these recommendations. A memorandum on this topic was included in the year 1 report.
3. In early-mid 2021, we had multiple meetings with UNRBA staff/modelers to address WARMF-watershed model calibration issues. A primary goal was to ensure that the model reasonably captured the sources and seasonality of nitrogen loading (nitrate, organic nitrogen, etc.). Suggestions were made for calibrating nitrogen transformation rates (e.g., nitrification, denitrification) and their associated temperature adjustment factors. Suggestions were also made regarding the representation of atmospheric nitrogen and phosphorus deposition. We also suggested using soil TP concentrations from the 2013 USGS report "Geochemical and Mineralogical Data for Soils for the Conterminous United States", which appear to have improved the model's phosphorus simulations. Finally, we suggested additional plots to compare model simulations and observations, which were generally adopted.
4. In 2021 meetings with UNRBA staff, questions arose regarding the relationship between the spatial resolution (of reservoir monitoring and modeling) and compliance with NC water quality criteria (standards). To explore these issues, a geostatistical model was developed to create statistical simulations of chl-a at various monitoring resolutions, considering the historical chl-a observations (2014-2018) and the spatial correlation structure of those observations. Results suggest that higher monitoring resolutions will modestly increase the probability of standards violations, especially when lake concentrations are near the 40 ug/L criterion. More details on this topic were included in the year 1 report.
5. In 2022-2023, we had multiple meetings with UNRBA staff/modelers to discuss simulations of nutrients and algae in the two lake models (EFDC and WARMF-lake). Comments on the initial simulations were provided in our year 2 report, with a focus on the magnitude and seasonality of internal nutrient fluxes (related to Section 3). To avoid over-fitting, we also recommended holding model parameters constant across the lake, unless there was a strong mechanistic case for changing them (e.g., settling rates in WARMF-lake should change, since the model cannot represent resuspension in shallow areas, etc.). UNRBA modelers were generally responsive to these comments as they

continued to refine the model calibration. We also made recommendations on how to handle comparisons with observations below detection limits, which were generally adopted. We are awaiting the draft modeling reports for review.

6. Beginning in 2023, I began to provide review and input to the Bayesian Network (BN) modeling. An important consideration in BN modeling is how to divide data into discreet categories (e.g., low, medium, and high) and how to aggregate data across time and space within the reservoir. For example, if the model is going to characterize relationships between load and concentration, then it may be inappropriate to aggregate data from both the tributary arms and main body of the reservoir (as they may have different concentrations at the same loading rate). We are awaiting additional updates on the BN model, which is still under development.
7. In 2023, questions arose regarding the strength of chlorphyll:nutrient relationships in Falls Lake. In addition, some modeling results indicated the reservoir was primarily nitrogen limited. To provide a more data-centric assessment, I analyzed chlorophyll:nutrient relationships based on long-term Falls Lake datasets. For the warm season (June-September), when the system is less likely to be strongly light limited, results suggest a combination of nitrogen and phosphorus limitation. During this season, which has relatively the high average algal concentrations, total nutrients (TN and TP) alone explain around 37-47% of the variability in chlorophyll concentrations. Additional details are provided in Appendix B. From a management perspective, the analysis results caution against focusing management on a single nutrient.

Appendix A: Review of WARMF-watershed modeling report

Review of *UNRBA Falls Lake Watershed Modeling Report – Preliminary Draft*

27 July 2002

Daniel R. Obenour, PhD

As the watershed modeling input data have already received substantial attention, this review focuses primarily on the modeling summary and results sections. In general, the report is well written and provides thorough explanations of many modeling issues. Relative to other watershed modeling efforts I have seen, this study reflects a high level of effort and attention to detail. At the same time, portions of the model description and assessment may benefit from further clarification and/or minor revision, as follows:

Section 5:

