Upstate Freshwater Institute, Inc.

QUALITY ASSURANCE PROJECT PLAN ADDENDUM for Phase 2: A Water Quality Model for the Phosphorus/Eutrophication Issues for Cayuga Lake

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Approvals:

Approved: W.S. (Larry) Joyce Cornell University Project Director Phone number: 607-255-6631	William S. Joyce Name	1/16/2015 Date
Approved: Steven Effler UFI Project Manager Phone number: 315-431-4962 ext. 102	Steven Effler Name	1/18/2015 Date
Approved: Gina Kehoe UFI Quality Assurance Officer Phone number: 315-431-4962 ext. 115	Gina Kehoe Name	1/19/2015 Date
Approved: [signature] NYSDEC Project Manager Phone number: 518 402-8179	Jeff Meyers Name	1/15/2015 Date
Approved: [signature] DOW QA officer NYSDEC Division of Water Phone number: (518) 402-8156	Jason Fagel Name	1/15/2015 Date

Prepared by
Susan O'Donnell, Senior Research Engineer
Upstate Freshwater Inst. Inc., 224 Midler Park Drive
Syracuse, NY 13206
www.upstatefreshwater.org
PH: 315-431-4962 x121 FAX: 315 431-4969

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An electronic (pdf) copy of this document has been distributed to the following people and locations.

Name	Title	Organization	Address	Phone	email	Electronic/ Hard copy
Steve Beyers	Facilities Engineering	Cornell University	201 Humphreys Service Building, Ithaca, NY 14853	(607) 255-5491	smb75@cornell.edu	electronic
William S. Joyce	Director of Utilities and Energy Management	Cornell University	135 Humphreys Service Building, Ithaca, NY 14853-3701	(607) 255-6631	wsj1@cornell.edu	electronic
Jeff Myers	Project Manager NYSDEC DOW	New York State Department of Environmental Conservation	625 Broadway, 4th Floor Albany, NY 12233-3502	(518) 402-8179	jeff.myers@dec.ny.us.gov	electronic
Jason Fagel	NYSDEC DOW QA Officer	New York State Department of Environmental Conservation	625 Broadway Albany, NY 12233-3502	(518) 402-8156	jason.fagel@dec.ny.gov	electronic
Antony Tseng	Project Manager for EPA Model Evaluation Group	US EPA Region 2 Clean Water Regulatory Branch TMDL/Standards Section	290 Broadway, 24th Fl New York, NY 10007-1866	(212) 637-3777	Tseng.Antony@epa.gov	electronic
Steven Effler	UFI Primary Project Manager	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext. 102	sweffler @upstatefreshwater.org	electronic
David Matthews	UFI Primary Assistant Project Manager	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext. 107	damatthews @upstatefreshwater.org	electronic
Gina Kehoe	UFI Quality Assurance Officer/ Laboratory Director	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext. 115	ginak @upstatefreshwater.org	electronic, original hard copy

Name	Title	Organization	Address	Phone	email	Electronic/ Hard copy
Anthony Prestigacomo	UFI Field Manager and Field QA Officer	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext. 118	tonyp @upstatefreshwater.org	electronic
Susan O'Donnell	UFI Senior Research Engineer, modeler	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext.121	susanod @upstatefreshwater.org	electronic
Rakesh Gelda	UFI Senior Research Engineer, modeler	Upstate Freshwater Institute	224 Midler Park Dr., Syracuse, NY 13206	(315) 431-4962 Ext.120	rkgelda@upstatefreshwater.org	electronic

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

Acronyms and Abbreviations

2-D - two dimensional
a_{CDOM} - absorption coefficient for CDOM
AOPs - apparent optical properties (SD, $K_d(\lambda)$, $K_0(PAR)$, Γ, K_L)
$a(\lambda)$ - spectral absorption coefficient
$a_x{*}(\lambda)$ - spectral absorption cross-section for component x
a_x - absorption coefficient for component x (x = POC, DOC, PAV, water)
$b(\lambda)$ - spectral scattering coefficient
$b_x{*}(\lambda)$ - spectral scattering cross-section for component x
$c(\lambda)$ - spectral beam attenuation coefficient
c_L - beam attenuation illuminance coefficient
c_{660} - beam attenuation coefficient (BAC), surrogate of turbidity (Tn), light scattering coefficient and TSS measured in the lab (c_{660}) or *in situ* (c_{660}_f)
CE-QUAL-W2 - a public access model developed by the U.S. Army Corps
Chl-*a* - fluorometric chlorophyll *a*, a trophic state metric, proxy for phytoplankton biomass measured in lab (Chl-*a*) and measured *in situ* (Chl-a_f)
CHWWTP - Cayuga Heights Wastewater Treatment Plant
CU - Cornell University
DOC - dissolved organic carbon; measured in lab; made up of two estimated fractions = LDOC + RDOC
DOW - division of water
DQOs - data quality objectives
$E_d(z)$ - downwelling irradiance
EL - EcoLogic
EPA - see USEPA; Environmental Protection Agency
FSS - fixed suspended solids; measured in the lab
IAWWTP - Ithaca Area Wastewater Treatment Plant
IPA - individual particle analysis
IOPs - inherent optical properties ($a(\lambda)$, $a_x{*}(\lambda)$, a_x, $b(\lambda)$, $b_x{*}(\lambda)$, $c(\lambda)$, c_L)
ISPM - inorganic suspended particulate matter
K_0(PAR) - scalar PAR attenuation coefficient
$K_d(\lambda)$ - spectral downwelling attenuation coefficient
K_L - downwelling attenuation illuminance coefficient
Γ - coefficient for SD radiative transfer function
Lake2K - a three layer lake water quality model developed by S. C. Chapra
LAN - local area network
LSC - lake source cooling
LDOC - labile DOC; estimated fraction of DOC
LPOC - labile POC; estimated fraction of POC

LPOP - labile POP; estimated fraction of POP
LPIP - labile PIP; estimated fraction of PIP
LSUP - labile SUP; estimated fraction of SUP
MEG - modeling evaluation group
N - nitrogen
NCDC - National Climatic Data Center
NOAA - National Oceanic & Atmospheric Administration
NO_3^- - nitrate; calculated by difference (= NO_X - NO_2^-)
NO_2^- - nitrite; measured
NO_X - the sum of nitrate and nitrite, measured; used as a phytoplankton nutrient
NYC - New York City
NYCDEP - New York City Department of Environmental Protection
NYSDEC - New York State Department of Environmental Conservation
NYSDOH - New York State Department of Health
OACs - optically active constituents (Chl-*a*, DOC, CDOM, POC, PAV_m, FSS, a_{CDOM})
OAC_{ax} - concentration of optically active constituents, x, contributing to absorption of irradiance
OAC_{bx} - concentration of optically active constituents, x, contributing to scattering of irradiance
P - phosphorus
PAR - photosynthetically active radiation (scalar irradiance)
PAV_m - projected area per unit volume, minerogenic particles; measured using SAX; sum of all particle size classes
$PAV_{m,\,i}$ - PAV_m for size class i; measured
PI - principal investigator
PN - particulate nitrogen; estimated from lab measurements = TN - TDN
PP - particulate phosphorus; calculated = TP - TDP or = POP + PIP
PIP - particulate inorganic phosphorus; calculated from laboratory measurements = TIP - SRP; made up of two estimated fractions = LPIP + RPIP
POC - particulate organic carbon; measured in the lab; made up of two estimated fractions = LPOC + RPOC
POP - particulate organic phosphorus; estimated; made up of two estimated fractions = LPOP + RPOP
Q - flow
QAPP - Quality Assurance Project Plan
QA - quality assurance
QC - quality control
RDOC - refractory DOC; estimated fraction of DOC
RPIP - refractory PIP; estimated fraction of PIP
RPOC - refractory POC; estimated fraction of POC
RPOP - refractory POP; estimated fraction of POP
RSUP - refractory SUP; estimated fraction of SUP
RMSE - root mean square error
RPD - relative percent difference

SAX - scanning electron microscopy interfaced with automated image and X-ray analyses
SC - specific conductance
SCM - software configuration management
SD - Secchi disc
SEM - scanning electron microscope
Si - dissolved reactive silica, a nutrient for diatoms (also called DRSi)
SRP - soluble reactive phosphorus; measured in lab
SUP - soluble unreactive phosphorus; calculated = TDP - SRP; made up of two estimated fractions = LSUP + RSUP
T - temperature
TAC - technical advisory committee
TIP - total inorganic phosphorus; measured in the lab
TOC - total organic carbon; calculated = POC + DOC
Tn - turbidity measured in lab (Tn) and *in situ (*Tn_f)
Tn_i - turbidity for size class i
TN - total nitrogen is the sum of the organic and inorganic forms of nitrogen; measured in the lab; made up of TDN + PN
t-NH_3 - total ammonia, a phytoplankton nutrient
TDN - total dissolved nitrogen; measured in the lab; made up of t-NH_3 + NO_x +DON
TDP - total dissolved phosphorus; measured in the lab; made up of SRP + SUP
TMDL - total maximum daily load, a limit for material loading set for a constituent by a regulatory agency
TP - total phosphorus; measured in the lab; made up of TDP + PP
TSS - total suspended solids, a gravimetric measurement of sediments; measured in the lab
UFI - Upstate Freshwater Institute
USACE - United States Army Corps of Engineers
USDA - United States Department of Agriculture
USEPA - United States Environmental Protection Agency
USGS - United States Geological Survey
YSI - Yellow Springs Instrumentation
W2/T - hydrothermal/transport submodel for CE-QUAL-W2
WWTP - waste water treatment plant

Introduction

The U.S. Environmental Protection Agency (USEPA) has developed the Quality Assurance Project Plan (QAPP) as a tool for project managers to document the type and quantity of data needed to make an environmental decision (USEPA, 2001;USEPA, 2002a; USEPA, 2002b). The QAPP documents the methods for data collection and assessment. USEPA's mandatory Quality System requires development, review, approval, and implementation of a QAPP. The QAPP is a blueprint for how the project will be carried out and integrates all the technical and quality aspects of the project. The USEPA provides guidelines for development of a QAPP; however, due to the large diversity in environmental projects they allow for considerable flexibility in adapting the QAPP requirements to a specific project. The USEPA defined a graded approach to QAPPs and modeling QAPPs in which the level of effort applied in designing a modeling QAPP is a function of the model(s) intended use and the project scope and magnitude (USEPA, 2002a). For example, projects that involve Congressional testimony, or development of new laws and regulations, or support of litigation would require a higher level of quality assurance and planning than a model with non-regulatory priorities (USEPA, 2002a). The USEPA states "Still lower levels of defensibility apply to basic exploratory research requiring extremely fast turn-around, or high flexibility and adaptability" (USEPA, 2002a). The USEPA has defined categories 1- 4 (1 requiring the highest level of effort and 4 the least) to aide those involved in designing a QAPP to determine the level of effort necessary (USEPA, 2006a). The USEPA also acknowledges that projects don't always fit nicely into one of these four categories and further supplied a list of requirements that may apply to specific situations (USEPA, 2006a).

This QAPP has been prepared under the guidance provided in *"EPA Requirements for Quality Assurance Project Plans* (USEPA, 2001), *"Guidance for Quality Assurance Project Plans"* (USEPA, 2002b), and *"Guidance for Quality Assurance Project Plans for Modeling"* (USEPA, 2002a). Further guidance on delineating the QAPP specifications was provided in two supplemental documents obtained from the USEPA web site (USEPA, 2006a). The first document lists the requirements when the project uses secondary data (USEPA, 2002c). The second document lists the requirements when the project involves development and/or application of a research model (USEPA, 2003). The project described in this QAPP is a 2 year effort involving modeling and associated data analysis, that corresponds to the second phase of an overall two-phase program. Review of the guidance documents for developing QAPPs (USEPA, 2001; USEPA, 2002b) and modeling QAPPs (USEPA, 2002a) showed that both types of QAPPs follow the same general outline.

