Considerations for Phase II Water Quality Modeling

Cayuga Lake

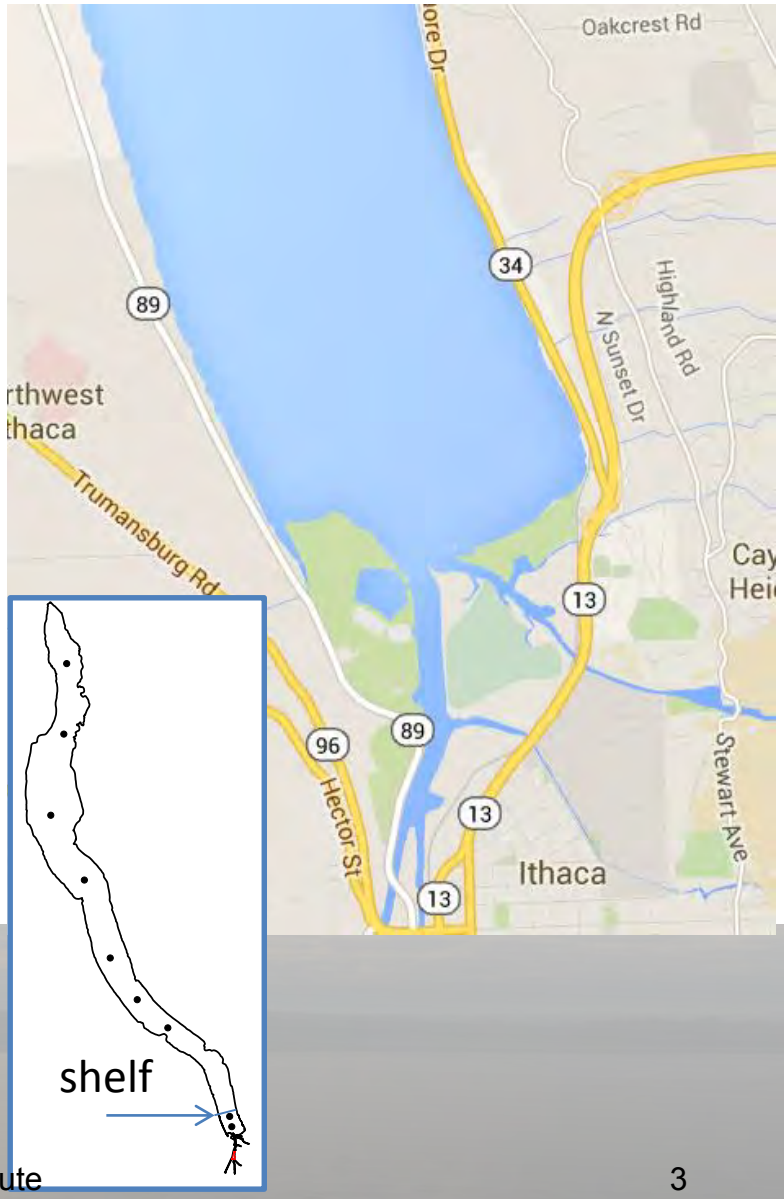
Cornell University

Talk Outline

1. Introduction/Background
2. Shelf-Pelagic Disconnect
3. Other Lake-wide Signatures
4. Model Needs
5. Submodels

The Issue

- the potential for phosphorus (P)-driven cultural eutrophication problems in the southern end (shelf) of Cayuga Lake
- shelf context/setting
  - localized tributary (dominant) and point source inputs
    - 40% of water inflow
    - similar to many reservoirs
  - water quality listings
    - phosphorus (irregular exceedances of TP guidance value), trophic state the concern
    - sediment (metric and limit not stated)
    - bacteria



Required: Quantitative Management Tool for P-eutrophication Issue for Cayuga Lake

- development, testing, and application of a credible mechanistic P-eutrophication model
- to be used to guide related management deliberations
  - focus on conditions on the shelf, but lake-wide capability necessary

Modeling Objectives

- model(s) to provide a quantitative tool with which to evaluate water resources management alternatives
- linking of watershed and lake water quality models
- resolve drivers/processes responsible for prevailing conditions

Identifying Key Model Needs from Limnological Review of Monitoring Data

1. 2013 observations the most complete in time and space
   - will support calibration
2. earlier observations, in support of LSC monitoring (also, CSI tributaries)
   - will support validation
3. model needs considered
   - temporal scales to be resolved
   - spatial scales to be resolved
   - processes to be represented
   - model state variables
   - model drivers

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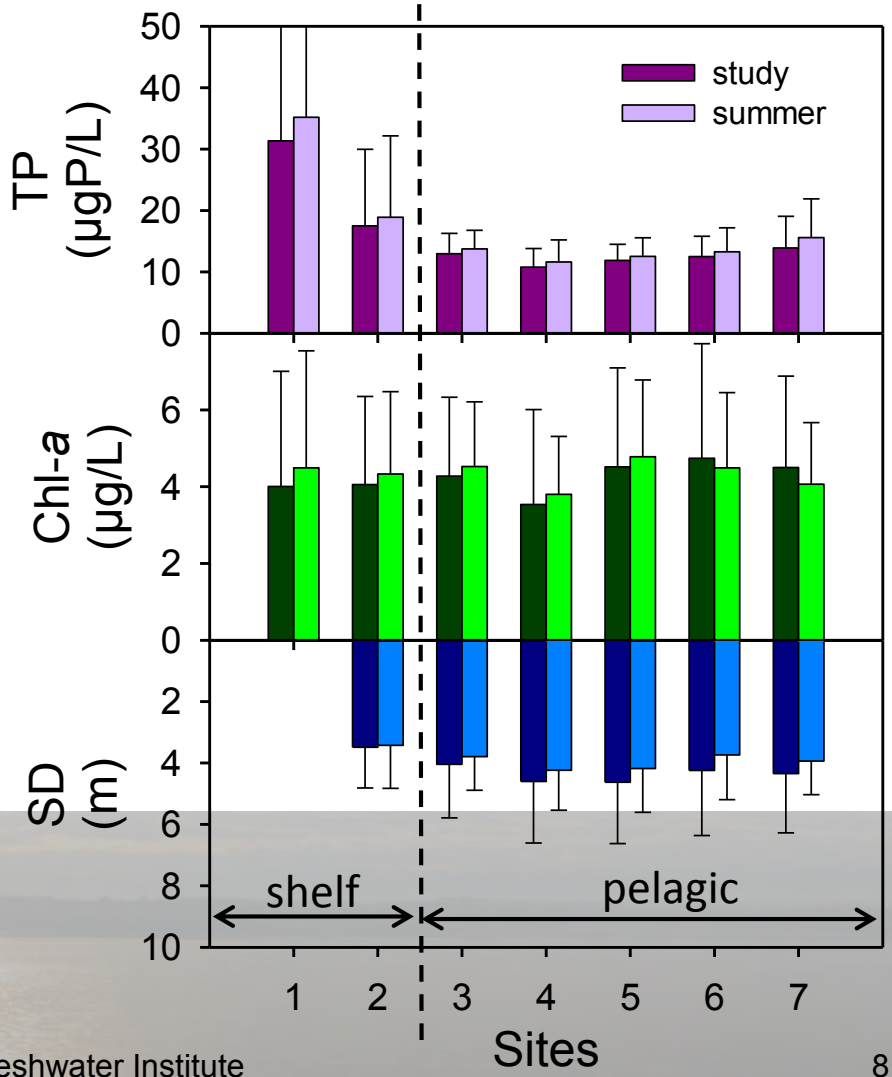
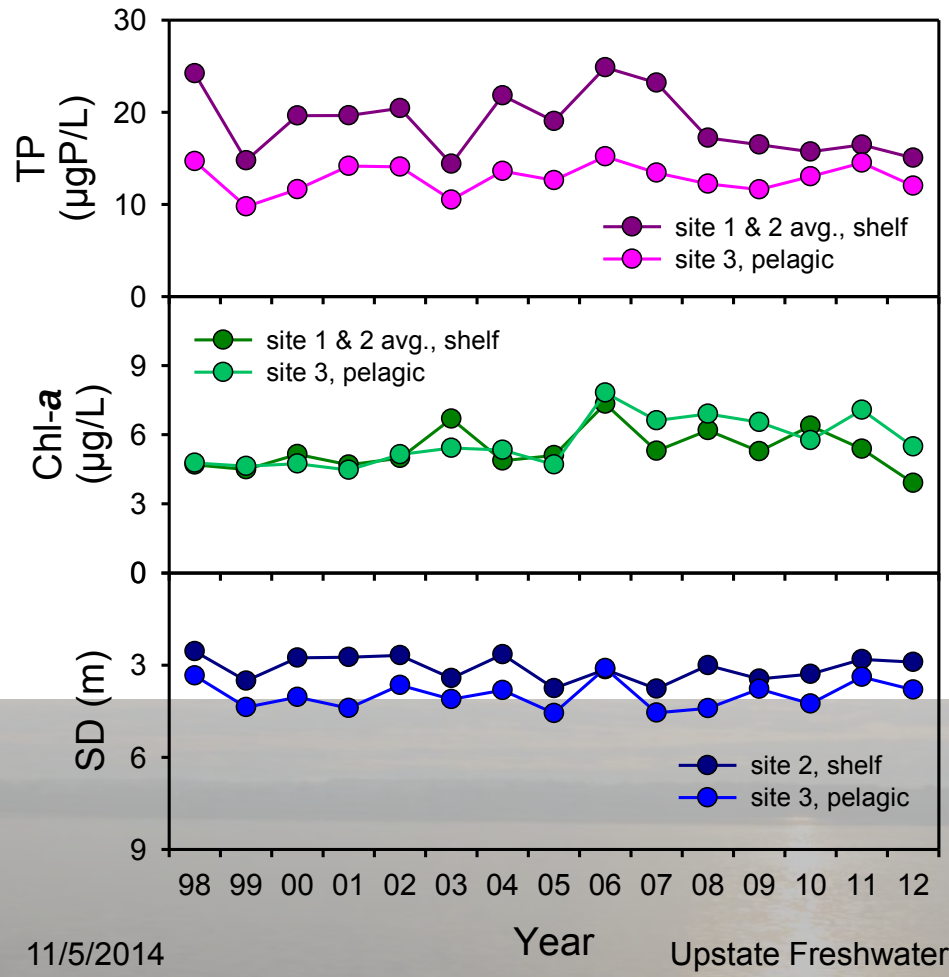
Shelf-Pelagic Disconnect in Trophic State Metrics, 2013

