Phase I: Monitoring and Modeling Support for a Phosphorus/Eutrophication Model for Cayuga Lake

Final Phase 1 Report

December, 2014

Executive Summary

Introduction

This report documents progress in the study of phosphorus (P) and trophic state metics in Cayuga Lake, NY. The overarching goal of the study is to develop and test a water quality model for this lake that represents P-eutrophication dynamics. It is intended that this model will be capable of supporting a P Total Maximum Daily Load (TMDL) analysis for on the shallow southern end of the lake that receives 40% of the lake's total inflow, described as the "shelf". The model will also have predictive capabilities for inorganic (minerogenic) sediment, because these particles also influence metrics of trophic state, including P concentrations and water clarity.

The study has five technical elements: (1) monitoring of the five largest tributaries for forms of P, sediments, and related metrics, (2) monitoring of the lake for multiple forms of P, metrics of trophic state, sediment metrics, and selected biological communities, (3) setup and testing of a two-dimensional hydrothermal/transport model for the lake, (4) setup and testing of a watershed/landuse model to quantify the dependence of tributary constituent loading on landuse, and (5) development, testing, and application of a P-eutrophication water quality model for the lake that will be suitable to support a P TMDL. The study is being conducted in two phases, with the first phase including the first four of the above elements. This report documents the findings of the first phase, and considers how these influence development of the model in the second phase.

2013 Monitoring Program

The tributary and lake monitoring programs were conducted concurrently over the April through October interval of 2013. These were both temporally intensive and spatially extensive. Five tributaries were monitored, Fall Creek, Cayuga Inlet Creek, Six Mile Creek, Salmon Creek and Taughannock Creek (first four gaged for flow), that together represent 60% of the lake's watershed. There were two primary components of tributary monitoring (1) fixed frequency, bi-weekly collections, and (2) runoff event-based collections, to represent changes in concentration over the time course of the events.

Lake monitoring included: (1) the conduct of *in situ* measurements, (2) sampling for laboratory measurements of an array of water quality constituents to address the P-eutrophication and related sediment issues, (3) sampling and characterization of phytoplankton and zooplankton communities, and (4) the conduct of a spatially detailed dreissenid (quagga and zebra) mussel survey. Water quality monitoring was conducted at nine sites along the entire length of the lake, with two sites (No.'s 1 and 2) located on the shelf. Lake wide monitoring was conducted bi-weekly at all sites over the April-October interval. The frequency was increased to twice per week in summer (June-September), at shallow sites 1 and 2, and at site 3, the nearest deep water ("pelagic") location.

Tributaries: Concentrations, P Bioavailability and Loads

The robust tributary data sets were analyzed, and together with flow rate (e.g., with units of m^3/d) information, were used to estimate constituent loading rates (e.g., with units of kg/d), that are necessary to drive mass balance type mechanistic models. The central element of this work was the development of loads that were calculated based on the bioavailability of each P form (ability of each form to support algal growth). Bioavailability bioassay experiments were conducted for three forms of P that sum to total P, soluble reactive P (SRP), soluble unreactive P (SUP), and particulate P (PP), for the major tributaries (Fall Creek, Cayuga Inlet Creek, Six Mile Creek and Salmon Creek) and two point sources. Tributary SRP, SUP, and PP were found to be completely, mostly, and less bioavailable, respectively. The estimated total bioavailable P load (BAP_L) for the study interval was only about 25% of the total P load, because the low bioavailability PP fraction dominated. Most of the BAP_L (> 70%) is received during high flow intervals. Point source contributions to the BAP_L are minor (~ 5%), reflecting the benefit of reductions from recent treatment upgrades. Salmon Creek represents a particularly potent source of P with a high BAP_L relative to its contribution to total inflow.

