Part II: Outline

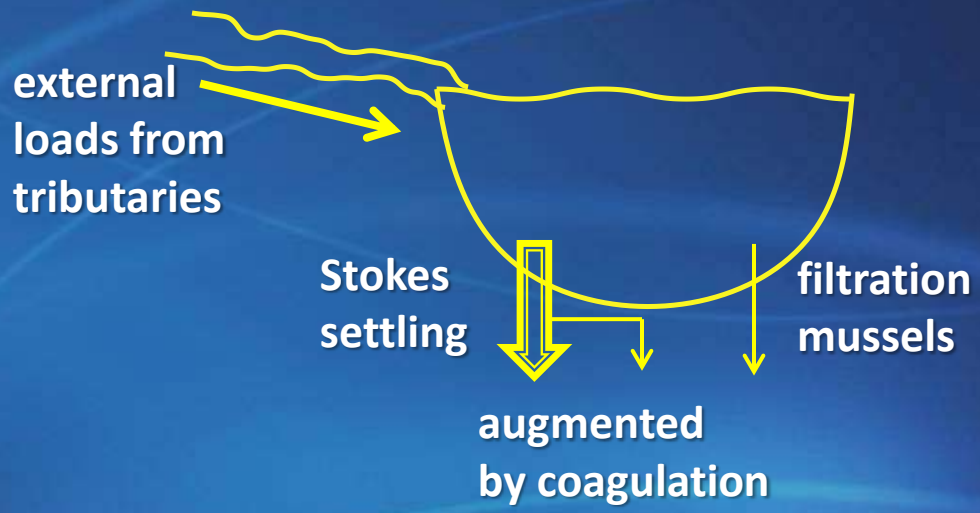
1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

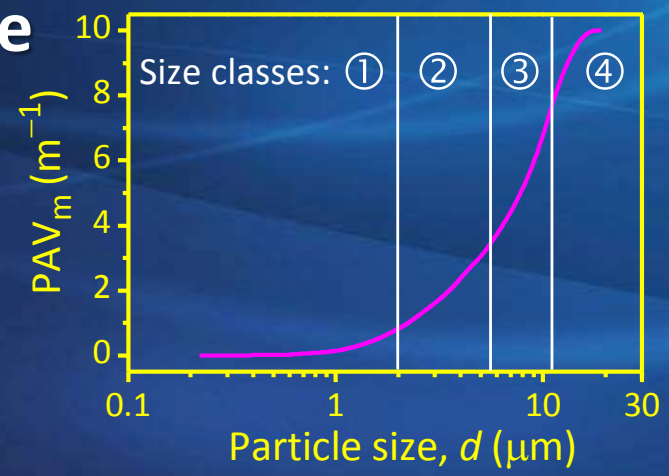
A first mechanistic mass balance type model for minerogenic particles in a lake

- drivers
  - demonstrate importance for multiple water quality metrics (T_n, PP_m, SD)—shelf vs. pelagic waters
  - value/implications for 'listing' of water quality issues—phosphorus and sediment
  - rich data sets of SAX–PAV_m measurements for lakes and tributaries

Conceptual model for PAV_m model

- model state variables—multiple size classes of PAV_m, $PAV_{m,n}$, $n = 4$
- sources and sinks





- size class contributions

$PAV_{m,4}$
$PAV_{m,3}$
$PAV_{m,2}$
$PAV_{m,1}$

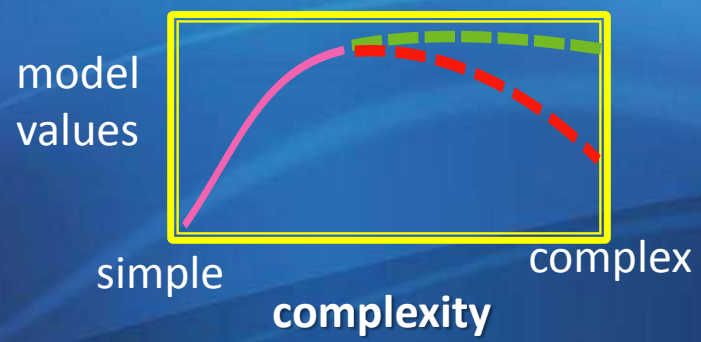
$$\sum_{i=1}^{n} PAV_{m,i} = PAV_m$$

- parsimonious approach
  - complex feature, $PAV_{m,n}$, but necessary
  - simplifying, number of sink processes and size classes

Post runoff event: Shelf

Parsimonious choices for PAV_m model structure: An appropriate approach

Model structural features	model complexity		
	simple	intermediate	complex
(1) particle size classes (*n*)	1	4	>> 4
(2) dimensions, transport submodel	1D	2D (W2/T)	3D
(3) aggregation	no	yes, simple M-M kinetics	yes, many coefficients
(4) filtration loss(es)	no	mussels, dry wt., survey	mussels, size classes, zooplankton
(5) internal production $CaCO_3$	no	specify from measurements	model kinetics, $CaCO_3$



* intermediate choices made

model values:

performance, management utility, credibility

Part II: Outline

1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

Model loss processes for PAV_m: Three represented (1)–(3)

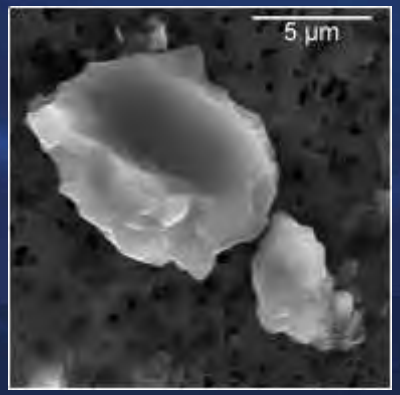
- the summation of the effects of three loss processes, for 4 size classes

$$S_i = \underset{(1)}{S_{i,\text{settling}}} + \underset{(2)}{S_{i,\text{aggregation}}} + \underset{(3)}{S_{i,\text{grazing}}}$$

- setting loss of $PAV_{m,i}$ (1), projected area conc. of one of the size classes

$$S_{i,\text{settling}} = -v_i \frac{\partial c_i}{\partial z}$$

v_i —settling velocity of the ith size class
c_i —PAV_m of the ith size class
z—vertical dimension



- $$v_i = \frac{\alpha g(\rho_p - \rho_w)}{18\mu} d_i^2$$ **(Stokes' Law)**

α—shape factor (platelet) = 0.5
g—gravitational constant
ρ_p *and* ρ_w—densities, particles and water
d_i —particle diameter for i^{th} size
μ—water viscosity

Model representation of enhanced deposition from particle aggregation

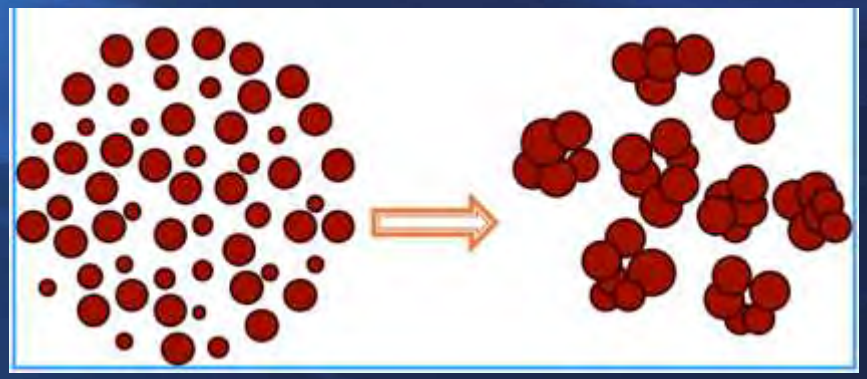
- **parsimonious approach—the three smallest of those size classes are subject to aggregation, through conversion to the largest, most rapidly settling size class**

for i = classes 1, 2, 3 $$S_{i,\text{aggregation}} = -k_{c,i}\left(\frac{c_i}{c_i + K}\right)c_i^2$$

for class 4 $$S_{4,\text{aggregation}} = \sum_{i=1}^{3} k_{c,i}\left(\frac{c_i}{c_i + K}\right)c_i^2$$

$k_{c,i}$ = 0.5 m·d^{-1}, aggregation rate constant for the ith PAV_m size class (i = 1, 2 and 3)
K = 0.05 m^{-1},Michaelis-Menten constant