Phosphorus (P) plays a critical role in supporting plant growth in aquatic ecosystems. Phosphorus has long been recognized as the most critical nutrient controlling phytoplankton growth in most lakes in the northern temperature zone. Degradation of water quality has been widely documented for lakes that have received excessively high inputs of P. The southern end of Cayuga Lake has been designated as impaired by the New York State Department of Environmental Conservation (NYSDEC). One feature of the impairment is concentrations of total P (TP) that are deemed high; e.g., summer average TP concentrations that in some years exceed the State guidance value of 20 µg/L. The overall Cayuga Lake study that is specified here will support the development and testing of a water quality phosphorus/eutrophication model. This initiative recognizes the bioavailability issue for external phosphorus inputs; e.g., that only a portion of the total loading is in a form that can support algal growth, and will effectively represent it in the overall program. Moreover, this initiative recognizes that inorganic (minerogenic) sediment can not be separated from the phosphorus/eutrophication issues and the associated model for this lake because this material interferes with common trophic state metrics. It is intended that this integrated model will be capable of supporting a phosphorus TMDL analysis, for the targeted area, that may be conducted subsequently by the NYSDEC.

The overall Cayuga Lake study initiative has five technical elements:

1. tributary monitoring to support specification of dynamic loading conditions, the bioavailability of the external phosphorus inputs, and testing and application of the watershed/land use model.
2. lake monitoring for water quality variables and related biological communities.
3. a two-dimensional hydrothermal/transport model for the lake.
4. watershed/land use modeling that will quantify the dependence of tributary loading on land use and meteorological drivers, and
5. a phosphorus/eutrophication model for the lake.

This work is being conducted in a phased manner, as agreed to by Cornell University (CU) and NYSDEC (Figure 1). Technical elements 1-4 were all part of Phase 1 of this overall two-phase project that was successfully completed in 2014. Technical element 5 corresponds to Phase 2. Phase 1 was covered in the first QAPP titled *"Phase 1: Monitoring and Modeling Support for a Phosphorus/Eutrophication Model for Cayuga Lake"*. This Phase 2 portion of the overall Cayuga Lake project is covered in this QAPP addendum titled "*Phase 2: A Water Quality Model for the Phosphorus/Eutrophication Issue for Cayuga Lake*". For convenience throughout the remainder of this QAPP it will simply be referred to as the Phase 2 project. This phased Cayuga Lake project included Phase 1 in which an integrated and balanced program of monitoring and hydrothermal/transport and watershed/landuse modeling was completed, and Phase 2 in which a phosphorus/eutrophication model that will be capable of supporting related management applications, will be produced. This model may be used by the NYSDEC to conduct a TMDL analysis for Cayuga Lake.

A. Project Management

A.1. Project Task/Organization

The purpose of this section is to present the organization and lines of communication for the technical aspects of this project. This project includes the following organizations:

- Cornell University (CU)
- New York State Department of Environmental Conservation (NYSDEC)
- EcoLogic (EL)
- Technical Advisory Committee (TAC)
- Modeling Evaluation Group (MEG)
- Upstate Freshwater Institute (UFI)

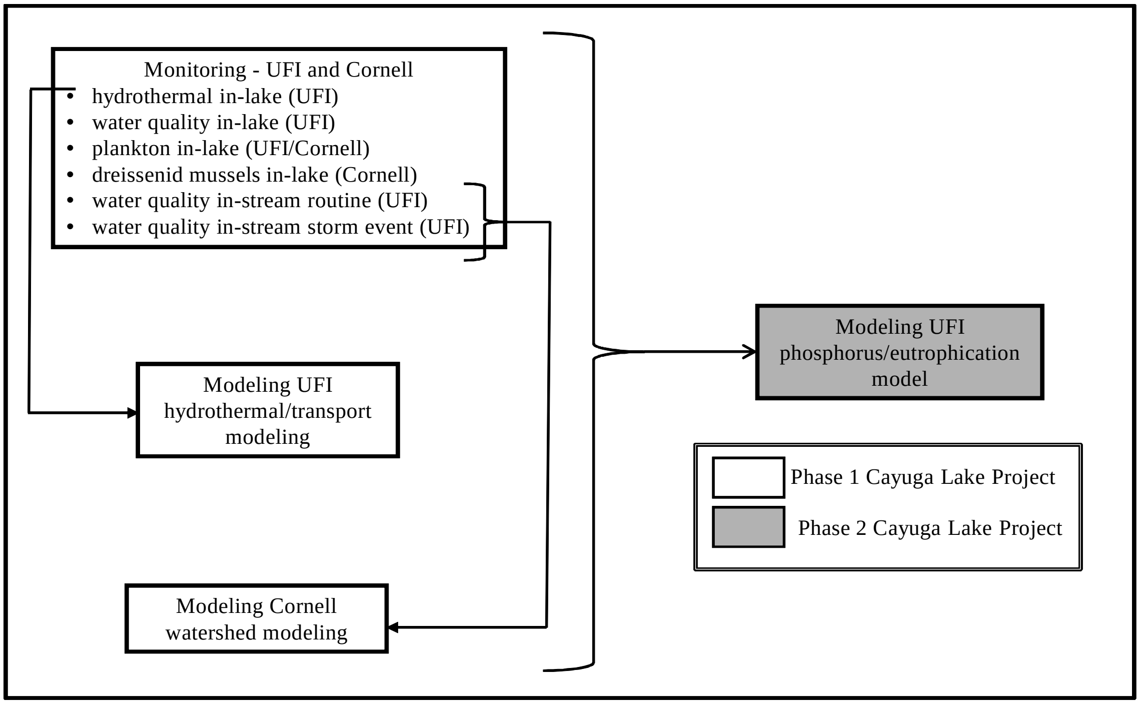

Figure 1 . Overall project chart showing the division of the project into Phase 1 and Phase 2.

For details on the Phase 1 project please refer to the QAPP titled *"Phase 1: Monitoring and Modeling Support for a Phosphorus/Eutrophication Model for Cayuga Lake"*. The Phase 2 project, is a collaboration between CU and NYSDEC, as illustrated in the organization chart (Figure 2). The Project Managers for CU and NYDEC are Steve Beyers and Jeff Myers, respectively. Liz Moran (EL) will support project management for CU. The scientist and engineers responsible for the conduct of the project are from the Upstate Freshwater Institute (UFI; Figure 2). Principal investigator (PI) and overall manager for UFI is Steven Effler; David Matthews will serve as a Co-PI and assistant manager. UFI's QC officer is Gina Kehoe. She is responsible for overseeing all of UFI's quality control (QC). UFI will be responsible for the water quality modeling. UFI will be responsible for generating the single comprehensive Phase 2 final report. Technical stakeholder input, including appropriate supporting data sets, will enter the project primarily from TAC and the MEG, through NYSDEC (Figure 2).

Information, insights and technical opinions will flow freely between UFI, EL, and CU staff through the respective project managers. Moreover two technical meetings are planned over Phase 2 to promote effective briefing of NYSDEC on findings and to receive technical input from the agency, the TAC and the MEG. Project key personnel, their affiliations and their project title/ responsibilities are summarized in Table 1. The project organization (Figure 2) features multiple forms of "checks and balances" to assure project quality. Technical oversight and assurances include: (1) the functioning and active communication among the project PI and project managers, (2) inputs from the respective QA officers, (3) inputs from NYSDEC technical staff, and (4) input from the TAC and MEG.

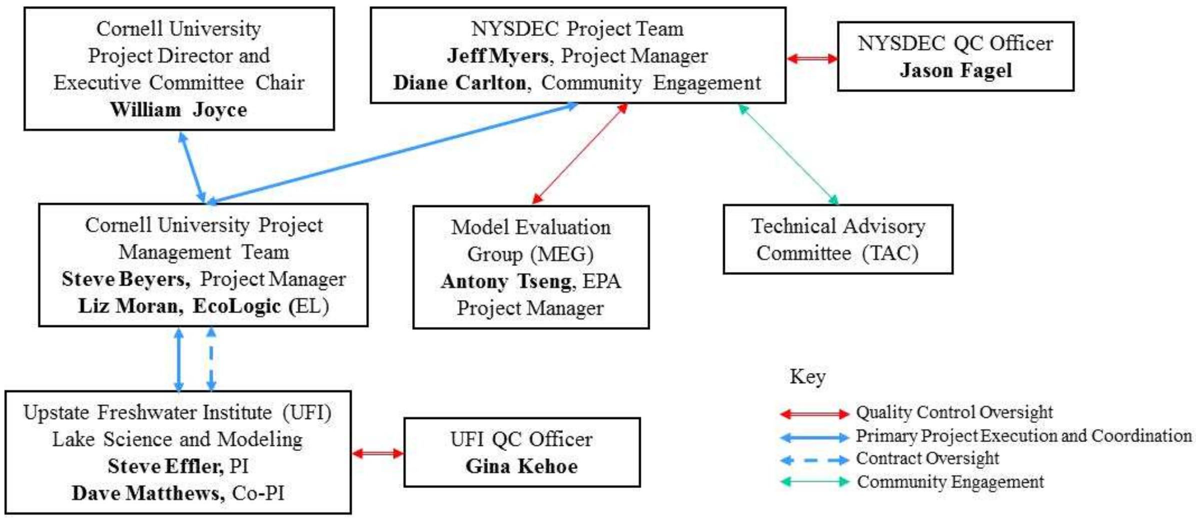

Figure 2 . Organizational chart for the overall Phase 2 project *"Phase 2: A Water Quality Model for the Phosphorus/Eutrophication Issues for Cayuga Lake"*.

A.2. Project Definition/Background

The Finger Lakes of central New York (Figure 3 a and b) consist of 11, elongated, north-south oriented lakes. These lakes originated as pre-glacial stream valleys, which were subsequently enlarged and deepened by a combination of ice and sub-glacial meltwater erosion during the Pleistocene (Mullins and Hinchey, 1989; Mullins et al., 1996). The modern Finger Lakes were last structured during the late Wisconsinan by a surge of the Laurentide ice sheet (Lajewski et al., 2003). Calcareous soil occurs widely, particularly in the watersheds of the eastern Finger Lakes Bloomfield, 1978). European settlement of these watersheds occurred in the late 1700s and early 1800s. The Finger Lakes were the focus of some of the earliest limnological investigations (Birge and Juday, 1914; Birge and Juday, 1921) in the United States. Most of the Finger Lakes are multi-use systems. This system of lakes presently supports a substantial tourism industry. The esthetics of these lakes is an important feature of their resource value.

Cayuga Lake (42.69 °N; 76.69 °W) is the fourth easternmost of the New York Finger Lakes (Figure 3b). It has the second largest volume ($9.38 \times 10^9 \cdot m^3$) and the largest surface area of the Finger Lakes (Schaffner and Oglesby, 1978). The mean and maximum depths are 55 and 133 m, respectively. This alkaline hardwater lake has a warm monomictic stratification regime, stratifying strongly in summer, but only rarely developing complete ice cover (Oglesby, 1978). The hypolimnion remains well oxygenated (Oglesby, 1978). The lake is mesotrophic with an intermediate level of biological productivity (Callinan, 2001). The average retention time of the lake is about 10 years (Shaffner and Oglesby, 1978). Much of the tributary inflow received by the lake enters at the southern end of the lake; e.g., about 40% of the tributary inflow is contributed by Fall Creek, Salmon Creek, Six Mile Creek, and Cayuga Inlet. Parts of the shallow southern end of the lake were bordered by a marsh before it was filled in the early 1900s to support development.

Table 1: Project Key personnel, affiliations and title/responsibility.