Reasonably strong empirical relationships between concentration and tributary flow (Q) were observed for forms of P, as well as a number of other constituents, that supported specification of concentrations on days without measurements for calculations of loading rates. The study period of 2013 had an above average flow, ranking 32nd in the 89 year record for Fall Creek, but the summer interval had particularly high flow ranking 6th highest of the record. Concentrations of particulate constituents increased dramatically in all of the tributaries during intervals of high Q; each of the tributaries demonstrated strong positive dependencies on Q for these constituents. The sediment delivered to Cayuga Lake was dominated by inorganic (minerogenic) material. Constituent loads were calculated at a time step of daily, to be consistent with the needs of the future mechanistic water quality model for the lake.

Cayuga Lake Watershed Modeling

The watershed model development for this project involved compiling the necessary meteorological, land cover, and land management data for the 860 square mile Cayuga Lake Watershed. Because there is interest in both particulate and soluble phosphorus, the decision was made to focus on the USDA Soil and Water Assessment Tool (SWAT), because it includes modules designed to simulate the necessary landscape phosphorus (P) transformations and in-stream P processes. The model has been set-up and tested for the major tributaries in the southern-end of the watershed. A primary focus has been the Fall Creek sub-watershed, because of the copious historical and on-going monitoring that provide data for calibrating and testing the model, and because it represents the largest sub-watershed area for Cayuga Lake. Additionally, the model team is working with local Soil and Water Conservation Districts, Pro-Dairy, and the New York State Soil and Water Conservation Committee to develop a land management algorithm for Fall Creek and a strategy for extending it to the entire watershed. At this time, we have a preliminary land management algorithm that we are testing in collaboration with the aforementioned stakeholders and a preliminary model calibration. We will continue to refine these through early 2015. Currently there are two issues with the SWAT model that we need to correct: (1) the storm flow-to-base-flow ratio is too high and (2) the organic-to-inorganic phosphorus ratio is not agreeing with the UFI measurements. SWAT model files will be submitted as soon as these two issues are resolved.

Hydrothermal/Transport Submodel

A two-dimensional longitudinal – vertical hydrothermal/transport model (W2/T; the transport submodel of CE-QUAL-W2) was set up, tested, and preliminarily applied for Cayuga Lake. The model was supported by long-term monitoring of meteorological and hydrologic drivers and calibrated and validated using in-lake measurements made at multiple temporal and spatial scales over sixteen years. Measurements included (1) temperature profiles at multiple lake sites for ten years, (2) near-surface temperatures at one end of the lake for sixteen years, including irregular occurrences of upwelling events, (3) timing and magnitude of seiche activity (oscillations of stratified layers) for two years, and (4) transport of a conservative tracer. The model demonstrates excellent temporal stability, maintaining good performance in uninterrupted simulations over a period of fifteen years. Performance is better when modeling is supported by on-lake versus local land-based meteorological measurements.

The validated model has been applied through numeric tracer experiments, to evaluate various features of transport of interest to water quality issues for the lake, including (1) residence times of stream inputs within the entire lake and the shelf, (2) transport and fate of negatively buoyant (i.e., tending to plunge) streams, and (3) the extent of transport from the hypolimnion to the epilimnion. Multiple factors contribute to making W2/T an appropriate transport submodel for the P-eutrophication model for Cayuga Lake, including (1) the basin morphology and associated transport characteristics, (2) longitudinal differences in water quality metrics imparted from localized inputs, particularly extending from the southern end, and (3) the demonstrated performance of W2/T in representing transport in this lake across multiple time scales.