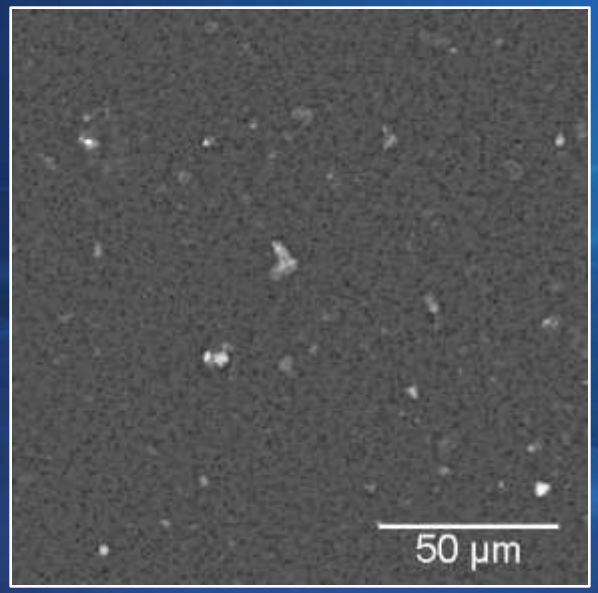
  - **positively dependent on particle concentrations, from increased collisions**



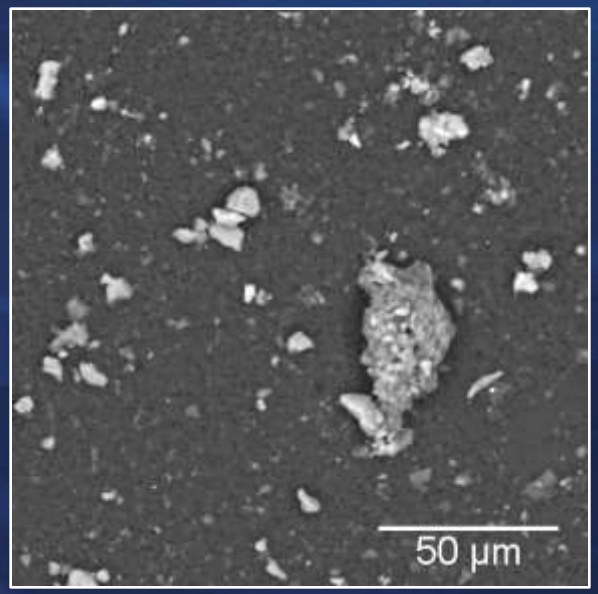
The aggregation process: SAX provides definitive supporting observations

- aggregates—multiple particle combinations
- defined by SAX observations
- advances beyond strictly model calibration support
- particle concentration dependence
  - low, dry weather
  - high, post runoff events

dry

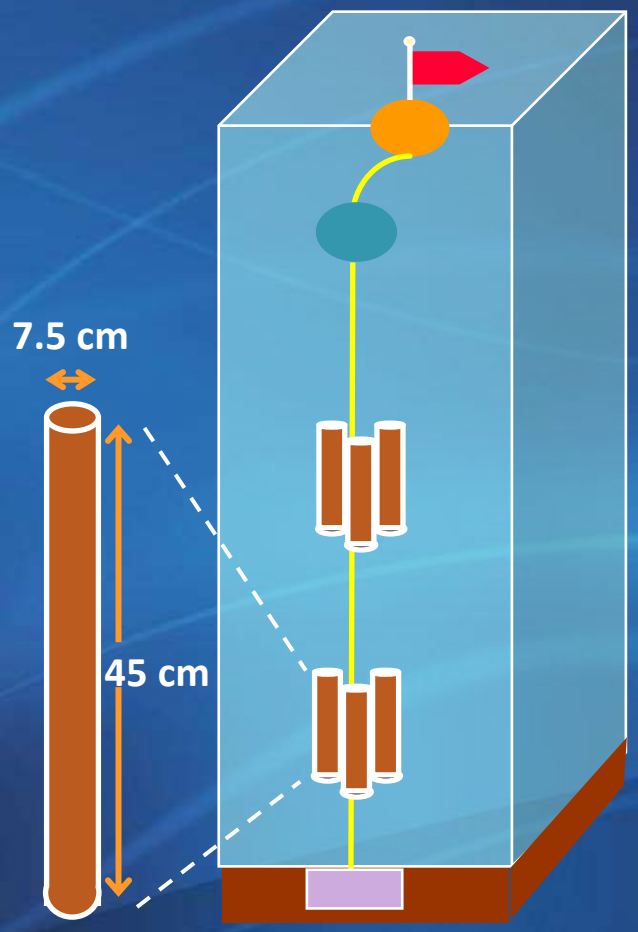


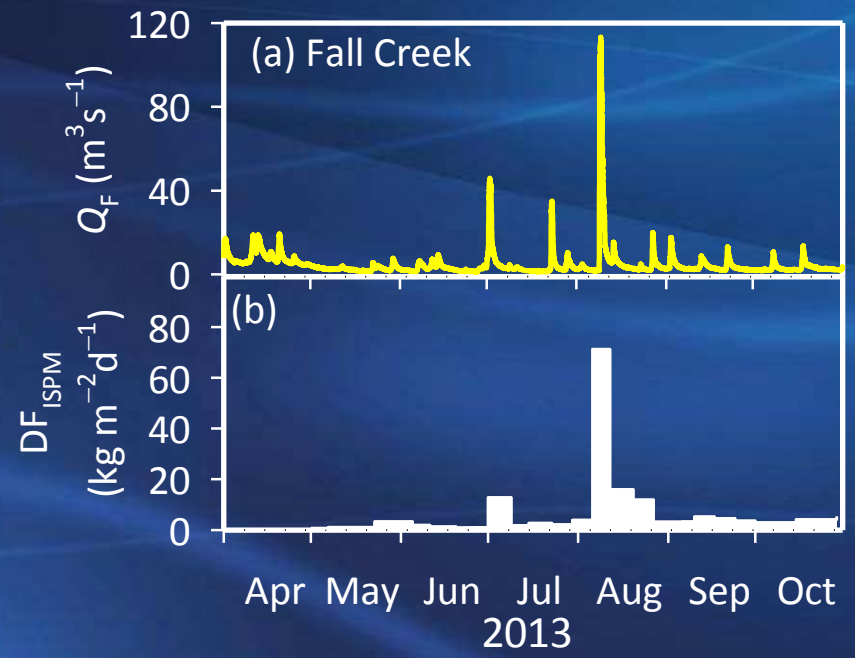
runoff event



Sediment traps: Support for testing model simulation of shelf deposition from runoff events

- trap design
  —size, shape, DF (g m^{-2} d^{-1})





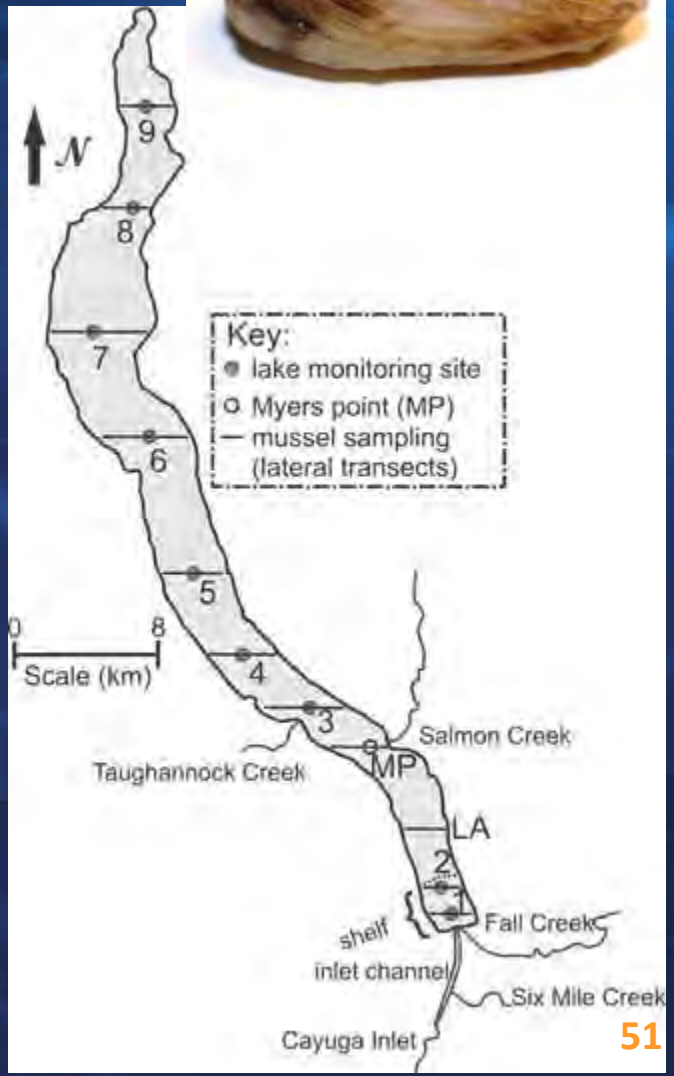
- conspicuous ISPM deposition signature from August event
- opportunity to support PAV_m model performance