No.	Project Personnel	Affiliation	Title/Responsibility
1	Jeff Myers	NYSDEC	Project Contact
2	Steve Gladding	NYSDEC	technical oversight
3	Diane Carlton	NYSDEC	Community Outreach
4	Susan VanPatten	NYSDEC	Community Outreach
5	Jason Fagel	NYSDEC	QC Officer
6	William Joyce	CU	Project Director and Executive Committee Chair
7	Steve Beyers	CU	Project Manager
8	Steve Effler	UFI	Lake Science and Modeling PI
9	David Mathews	UFI	Lake Science and Modeling Co-PI
10	Gina Kehoe	UFI	QC Officer
11	Liz Moran	EL	project management support
12	Antony Tseng	EPA	EPA project manager
13	Dave Mitchell	Abt Associates	manager of MEG
14	Brian Cummings	Queens University	MEG member
15	Devendra Amatya	US Forest Service	MEG member
16	Stewart Rounds	USGS	MEG member
17	Scott Wells	Portland State University	MEG member
18	Aaron Ristow	Tompkins County Soil & Water	TAC member
19	Dick Yager	USGS	TAC member
20	Roxy Johnston	City of Ithaca Watershed Coordinator	TAC member
21	John Halfman	Finger Lakes Institute/ Hobart William Smith Colleges	TAC member
22	Rosella O'Conner	EPA	TAC member

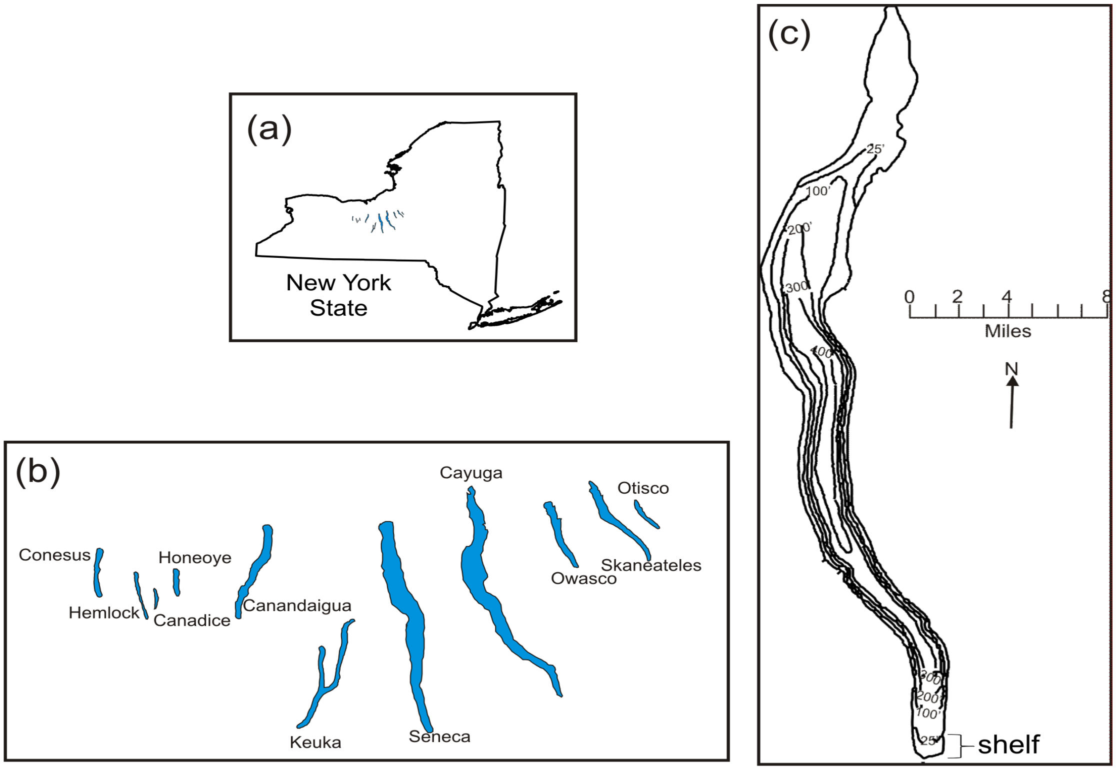

Figure 3 . Map of (a) Finger Lakes location in New York State, (b) Cayuga Lake’s position within the Fingers Lakes System, and (c) a bathymetric map of Cayuga Lake.

Phytoplankton growth in the lake is P limited (Oglesby, 1978). Zebra mussels invaded this lake and other waters of the region in the early to mid-1990s (New York Sea Grant, 2000). Quagga mussels had invaded the lake by the early 2000s. The City of Ithaca (population ~30,000) borders the southern end of the lake and is the largest urban center in the watershed.

Cayuga Lake is an invaluable resource to the region that is used for contact recreation, fishing, navigation, as a water supply by several communities, a source of cooling water, and for disposal of treated municipal wastewater. The shallow southern end of the lake receives effluent from two domestic wastewater treatment facilities (Ithaca Area Waste Water Treatment Plant (IAWWTP), Cayuga Heights Waste Water Treatment Plant (CHWWTP)) with average discharge flows of 0.3 and 0.05 m^3/s, and spent cooling water from a "lake source cooling" (LSC) facility (Cornell University). The limit for the concentration of total phosphorus (TP) of the WWTP effluents had been 0.4 mg/L for IAWWTP and 0.5 mg/L for the CHWWTP. Substantial reductions in effluent concentrations and loading of P from the CHWWTP and IAWWTP have been achieved recently from upgrades in treatment. Presently point source contributions to the total bioavailable P load to the lake are less than 5% (Prestigiacomo et al., 2015; UFI, 2014).

Since early July 2000, cold water has been withdrawn from a depth of 73 m by the LSC facility and returned to the shallow waters of the southern end of the lake. The discharge flow varies seasonally, from ~0.6 m^3/s in the cold months to ~2 m^3/s in summer. This represents an artificial form of internal cycling of P. Conditions in the shallow southern end of the lake have generally been considered degraded relative to the pelagic zone (Oglesby, 1978). This shallow southern zone, demarcated as the southernmost 2 km where depths are less than 6 m (Figure 3c), is designated here as the "shelf". There is great concern for water quality on the shelf because of the localized inputs, the proximity to the area's largest population center, and the associated demand for the lake's resources. Government regulators have identified phosphorus (P; cultural eutrophication), "silt/sediment" and bacteria (public health indicator) as water quality issues of concern for the shelf.

Phosphorus has long been recognized as the most critical nutrient controlling phytoplankton growth in most lakes in the north temperature zone. Degradation of water quality has been widely documented for lakes that have received excessively high inputs (loads) of P (Wetzel, 2001). One feature of the designated impairment of the southern end of Cayuga Lake is high total P concentrations. In certain years the NYSDEC's guidance value of 20 µg/L (as a summer average in the upper waters) has been exceeded. Elevated concentrations of P may be accompanied by high concentrations of phytoplankton biomass, as indicated by the concentration of chlorophyll *a* (Chl-*a*), and diminished water clarity, as measured with a Secchi disc. Contemporary water quality management is usually guided by mathematical models that quantitatively couple the effect of inputs, both external (point and non-point) and internal (within lake cycling), with in-lake concentrations and associated attributes of water quality (Chapra, 1997).

Thermal stratification is an ubiquitous phenomenon in deep lakes in temperate climates and is an important regulator of commonly monitored features of water quality (Wetzel, 2001). Features of stratification and its interplay with water motion mediate the cycling of key constituents, including phosphorus, and metabolic rates. These features are dependent on a number of factors (or drivers), including basin morphometry, setting, hydrology, and meteorological conditions. Substantial year-to-year variations in stratification/mixing occur as a result of natural variations in meteorological conditions. A mechanistic mathematical model is necessary to simulate the thermal stratification/mixing regime, as a function of the various drivers, as part of an overall initiative to develop a mechanistic lake water quality model, where the water quality feature(s) of interest depends on this regime. Accordingly, a hydrothermal/transport model serves as the underpinning physical framework (a key sub-model) for the overall water quality model. To first set-up and test (separate from the overall water quality model) the hydrothermal/transport model, as adopted in this project's phased approach, is good modeling practice. This was successfully completed in Phase 1 of the study (Gelda et al., 2015; UFI 2014)

It is now well recognized that all forms of phosphorus are not immediately, nor ultimately, available to support algal growth. Dissolved forms of phosphorus are generally more available to support algal growth than particulate forms (Effler et al., 2012). The fraction of particulate phosphorus that is bioavailable can differ widely amongst tributaries and between effluents for different municipal wastewater treatment facilities (Young et al., 1982). Resolution of the bioavailability of the important inputs of phosphorus is important in driving phosphorus/

eutrophication models, and in evaluating various sources to guide effective rehabilitation initiatives. Bioavailability bioassays were conducted for both key tributaries and the primary waste discharge to guide the development of loads for a phosphorus/eutrophication model for Onondaga Lake, that was implemented in a phosphorus TMDL analysis.

The bioavailability bioassays for this Cayuga Lake study were conducted in Phase 1 in the same manner as those performed for the Onondaga Lake study (Effler et al., 2012). The bioassays were conducted using modifications of the Dual Culture Diffusions Apparatus (DCDA) developed by DePinto (1982), as applied to inputs of the Great Lakes (DePinto et al., 1981; Young et al., 1982), the New York City reservoir system (Auer et al., 1998), various receiving waters in Finland (Ekholm and Krogerus, 2003), and Onondaga Lake (Effler et al., 2002; Effler et al., 2012). In these bioassays, phosphorus mobilized from concentrated particulates diffuses across a semi-permeable membrane and is taken up by phosphorus-starved algae (*Selenastrum capricornutum*). The bioassays provided both the fraction of the particulate phosphorus that is bioavailable and a representation of the rate of conversion to a bioavailable form.

A.3. Project/Task Description

A.3.1. Project Description

The Phase 2 project is organized into tasks (or elements) and sub-tasks. Together these tasks will result in a tested mechanistic water quality model that is focused on the P-eutrophication issues for Cayuga Lake. These tasks or elements are listed below.

A. satisfy quality assurance (QA) requirements through the preparation of a Phase 2 addendum (this document) to the Phase 1 QAPP, and execution of the various QA elements stipulated therein.

B. individual constituent model analysis

C. analysis of Cayuga Inlet Channel data to adjust constituent loads from contributing streams for the effects of deposition within the channel

D. minerogenic particle submodel development and testing

E. optics submodel development and testing

F. development and testing of the nutrient-phytoplankton submodels, within the framework of the overall integrated water quality model

G. development of external loading drivers for model validation years

H. development of linkage(s) between the landuse and lake water quality models

I. conduct and interpret long-term simulations with the tested lake water quality model to demonstrate effects of natural variations in drivers

J. prepare Phase 2 final project report

K. transfer of P-eutrophication water quality model to NYSDEC

The overall Cayuga Lake project (see the *Introduction* of this QAPP for detailed description of both Phase 1 and 2 project phases) goal is to develop and test a phosphorus/eutrophication model (in Phase 2) for Cayuga Lake that addresses the related water quality issues and is capable of supporting a phosphorus TMDL analysis for the southern portion of the lake. These tasks receive more treatment in the following *Section (A.3.2.)*.

A.3.2. Project Tasks

This section expands on some of the tasks or elements, listed above in *Section A.3.1*, providing related sub-tasks or components.

A. satisfy quality assurance (QA) requirements through the preparation of a Phase 2 addendum (this document) to the phase 1 QAPP.

B. individual constituent model analyses

This task will provide diagnostic support for the overall modeling initiative by developing interim estimates of the magnitude of in-lake sink processes for selected constituents. As a minimum it will be conducted for nitrate + nitrite (NO_X; = nitrate (NO_3^-) + nitrite (NO_2^-); NO_3^- dominates). Other prospective constituents include dissolved organic carbon (DOC), particulate organic carbon (POC), total phosphorus (TP), and soluble unreactive phosphorus (SUP). Elements of analyses include:

1. use of a previously tested (Phase 1) two-dimensional hydrothermal/transport submodel (W2/T; Gelda et al., 2015; UFI, 2014) as the physical transport framework
2. use previously calculated (Phase 1) external loadings rates of selected constituent, at a daily time step, for the study period of 2013 (Pestigiacomo et al., 2015; UFI, 2014).
3. use of in-lake measurements of the constituent, for the study period of 2013, as previously reported (UFI, 2014), as a basis for calibration
4. adjustment of net loss rate values, as necessary to match in-lake pattern (e.g., estimated from calibration).
5. use hydrothermal/transport model to support limnological and preliminary mass balance analyses.
6. performance will be evaluated graphically by degree of match to observations and statistically according to the root mean-square error (RMSE) statistic.