1. On page 5-2, you report percent nutrient reductions through watershed processes. I assume that these numbers are based on the calibrated model. In any case, this should be clarified (since you haven't presented the model calibration yet).
2. On page 5-2, you state that atmospheric deposition is removed with crop harvesting. Along similar lines, what about retention of nutrients in forests (e.g., carbon offsets)?
3. Regarding Figures 5-1 to 5-3, suggest clarifying why other potential urban sources (e.g., pet waste, leaking sewers, unreported overflows) were not included in the model. I know you don't have good data for them, but are they expected to be negligible? It would be good to clarify your assumptions along these lines.
4. Regarding Figure 5-3, suggest clarifying why leaf litter decay is only included as a carbon source, and not an N or P source.
5. On page 5-5, could you report the percent reduction in "agricultural production acres"? I think readers may be interested in how much of the agricultural loading reduction is associated with reduced production acres. (I think this is 44% based on page xxviii).
6. On page 5-6, you state that atmospheric N deposition has declined by 25.9% based on CASTNET. This is higher than the reduction implied by the annual CASTNET data for the RTP and Duke sites, which suggest about a 10% reduction (see Karimi N deposition report in Appendix D). The data for these local sites are from a model-data hybrid approach, and actual data were apparently very limited at these stations (as described in Section 4.2.1). For long-term trend analysis, it is unclear whether data from a station 75 miles from the lake (i.e., Candor) should supersede local data based on a hybrid model. In general, it could be good to acknowledge our uncertainty in long-term N deposition trends.

Section 6:

1. The term "parameters" is sometimes used to represent coefficients and other times used to represent state variables. Suggest revising for consistency and/or clarifying terminology.
2. Are model parameter (coefficient) estimates clearly presented, including their justification (e.g., model default, literature review, or calibration)? This seems important for model documentation and results interpretation.
3. Suggest expanding the Figure 6-1 caption (or supporting text) to clarify what was adjusted and what the conclusion of the test was. I think this will help clarify the example.
4. Tables 6-1 and 6-2 use terms like "prediction error" and "% difference". Suggest using consistent terminology ("percent bias"?) if appropriate, or else explain the differences.
5. Around Page 6-16, it would be helpful to provide a map where the locations of the 5 calibration stations are clearly shown (or refer to an earlier map where they are clearly shown).
6. On page 6-18, when referring to "missing information" for Knap of Reeds Creek, suggest referring to the report section where this is described (Section 6.2).
7. On page 6-26, the calculation used to determine the 95% intervals for observations (shown in Figures 6-12 to 6-21) does not appear to be correct. In general, it will lead to intervals that are much wider than true 95% intervals. The probability of the sample error falling outside the 95% interval and the flow being above/below the max/min 15-min flow at the same time is much less than 5%. Also, if the goal is to compare daily loading estimates, the rationale for using the max/min 15-min flow is unclear.
8. On page 6-37, provide a reference that reports the methodology for determining the 95% LOADEST intervals. I would assume the LOADEST software package is being used, but not sure.
9. For Table 6-7, modify the caption to clarify whether a positive value means that the WARMF or LOADEST model is higher.
10. On page 6-39, suggest replacing "LOADEST Simulated Load" with "LOADEST Estimated Load".
11. On page 6-40, the report describes scenarios with and without BMPs. It would be helpful to provide a summary % reductions associated with the BMPs in the main text.

Section 7:

1. On page 7-3, I agree that Osburn et al. (2016) indicates the importance of background "reference" sources of nitrogen loading. At the same time, I'd be careful about equating Osburn's source categories with land uses/covers. Note that forested land cover was not positively correlated with the reference source category across subwatersheds (Table 4 of Osburn et al., 2016).
2. On page 7-8, the discussion of SPARROW results should be revisited. Phosphorus export from parent rock material is highly elevated in particular regions of the southeast (e.g.,

portions of Mississippi, Tennessee), but not North Carolina. Based on the estimates of Garcia et al. (2011), urban lands export 88 kg/km^2/year of TP on average (Table 3), while background export is < 15 kg/km^2/yr in our study area (Figure 6). In a more recent SPARROW model developed specifically for NC (Gurley et al., 2019), the developed TP export rate is 0.635 kg/ha/yr. TN is per unit of road length, so it is difficult to interpret. Using the online mapper to examine the Falls Lake watershed, TP export typically ranges from around 0.5-0.75 kg/ha/yr in urban catchments to 0.1-0.2 kg/ha/yr in relatively undeveloped catchments. TN export typically ranges from around 5-10 kg/ha/yr in urban catchments to 1-2 kg/ha/yr in relatively undeveloped catchments.