PAV_m → particle volume deposited → mass (ISPM) deposited

density

Filtration losses by dreissenid mussels: Supporting measurements

- benthic bivalves, non-selective filter feeders, including important minerogenic particle sizes
- invaded lake in mid-1990s zebra initially, guagga dominate now
- dense populations in 2013 survey (279 samples from 11 lateral transects) for pelagic waters (~85 $gDW \cdot m^{-2}$), diminished on shelf (~9 $gDW \cdot m^{-2}$)
- potential for substantial impact on lake metabolism, including loss pathway for particles



Filtration losses by dreissenid mussels: Model representation

- **benthic areal filtration rates (k_f, $m^3 \cdot m^{-2} \cdot h^{-1}$)**

$$k_f = f_r M_a \theta^{(T-20)}$$

f_r —biomass-specific filtering rate ($m^3 \cdot gDW^{-1} \cdot h^{-1}$, at 20 °C); θ —T coefficient

M_a —areal biomass of quagga mussels ($gDW \cdot m^{-2}$), from surveys, according to model cell from interpolation process

- **sink term for PA_m, for i^{th} size class ($S_{i,grazing}$, $m \cdot s^{-1}$)**

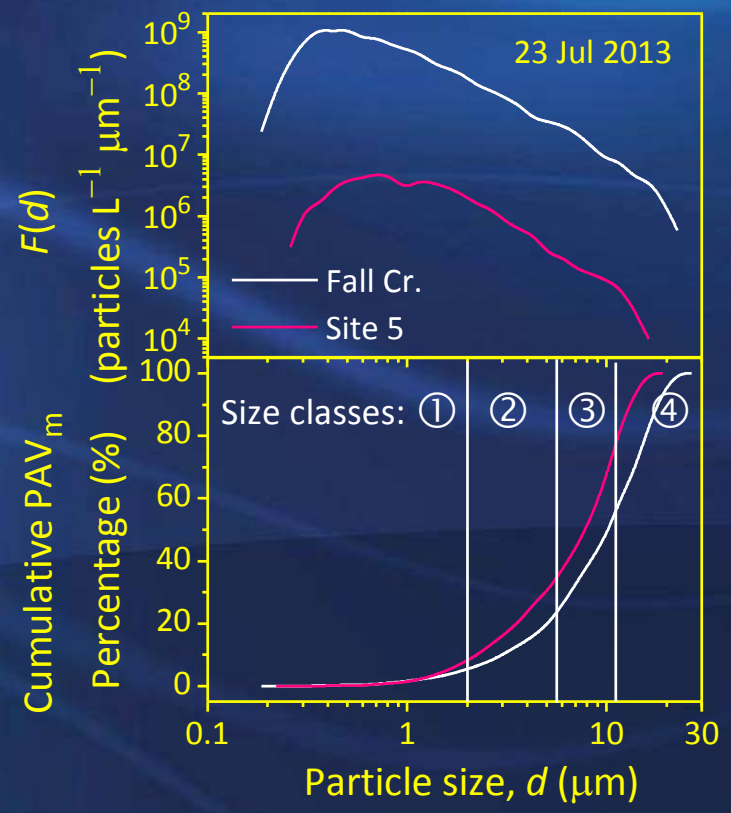
$$S_{i,\text{grazing}} = -k_f c_i \frac{A_{\text{sed}}}{V}$$

A_{sed} —sediment surface area (m^2)
V —computational cell volume (m^3)

- **potential grazing effect of mussel grazing large during high lake turbulence—effect limited otherwise from boundary layer effects**

A mass balance type model for PAV_m for Cayuga Lake (Gelda et al. 2015b)

- a necessary major advancement for addressing the effects of minerogenic particles, beyond being based on mass measurements (ISPM)
  - behavior of polydispersed (i.e., multiple size classes) particle populations cannot be represented by such a single state variable
- also, a necessary building block to support predictions of PP_m (PP associated with minerogenic particles)
  - ➢ PAV_m model has four size classes, guided by PSDs and contributions of the size classes to PAV_m