- $TP_{shelf} > TP_{pelagic}$
- $Chl_{shelf} \sim Chl_{pelagic}$
- $SD_{shelf} < SD_{pelagic}$



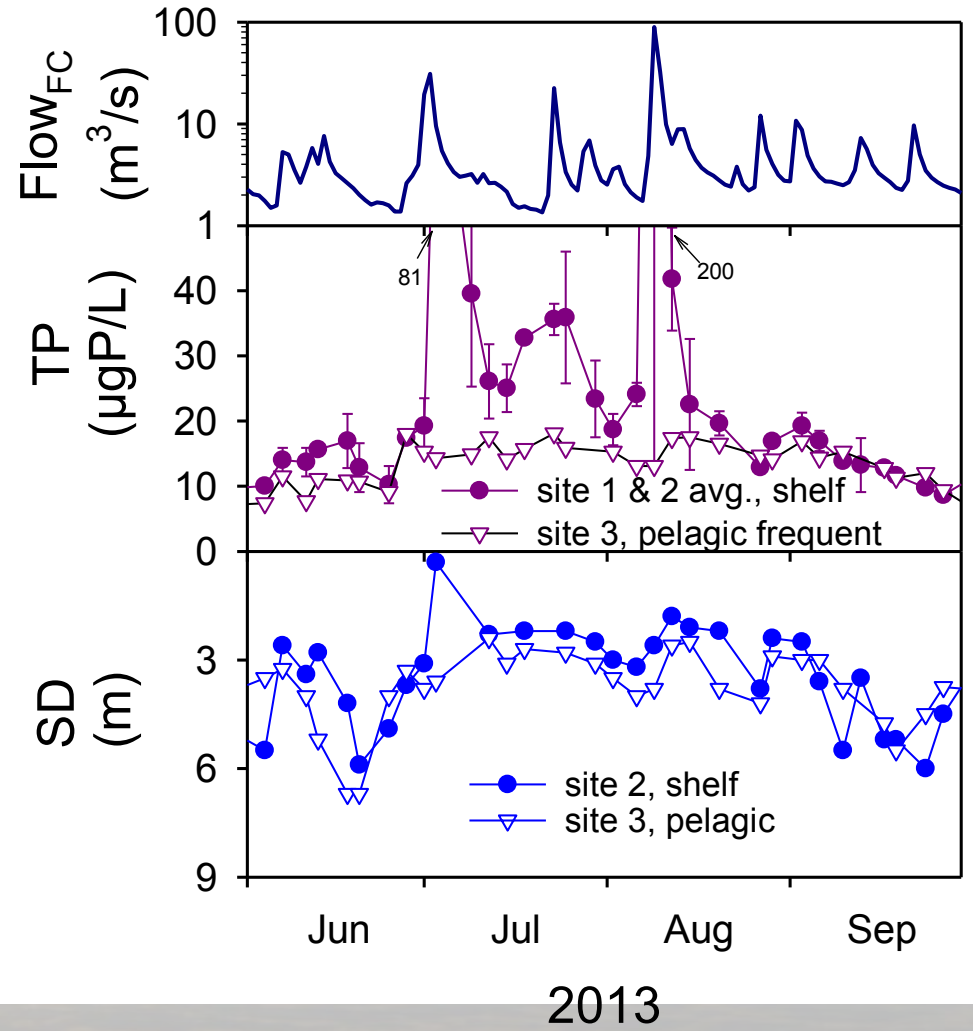
Shelf-Pelagic Disconnect in Trophic State Metrics is Recurring, 1998-2012



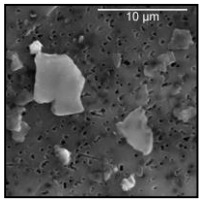
- the disconnect must be effectively represented in the model
- "the disconnect" - worse trophic state on shelf indicated by TP and SD data, but not supported by Chl-*a*

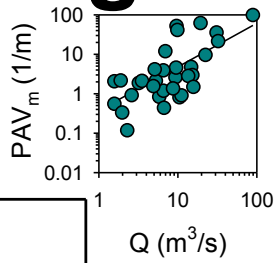
Runoff Events Contribute to the Shelf-Pelagic Disconnect

- shelf more strongly impacted by runoff events
- TP increasing and SD decreasing linked to runoff events
- effects of runoff events must be simulated (i.e., short time scales addressed)

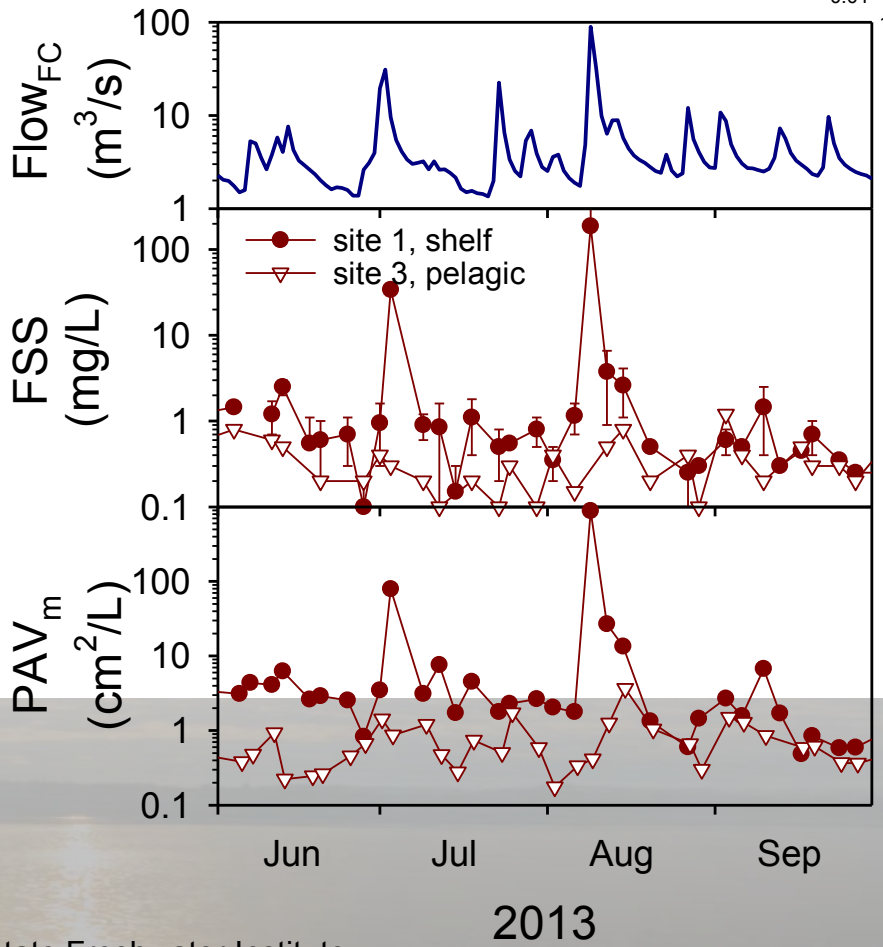


Minerogenic Particles Delivered During Runoff Events Cause the Shelf-Pelagic Disconnect

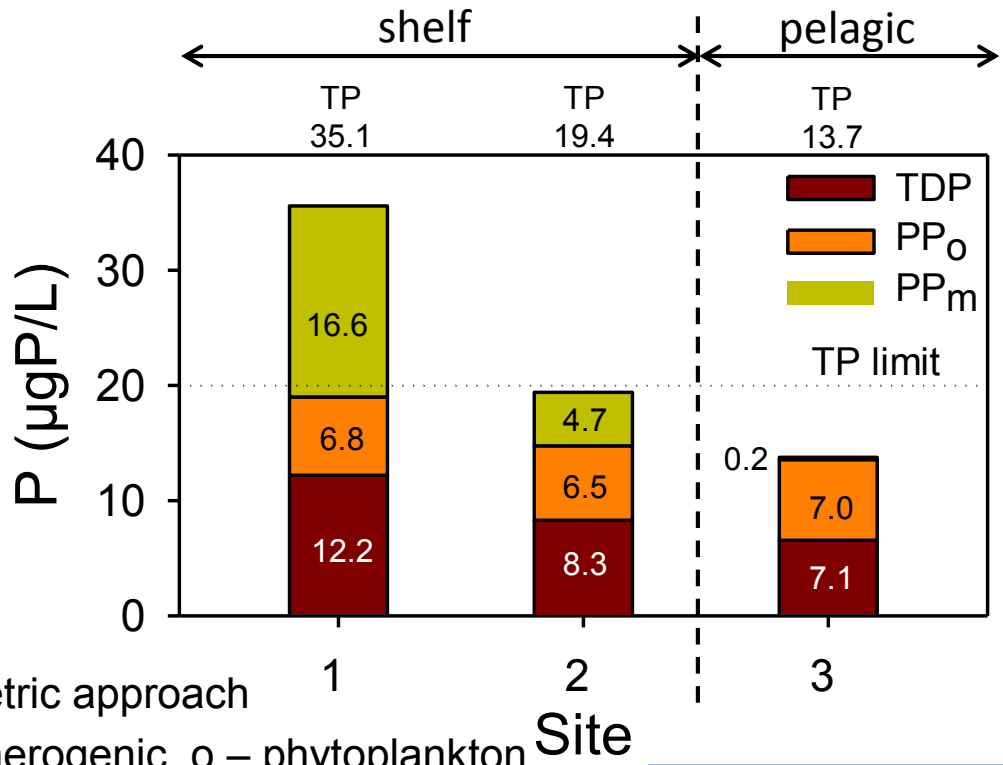




- shelf more strongly impacted by runoff events
- PAV_m – projected area of minerogenic particles per volume
- FSS and PAV_m increasing linked to runoff events
- the need to simulate minerogenic particle dynamics
  - short-term loads