3. In general, a high ratio of urban:undeveloped nutrient loading is a common feature of most watershed modeling studies (as described in previous correspondences). Comparisons with WARMF are somewhat complicated (e.g., streambank erosion is accounted for separately in WARMF, and results are typically reported after stream/impoundment processing). Also, Falls Lake appears to have a relatively high level of watershed management activity (e.g., BMPs, SCMs), and much of the heavily forested region is near the reservoir where there is less opportunity for stream/impoundment processing. I think UNRBA has done a thorough job documenting their approach, which is based on extensive data and literature review. They have also made modifications to their modeling approach (e.g., longer warmup period) so that soil processes and nutrient export can better equilibrate with nutrient inputs, resulting in greater differences between urban and undeveloped land export. At the same time, structural constraints within the model may limit its ability to fully represent different land use types. For example, the same hydraulic conductivity must be assigned throughout a subwatershed regardless of variations in land use type. UNRBA has been open about this limitation (page 3-1; H-42 to H-43 of Appendix H). I expect that such limitations will be considered if and when the model is applied to alternative land use scenarios (e.g., perhaps hydraulic conductivities should be adjusted upward for a scenario of increasing urbanization, given the compaction of pervious surfaces associated with urban development).

Miscellaneous:

1. There is a repeated assertion that non-DOT road right-of-way is “low intensity” (e.g., page xxiv). Please clarify, as much of the road right-of-way would presumably include the roads themselves (impervious cover). If roads are being accounted for in a different land classification, please clarify this.
2. On page xiii, suggest replacing “This is a much more accurate way to project” with “This approach is much more capable of projecting”. This is less debatable and more to the point, in my opinion.

References:

García, A. M., Hoos, A. B., & Terziotti, S. (2011). A Regional Modeling Framework of Phosphorus Sources and Transport in Streams of the Southeastern United States. Journal of the American Water Resources Association, 47(5), 991–1010. https://doi.org/10.1111/j.1752-1688.2010.00517.x

Gurley, L.N., A. M. Garcia, S. Terziotti, & Hoos, A.B. (2019). SPARROW model datasets for total nitrogen and total phosphorus in North Carolina, including simulated streamloads. USGS data release, https://doi.org/10.5066/P9UUT74V. Online mapper: https://www2.usgs.gov/water/southatlantic/nc/projects/sparrow/.

Osburn, C. L., Handsel, L. T., Peierls, B. L., & Paerl, H. W. (2016). Predicting sources of dissolved organic nitrogen to an estuary from an agro-urban coastal watershed. Environmental science & technology, 50(16), 8473-8484. https://doi.org/10.1021/acs.est.6b00053.