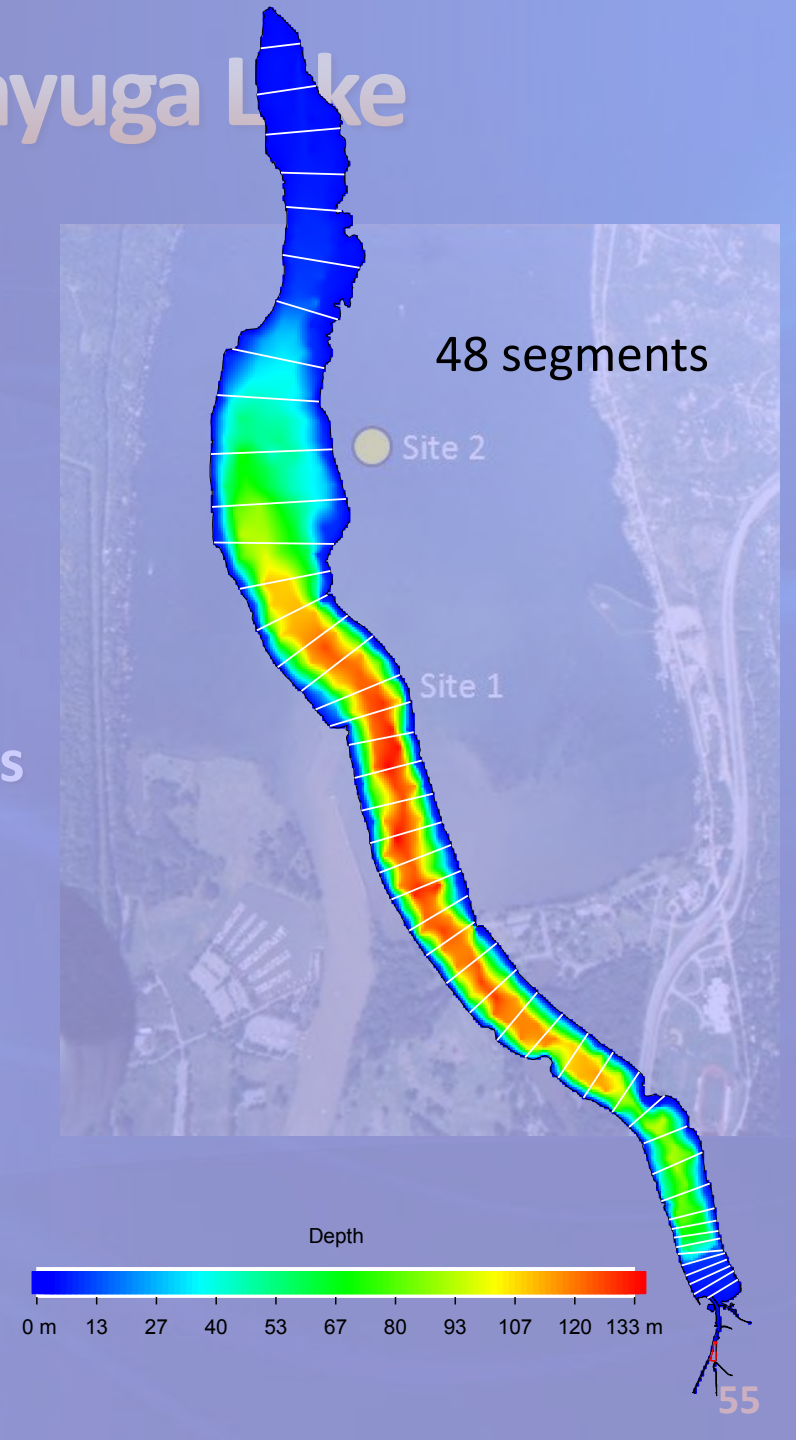


Part II: Outline

1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

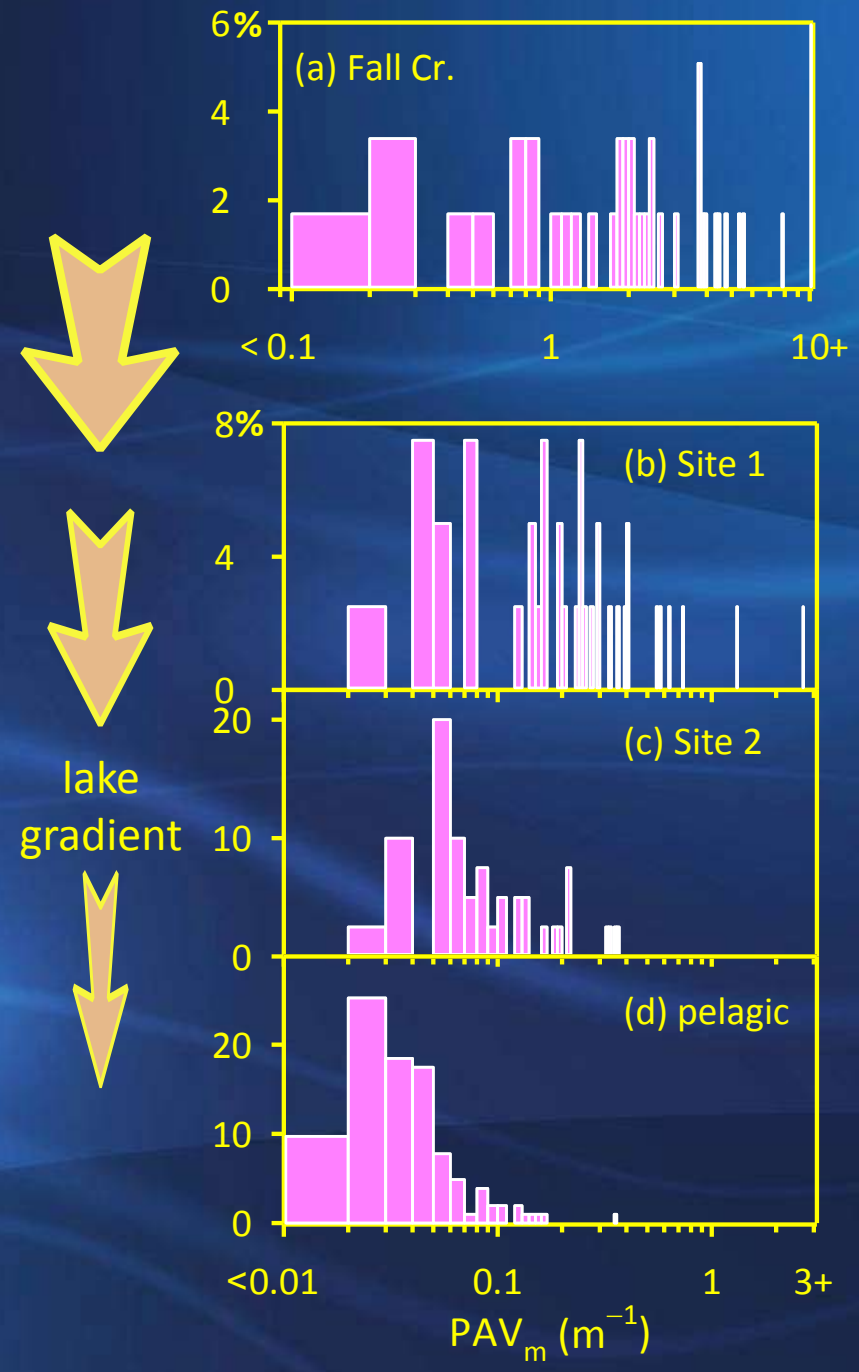
Performance targets for Cayuga Lake PAV_m model

- higher PAV_m levels on shelf compared with in pelagic waters in response to runoff events
- dependency of shelf response on magnitude of a runoff event
- extent of lake-wide effects from events
- increases in minerogenic particle deposition on the shelf from local inputs of the events
- independently validated two-dimensional (W2/T) serves as the hydrothermal/transport submodel (Gelda et al. 2015a)



Performance targets: Simulate distributions and patterns of PAV_m observations on the shelf and in Lake

- narrowing of distributions
- decreases in central metrics



PAV_m model performance target: Historic shelf observations

- runoff events were not specifically targeted in LSC monitoring
- however, 16 events were in part encountered in that monitoring program for the shelf
  - features of the historic events in the table →

Table 2. Features of selected Fall Creek runoff events and subsequent PAV_m monitoring observations for the shelf of Cayuga Lake, NY for the 2000–2013 period.

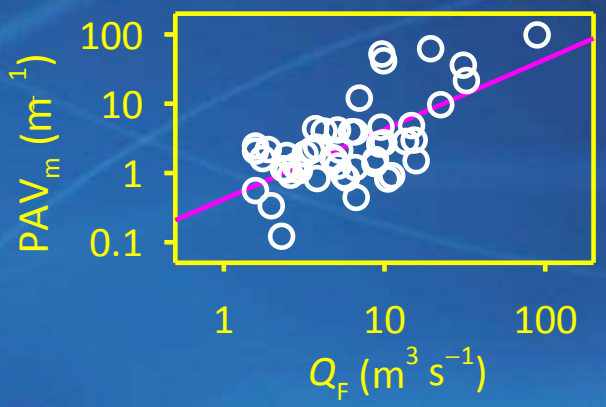
Event No.	Sampling Date	Peak Q_F (m^3/s)	Δt (hr)	PAV_m (m^{-1})	T_n (NTU)
1	15-Jun-2000	41.6	74	1.01	1.3
2	28-Jun-2001	51.0	107	0.98	11.7
3	18-Apr-2002	35.1	84	0.90	4.4
4	16-May-2002	72.8	63	2.60	15.4
5	05-Jun-2003	34.3	94	0.60	2.2
6	06-May-2004	21.7	71	0.55	3.7
7	14-Apr-2005	175	272	0.95	7.2
8	29-Jun-2006	65.7	32	7.63	42.4
9	01-May-2007	15.5	120	0.28	2.9
10	16-Apr-2008	10.6	92	0.20	2.0
11	11-Aug-2009	17.7	7	0.08	2.2
12	20-Apr-2011	51.5	75	2.03	13.7
13	27-Apr-2011	38.2	89	4.47	18.8
14	03-Jul-2013	20.3	37	1.98	46.1
15	09-Aug-2013	113	12	86.02	374
16	12-Aug-2013	113	86	2.67	9.1

Part II: Outline

1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

Good performance of PAV_m model for Cayuga Lake: General spatial patterns

- predicted distributions for Sites 1, 2, and 3 in 2013 were generally similar to those formed from observations
  - driving conditions: Fall Creek