Minerogenic Particles Delivered During Runoff Events Causes the Disconnect: TP



- refinements may evolve in Phase 2
- TDP, PP_o and PP_m to be predicted

- June - September
- particulate P, a stoichiometric approach

  $PP = PP_m + PP_o$; m – minerogenic, o – phytoplankton

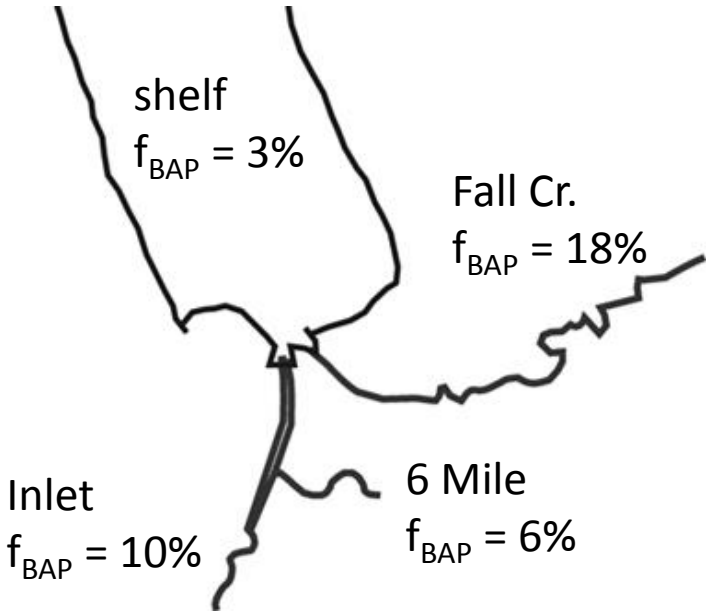
  $PP = (PP_m{:}PAV_m) \cdot PAV_m + (PP_o{:}Chl\text{-}a) \cdot Chl\text{-}a$

  stoichiometric ratios

  Effler et al. 2014. Inland Waters (see manuscript)
- PAV_m as a state variable, need loads

Low Bioavailability of Runoff Event PP Consistency with the Disconnect

- runoff event of July 1, 2013
- f_{BAP} – fraction of PP bioavailable



Site	PP (µg/L)
Fall Cr.	444
6 Mile Cr.	271
Cay. In.	202
Inlet Channel	104
shelf	46

- demonstrated: shelf PP (post-runoff event) is essentially unavailable to support algae growth; i.e., uncoupled from trophic state
- implications: these features are not supportive of the inclusion of post-runoff event TP observations for assessment of trophic state status

Minerogenic Particles Delivered During Runoff Events Cause the Disconnect: SD

- clarity, measured by Secchi depth (SD)

  $SD^{-1} \propto b_p$

  b_p = scattering coefficient for particulate material, bulk measurements

  $b_p = b_m + b_o$

  b_m = scattering coefficient associated with minerogenic particles

  b_o = scattering coefficient associated with organic (e.g., phytoplankton) particles

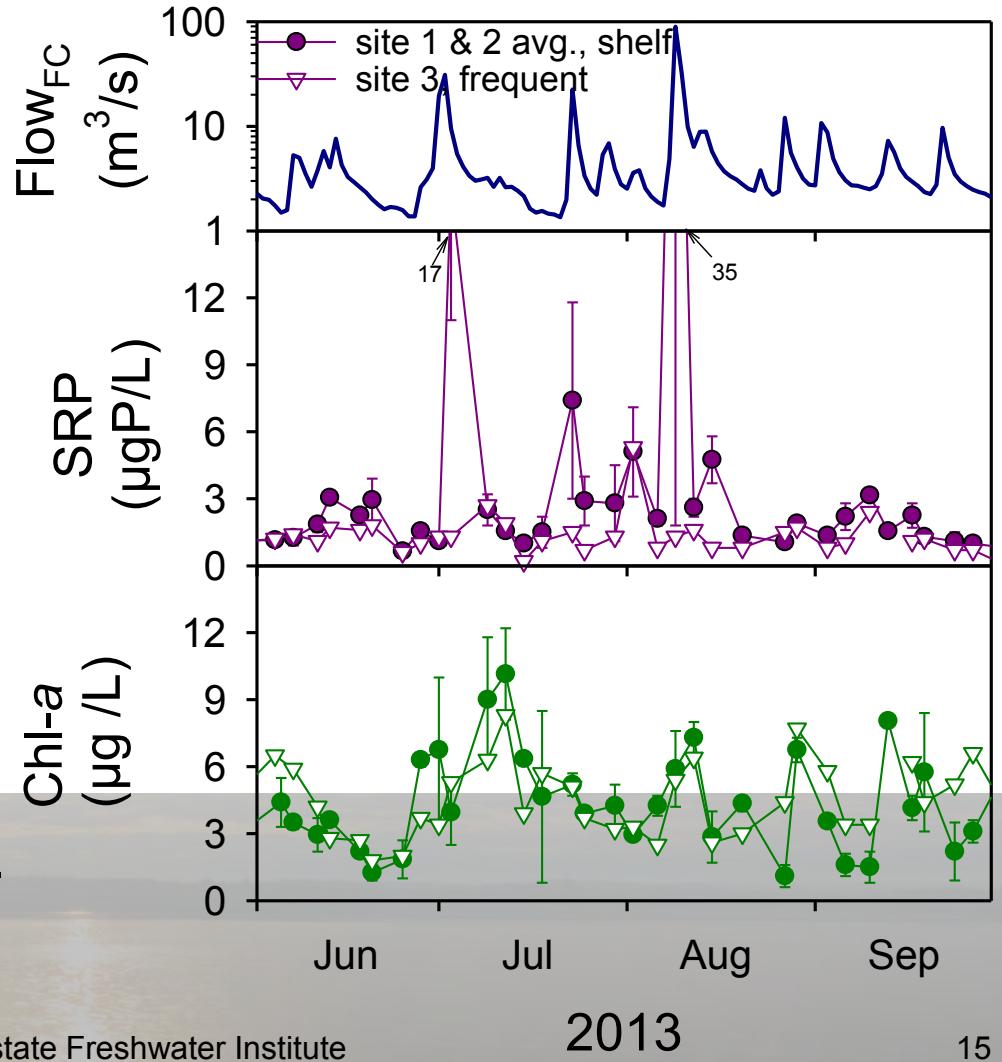
- increase in b_m from runoff events cause decrease in SD (Effler and Peng 2014)

  $b_m = 2.3 \times PAV_m$

  PAV_m as a model state variable

Second Part of the Shelf-Pelagic Disconnect

- elevated SRP (phytoplankton growth potential) on shelf does not result in higher Chl-*a*
- contributing processes
  - rapid flushing
  - dilution from tributaries
  - reduced light availability, particularly during runoff events
- Chl-*a* pattern reflects lake-wide conditions