C. analysis of Cayuga Inlet Channel data to adjust constituent loads from contributing streams for the effects of deposition within the channel

It is acknowledged that deposition occurs in the Inlet Channel, thereby diminishing the effective external loading from contributing streams (including Cayuga Inlet Creek and Six Mile Creek). Adjustments of the external loads will be based on measurements made with deployed instrumentation made near the mouth of the channel during the study period of 2013. The analysis has two elements

1. determination of outflow from the channel to the lake, and

2. use of turbidity-constituent relationships established for multiple particulate constituents for these tributaries, to establish the effective concentration as these exit the channel into the lake.

D. minerogenic particle submodel development and testing

The primary state variable to be predicted by this submodel is the projected area of minerogenic particles per unit volume (PAV_m). Predictions of PAV_m are invaluable as they are linearly related to the effects of these particles on P concentrations and common optical metrics of water quality. Testing of this submodel can be conducted outside of that for the overall water quality model, as primary production (phytoplankton growth) does not influence the minerogenic particles. Elements of this modeling include:

1. use of previously tested (Phase 1) two-dimensional hydrothermal/transport submodel (W2/T; Gelda et al., 2015; UFI, 2014), and its drivers, as the physical framework
2. use of previously calculated external loading rates (Phase 1) of multiple size class contributions to PAV_m, at a daily time step, for the study period of 2013 (UFI, 2014)
3. use of in-lake measurements of PAV_m (Phase 1) associated with the same size classes, as previously reported for the study period of 2013 (UFI, 2014), as a basis for calibration
4. adjustment of loss rates associated with deposition, and perhaps aggregation, necessary to match in-lake patterns of overall PAV_m and the contribution from the various size classes (calibration)
5. validation of the submodel (good performance with the same coefficients) for observations from a different year(s) (Peng and Effler, 2005; Effler and Peng, 2014)

E. optics submodel development and testing

Optical metrics of water quality such as Secchi depth, turbidity, and the attenuation coefficient for scalar irradiance are an important issue for the lake and interact with phytoplankton growth. Simple empirical relationships between light attenuating constituents, described as optically active constituents (OACs), and these optical measurements have been found to be weak. Instead a theoretically sound submodel will be developed and tested. Elements of this modeling include:

1. use of previously reported (Phase 1) time series of OACs from the lake (UFI, 2014)
2. development of coefficients, often described as cross-sections in the optics literature. Some have already been developed and reported for Cayuga Lake (Effler et al., 2015b; UFI, 2014)
3. use of previously reported time series of inherent optical properties (IOPs), including absorption and scattering coefficients (Effler et al., 2015a)
4. use of accepted equations to predict the optical measurements of water quality of interest (Secchi depth (SD), and attenuation coefficients for scalar irradiance; UFI, 2014)
5. compare these predictions to measurements made in Phase 1 (Effler et al., 2015a; UFI, 2014)
6. adjust coefficients as necessary to calibrate
7. validate for a different set of measurements made as part of LSC monitoring (Effler and Peng, 2014)

F. development and testing of the nutrient-phytoplankton submodels, within the framework of the overall integrated water quality model

This critical step requires the integration of the other separately tested submodels and will yield the overall water quality model for the lake, consistent with stated goals to support simulations that target the P-eutrophication issues. Elements of this modeling include:

1. use of a previously tested (Phase 1) two-dimensional hydrothermal/transport submodel (W2/T; Gelda et al., 2015; UFI, 2014), and its drivers as the physical framework.
2. use of the separately tested minerogenic particle submodel (D. above), that influences/ contributes to the issues of nutrient (P) and phytoplankton biomass and its effects
3. use of the separately tested optics submodel (E. above), that influences/contributes to the issue of phytoplankton biomass and its effect on optical metrics of water quality
4. use of previously calculated external loading rates for multiple constituents (e.g., forms of sediment (including PAV_m) and other nutrients), necessary to support simulations of the overall model (subsequently listed). These will be used at a daily time step for the study period of 2013.
5. use of in-lake measurements that correspond to the state variables of the overall model, for the study period of 2013, as a basis for calibration
6. appropriately represent the effects of zebra and quagga mussel metabolism including grazing and nutrient excretion
7. adjustments of coefficients that describe the P cycle and phytoplankton growth and biomass, as well as the behavior of other modeled constituents, to match the primary features of patterns
8. validation of the overall model, and thereby the nutrient-phytoplankton submodels (good performance with the same coefficients) for observations from a different year (s).

G. development of external loading drivers for model validation years

The primary bases to develop constituent loads for years selected for validation testing are the generally strong constituent-tributary flow (Q) relationships developed from the intense 2013 program in Phase 1. Accordingly, the concentrations can be estimated from the Q records, with loads calculated (daily time step) as the product of concentration and Q. These estimates may be enhanced for intervals when measurements were made.

H. development of linkage(s) between the landuse and lake water quality model

This task enables the evaluation of landuse management scenarios, by allowing output from the landuse model to provide, or guide, the specification of loading inputs to the lake water quality model. This may include creating linkages for imperfectly matched land use model outputs and lake model inputs, such as related to differences in state variables of the models.

I. conduct and interpret long-term simulations with the tested lake water quality model to demonstrate effects of natural variations in drivers

These simulations will represent the extent to which natural (e.g., year-to-year) variations in model (lake water quality) drivers such as tributary flows and constituent loads, can cause interannual variations of key metrics of lake water quality, and thereby potentially mask the effects of systematic management actions. Key features enabling such model analyses include:(1) long-term flow rate records for key tributaries, (2) reasonably long-term records of constituent concentrations for key tributaries, and (3) reasonably strong constituent concentration versus stream flow relationships for key constituents. Model output will be interpreted and presented in a probabilistic format.

J. prepare Phase 2 final project report

The report will summarize the development and testing of the submodels and overall modeling conducted in Phase 2. Parts or all of the report may consist of manuscripts submitted to (e.g.,in review) or published in professional journals.

K. transfer of P-eutrophication water quality model to NYSDEC

The model, to be provided by UFI as a product of the Phase 2 work, will be suitable to provide quantitative support for a P TMDL analysis; e.g., that may be conducted by NYSDEC. Cornell University would not be involved in such an analysis; i.e., not as an active participant nor as a funder. The conduct of a P TMDL analysis would be outside of the scope of Phase 2 and therefore is not covered in this Phase 2 QAPP.

A.3.3. Overview of Modeling Framework and Approach

A.3.3.1. Required Attributes of the Phosphorus-Eutrophication Model

A model is a theoretical construct that assigns numerical values to parameters and related external inputs of forcing conditions to system variable responses (Thomann and Mueller, 1987; Chapra, 1997). The results and limnological analyses of Phase 1 of this project provided invaluable guidance in identifying the attributes required for a phosphorus (P)-eutrophication model focused on the shelf of Cayuga Lake. This supporting information was provided in the final report for Phase 1. The presentation provided here is consistent with that of the Phase 1 report (UFI, 2014).

A clear recurring “disconnect” of the three common trophic state metrics, the concentration of TP, the concentration of Chl-*a*, and Secchi depth (SD), has prevailed for the shelf versus pelagic waters of the lake. This disconnect is 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 relative to pelagic waters. The model will need to successfully represent these different signatures. There are sound limnological explanations for these differences (UFI, 2014) that will need to be quantified appropriately in the overall model. The disconnect can be considered to have two primary elements (1) the greater contributions of minerogenic particles from the watershed to TP and SD conditions on the shelf, and (2) the absence of locally greater phytoplankton growth (and biomass) on the shelf despite higher concentrations of immediately bioavailable forms of P (soluble reactive P (SRP)).

The first element requires a robust treatment of minerogenic particles in the model that is being addressed by a submodel, described subsequently. This important role of minerogenic particles supports the position that the sediment issue for the shelf can not be separated from the P issue. The second of the above elements requires model attributes that appropriately represent the effects of (1) the short residence time of the local tributary and point source 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 local inflows. The temporal patterns of Chl-*a* for the shelf generally track lake-wide pelagic patterns, supporting the position that shelf levels and dynamics reflect lake-wide conditions. A number of P and biomass signatures were resolved for pelagic waters in Phase 1 (UFI, 2014) that will be valuable in developing and testing the P-eutrophication model to simulate these lake-wide patterns.

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 increased uncertainty and excessive computational demands. Robust ranges of temporal and spatial scales will be represented in the modeling to address the primary signatures resolved in monitoring (Phase 1; UFI, 2014). Short-term patterns in response to runoff events, that are primary drivers of the shelf versus pelagic waters differences, need to be resolved. The seasonality in phytoplankton growth, manifested lake-wide, and the potential effects of year-to-year differences in runoff and associated external loading, will also have to be represented. Spatial structure of the overall model must be capable of resolving longitudinal differences on the shelf, between the shelf and pelagic waters, and lake-wide mixing and the effects of the thermal stratification regime (UFI, 2014; Gelda et al., 2015).

The overall water quality model will require multiple types of drivers, including (1) local meteorological conditions, (2) local hydrologic conditions, and (3) external loading rate estimates for multiple constituents. These drivers have been comprehensively documented in Phase 1, and have been described, presented and utilized in multiple ways in the final Phase 1 report (UFI, 2014) and have been integrated into multiple manuscripts to appear in professional journals (Gelda et al., 2015; Prestigiacomo et al., 2015). A preliminary listing of the state variables of the overall model is presented as Table 2. A list of preliminary derived state variables is presented in Table 3. The overall water quality (P-eutrophication) model will be composed of several submodels that are identified and described below. Conceptual models depicting structural features are presented for each except for the two-dimension hydrothermal/transport model that was successfully completed in Phase 1. Each of these conceptual models reflect insights and results from Phase 1, earlier journal manuscripts on the system, or related studies in the literature for other systems. Moreover, these submodels and related approaches were presented to NYSDCEC and review panels in the presentation of November 5, 2014 (without critical comment) and in the Phase 1 report (UFI, 2014).

A.3.3.2. Submodels of the Water Quality Model

A.3.3.2.1. Hydrothermal/Transport Submodel

The two-dimensional hydrothermal/transport model, W2/T, has been set-up, rigorously tested, and preliminarily applied for Cayuga Lake, as described in Section 6 (UFI, 2014; Gelda et al., 2015) of the Phase 1 report. This model serves as the transport submodel of the water quality model, CE-QUAL-W2, a public access model developed by the U.S. Army Corp. This model will serve as the transport submodel of the Cayuga Lake P-eutrophication model. The two-dimensional model simulates the thermal stratification regime and mixing/transport processes in the vertical and longitudinal dimensions. The model was calibrated for the conditions of 2013, and validated for the 1998- 2012 period through continuous simulations.

Table 2: Tentative list of state variable names and abbreviations.

Pool	Name	Abbreviation
carbon	labile dissolved organic carbon	LDOC
	refractory dissolved organic carbon	RDOC
	labile particulate organic carbon	LPOC
	refractory particulate organic carbon	RPOC
plankton	algal biomass	ALG
phosphorus	soluble reactive phosphorus	SRP
	labile soluble unreactive phosphorus	LSUP
	refractory soluble unreactive phosphorus	RSUP
	labile particulate organic phosphorus	LPOP
	refractory particulate organic phosphorus	RPOP
	labile particulate inorganic phosphorus	LPIP
	refractory particulate inorganic phosphorus	RPIP
optics/ particles	turbidity for size class i	Tn_i
	Secchi disc	SD
	projected area of minerogenic particles per unit volume, for size class i	$PAV_{m,i}$
	scaler PAR attenuation coefficient	K_0(PAR)

The time (daily to multiple years) and space (Figure 4, Figure 5) features of W2/T are consistent with the water quality issues identified for Cayuga Lake (Gelda et al., 2015; UFI, 2014), and particularly to resolve the effects of runoff events and the differences between the shelf and pelagic areas. The model is capable of representing various complexities of transport processes that may be noteworthy with regards to the water quality issues of the lake, including the residence time of local tributary inputs on the shelf, the seasonal plunging of tributaries, and vertical transport from the hypolimnion to the productive epilimnion (Gelda et al. 2015).

Table 3: Derived state variables.