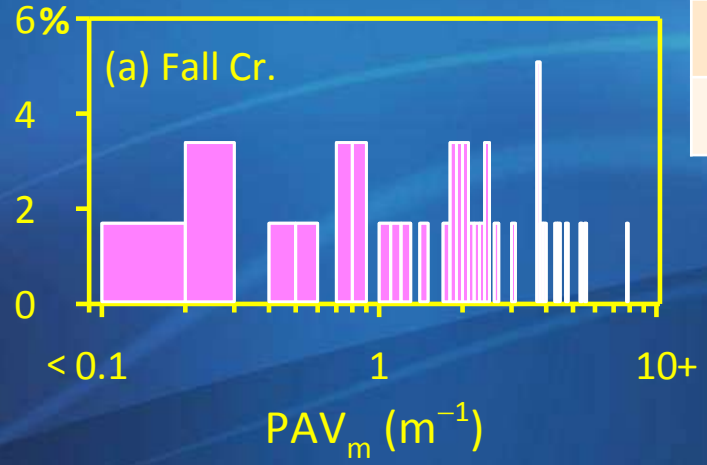
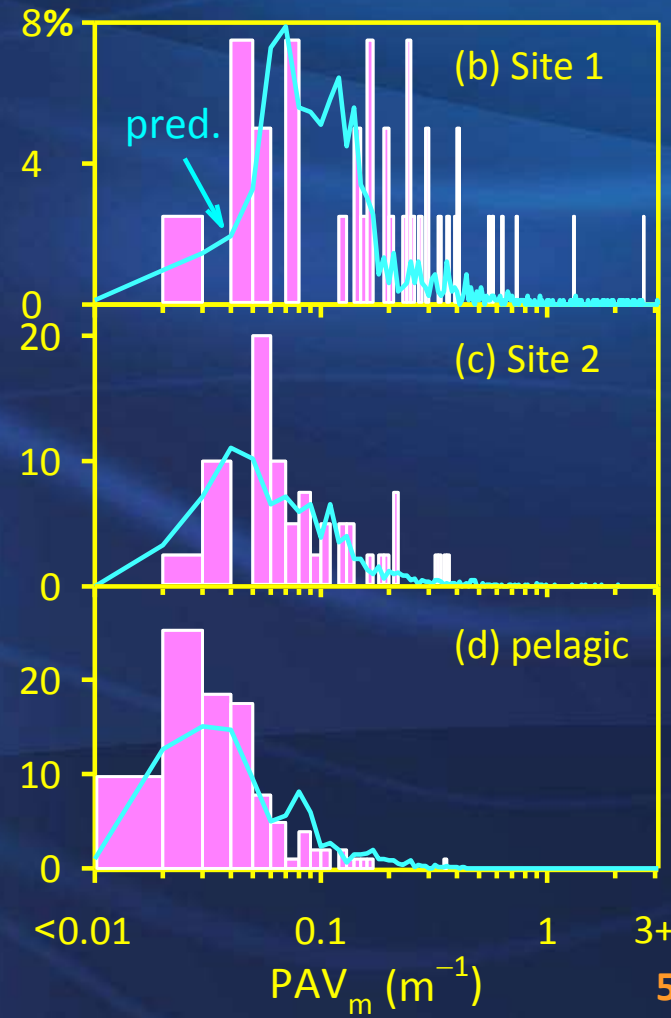
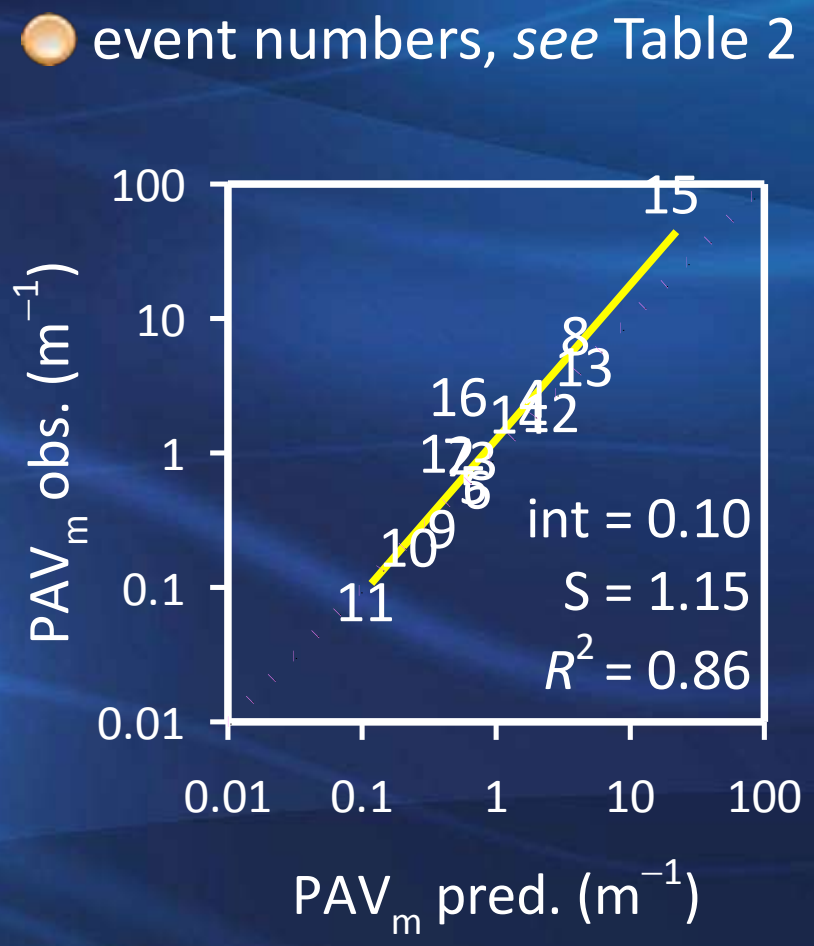


Fig. ID	n	med.	med_p
(a)	59	3.8	
(b)	40	0.24	**0.17**
(c)	40	0.08	**0.08**
(d)	102	0.04	**0.05**



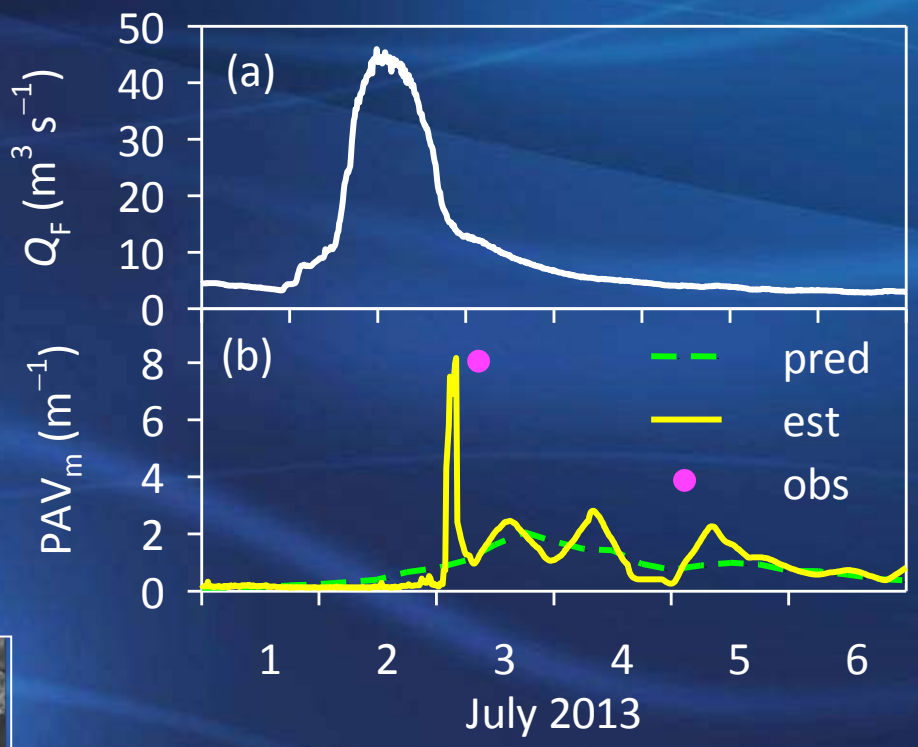
Good performance of PAV_m model for Cayuga Lake, shelf: Historic observations

- 16 runoff events captured during LSC monitoring program for the shelf
- good performance across the wide range of events