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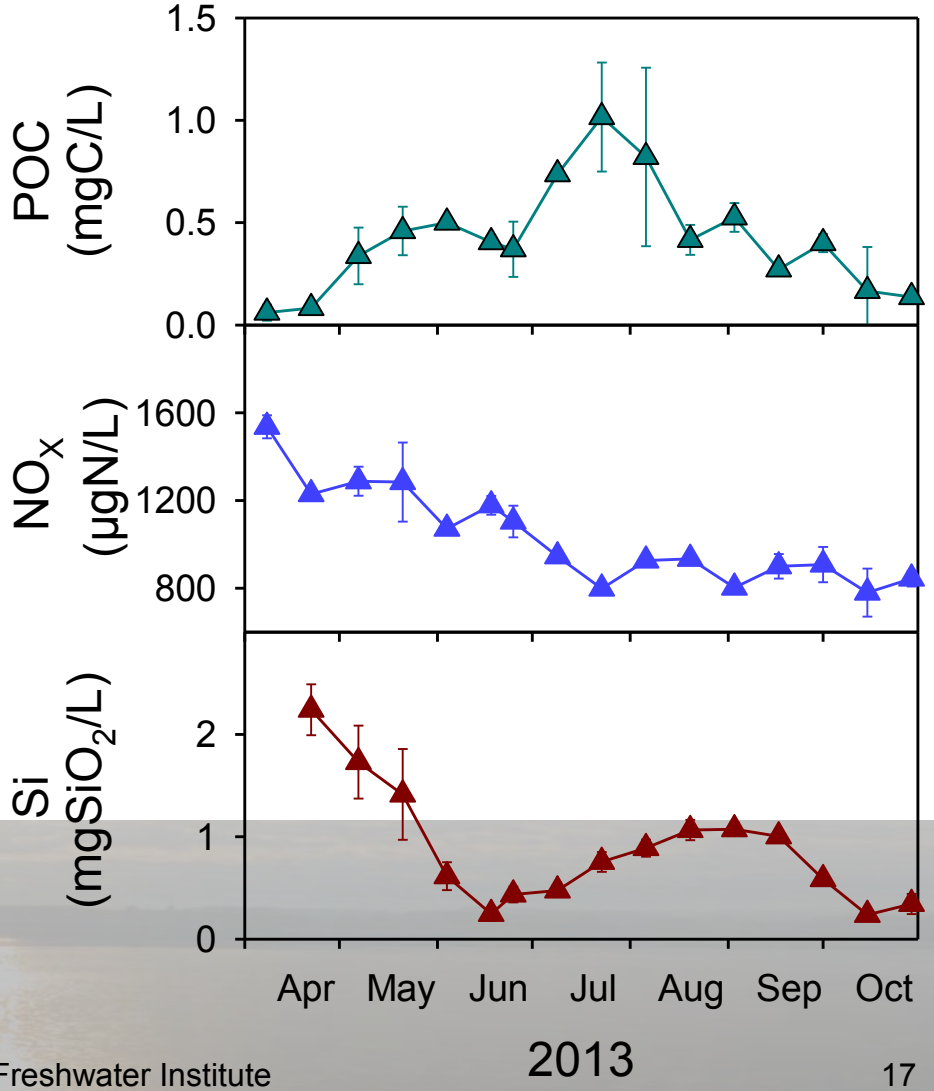
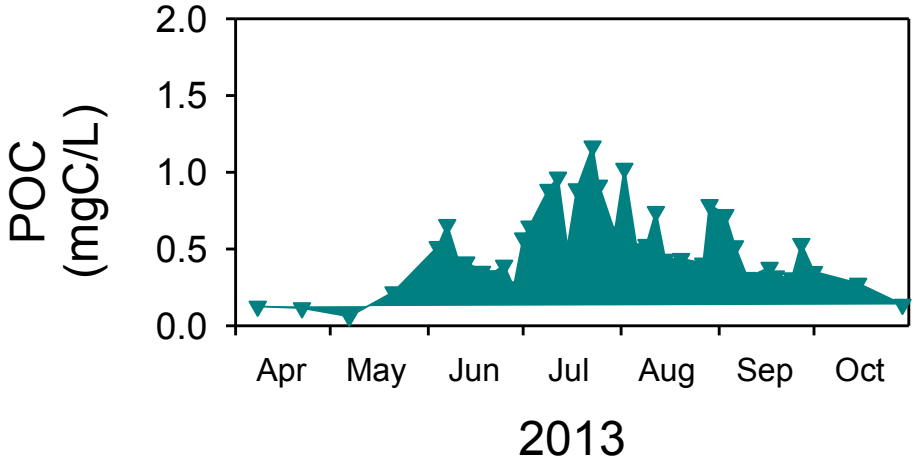
Other Lake-Wide Signatures of Interest

- POC alternate metric of phytoplankton biomass
- NO_X seasonal depletion, but non-limiting levels
- Si interaction with diatom dynamics