Limnology

A number of noteworthy limnological signatures were resolved through routine *in situ* instrumentation measurements, including (1) the development of strong thermal stratification in summer, (2) occurrences of seiche activity, (3) entry of turbid waters from the shelf area toward northern areas, (4) occurrences of deep chlorophyll maxima (DCM) in metalimnetic depths, and (5) abrupt changes on the shelf coupled to runoff events. Conditions on the shelf with respect to optical metrics of water quality, including Secchi depth (SD, a measurement of clarity), were on average degraded relative to the deeper pelagic portions of the lake. These conditions were particularly acute following runoff events, primarily associated with inorganic (minerogenic) sediment received from the local streams. Differences between the pelagic sites for these metrics were generally minor, a recurring feature also observed for most of the laboratory measurements of collected samples. Spatial patterns for the upper waters for laboratory measurements for the nine sites were resolved on a time-averaged basis. A gradient in concentrations was observed for most parameters including multiple forms of P and metrics of sediments, with tributaries > site 1 (shelf, adjoining tributaries) > site 2 (shelf) > pelagic sites. Particularly noteworthy exceptions were chlorophyll *a* (Chl-*a*) and nitrate nitrogen (NO_3^-), for which no significant differences between the shelf and pelagic sites were observed. The New York State guidance value for the summer average concentration of total P (TP) of 20 µgP/L was exceeded at site 1 (shelf) and approached at site 2 (shelf).

Strong temporal variations were resolved for the shelf for most laboratory analytes that were linked to runoff events, during which the greatest differences with pelagic conditions prevailed. A key metric of the effects of minerogenic particles was demonstrated to be the projected area of minerogenic particles per unit volume (PAV_m). PAV_m is reported to be linearly related to contributions of minerogenic particles to PP, the minerogenic component of turbidity, the scattering and beam attenuation coefficients, and inversely related to SD. The vast majority of PAV_m delivered to the lake and found within the lake is clay mineral particles from the watershed. Increases in PAV_m on the shelf following runoff events, and lake-wide for the major events, were clearly resolved. The contributions of four particle size classes to PAV_m were represented in anticipation of the need for such an apportionment in model simulations of this attribute in the lake. The large contributions of these particles to PP on the shelf following runoff events and the low bioavailability of this P is not supportive of inclusion of such shelf observations in assessments of trophic state (e.g., state guidance value) status for that portion of the lake. A number of signatures were resolved for other metrics in pelagic waters that will be valuable to support testing of the water quality model for lake-wide conditions, including (1) depletions of soluble reactive P (SRP), dissolved silica (Si), and nitrate nitrogen (NO_3^-) in the upper waters over the spring to early summer interval, (2) increases in soluble unreactive P (SUP) in the upper waters in early summer, (3) mid-summer increases in particulate (PP) and particle organic carbon (POC) in the upper waters, and (4) increases in SRP in the near-bottom waters through early fall.

The DCM observed in the lake's metalimnion was not indicative of phytoplankton biomass maxima in those stratified layers. The relationship between the two common measures of phytoplankton biomass, POC and Chl-*a*, in the lake's upper waters was weak. POC was a better predictor of light scattering, SD, and PP than Chl-*a*. The long-term monitoring data associated with Cornell's Lake Source Cooling (LSC) facility was analyzed in an effort to identify trends. Higher TP concentrations and lower SD on the shelf compared to pelagic conditions, based on summer average values, were recurring over the entire record (1998-2012). However, the lack of noteworthy differences in summer average Chl-*a* values between these areas was also recurring over the same period. Multiple statistical analyses were conducted on the three common trophic state metrics, TP, SD, Chl-*a*, to test for significant changes in the lake's upper waters. The only indication of a change was an increase in Chl-*a* in pelagic waters. However, given the indicated weakness of the trend and the inherent limitations in the metric, the change is not considered noteworthy. Significant increases in deep (hypolimnetic) water concentrations of SRP, and thereby total dissolved P (TDP) and TP, starting in 2004, as assessed by monitoring of the LSC discharge, have occurred.

The spring increase in phytoplankton (bloom) was dominated by the diatom group in 2013. The termination of this bloom was consistent with both limitation of this group by decreased Si concentrations and the timing of an increase in grazing zooplankton, patterns that are typical of north-temperate zone lakes in general. Cyanobacteria (previously blue-green algae) did not become sufficiently dense to form nuisance blooms or floating scums. Large *Daphnia*, a particularly efficient grazing zooplankton, capable of causing near-elimination of phytoplankton and other particles, and associated major increases in SD, were not present.