Good performance of PAV_m model for shelf for a July (2013) runoff event

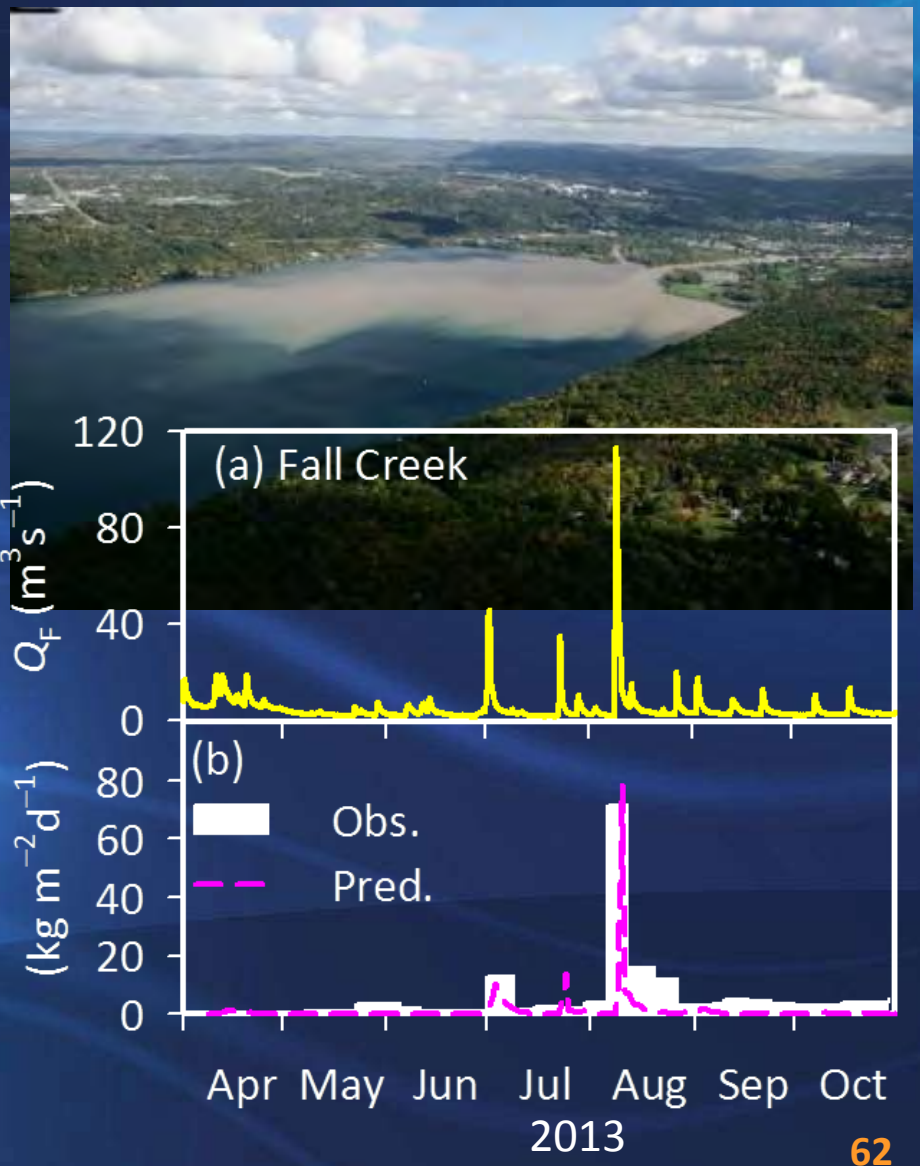
- well defined major runoff event, early July
- model performed reasonably well for the subsequent interval
- variable short-term trajectories of turbid plumes for streams contribute to deviations
  - illustrated in aerial photo



- lateral differences

Good PAV_m model performance for shelf—enhanced local deposition from runoff events

- comparisons of simulations of deposition of minerogenic particles to observations with sediment traps
- observations and predictions were both elevated for the major runoff events
- semi-quantitative support, given the variable operation and trajectories of the turbid shelf plumes

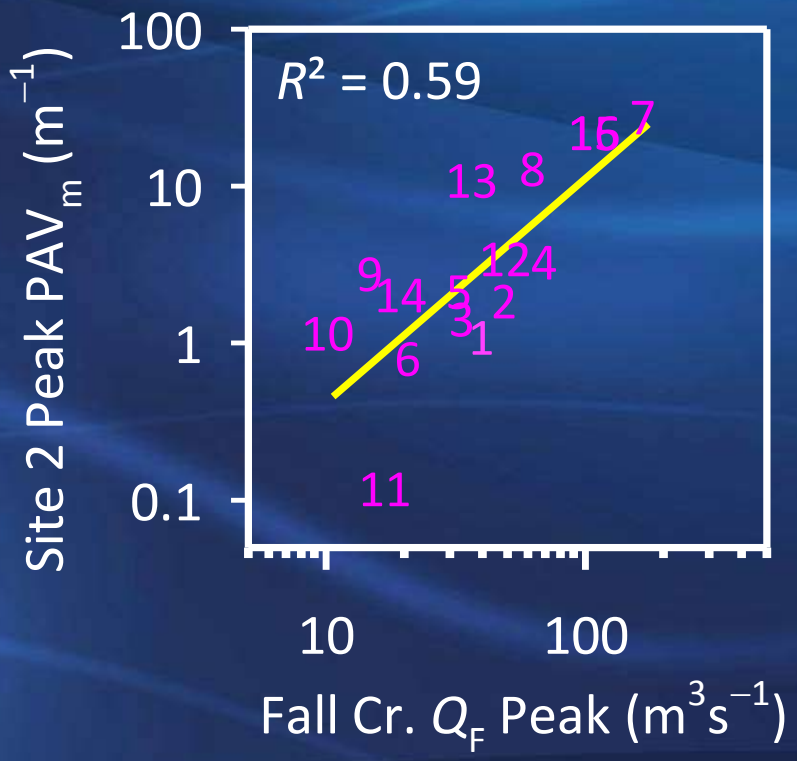


Part II: Outline

1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

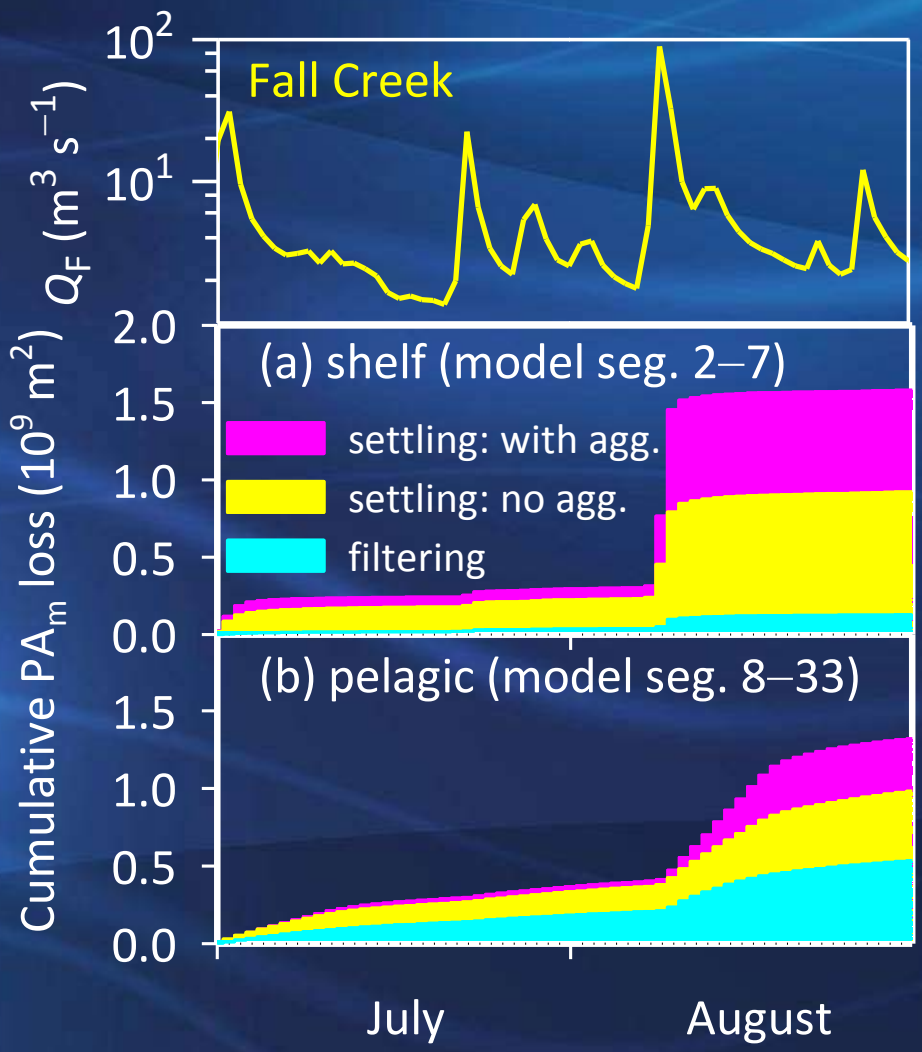
Application of the PAV_m model: Dependence of shelf response on runoff event magnitude