Pool	**Name**	**Abbreviation**	**Components**
carbon	dissolved organic carbon	DOC	= LDOC + RDOC
	particulate organic carbon	POC	$= LPOC + RPOC + ALG \cdot a_{C\text{-}ALG}$ (1)
	total organic carbon	TOC	= DOC + POC
algal biomass	total chlorophyll *a*	Chl-*a*	$= ALG \cdot a_{Chl\text{-}ALG}$ (2)
phosphorus	soluble unreactive phosphorus	SUP	= LSUP +RSUP
	particulate organic phosphorus	POP	$= LPOP + RPOP + ALG \cdot a_{P\text{-}ALG}$ (3)
	particulate inorganic phosphorus	PIP	= LPIP + RPIP
	total dissolved phosphorus	TDP	= SRP + SUP
	particulate P	PP	= POP + PIP
	total phosphorus	TP	= TDP + PP
optics particles	total turbidity	Tn	$= \sum_{i=1}^{N} Tn_i$
	total PAV	PAV_m	$\sum_{i=1}^{N} PAV_{m,i}$
	total suspended solids	TSS	empirical relationship with Tn
	total inorganic suspended solids	FSS	empirical relationship with Tn

(1) $a_{C\text{-}ALG}$ - carbon to algal biomass stoichiometric ratio
(2) $a_{Chl\text{-}ALG}$ - chlorophyll to algal biomass stoichiometric ratio
(3) $a_{P\text{-}ALG}$ - phosphorus to algal biomass stoichiometric ratio

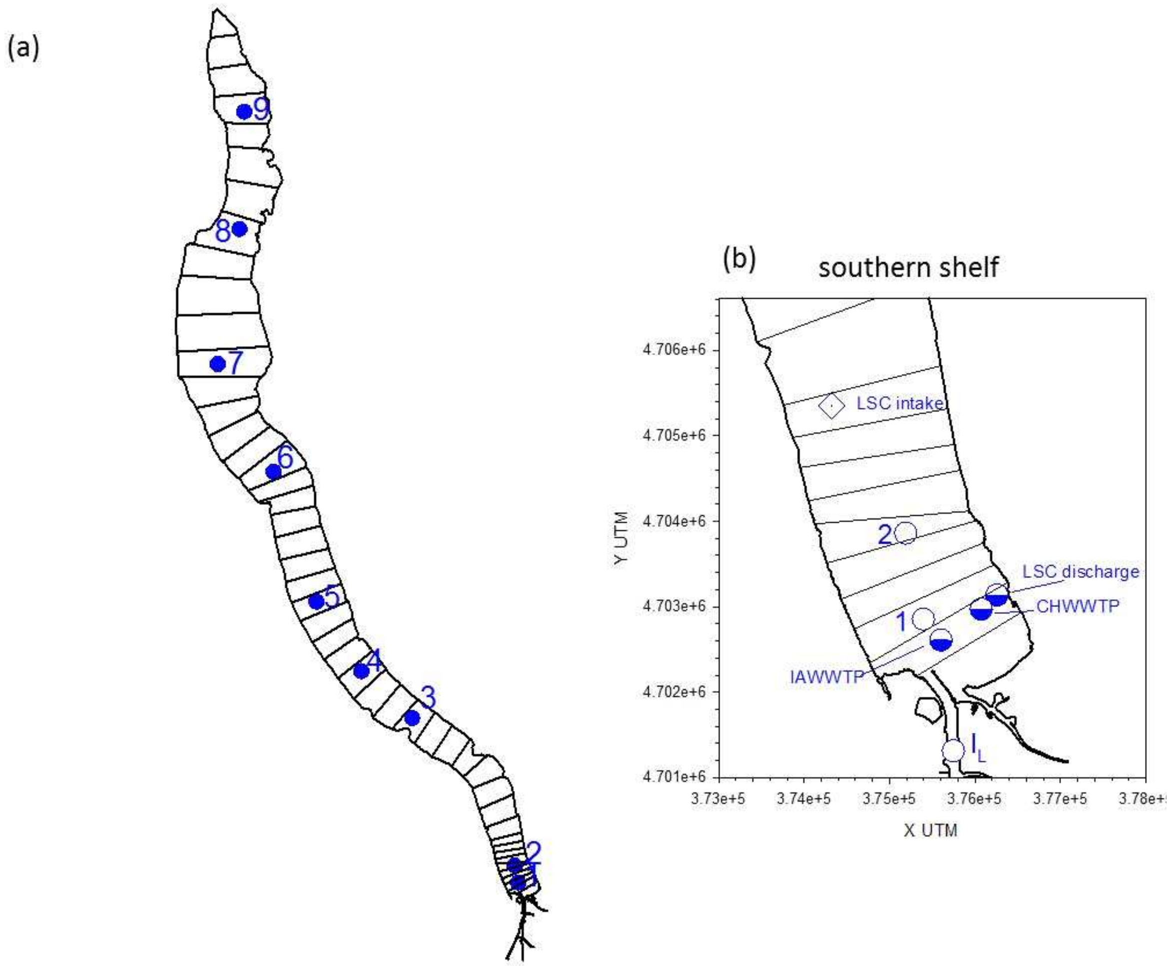

Figure 4 . Cayuga Lake for (a) longitudinal segments for the entire lake as adopted in the model, along with the monitoring sites for 2013, and (b) model segments for the shelf at the southern end of the lake. Locations of WWTP and LSC intake/discharge are identified.

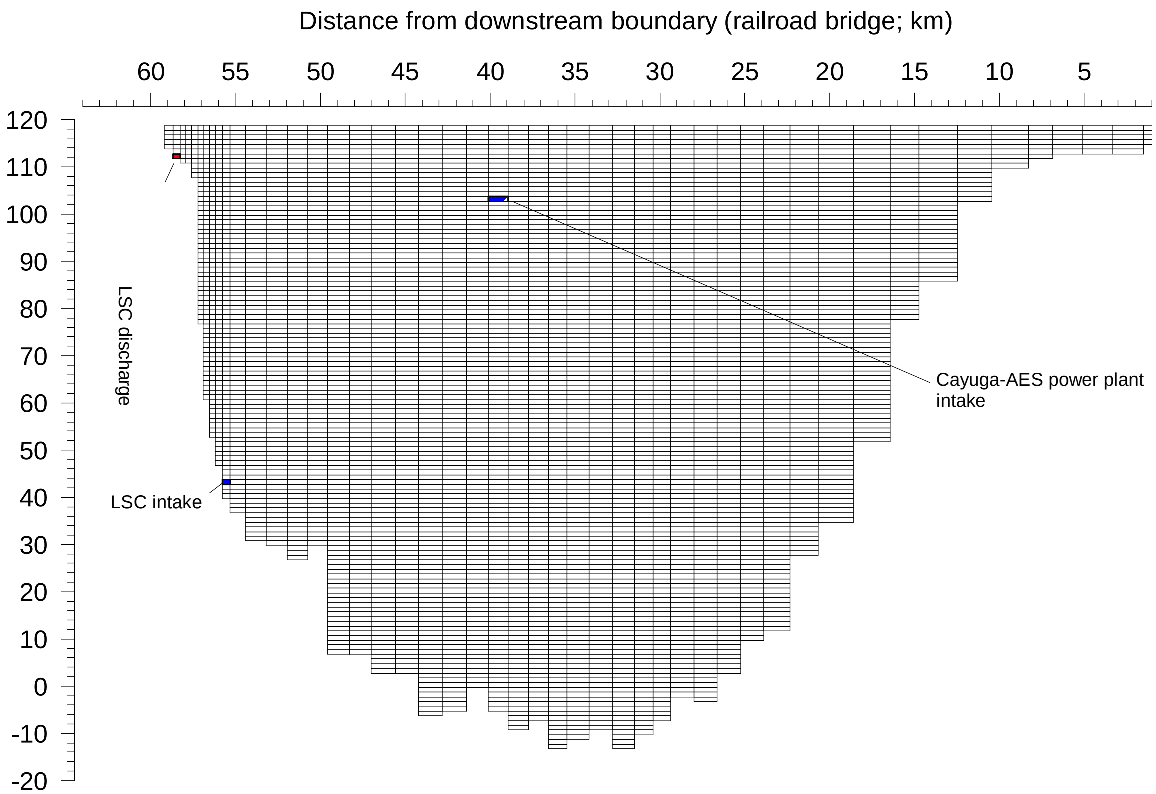

Figure 5 . Longitudinal-vertical computational grid of the lake adopted in the model. Model cell with LSC intake, LSC discharge, and Cayuga-AES power plant intake are identified.

A.3.3.2.2. Minerogenic Particle Submodel

As described in Section 5 of the Phase 1 report (UFI, 2014) and the peer-reviewed literature, minerogenic particles delivered to Cayuga Lake from its watershed play an important role in metrics of water quality in the lake, including phosphorus, turbidity, clarity and light penetration (UFI, 2014; Effler and Peng, 2014; Effler et al., 2014). The key model state variable is the projected area of minerogenic particles per unit volume (PAV_m). The modeling approach (multiple size classes, Figure 6) is similar to that developed and successfully tested and applied for turbidity (Tn) in the New York City water supply reservoirs (Gelda and Effler, 2007; Gelda et al., 2009; Gelda et al., 2012; Gelda et al., 2013). PAV_m will be partitioned into the contributions of multiple size classes. Four size classes have been adopted in data analyses presented in the Phase 1 report (UFI, 2014), though other segmentation schemes may be adopted to represent the associated behavior responsible for temporal patterns observed following external inputs (Figure 4).

External loads of PAV_m will be received for the same size classes, as specified by measurements for the calibration year of 2013, and based on PAV_m-Q relationships (Figure 6) for days without observations in 2013, as well as for model validation years. The size classes will be subjected to size-dependent settling losses (Stokes' Law) and conversions to other size classes associated with aggregation/disaggregation processes (Figure 6). The aggregation/disaggregation processes will likely be represented by a "net" aggregation that will be quantified through calibration of the submodel to track observations of in-lake patterns. Predictions of PAV_m in time and space will be the summation of the contributions for the different size classes. Predictions of particle volumes of minerogenic particles per unit volume (PVV_m) will be calculated from the PAV_m size class values (Figure 6) assuming a particle geometry (initially spherical, but may be platelets). Predictions of PAV_m can support predictions of (Figure 6) (1) the minerogenic component of PP (PP_m), (2) the minerogenic component of Tn ($Tn_{/m}$), and (3) levels the absorption (a_m) and scattering (b_m) coefficients for minerogenic particles, that serve as inputs

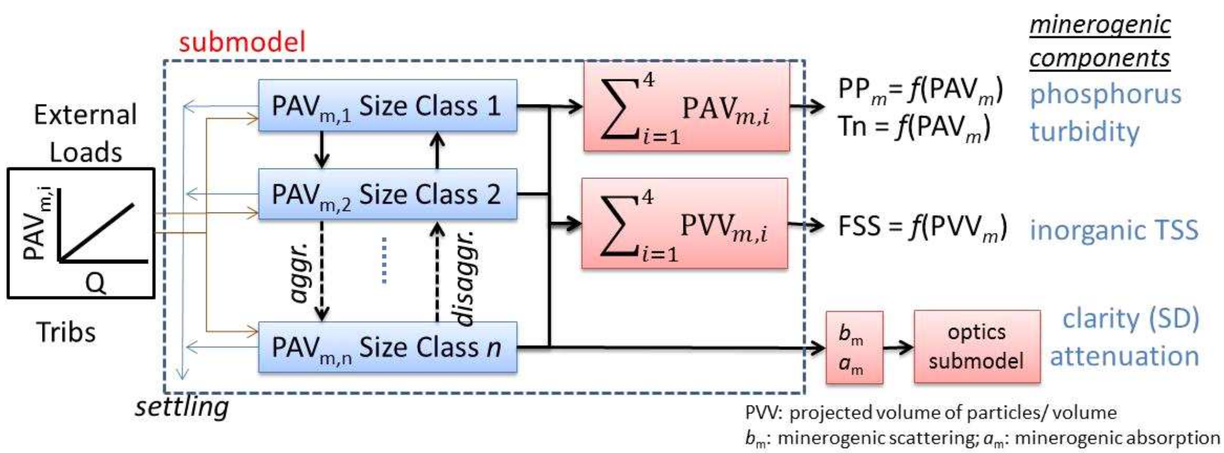

Figure 6 . Conceptual diagram for a minerogenic particle submodel.

to the optics submodel (described subsequently). The predictions of PVV_m could serve to support predictions of inorganic (fixed) suspended solids (FSS). The submodel will be integrated into the overall water quality model.