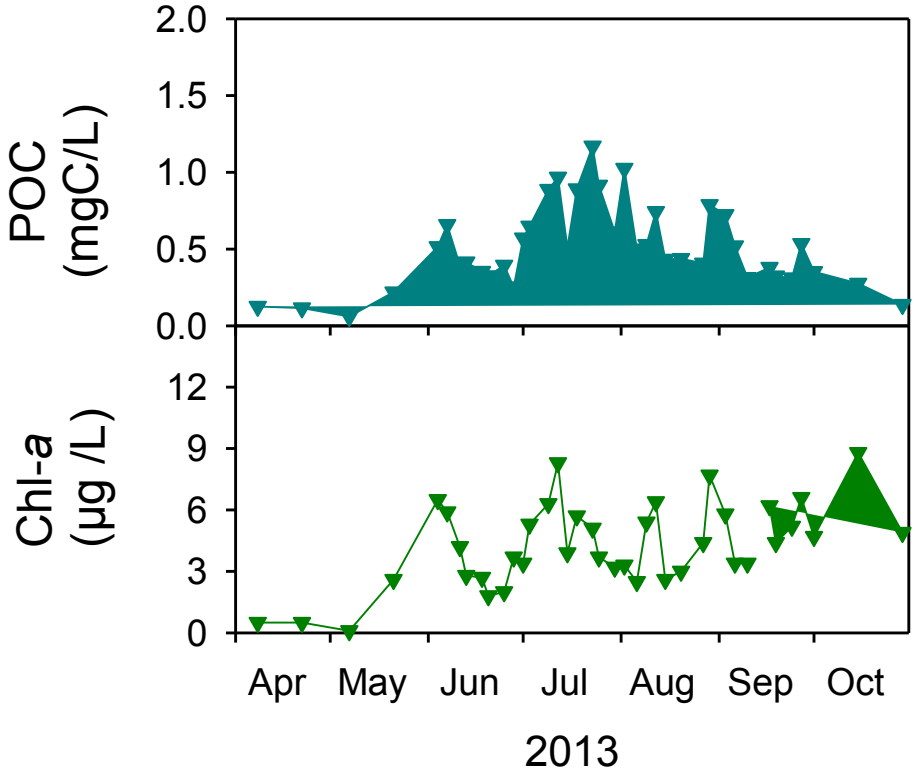


Metrics of Phytoplankton Biomass



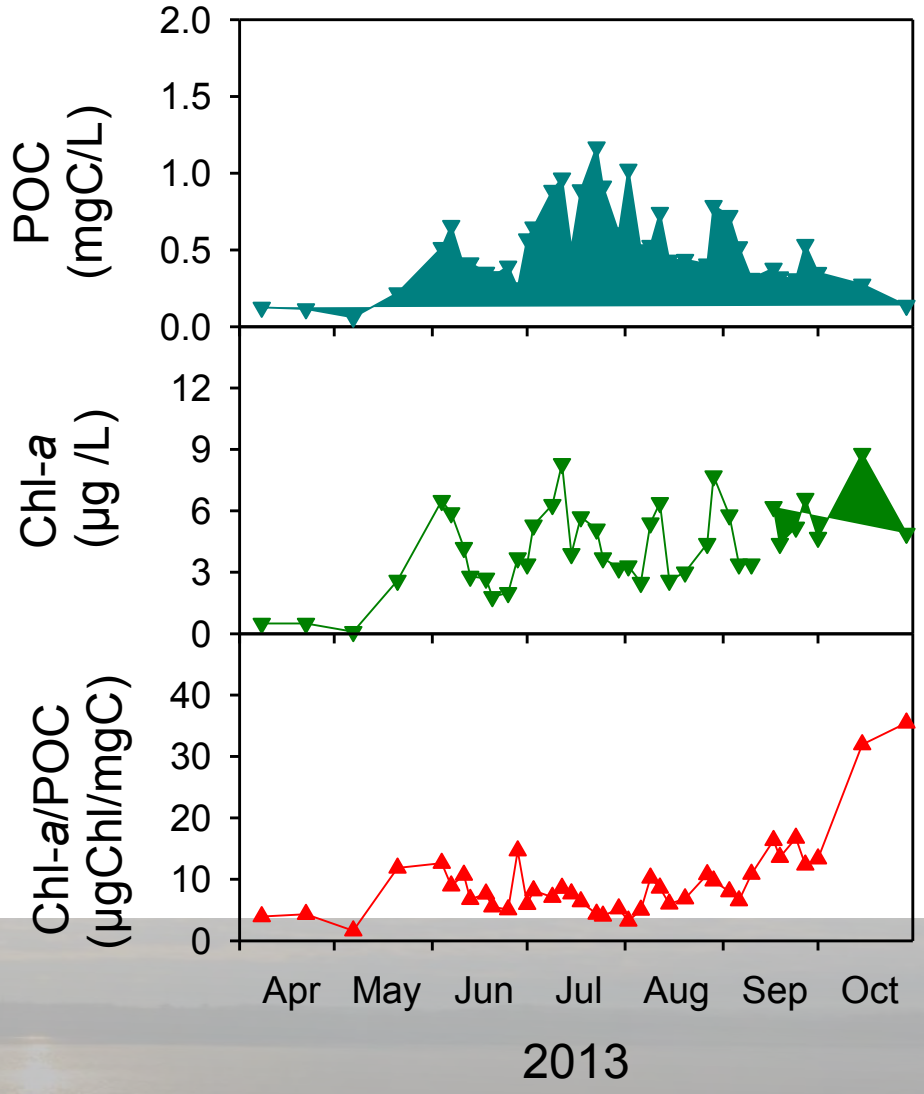
Metrics of Phytoplankton Biomass

- difference in patterns of the two metrics



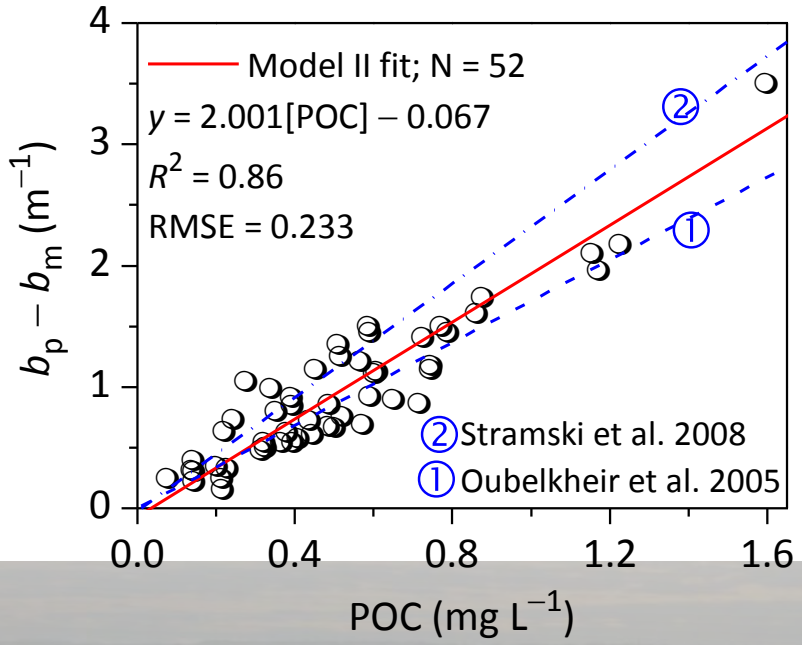
Metrics of Phytoplankton Biomass

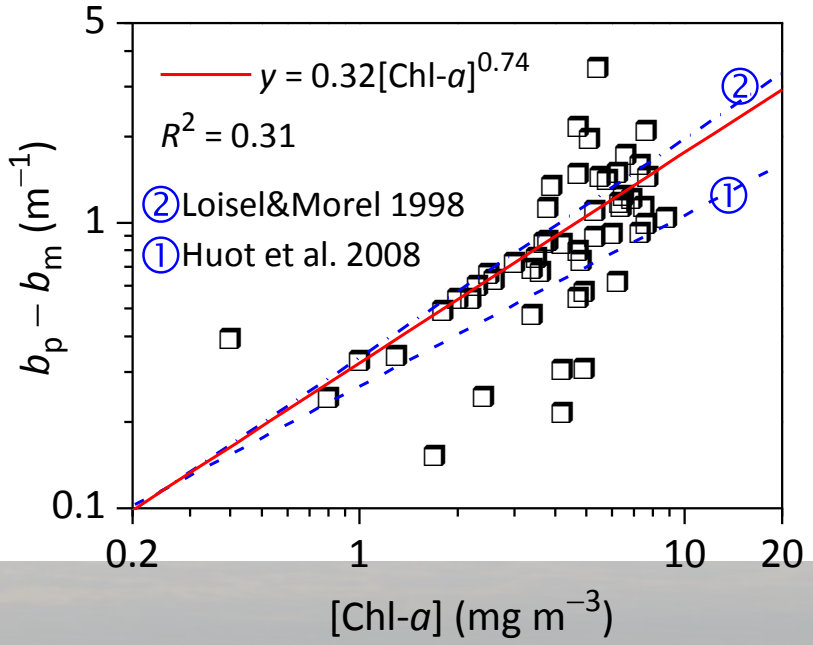
- site 3
- temporal variations
- dependency on ambient conditions
  - nutrients
  - light
- within literature range
- dynamic drivers not empirically obvious
- indicates limitation in a metric of phytoplankton biomass



POC Performs Better Than Chl-*a*, Optically

- b_p – scattering coefficient for particulate material, bulk measurements
- $SD^{-1} \propto b_p$ (Davies-Colley et al. 2013)
- $b_p = b_m + b_o$; *m – minerogenic, o – organic* (Peng and Effler 2012)
- $b_m = 2.3 \times PAV_m$; in Cayuga (Effler and Peng 2014) and others
- $b_o = b_p - b_m$

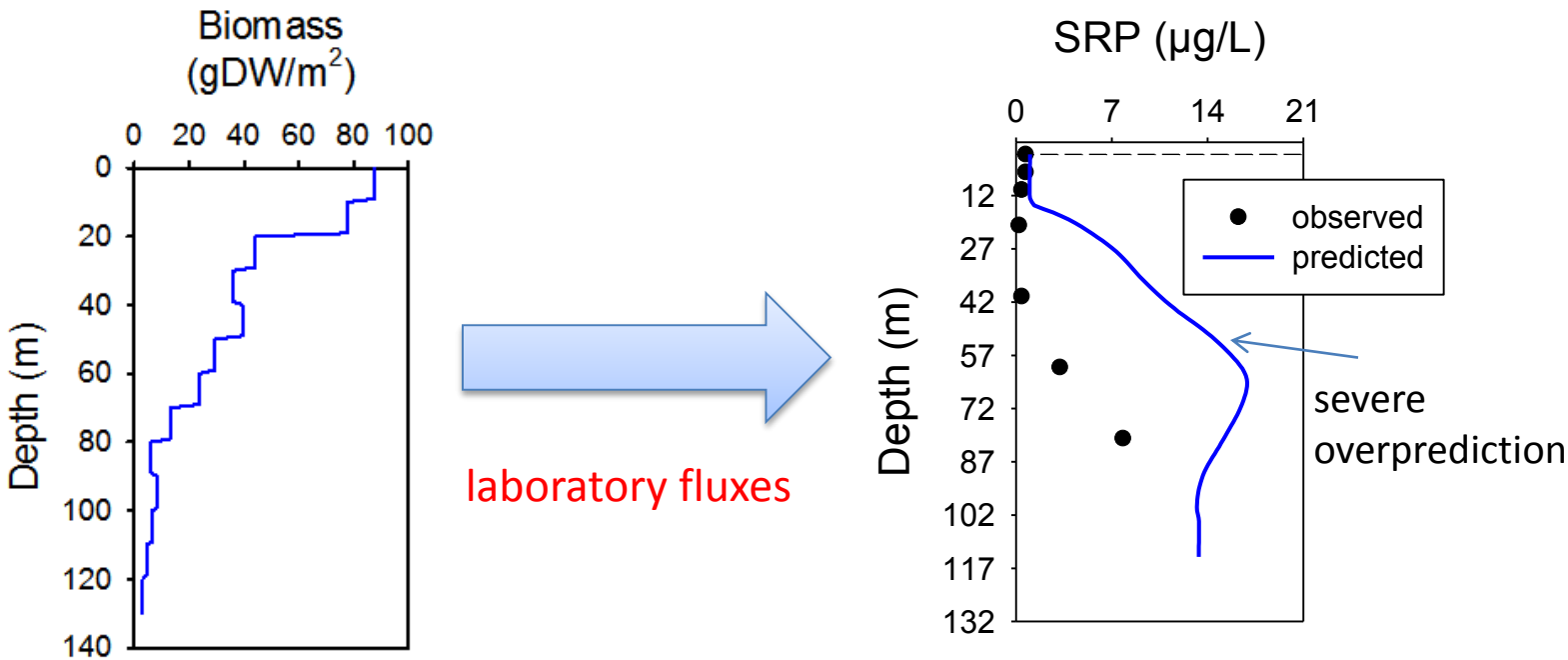




- dependencies of b_o on POC and Chl-*a* consistent with open ocean literature
- POC-based relationship much stronger

Lake-wide Role of Quagga Mussel Metabolism?
Example – Phosphorus Excretion

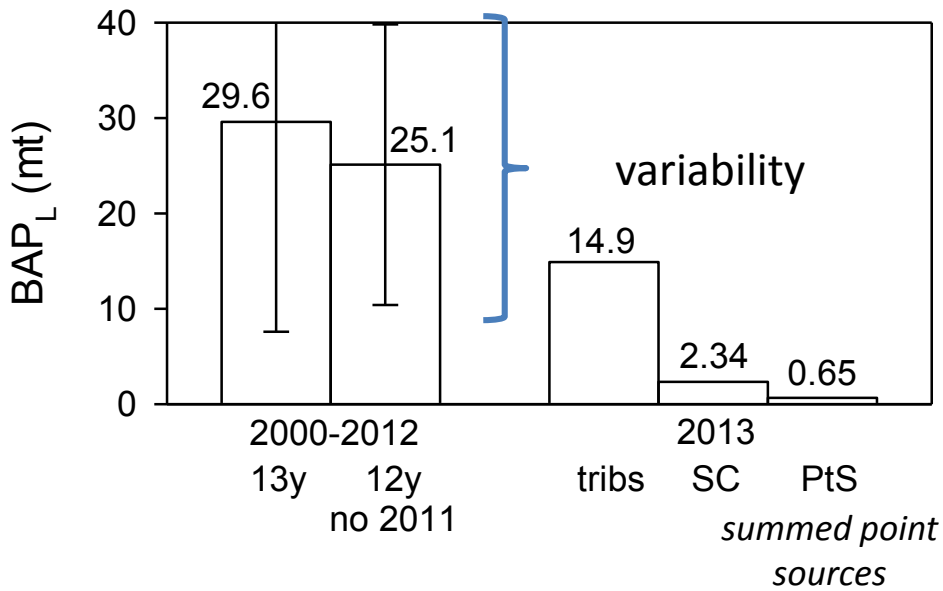
- prevailing simulations over-represent the effects of mussel excretion for case of adopting laboratory flux determinations