- Fall Creek peak Q_F for the earlier runoff events
- corresponding predicted peak PAV_m at Site 2 on shelf
- strong, positive dependency on event magnitude
- sources of variance—variations in ambient mixing, limitations in peak Q_F defining external loads



Application of the PAV_m model: Loss pathways for PAV_m for shelf vs. pelagic waters

- the dominance of runoff events, particularly in early Aug., in timing of loads and losses
- mussel filtration minor (maybe less) on shelf, but more important in pelagic waters
- abrupt and large short-term minerogenic sediment losses on shelf (i.e., more than lake-wide)
- aggregation process(es) contributes importantly to overall settling (or deposition) losses



Application of the PAV_m model: Predictions of related water quality attributes, PAV_m and Chl-*a* contributions

- predictions of spatial differences in the contributions of minerogenic vs. organic (phyto.)
- water quality attributes
  - b_p—overall scattering coefficient, related to Secchi depth
  - b_{bp}—backscattering coefficient, related to remote sensing
  - T_n—turbidity
  - $PP_{m/u}$ —unavailable minerogenic particulate P
- summations;
  e.g., $PP = PP_{m/u} + PP_o$

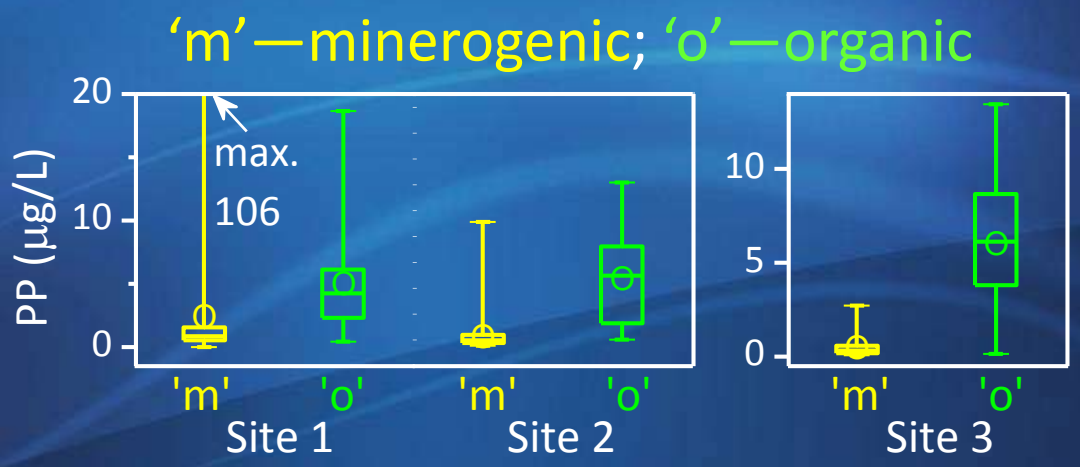
Table 3. Equations to estimate the contributions of PAV_m-based minerogenic vs. Chl-*a*-based organic particles to bulk water quality metrics in Cayuga Lake, NY, 2013.

Equations	Reference
$b_p(660)$	
$b_m = 2.34 \times PAV_m$	Peng and Effler 2015
$b_o = 0.267[\text{Chl-}a]^{0.6}$	Huot et al., 2008
$b_{bp}(660)$	
$b_{b,m} = 0.063 \times PAV_m$	Peng and Effler 2015
$b_{b,o} = 0.0017[\text{Chl-}a]^{0.618}$	Huot et al., 2008
T_n	
$T_{n/m} = 4.8 \times PAV_m$	Effler et al., 2014
$T_{n/o} = 0.08[\text{Chl-}a]$	
PP	
$PP_{m/u} = 7.1 \times PAV_m$	Effler et al., 2014
$PP_o = 1.53[\text{Chl-}a]$	

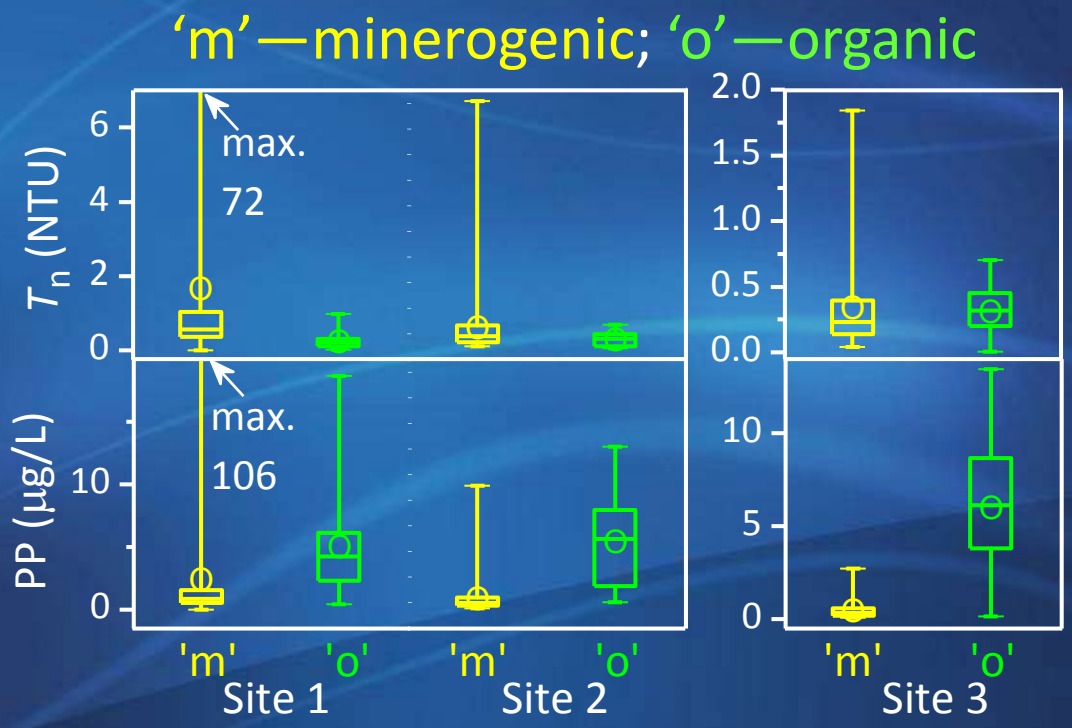
Application of the PAV_m model: Predictions of spatial differences in dependent water quality attributes

- means, medians, and ranges for Sites 1, 2, 3
  - four differences between minerogenic and organic components

(1) spatially uniform organic
(2) greater minerogenic particle effects on shelf
(3) extreme degradations on shelf associated with runoff events
(4) metric-based differences in relative effects of minerogenic particles