A.3.3.2.3. Optics Submodel

Predictive capabilities are required for the optical metrics of water clarity, as represented by Secchi depth (SD), and the attenuation coefficient for scalar irradiance (K_0(PAR)). SD is a primary trophic state and water quality metric of concern for lacustrine systems, including Cayuga Lake. K_0(PAR) is important as it specifies the light available at various depths to support photosynthesis and phytoplankton growth. Empirical relationships between each of these metrics and Chl-a, as a measure of phytoplankton biomass, have been adopted elsewhere as part of P-eutrophication modeling. However, in Cayuga Lake, as well as many other lakes, this is inadequate (e.g., performs poorly) because other substances contribute importantly to these optical conditions, and these do not necessarily covary with phytoplankton. In such cases, a mechanistic framework, one that is consistent with optical theory, is adopted.

A theoretically sound mechanistic framework is described in the schematic of Figure 7 (see Table 4 for definition of symbols). Accordingly (moving left to right), the constituents that influence the optical measures of concern (SD and K_0(PAR)) described as apparent optical properties (AOPs)) are described as the optically active constituents (OACs). The OACs are mostly state variables of the water quality model or can be independently specified. These include measures of phytoplankton biomass (Chl-*a* or POC) and minerogenic particles (PAV_m or FSS (ISPM)). Associated components of the absorption (*a*) and scattering (b) coefficients, both described as inherent optical properties (IOPs), are estimated according to OAC – specific coefficients (cross-sections; Figure 7). The desired AOPs are predicted from IOPs using well – established equations (radiative transfer expressions; Figure 7). Most of the elements of the model have been developed and successfully tested for Cayuga Lake (Effler et al., 2015b), including (1) development of cross-sections, (2) closure of the summation of absorbing components with overall absorption, and (3) closure IOPs and AOPs through application of the radiative transfer equations. Testing of the overall submodel will be conducted based on a robust set of observations of OACs, IOPs and AOPs (UFI, 2014; Effler et al., 2015b). The submodel will be integrated into the overall water quality model (Figure 8).

A.3.3.2.4. Phosphorus Submodel

A robust representation of the overall P pool and cycle is required to address the various issues identified here for Cayuga Lake (Figure 9). This will include multiple dissolved forms; SRP, and both labile (LSUP) and refractory SUP (RSUP). Particulate (PP) forms will include both organic (POP) and inorganic (PIP) forms and partitioning between labile and refractory components. A robust array of source and sink processes will be represented (Figure 9), including: (1) uptake of SRP to support phytoplankton growth, (2) adsorption and desorption of SRP from PIP, (3) hydrolysis of POP to form dissolved species, (4) mineralization/hydrolysis of SUP to form SRP, and (5) deposition of particulate forms.

The details of the framework for the submodel and specification of values of kinetic coefficients that quantify the various processes will be guided by established public domain models (e.g., CE-QUAL-W2, Lake2K), UFI's P-eutrophication model applied to New York City's reservoirs, as well as recent reviews of related models (Arhonditsis and Brett, 2004; Arhonditsis et al., 2006; Robson, 2014). Cycling of P associated with the metabolism of biological communities will also be considered, including excretion by dreissenid mussels and zooplankton and uptake by phytoplankton. Data analyses will support decisions regarding the need for inclusion of these pathways. The minerogenic particle submodel will support simulations of the refractory PIP (RPIP; Figure 9). The concentration of TP will be predicted as the summation of the individual forms.

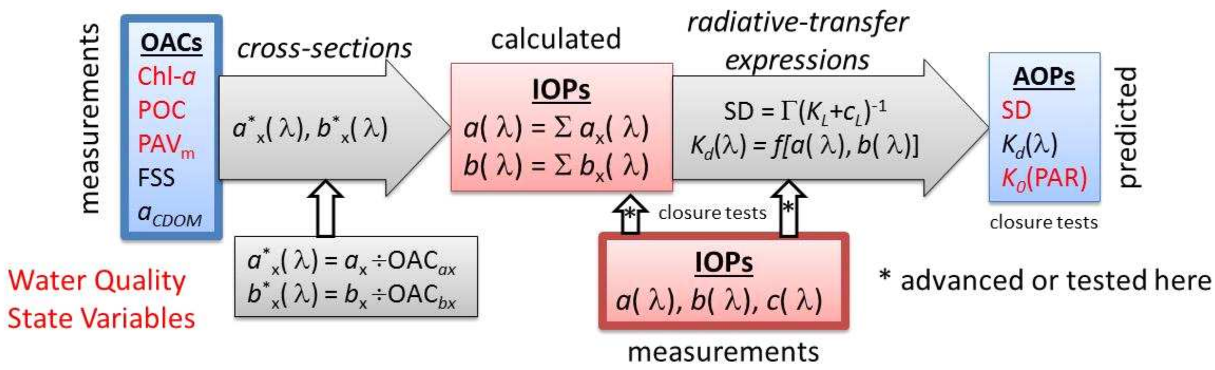

Figure 7 . Conceptual diagram for an optics submodel.

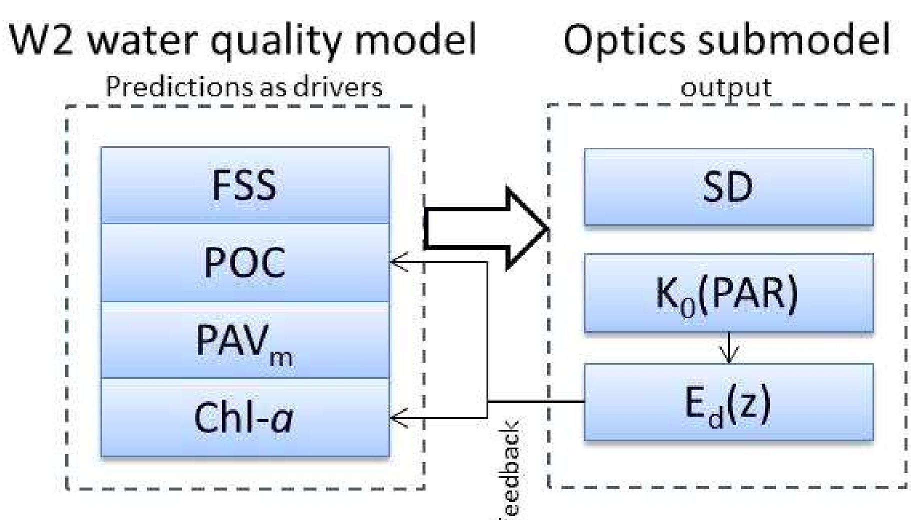

Figure 8 . Conceptual diagram for optics submodel linkage with W-2 water quality submodel.

Table 4: Specifications of symbols in the optics submodel.

Symbol	Specifications
OAC	optically active constituents
Chl-*a*	chlorophyll *a* concentration
POC	particulate organic carbon concentration
PAV_m	projected area of minerogenic particles concentration
FSS	inorganic suspended particulate material concentration (ISPM)
a_{CDOM}	absorption coefficient for CDOM
OAC_{ax}	OAC for a_x
OAC_{bx}	OAC for b_x
IOPs	inherent optical properties
$a(\lambda)$	spectral absorption coefficient
$b(\lambda)$	spectral scattering coefficient
$c(\lambda)$	spectral beam attenuation coefficient
$a_x*(\lambda)$	spectral absorption cross-section for component x
$b_x*(\lambda)$	spectral scattering cross-section for component x
a_x	absorption coefficient for component x
c_L	beam attenuation illuminance coefficient
AOPs	apparent optical properties
SD	Secchi depth
$K_d(\lambda)$	spectral downwelling attenuation coefficient
$K_0(PAR)$	scalar attenuation coefficient for PAR
Γ	coefficient for SD radiative transfer function
K_L	downwelling attenuation illuminance coefficient
other	other variables
$E_d(z)$	downwelling irradiance

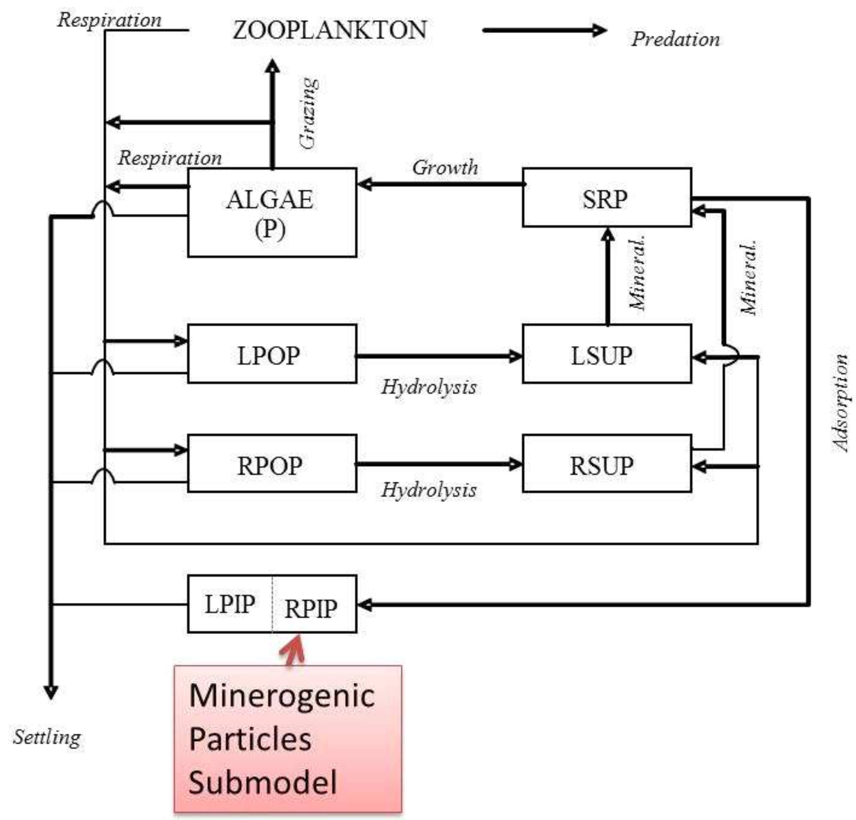

Figure 9 . Conceptual diagram for a phosphorus submodel.

A.3.3.2.5. Phytoplankton Growth/Biomass Submodel

Prediction of phytoplankton biomass is a primary goal of the P-eutrophication modeling initiative. The predictions will be made with a mechanistic phytoplankton growth/biomass submodel (Figure 10). The primary metric of phytoplankton biomass will be POC; prediction of Chl-a will be a secondary goal, at a longer time-scale of seasonal average. The quantitative details of the framework will draw upon other models, including the public domain CE-QUAL-W2 and Lake2k, UFI's P-eutrophication model applied to New York City's reservoirs, as well as appropriate professional literature, including recent reviews of related models (Arhonditsis and Brett, 2004; Arhonditsis et al., 2006; Robson, 2014). This will include representations of the phytoplankton community, kinetic expressions, and values of various coefficients.