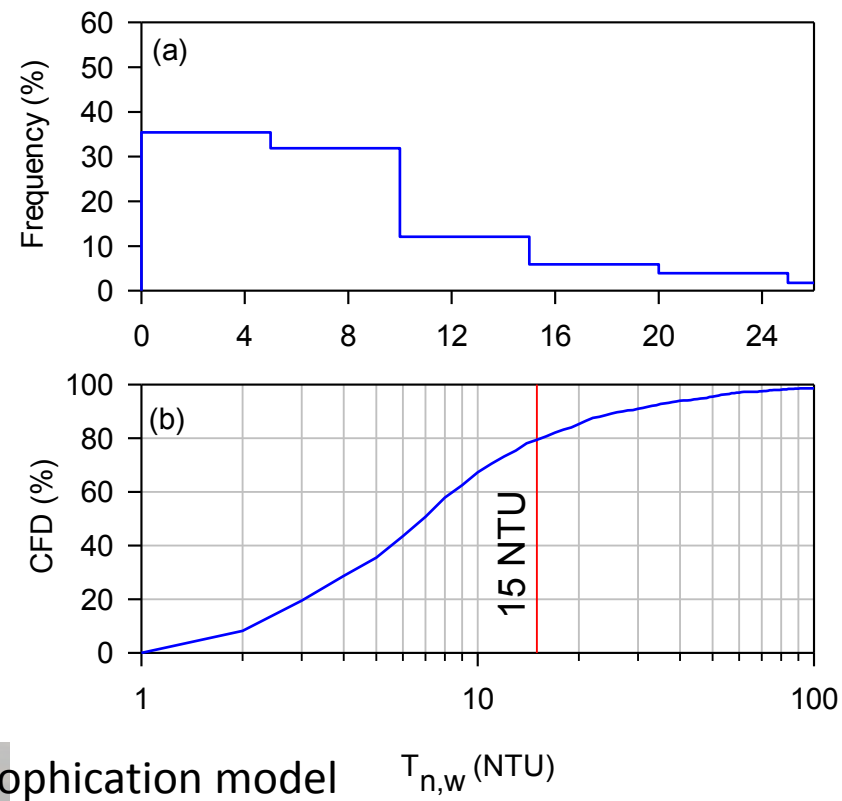
- a process(es) diminishes the effective fluxes on a water column basis
  - will need to be identified, integrated into model, and be tested as part of overall model testing
  - work of Boegman et al. on this issue is being considered

Need for Probabilistic Model Predictions that Represent the Effects of Natural Variations in Drivers

- wide variations in hydrology and meteorological conditions



Example: turbidity in NYC reservoir intake probabilistic model projections



- long-term probabilistic projections with P-eutrophication model may demonstrate small changes in loading masked by interannual variations in hydrology

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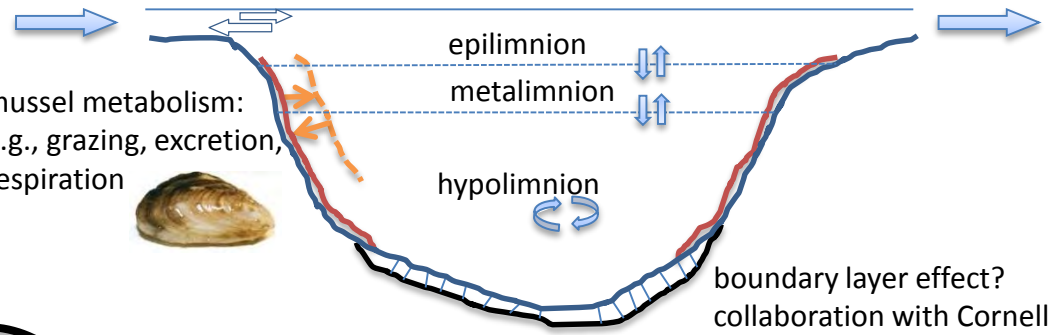
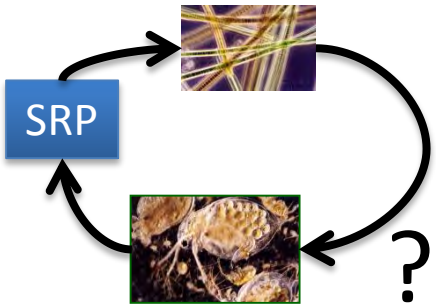
Process Representation

- model philosophy of parsimony – only as complex as necessary to address the issue and management alternatives

stratification,
mixing regimes
T of layers,
stratification,
ambient mixing

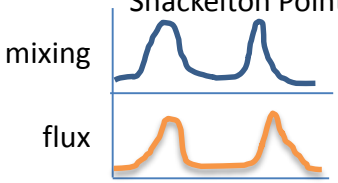


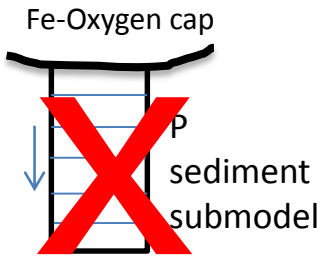
mussel metabolism:
e.g., grazing, excretion,
respiration



plankton:
we don't know,
may be potential
should be built-in

boundary layer effect?
collaboration with Cornell
Biological Field Station,
Shackelton Point





mussel dynamics:
e.g., bioenergetics
submodel

Model Needs from the Shelf-Pelagic Disconnect Analysis

1. temporal scales – broad
   - short-term, days – e.g., runoff events
   - seasonal – lake-wide effects, regulatory concerns
   - multi-year – meteorological/hydrologic variability
2. spatial scales – broad
   - within shelf
   - shelf extended to pelagic
   - entire water column

supported by 2-D model

3. drivers – both short-term resolution and long-term capabilities
   - hydrology
   - constituent loads – e.g., P forms and minerogenic particles
   - meteorological conditions

see P loading paper

4. state variables – direct and derived
   - forms of P
   - metrics of minerogenic particles (e.g., PAV_m)
   - SD and light levels
   - metrics of phytoplankton biomass (e.g., Chl-*a*)

Model Testing Targets – Evolved from Monitoring and Analysis

<u>primary</u>

1. shelf vs. pelagic waters – central role of runoff events
   a) TP, TDP, SRP, PP
   b) PAV_m, FSS, Tn, clarity

   elevated on shelf, the role of minerogenic particles

   c) the phytoplankton/Chl-*a* disconnect
      - absence of higher shelf levels despite higher P (including SRP)
      - POC and Chl-*a* in 2013, Chl-*a* for < 2013
      - includes years of higher local loads from point sources
      - comparative light availability

   calibration
   validation

2. pelagic and shelf
   a) phytoplankton – upper waters
      1) calibration – seasonality for POC, summer avg. Chl-*a*
      2) validation – summer avg. Chl-*a*
   b) clarity – contribution of phytoplankton and minerogenic particles, summer avg
   c) representation of metabolic effects of prevailing mussel population on pelagic waters
   d) effects of variations in drivers

   calibration
   validation

Tentative List of State Variables

State Variable Names	Abbr.
Soluble reactive phosphorus	SRP
Labile dissolved organic carbon	LDOC
Refractory dissolved organic carbon	RDOC
Labile particulate organic carbon	LPOC
Refractory particulate organic carbon	RPOC
Phytoplankton biomass	ALG
Labile soluble unreactive P	LSUP
Refractory soluble unreactive P	RSUP
Labile particulate organic P	LPOP
Refractory particulate organic P	RPOP
Labile particulate inorganic P	LPIP
Refractory particulate inorganic P	RPIP
Turbidity	Tn_i
PAV	$PAV_{m,i}$

Derived State Variable Names	Abbr.
Dissolved organic carbon	DOC
Particulate organic carbon	POC
Total organic carbon	TOC
Dissolved organic phosphorus	SUP
Particulate organic phosphorus	POP
Total organic phosphorus	TOP
Total phosphorus	TP
Total chlorophyll *a*	CHLA
Total suspended solids	TSS
Total inorganic suspended solids	FSS
Total turbidity	Tn
Total PAV	PAV_m

optics state variables: SD, K_o(PAR), Irradiance

SUP ≈ DOP

* silica and nitrogen signatures may be tested

Driver Information Availability

Driver Type	Calibration 2013	Validation 1998 – 2012 [1]
Hydrology	✓	✓[2]
Meteorology	✓	✓[3]
Loads		
Nutrients	✓	✓[4]
Sediment	✓	✓[4]

[1]potential years involved in validation; evolving – LSC monitoring, CSI monitoring

[2]gaged tributaries – Fall Creek, Inlet, Sixmile

[3]land-based before 2012

[4]CSI monitoring and 2013 conc.-driver relationships

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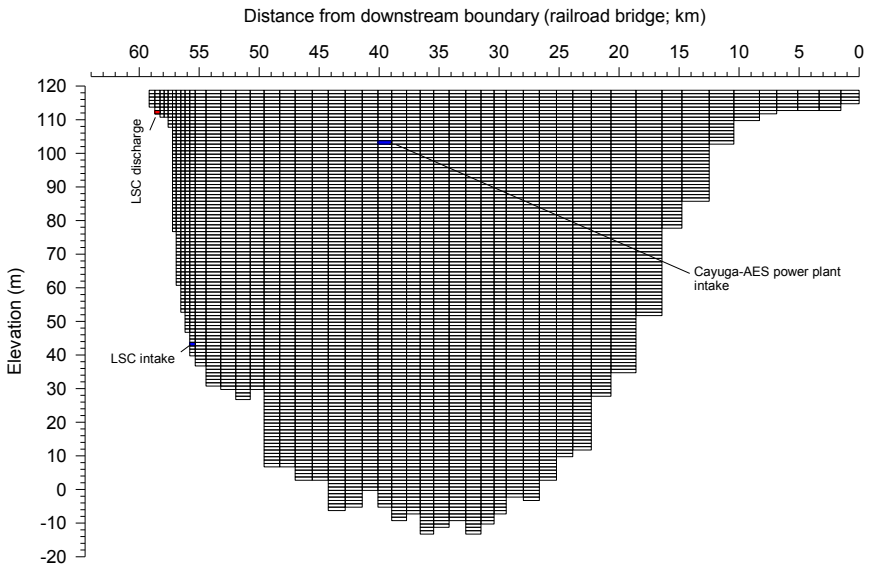
Model Submodels for Cayuga Lake Initiative