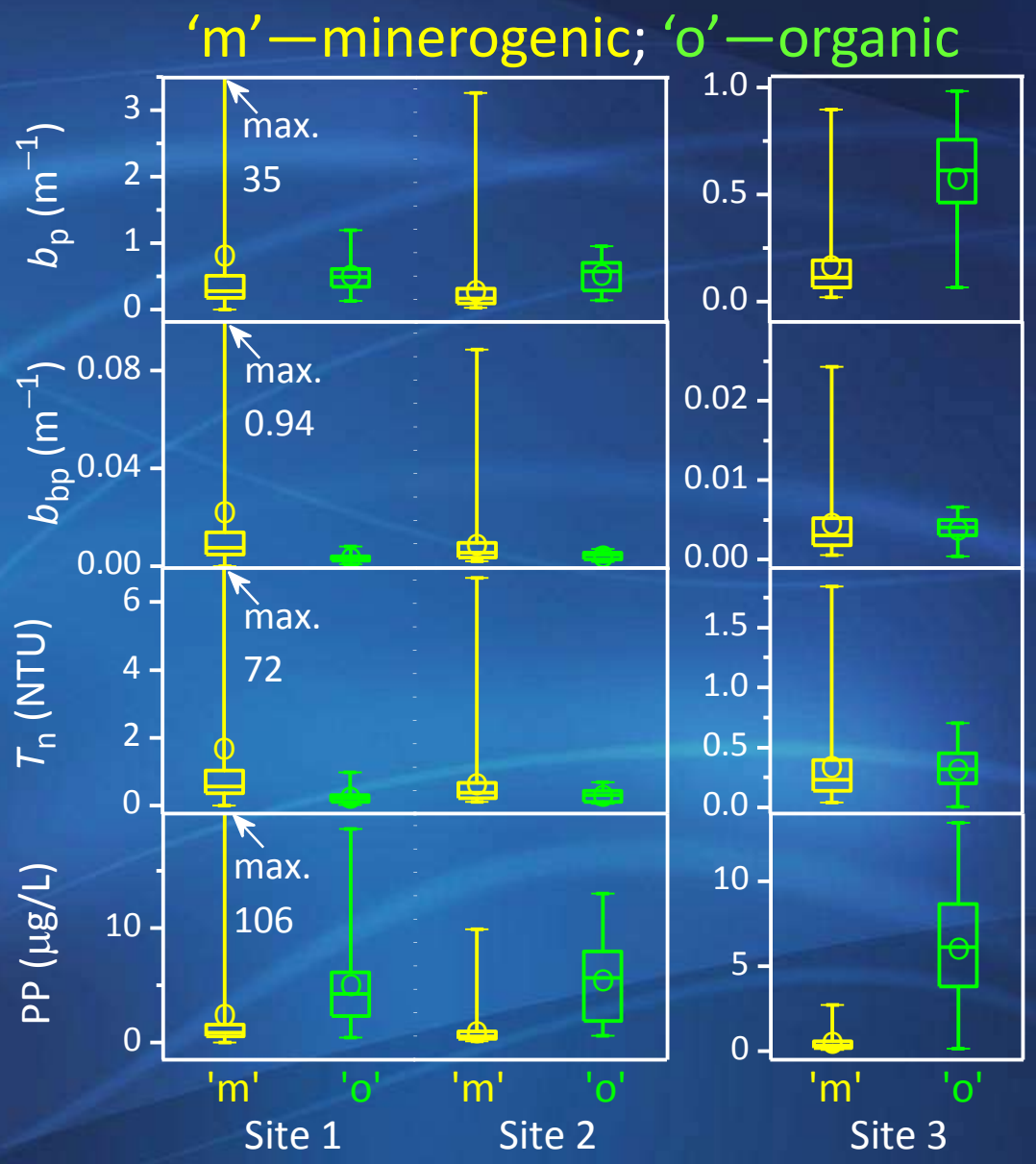
Application of the PAV_m model: Predictions of spatial differences in dependent water quality attributes



- means, medians, and ranges for Sites 1, 2, 3
  - four differences between minerogenic and organic components

(1) spatially uniform organic
(2) greater minerogenic particle effects on shelf
(3) extreme degradations on shelf associated with runoff events
(4) metric-based differences in relative effects of minerogenic particles

Application of the PAV_m model: Predictions of spatial differences in dependent water quality attributes

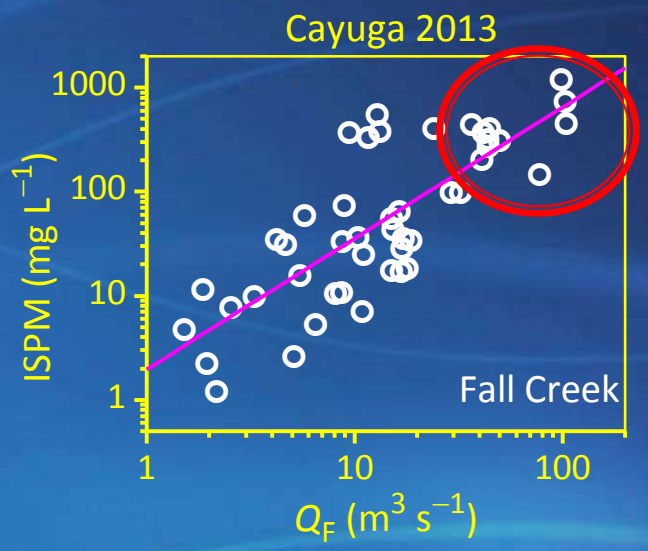


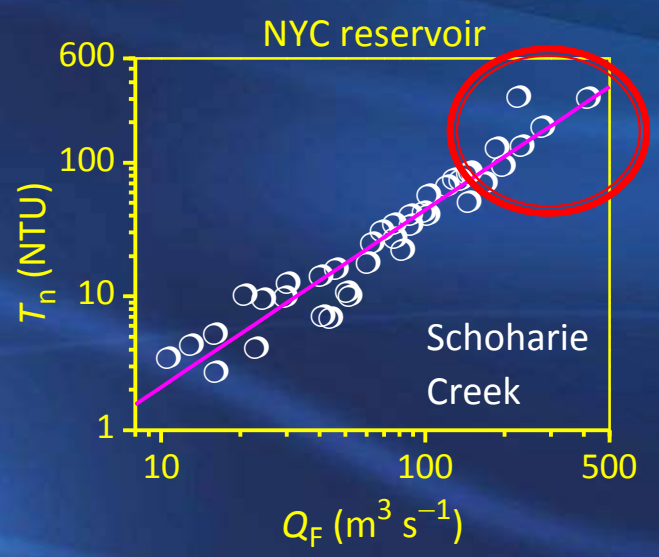
- means, medians, and ranges for Sites 1, 2, 3
- four differences between minerogenic and organic components

(1) spatially uniform organic
(2) greater minerogenic particle effects on shelf
(3) extreme degradations on shelf associated with runoff events
(4) metric-based differences in relative effects of minerogenic particles

Potential applications: Climate change and expectations for future sediment loading

- observations for the Cayuga Lake system and elsewhere demonstrate the positive dependence of sediment loading on stream flow (Q_F)



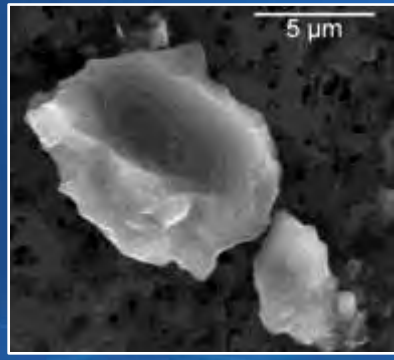


- systematic increases expected in response to predicted climate change in this region, increases in occurrence and severity of runoff events (NOAA, 2013)
- in-lake impacts from increased sediment loading and in-lake PAV_m could be pursued with the model

Part II: Outline

1. PAV_m model concepts
2. modeled particle loss processes
3. model performance targets
4. model performance evaluations
5. model applications
6. summary

Summary: Mass balance type model for PAV_m for Cayuga Lake

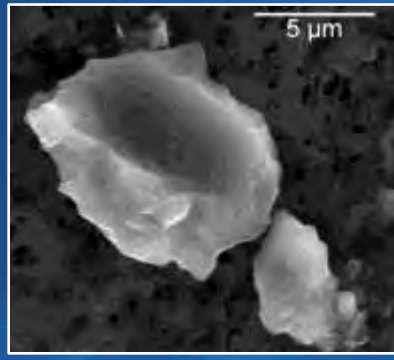


See Abstract:

Gelda, Effler, Prestigiacomo, Peng, and Watkins. 2015b. "Simulation of minerogenic particle populations in time and space in Cayuga Lake, New York, in response to runoff events", submitted to *Inland Waters*

- mass balance type model for PAV_m, partitioned into four size class contributions, has been developed and successfully tested for Cayuga Lake
- supported by long-term monitoring of PAV_m in the lake, shorter-term for the tributaries
- sources of PAV_m—inputs from tributaries, primarily during runoff events
- sink processes (n = 3) represented: (1) settling, (2) enhancement from aggregation, and (3) grazing by mussels

Summary: Mass balance type model for PAV_m for Cayuga Lake



- localized external loads of minerogenic sediment and increases from runoff events were well simulated, including:
  1) higher PAV_m levels on the shelf following events
  2) positive dependence of the shelf increases on magnitude of the event
  3) shelf deposition predictions consistent with sediment trap observations
- settling/aggregation losses large for PAV_m on the shelf for major runoff events
- protocols to use PAV_m predictions to quantify the important effects of these particles on optical and P water quality metrics, particularly for the shelf, are demonstrated