Quagga mussels were collected at all depths and in 96% of the samples collected in the extensive September-October survey of 2013. Zebra mussels were only collected at shallow depths (< 10 m), in 24% of the samples. Overall, dreissenid (includes quagga and zebra mussels) biomass decreased with depth in the lake from levels of 95 g/m^2 to less than 10 g/m^2 at depths deeper than 80 m. Application of literature-based and site specific P excretion rates to the lake wide biomass estimate support the hypothesis that mussel excretion has made a large contribution to the SRP increase in the hypolimnion. Although historic data are limited, the timing of the mussel expansion in the lake is consistent with that of the increase in hypolimnetic SRP after 2004.

Approach for Phase 2 Water Quality Modeling

The presentation and analyses of monitoring information for Cayuga Lake, particularly the detailed data set collected in 2013 as part of this study (Phase 1), have provided invaluable insights to guide Phase 2 of this study. In Phase 2 a mechanistic P-eutrophication model will be developed, tested and preliminarily applied to address the potential cultural eutrophication issue for the lake, with particular focus on the shelf. Extensive data analysis confirms that the P and sediment issues cannot be separated for this system.

The character of the conspicuous "disconnect" in the three common trophic state metrics (the concentration of TP, Chl-*a*, and Secchi depth) that has emerged in the limnological analyses established model attributes that will be necessary to adequately address these features. The disconnect refers to the lack of significant differences in Chl-*a* between the shelf and pelagic waters of the lake, despite clearly degraded TP (higher) and SD (lower) conditions on the shelf.

The disconnect has two primary elements (1) the greater contributions of minerogenic particles to TP and SD levels on the shelf from local tributary inputs, and (2) the absence of locally greater phytoplankton growth on the shelf despite higher concentrations of immediately bioavailable forms of P. The first element requires a robust treatment of minerogenic particles in the model. The second element requires attributes that appropriately represent the effects of (1) the short residence time of tributary inflows on the shelf, (2) the more limited availability of light on the shelf, particularly following runoff events, and (3) the diluting effect on local phytoplankton biomass concentrations from tributary inputs. Given that the Chl-*a* patterns for the shelf generally track lake-wide pelagic conditions, there are several nutrient and phytoplankton biomass signatures that were identified for pelagic waters that will be valuable in testing the P-eutrophication model for the entire lake.

Modeling activities in Phase 2 will embrace the principle of parsimony. Accordingly, there will be an effort to avoid overly complex components and submodels that can be accompanied by greater uncertainty and excessive computational demands. Robust temporal and spatial scales will be represented to address the primary signatures resolved in monitoring related to the project goals. Short-term patterns in response to runoff events, which are primary drivers of the shelf versus pelagic waters differences, need to be resolved, as well as the seasonality in phytoplankton growth manifested lake-wide, and the potential effects of year-to year differences in runoff. Spatial structure must resolve longitudinal differences on the shelf, between the shelf and pelagic waters, and lake-wide mixing and the effects of the thermal stratification regime. The two-dimensional model (W2/T) and the adopted segmentation scheme will provide a robust representation of these features. Drivers for the water quality model will include (a) local meteorological data, (2) hydrologic data for primary tributaries, and (3) loading rate estimates for multiple constituents, as described in this report.

A tentative listing of model state variables (n~30) has been presented that establishes that the water quality model to be developed and tested in Phase 2 will have robust predictive capabilities. The overall water quality model will be composed of several submodels, that include: (1) the two-dimensional hydrothermal/transport submodel, (2) a minerogenic particle submodel, (3) an optics submodel, (4) a phosphorus submodel, and (5) a phytoplankton growth/biomass submodel. Conceptual models depicting structural features are presented for each of the submodels in this report, which reflect insights and results of analyses derived from the Phase 1 work. However, the focus of the model remains P-eutrophication; specifically, the sediment sub-model is not being designed explicitly to support a sediment TMDL, which is outside the scope of this project.