1. transport submodel – 2D, calibrated and validated, applications ongoing
2. minerogenic particle submodel – supporting data sets
3. optics submodel – early stages supported by NASA grant
4. tributary loads specification
   a) empirical – e.g., concentration-driver relationships
   b) mechanistic – watershed/land use
5. nutrient (P) cycling submodel
6. phytoplankton growth and biomass submodel

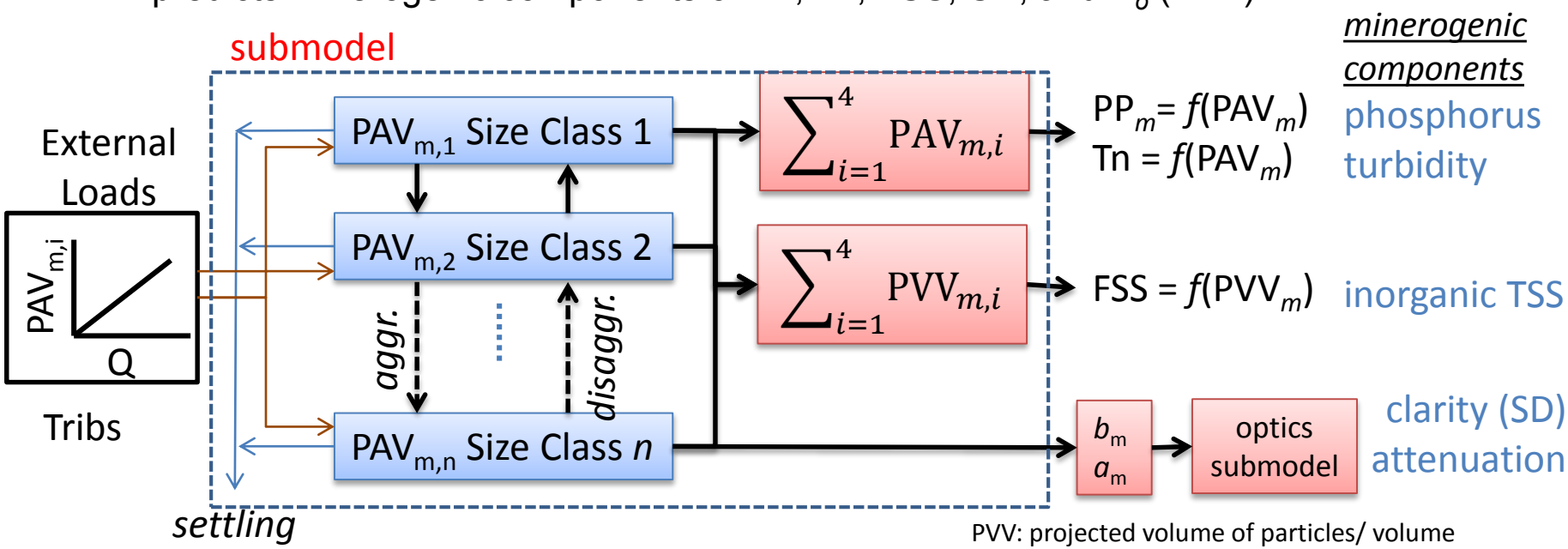
Transport Submodel

- part of CE-QUAL-W2
- 2-D, longitudinal-vertical hydrothermal/transport model
- setup, calibrated (2013), and validated (1998-2012; continuous simulation)
- high performance
  - seasonal thermal stratification
  - seiche activity – oscillations, upwelling events
  - long-term simulations – applicability for probabilistic projections
- applications related to water quality issues – shelf residence time, plunging tributaries, vertical transport
- time and space features consistent with water quality issues
- see manuscript



Minerogenic Particle Submodel

- partitions the minerogenic particle populations according to the contributions of multiple (e.g., n = 4) size classes
- state variable PAV_m – projected area of minerogenic particles per unit volume
- predicts minerogenic components of PP, Tn, TSS, SD, and K_o (PAR)



PVV: projected volume of particles/ volume

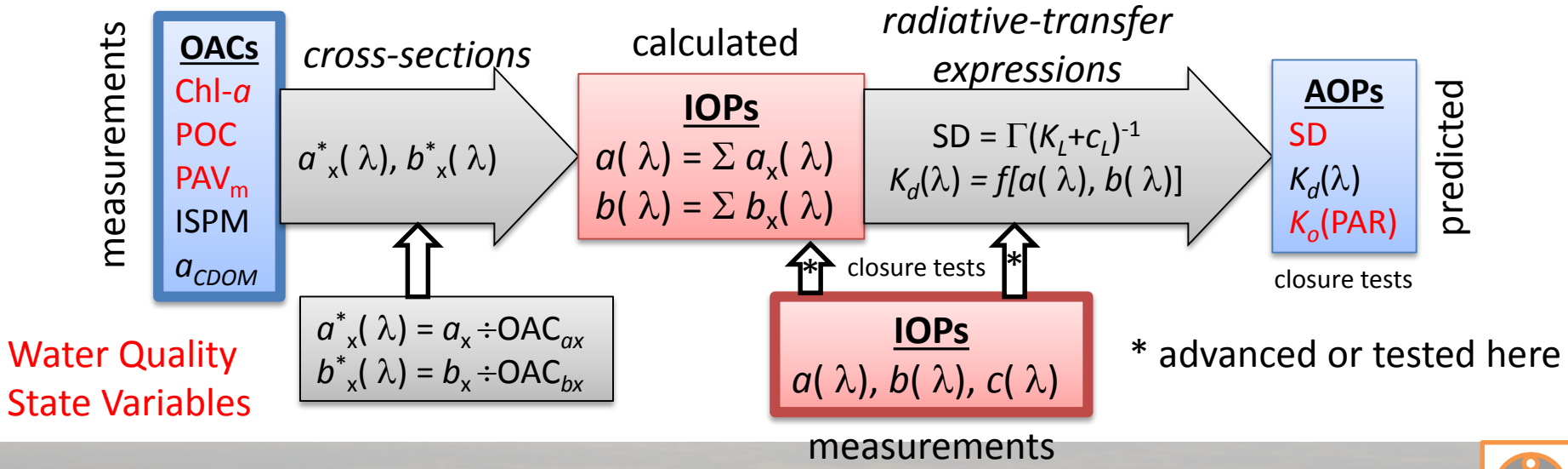
b_m: minerogenic scattering; a_m: minerogenic absorption

Processes: settling (Stokes Law); aggregation/disaggregation (calibration); resuspension (?)

* similar approach for turbidity in NYC reservoirs (Gelda et al. papers)

Optics Submodel for Cayuga Lake

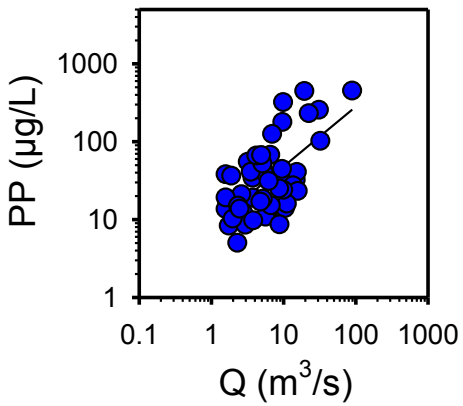
- mechanistic – quantifies relationship between optically active constituents (OACs; e.g, Chl-*a*), inherent optical properties (IOPs), and in turn, apparent optical properties (e.g., Secchi depth, SD)
- simple empirical relationships [e.g., SD = *f*(Chl-*a*)] perform poorly
- the supporting advanced measurements funded under a parallel NASA grant

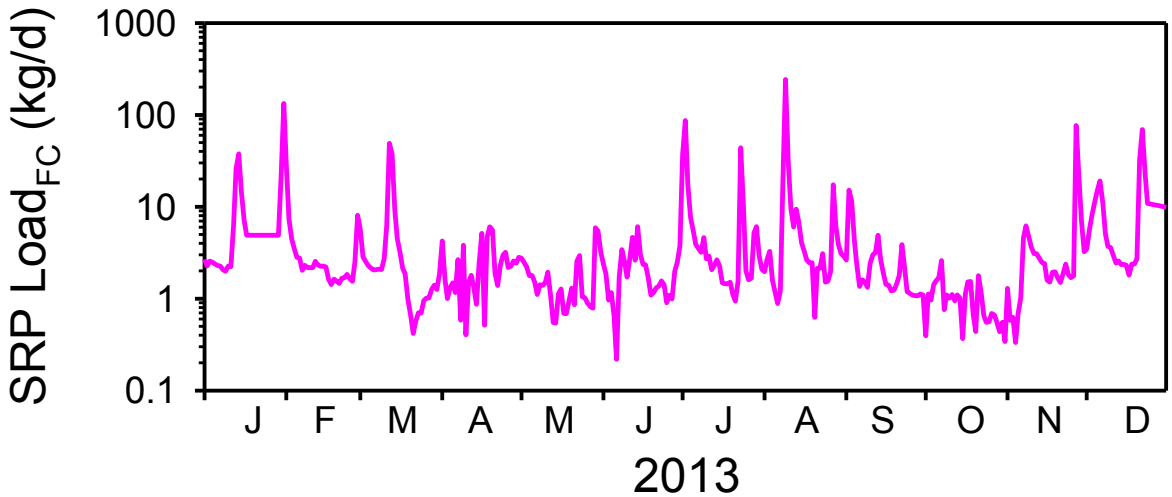


4. Tributary Loads Specification

a). Empirical

- example concentrations driver relationships





- driven by records of ambient drivers – multiple time scales possible
  - stream Q
  - air T