Appendix B: Chlorophyll-nutrient Relationships

Daniel Obenour, 30 October 2023

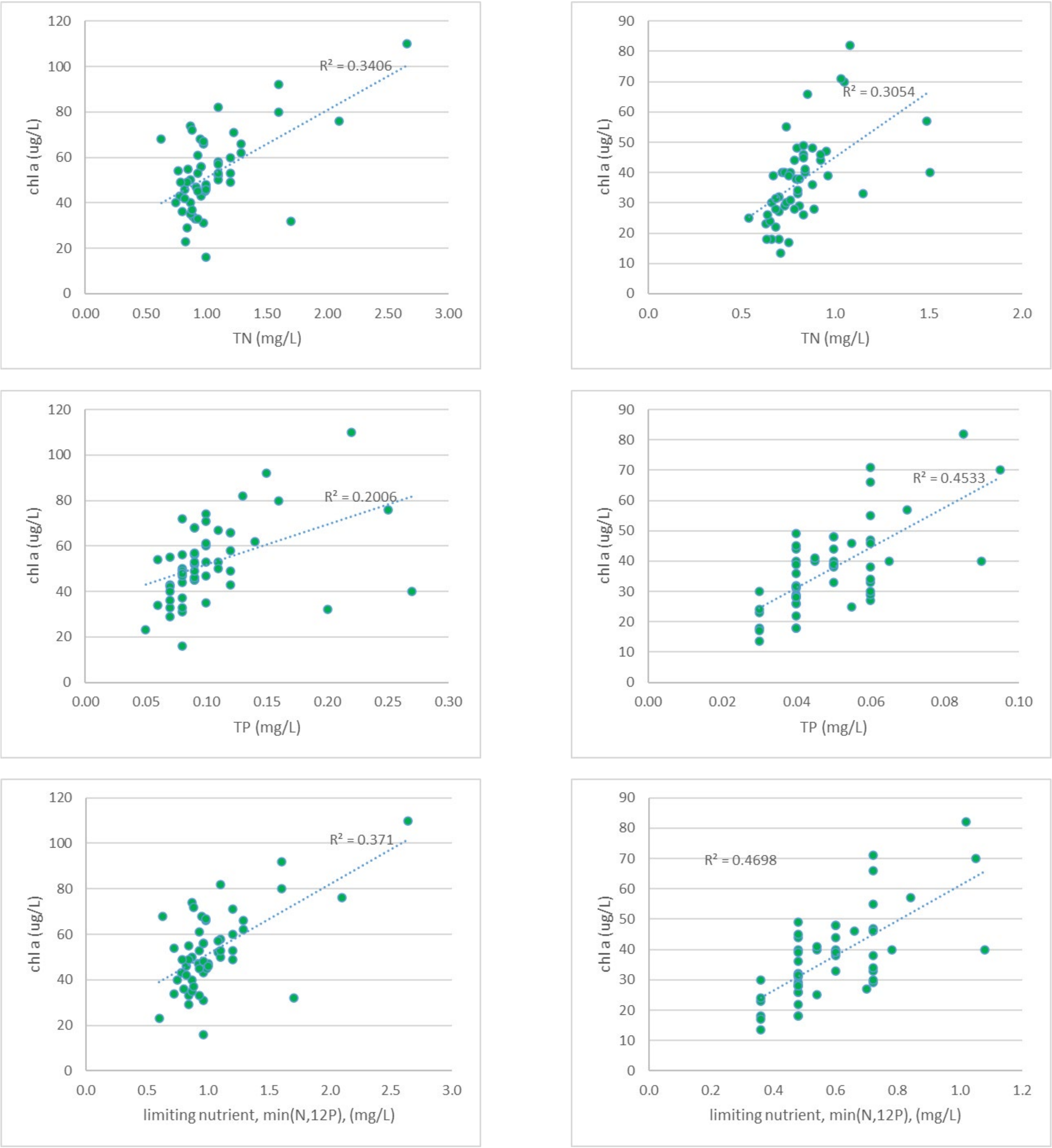
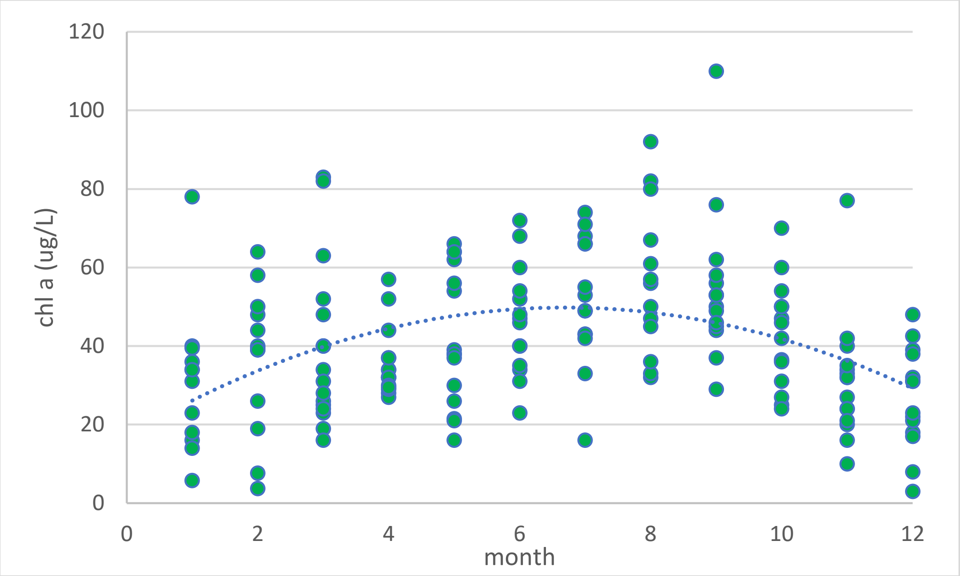