The dynamics of phytoplankton biomass will reflect the dynamics of the source (growth) and sink (respiration, settling, and grazing) processes (Figure 10). Grazing will reflect the effects of dreissenid mussels and potentially zooplankton (if found to be noteworthy). The effects of their ambient drivers of phytoplankton growth will be quantitatively represented in the model, including (1) temperature, (2) light availability, and (3) nutrients (Figure 10). Phosphorus (P) is the primary nutrient to be considered. Nitrogen (N) and silica (Si) will be secondary. Nitrogen concentrations in the lake are above levels considered to be limiting to phytoplankton growth. Si

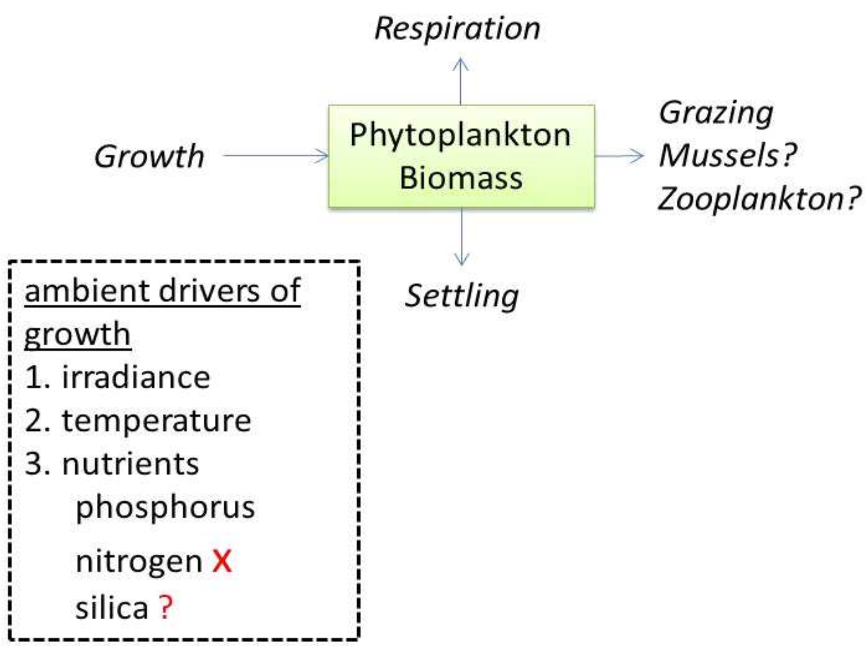

Figure 10 . Conceptual diagram for a phytoplankton growth/biomass submodel.

will need to be considered if the diatom group is to be differentiated in the simulations. Partitioning of the phytoplankton community according to multiple groups has not been established as a modeling goal, but may emerge as the analysis progresses.

A.3.4. Work Schedule

The project/work schedule for the overall Phase 2 project is described in the chart below (Table 5), according to the major tasks. The timeline is both aggressive and feasible. The timing depicts a progression from preliminary single constituent modeling, supporting analyses, and individual submodels in 2015, to the continuation of nutrient-phytoplankton submodels, overall water quality model, landuse-lake model linkages, long-term simulations, and reporting in the following year (2016). Two major project meetings are recommended in early fall of both years.

A.3.5. Project Deliverables

The Phase 2 project deliverables include

1. a QAPP for the project.
2. two project meetings with UFI, Cornell, NYSDEC, and technical review panels to present and discuss progress
3. electronic versions of the model input and in-lake state variable data sets
4. electronic versions of the tested overall water quality model that includes all submodels (transferred by UFI to NYSDEC).

Table 5: Project work schedule for the Phase 2 phosphorus/eutrophication modeling project. (● project meetings).

No.	Component Description	2015 ●				2016 ●			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	individual constituent modeling analysis NO_X, DOC, TP, SUP, POC	→	→	→					
2	inlet channel adjustment to loads	→	→	→					
3	minerogenic particle submodel	→	→	→	→				
4	optics submodel			→	→	→			
5	nutrient-phytoplankton submodel development			→	→	→	→		
6	overall water quality model			→	→	→	→	→	
7	land use - lake models linkages					→	→		
8	long-term model simulations						→	→	
9	Phase 2 report							→	→

5. a final Phase 2 report

A.4. Quality Objectives and Criteria

The overall quality assurance objectives for UFI data analysis and modeling is to analyze, model and accurately report data collected and analyzed by the UFI field and laboratory staff under the Phase 1 work and other approved data sources. For data analysis and modeling the Data Quality Objectives (DQOs) are qualitative and quantitative statements that

- clarify the intended use of data,
- define the type of data needed to support a decision,
- identify the conditions of collecting the data

The DQOs for input data for the phosphorus/eutrophication model are

- data quality for key model inputs (e.g., meteorological, hydrological, external constituent loads) will be representative to support specification of representative driving conditions within the phosphorus/eutrophication model.

- data quality for phosphorus/eutrophication model state variable(s) will be representative to provide a robust test of model performance.
- data quality for both hydrothermal/transport model inputs and state variables will be representative seasonally and for multiple years.

The DQOs for model output (e.g., predictions, simulations) include both qualitative and quantitative perspectives.

- output will be consistent with well accepted limnological paradigms (e.g., Wetzel, 2001)
- output will be consistent with mass balance constraints
- patterns of output in time and space will be consistent with the biogeochemical features of limnological paradigms
- appropriate responses of models to reasonable variations
- performance, according to metrics widely reported in similar modeling initiatives, is consistent with levels reported for other similar efforts

The following table (Table 6) provides target thresholds for the performance of specific predicted metrics for the water quality model to be produced in Phase 2. The metrics are consistent with the prevailing water quality issues, the goal(s) of the Phase 2 modeling, and the potential use of the model to support a TMDL analysis. There are temporal and spatial features for these thresholds. These will be applied on a summer average basis, consistent with common regulatory and trophic state literature representations. Spatially, conditions on the shelf will be contrasted to conditions within the pelagic waters of the lake, consistent with the findings of Phase 1. Should targeted thresholds of performance be unattainable after reasonable effort, UFI will report specifically on the performange issue and qualify the results as appropriate.

Table 6: Targeted thresholds of model performance for multiple metrics of interest.

Predicted Metric	**Targeted Thresholds of Performance [+] % Error[x]**
TP	< 25%
SD	< 25%
Chl-*a*	< 50%
POC	< 30%
PAV_m	< 30%
K_0(PAR)	< 25%

[+] summer average values for the upper waters; [x] % Error = $|$prediction - observation$|$/observation

A.5. Special Training/Certification

No further training is needed by UFI data analysis and modeling staff. They will perform the analysis and phosphorus/eutrophication modeling tasks in this project. The modeling staff are individuals with highly specialized expertise in their respective modeling and data analysis tasks. The staff has been involved in data analysis, model code development and model set up at least 15 years.

A.6. Documents and Records

The UFI data analysis and modeling teams will be responsible for documenting key data analyses, phosphorus/eutrophication model development, testing, and findings, data files and software. Each modeling staff member will be responsible for documenting all assumptions and supporting analyses. They will maintain records of written correspondence, emails between the modeling team members and other project members. Progress will be documented as part of the technical meetings (n = 2) between UFI, Cornell University, NYSDEC technical staff and technical review groups (project work schedule, *Section A.3.4*). Record keeping for each step of the modeling process will consist of various types of information, in the form of progress presentations, and multiple forms of graphics. Examples are given below:

- assumptions
- parameters and their source
- conceptual model designs and evolution
- input used, their sources, and any action to compensate for missing data
- setup input and output files
- coefficient values

All files from the modeling study will be maintained for auditing purposes and post-project reuse, including

- source code and executable code
- output from model runs
- interpretation of output
- setup and testing procedures and results

All modifications of the source code will be tested and documented in internal memos. Such modifications would be tested throughout the setup process by experienced modelers reviewing the model output to determine that it demonstrates expected behavior and responds in the expected manner for each model run.

All files from the modeling study will be maintained for auditing purposes and post-project reuse, including

- source code and executable code
- output from model runs
- interpretation of output
- setup and testing procedures and results

Any changes in this QAPP during the study period will be documented and noted in the revision table at the beginning of this document. After approval by the appropriate persons, the revised QAPP will be sent to each person listed on the distribution list. This QAPP is a UFI controlled document and will be managed by our quality assurance officer and is subject to rules set by UFI as part of our overall quality system (UFI, 2010). The QAPP will be reviewed annually.

The final report will be submitted in electronic format. All electronic records discussed in this section will be stored on a secure server, write protected, and backed up for a period of five years beyond completion of the project. This server is part of a LAN network and is password protected and protected externally via a firewall (UFI, 2010).

B. Measurement and Data Acquisition

B.1. Sampling Process Design

No sampling process design is necessary as part of this Phase 2 project since no new sampling will be conducted. Data were collected as part of the Phase 1 project. Please refer to the Phase 1 QAPP (UFI, 2013) and the Phase 1 final report (UFI, 2014) for more details on the sampling process design used in the Phase 1 Cayuga Lake sampling in 2013.

B.2. Sampling Methods

No sampling methods will be required as part of the Phase 2 project since no sampling will be conducted. Data were collected as part of the Phase 1 project. Please refer to the Phase 1 QAPP (UFI, 2013) and the Phase 1 final report (UFI, 2014) for more details on the sampling methods used during sampling on Cayuga Lake in 2013.

B.3. Sample Handling and Custody

No sample handling or sample custody will be required as part of the Phase 2 project since no sampling will be conducted. Data were collected as part of the Phase 1 project. Please refer to the Phase 1 QAPP (UFI, 2013) for more details on the sampling handling and custody used on Cayuga Lake in 2013.

B.4. Analytical Methods

No analytical methods will be necessary in the Phase 2 project since no new sampling will be conducted. For more information on analytical methods and SOP's used for data collected during the Phase 1 project when sampling was conducted on Cayuga Lake in 2013, please refer to the Phase 1 QAPP (UFI, 2013).

B.5. Quality Control

No sampling will be conducted as part of the phase 2 project. Data were collected as part of the phase 1 project. Please refer to the Phase 1 QAPP (UFI, 2013) for more details on the quality control methods used during the sampling of Cayuga Lake in 2013.

B.6. Instrumentation/Equipment Testing/Inspection and Maintenance

No sampling will be conducted as part of the Phase 2 project. Therefore no instrumentation/ equipment will need to tested/inspected and maintained during this project. For details of instrumentation/equipment testing/inspection and maintenance used as part of the Phase 1 project, please refer to the Phase 1 QAPP (UFI, 2013).

B.7. Instrument/Equipment and Model Calibration

B.7.1. Instruments and Equipment

No sampling will be conducted as part of the phase 2 project. Therefore no instrumentation / equipment calibration will need during this project. For details of instrumentation/equipment calibration used as part of the phase 1 project, please refer to the phase 1 QAPP (UFI, 2013).

B.7.2. Model Testing

Model testing, as used here, refers to the processes of calibration, validation and sensitivity analyses. During calibration, the model or submodel is tested by adjusting or tuning model calibration parameters to achieve a model fit to a set observations. The adjustment or tuning is based on a rational set of theoretically defensible parameters and is not merely a curve fitting exercise (Thomann and Mueller, 1987; and Chapra, 1997). Boundary conditions, initial conditions, forcing conditions and physical system parameters (e.g., bathymetry) are measured or determined before the calibration process begins and are not varied during the calibration process. The calibration parameters, or model kinetics, are varied within a reasonable range to obtain the best model fit (Chapra, 1997). The next step in model testing is validation. The model or submodel is said to be validated once it is tested against an additional set of observations, preferably under different external conditions (Thomann and Mueller, 1987). During the validation process the model calibration parameters or kinetics are not varied from the original calibration. If the model fits, using the original calibration parameters, the model is said to be validated; otherwise the model may need modest recalibration (Chapra, 1997). The modeling process also typically involves sensitivity tests to determine the effect of various model inputs and coefficients. Sensitivity analyses typically give the modeler some qualitative insight into model performance. Summary features of modeling activities and testing for the various submodels are presented in Table 7.

Where feasible, it is preferred to test submodels separately from the overall model (Chapra, 1997). This was done successfully for the two-dimensional hydrothermal/transport submodel (UFI, 2014; Gelda et al., 2015) as part of Phase 1. There are two other submodels of the overall

Table 7: Summary features of modeling activities and testing for the various submodels for the Phase 2 water quality model.