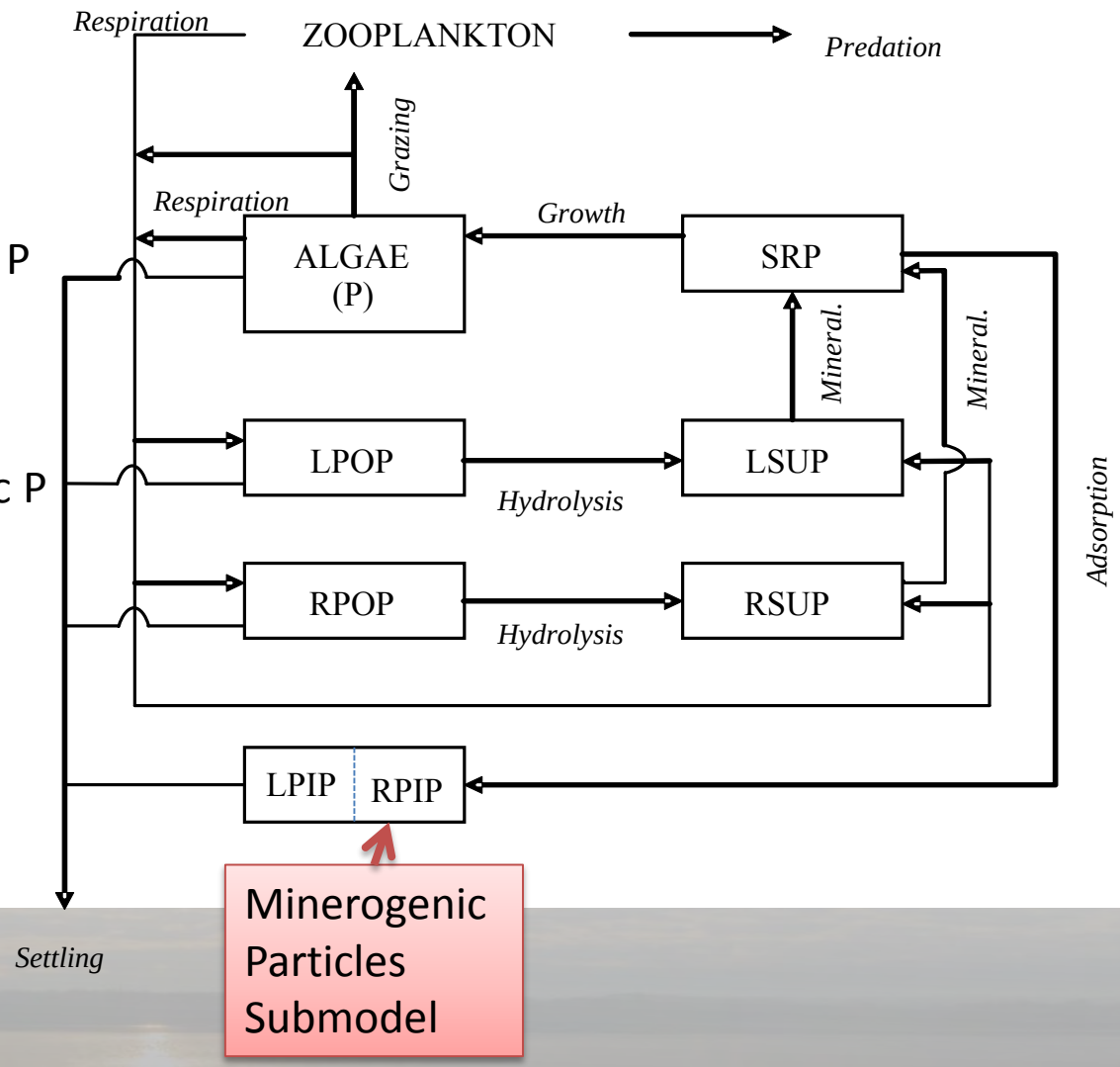
b). Landuse Model output becomes input to lake water quality model

Phosphorus Submodel

LPOP: labile particulate organic P
RPOP: refractory particulate organic P
LSUP: labile dissolved organic P
RSUP: refractory dissolved organic P
LPIP: labile particulate inorganic P
RPIP: refractory particulate inorganic P

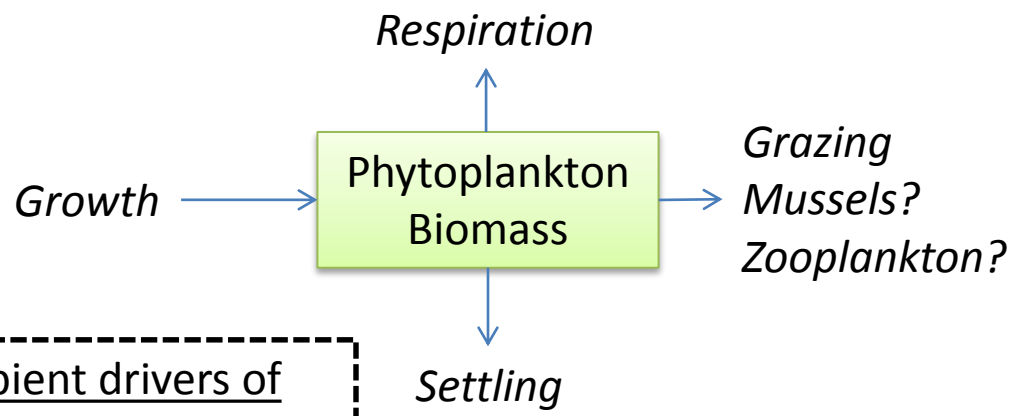
details may track:
CE-QUAL-W2
Lake2K
other models

additionally, include quagga mussel recycling



Phytoplankton Growth/Biomass

- issues – sources/sinks representation, metrics
- metric of phytoplankton biomass
  - carbon (POC; organic matter) model
  - most models
  - Chl-*a*, secondary



ambient drivers of growth
1. irradiance
2. temperature
3. nutrients
   phosphorus
   nitrogen X
   silica ?

details may track:
CE-QUAL-W2
Lake2K
other models

Tentative Timeline

No.	Component Description	2015				2016			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	Individual Constituents Modeling Analyses NO_X, DOC, TP, SUP, POC								
2	Inlet Channel – adjustment to loads								
3	Minerogenic Particle Submodel								
4	Optics Submodel								
5	Nutrient-Phytoplankton Submodel								
6	Linking of Submodels								

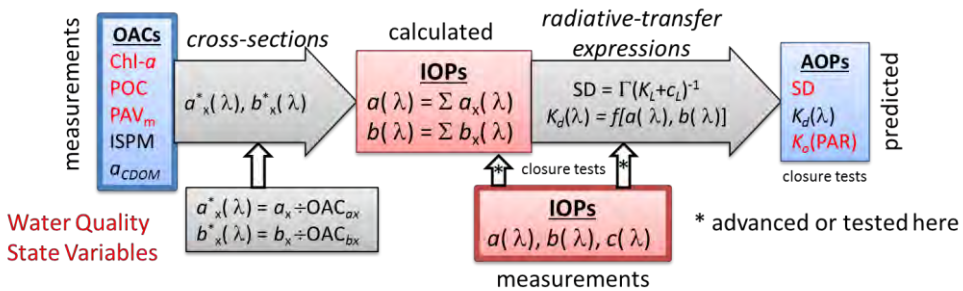
The End

Questions?

Next Steps

1. TAC and MEG comments and responses (ASAP)
2. complete Phase I report – December 15, 2014
3. prepare modeling amendment for QAPP
   - items 1-3 in parallel
4. commence modeling program beginning of 2015

Optics Submodel for Cayuga Lake



Specification of symbols

OACs – optically active constituents
Chl-*a* – conc. chlorophyll *a*
POC – particulate organic carbon
PAV_m – projected area conc. of minerogenic particles
OAC_{bx} – OAC for b_x
ISPM – conc. inorganic suspended particulate material
$b(\lambda)$ – spectral scattering coefficient
a_{CDOM} - absorption coefficient for CDOM
$a_x^*(\lambda)$ – spectral absorption cross-section for component x
$b_x^*(\lambda)$ – spectral scattering cross-section for component x
a_x – absorption coefficient for component x
b_x – scattering coefficient for component x
OAC_{ax} – OAC for a_x
OAC_{bx} – OAC for b_x
$a(\lambda)$ – spectral absorption coefficient
$b(\lambda)$ – spectral scattering coefficient
$c(\lambda)$ – spectral beam attenuation coefficient
SD – Secchi depth
Γ - coefficient for SD radiative transfer function
$K_d(\lambda)$ – spectral downwelling attenuation coeff.
K_L – downwelling attenuation illuminance coeff.
$K_o(PAR)$ – scalar attenuation coeff. for PAR
c_L – beam attenuation illuminance coeff.