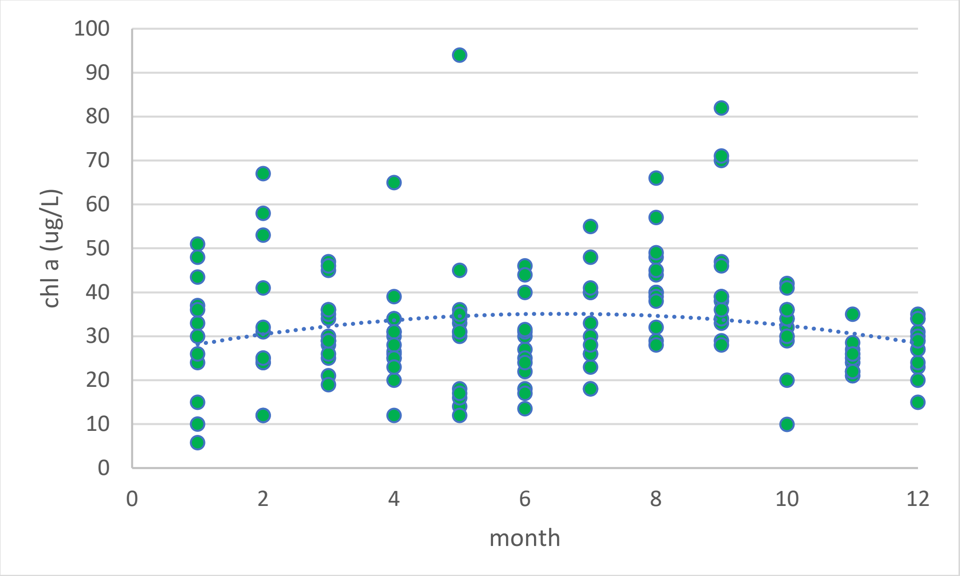
Figure 1: Chlorophyll-nutrient relationships for Station NEU013B in Upper Falls Lake (left) and for Station NEU018E in Middle Falls Lake (right). Top row is based on TN, middle row is based on TP, and bottom row uses a limiting nutrient approach (optimized critical TN:TP ratio=12). Analysis is based on June-September data collected from 2005-2021.

Notes:

1. This analysis focuses on warm season samples (June-September) for 2005-2021, when chlorophyll levels are relatively high (see figures on following page).
2. Across both stations, the critical N:P ratio was optimized to be 12:1 (by mass). Based on this ratio, the system was N-limited 76% of the time in the upper lake (station 13B) and 6% of the time in the middle lake (station 18E).
3. Critical N:P ratios can be optimized by station. For station 13B, the optimal critical N:P ratio was 11:1, which indicates N-limitation 58% of the time. For station 18E, the optimal N:P ratio was 14:1, which indicates N-limitation 19% of the time.
4. In cooler months, the variability explained by nutrients decreases (R^2 ~0.1 to 0.2), as expected, likely due to increased light limitation and lower algal growth rates relative to system flushing rates. Interestingly, the critical N:P ratio for station 18E appears to substantially increase in the cooler months, indicating N limitation.
5. The critical N:P ratio approach used here largely follows:
   Dolman, A. M., & Wiedner, C. (2015). Predicting phytoplankton biomass and estimating critical N: P ratios with piecewise models that conform to Liebig's law of the minimum. *Freshwater Biology*, 60(4), 686-697.
6. The spreadsheet used to develop this analysis is available upon request. It has already been shared with UNRBA.



Station NEU013B (Upper Falls Lake): chlorophyll concentrations by month



Station NEU018E (Middle Falls Lake): chlorophyll concentrations by month