No.	Model Submodel	Software	Prominent input variables (model drivers)	Prominent input sources (calibration data)	Prominent Processes[5]	Status
1	hydrothermal/ transport	W2/T	meteorological and hydrologic conditions	2013 (Phase 1)	hydrodynamic and thermal stratification	completed in Phase 1 (UFI, 2014; Gelda et al., 2015)
2	minerogenic particles (Task D)	custom[1]	meteorological and hydrologic conditions PAV_m external loads	2013 (Phase 1)	settling, net aggregation	Phase 2
3	optics	custom[2]	in-lake conditions for POC (or Chl-*a*, PAV_m and a_{CDOM})	2013 (Phase 1) and Effler and Peng (2014)	light absorption and light scattering	Phase 2
4	phosphorus[3]	hybrid of CE-Qual-W2, LAKE2K, and UFI NYC frameworks	meteorological conditions, hydrologic conditions and multiple constituent[4] loading	2013 (Phase 1); calculated loads section 3 of Phase 1 final report (UFI, 2014)	P-algal uptake, settling, hydrolysis, desorption, mussel excretion	Phase 2
5	phytoplankton[3]	hybrid of CE-Qual-W2, LAKE2K, and UFI NYC frameworks	meteorological conditions, hydrologic conditions and multiple constituent[4] loading	2013 (Phase 1); calculated loads section 3 of Phase 1 final report (UFI, 2014)	phytoplankton growth, settling, nutrient uptake, respiration, grazing losses	Phase 2

[1] see Gelda et al., 2013 for similar model; W2/T as hydrothermal/transport framework; [2] see Effler et al., 2008 for similar model
[3] phosphorus and phytoplankton submodels are integrated; [4] particularly multiple forms of P; [5]effects of these processes will be represented by associated coefficient values

water quality model that can, and will, be tested separately - the minerogenic particle and optics submodels (Table 7). This is reflected in the planned timing of modeling activities (Table 5). This separate testing of submodels promotes greater success in testing of the overall water quality model by reducing the coefficients subject to adjustment/tuning (e.g., reduces the degrees of freedom in the process).

Sensitivity analysis consists of varying model inputs, often by plus and minus equal fractions, to determine the relative extent of changes that result (Chapra, 1997). The goal is to establish those inputs that are most critical in influencing model predictions. It's not uncommon to adopt uniform fractional limits for the calibration coefficients and other model inputs for such analyses, a process also described as parameter perturbation (Chapra, 1997). Alternatively, sensitivity limits are set to reflect insights concerning the actual levels of uncertainty of various model inputs These may correspond to known levels of accuracy of measurements, insights from experiments or process studies, or guided by the literature and previous experience. Both types of sensitivity analyses will be conducted where appropriate.

Performance of the submodels subject to separate testing and the overall water quality model will be evaluated both qualitatively and quantitatively. The timing and approximate magnitude of the various short-term signatures imparted to the shelf from runoff events are targets for the minerogenic particle and optics submodel and the overall water quality model. Seasonal lake signatures for forms of P and POC (metric of phytoplankton biomass) are targeted for lake-wide simulations. Absolute relative error will be used as a measure of performance as indicated in Table 6, for summer average conditions. Various other statistics will be considered to quantitatively represent submodel and model performance. The root mean square error (RMSE) is often a robust and appropriate representation (Thomann 1982), calculated according to

$$RMSE = \sqrt{\sum_{i=1}^{N} (X_{i,obs} - X_{i,pred})^2 / N}$$

where $X_{i,\ obs}$ and $X_{i,\ pred}$ are the ith paired observations and predictions of parameter X respectively and N is the number of these pairs. The RMSE is statistically well-behaved and is an indicator of the average error between observations and predictions. Lower relative error and RMSE indicate a better model fit to observations. The results of sensitivity analyses are most often represented by the percent difference from calibration values associated with the specified sensitivity limits.

B.8. Inspection/Acceptance Requirements for Supplies and Consumables

No laboratory or field measurements will be made as part of the Phase 2 project, therefore no inspection/acceptance requirements for supplies and consumables are necessary. For details of the inspection/acceptance requirements for supplies and consumables used during the Phase 1 project see the Phase 1 QAPP (UFI, 2013).

B.9. Non-direct Measurements

Handling of non-direct measurements to be used in the verification modeling was conducted under the Phase 1 project. For more details of the handling of non-direct measurements refers to the Phase 1 QAPP (UFI, 2013).

B.10. Data Management

Data management for the Phase 2 project is the same as the Phase 1 work (UFI, 2013). All data have been previously entered into an electronic database style format in a commercial spreadsheet with system, station, date, time and any data that exist along with the source of the data. All data obtained for this project including all data used in the modeling, will be compiled and placed in a centralized location, organized by data source. Records of hard copy data will be maintained by UFI staff. Electronic data will be stored on a secured server accessible to UFI staff only. Electronic backups of the data will be maintained and will be write protected. The data will be formatted into the appropriate input files for analysis and modeling. The original data, as well as the input files and QA/QC graphs, will be maintained by UFI in hardcopy and electronic format to document the data management process. All data will be maintained for at least 5 years beyond completion of the project.

C. Assessment and Oversight

C.1. Assessment and Response Actions

No new data will be collected in the Phase 2 project. The Phase 1 QAPP (UFI, 2013) covers assessment and response actions for all types of data collected under the Phase 1 Cayuga Lake sampling. Model performance assessments will be made frequently by the UFI modeling staff during the testing phase for the model. Performance audits will consist of comparing the model output to observed data collected on the system. The individual modeling team members will review model performance to ensure the model behavior of the state variable makes sense and is consistent with historic data and the modeler’s understanding of the system and experience with this particular model. During Phase 2 modeling process comparisons of data to model outputs will be examined to determine if discrepancies in parameter predictions and observations are a result of modeling errors. If any code errors are found, these errors will be fixed, documented and the overall effect of the errors on model calibration/validation will be documented.

Model performance assessments will be made frequently by the UFI modeling staff during the testing phase for the submodels and overall water quality model. Performance audits will consist of comparing the model output to observed data collected on the system. The individual modeling team members will review model performance to ensure the model behavior of the state variables makes sense and is consistent with historic data and the modeler’s understanding of the system and experience with the particular model. The hydrothermal model developed in Phase 1 (UFI, 2013; UFI, 2014) will be linked to the overall water quality model in Phase 2. During Phase 2 the modeling process will include comparing data to model output and modeling code will be examined to determine if discrepancies in parameter predictions and observations are a result of modeling error. If any code errors are found, these errors will be fixed, documented and the overall effect of the errors on model performance will be documented in internal memos.

Testing of the models is covered in *Section B.7*. This section covers QA/QC of the testing process. One primary point of concern in modeling is QA/QC of model inputs. Data files for task B, D, E, F, H and I will be generated from the data source files into the proper file format required for the individual model's inputs. QA/QC of these data will take three main forms. The model input data will be graphed and inspected visually by the modeling staff. These graphs will be reviewed to determine if they fall in expected ranges. Any anomalies will be checked against original source data. Data format will be QA/QC'ed by running it in the model. Typically format problems show up during the original model run because the model either will not run or the model runs and gives obviously erroneous results. The final QA/QC of input data are the model output results themselves. Errors in input results typically lead to model parameters behaving in a way not expected based on experience with the model. The model input files, setup programs and code will be tracked with a software configuration management (SCM) tool. This software is discussed in more detail later in this section.

Technical insights and questions from the TAC and MEG (Figure 2) from presentations of progress (see Table 5) by the project modeling team serve to contribute to assessment and oversight of the work. The form and extent of interplay with these groups will be consistent the precedents established in Phase 1. Oral comments from these groups provided at the time of the presentations are responded to, either at the presentation or subsequently in a timely fashion. Written comments and questions from these two groups are responded to, in writing, and in a timely manner. Again, these protocols were established and executed successfully in Phase 1. Other opportunities for input from these two groups are provided associated with manuscripts and reports provided during the project.

Sensitivity analyses are model runs conducted with coefficient ranges that differ from the calibration values, often with limits that are below and above the calibration values by a certain percentage. Such analyses are routinely included in an overall modeling analysis. Sensitivity analyses yield insights into model behavior and illustrate the reliability of model predictions relative to acknowledged or independently quantified uncertainty in model inputs and coefficients. Sensitivity analyses were covered in more detail in *Section B.7.2* of this modeling QAPP.

UFI developed software is logged and tracked with a software configuration management (SCM) tool, using the Subversion Version Control System. This tool tracks changes made to the individual submodels as well as the overall water quality model over time. Additionally the SCM tool allows multiple developers to work together on common source code, tracking individual developer's changes and merging these changes into a single source. The SCM tool provides the modelers with a documented history of the model changes. Any errors that may be found, and code development and enhancements made to the code, will be documented in the final report. All model coding is done in Fortran.

Prior to release, the model will be assigned a version number. During the modeling process of Phase 2 all bug-fixes and model enhancements will be documented in internal notes and memos. The submission letter will clearly state the version numbers for each piece of software. In the event that changes are required or bugs are found after this submission, UFI protocol is to make all fixes/changes and re-submit the software with the appropriate version number changes. Any changes between the original submission and this supplemental submission will be documented in a memo to the project managers.

The software and hardware requirements for the model (Task F) are as follows:

Computer Hardware:

- > 1 GHz processor
- Minimum 32 MB of memory
- Minimum 124 MB hard drive space available

Software:

- Windows Version Windows 9x, 2000, XP, Vista, Windows 7 operating system
- Optional software - a word processor and spreadsheet software to prepare and process various input and output files

The potential application of the model to support a TMDL analysis, following transfer of model to the regulatory community, is beyond the scope of Phase 2. Cornell University would not be involved in such an analysis.

C.2. Reports to Management

There will be two progress meetings between Cornell, NYSDEC, and UFI and the review panel. A single final technical report will be submitted at the end of the Phase 2 project. This report will document the development, testing, and preliminary applications of the overall water quality (P-eurtrophication) model, and the separately tested submodels. Components of the report may be peer-reviewed journal manuscripts that describe and document a portion of the Phase 2 work. The report will be maintained and stored on a secure server for at least five years beyond completion of the project in accordance with UFI's overall quality system (UFI, 2010). Any major deviation from this QAPP will be documented in the final report.

D. Data Validation and Usability

D.1. Data Review, Verification and Validation

This section discusses the criteria for determining whether to accept, reject or qualify data collected for this project. Validation critical are those that are used to determine whether the data satisfies the users requirements and verification criteria determine whether the data are sufficient for drawing conclusions related to the data quality objectives. No new data will be collected as part of the Phase 2 project. Data validation and usability were covered in the Phase 1 QAPP (UFI, 2013). This includes the calibration data collected by UFI in 2013 on Cayuga Lake and the validation data which is the historic LSC in-lake monitoring data.

Prior to modeling, all data will undergo extensive review. Much of this review was completed as part of the preparation of the Phase 1 report (UFI, 2014). This was described in, and covered by, the Phase 1 QAPP (UFI, 2013). Any additional review will be conducted in the same manner by experienced professionals. Modeling staff will be responsible for reviewing input data for completeness and adherence to QA requirements. Data will be scanned to determine that all parameters fall within a typical range (e.g., similar patterns and ranges as measured historically in these systems). Data manipulations will be done using specialized programs or commercial spreadsheet programs. Values outside typically ranges will not be used to develop model calibration data sets or modeling kinetic parameters. Data quality will be assessed by comparing data to hard copy originals or by comparing to model results as discussed in the Phase 1 QAPP (UFI, 2013).

D.2. Verification and Validation of Methods

The data are said to be validated if these pass a general review of QC coupled with a limnological analysis and understanding of the system. During the modeling process no new data will be collected. Data were reviewed by the modeling team under the Phase 1 project (UFI, 2013). All data were reviewed prior to its use to determine if data fell outside of typical ranges for the parameter in question. All data problems and gaps were clearly documented in modeling memos and internal notes by the modeling team as part of the Phase 1 project. For the methods used for data verification and validation see the Phase 1 modeling QAPP (UFI, 2013). If any data issue arises during this modeling endeavor these same methods will be implemented.

D.3. Reconciliation of User Requirements

This section of the QAPP addresses issues of whether data collected during field sampling meet data quality objectives. Each data type is reviewed for adequacy in terms of precision, accuracy, representativeness, completeness and comparability. No new data are being collected for this Phase 2 project. For a a discussion of the reconciliation of user requirements please see the Phase 1 QAPP (UFI, 2013).

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