C. Minerogenic particles and the sediment issue
—SAX and a lake model
Part I: Outline

1. system-specific issues; limitations of conventional approach
2. SAX: technical details, advantages, and applications
3. Cayuga Lake 2013 water quality studies
   a. tributaries
   b. lake dynamics
   c. assessments of water quality impacts
4. model framework and summary
Selected related issues, Cayuga Lake

aerial photo of the southern shelf during a high runoff event

clay mineral particles
Selected related issues, Cayuga Lake

stream bank erosion
Minerogenic particles and sediment: Importance to lakes and origins

**importance**
- transport, cycling, and apportionment of forms of nutrients and contaminants
- levels of light scattering and absorption and thereby optical metrics of water quality (optics sub-model) and remote sensing signal (NASA projects)
- metabolic activity and composition of biological communities
- net sediment accumulation

**origins**
- terrigenous (allochthonous, particularly runoff events)
- resuspension (internal)
- autochthonous (internal; CaCO$_3$ precipitation)
History of sediment measurements

- gravimetric—mass per unit vol. of water; unit in mg/L, for example
- suspended particulate material (SPM, or TSS)
  - organic and inorganic components (VSS and FSS)
- SPM = OSPM + ISPM (TSS = VSS + FSS)
  - organic + inorganic
    - operationally defined, burn temperature
- ISPM an attempt to represent minerogenic particles
- streams/rivers vs. lakes/reservoirs
  - higher vs. lower concentrations
  - composition differences,
    - terrigenous vs. lacustrine components

problems
Features of natural minerogenic particle populations
— influence transport, fate and impacts

features

- number concentration — $N$ (i.e., number per unit volume of water)
- particle size distribution (PSD)
- elemental composition of individual particles
- particle shape (least important)

Cannot be done from ISPM

points to be expanded upon

* strong linkage between the common term “sediment” and minerogenic particle populations; e.g., Cayuga Lake
* limitations of older sediment measurement protocols
* superior capabilities of SAX—scanning electron microscopy interfaced with automated image and X-ray analyses
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SAX
— Scanning electron microscopy coupled with Automated image and X-ray analyses

- morphology and composition analyses for individual mineral particles
  - a platelet clay mineral particle
    — dominant form in many systems, including Cayuga Lake
  - $P_{A_m}$ — projected area of a minerogenic particle
  - $P_{AV_m}$ — total projected area of minerogenic particles per unit volume of water ($m^{-1}$)
    — a powerful summary metric

![Graph showing X-ray counts and energy spectrum](image)

![Scanning electron microscopy image of mineral particles](image)
The ‘new’ measurement capabilities for minerogenic particles by SAX

— recognized to be established and powerful

- started in NYC watershed turbidity studies (late 1990s)
- expanded through NY and Great Lakes
- multiple key water quality issues quantitatively connected
- documentation in peer-reviewed literature
  - cumulative growth
- central role and value of the \( PAV_m \) metric

**PAV\( _m \)**— total projected area of minerogenic particles per unit volume of water (i.e., area conc., m\(^{-1}\))
Table 2. Summary of closure or consistency demonstrated by SAX-based approach (PAV_m) for North America Fresh Waters.

<table>
<thead>
<tr>
<th>System</th>
<th>Closure (✓) or Consistency (*)</th>
<th>No. of Components</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York City (NYC)</td>
<td></td>
<td>1</td>
<td>Peng et al. (2002, 2004)</td>
</tr>
<tr>
<td>Reservoir Systems (9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finger Lakes (NY)</td>
<td>✗</td>
<td>2</td>
<td>Peng and Effler (2005)</td>
</tr>
<tr>
<td>Schoharie Creek (NY)</td>
<td>✗</td>
<td>1</td>
<td>Effler et al. (2007)</td>
</tr>
<tr>
<td>Schoharie Reservoir and Schharie Creek (NY)</td>
<td>✓</td>
<td>1</td>
<td>Peng and Effler (2007)</td>
</tr>
<tr>
<td>Central NY lakes (4) and a river</td>
<td>✗</td>
<td>2</td>
<td>Peng et al. (2007)</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>✓</td>
<td>2</td>
<td>Peng et al. (2009a), Effler et al. (2010a)</td>
</tr>
<tr>
<td>NYC Reservoir Systems (6)</td>
<td>✗</td>
<td>1</td>
<td>Peng et al. (2009b)</td>
</tr>
<tr>
<td>Lake Erie</td>
<td>✓</td>
<td>1</td>
<td>Peng and Effler (2010)</td>
</tr>
<tr>
<td>Lake Ontario</td>
<td>✓</td>
<td>2</td>
<td>Effler and Peng (2011)</td>
</tr>
<tr>
<td>Onondaga Lake (NY)</td>
<td>✓</td>
<td>2</td>
<td>Effler and Peng (2012)</td>
</tr>
<tr>
<td>Ashokan Reservoir and Esopus Creek (NY)</td>
<td>✓</td>
<td>1</td>
<td>Peng and Effler (2012)</td>
</tr>
<tr>
<td>Great Lakes (3) and Central NY lakes (4)</td>
<td>✗</td>
<td></td>
<td>Effler et al. (2013)</td>
</tr>
<tr>
<td>Lake Erie</td>
<td>✗</td>
<td>1</td>
<td>Peng and Effler (2013a)</td>
</tr>
<tr>
<td>Skaneateles Lake (NY)</td>
<td>✗</td>
<td>3</td>
<td>Peng and Effler (2013b)</td>
</tr>
<tr>
<td>Cayuga Lake (NY)</td>
<td>✓</td>
<td>2</td>
<td>Effler and Peng (2014)</td>
</tr>
<tr>
<td>Cayuga Lake (NY)</td>
<td>✓</td>
<td>2</td>
<td>Effler et al. (2014)</td>
</tr>
<tr>
<td>Great Lakes</td>
<td>✗</td>
<td></td>
<td>Peng and Effler (2015)</td>
</tr>
</tbody>
</table>
SAX separates minerogenic particles from phytoplankton
• example micrographs from scanning electron microscopy

phytoplankton (greens)
  – organic

phytoplankton (diatoms)
  – mixed organic
  inorganic (Si)

minerogenic clay minerals, quartz, etc.
  – inorganic

produced in lakes

inorganic

watershed

• particle origins and impacts central to management issues
  * phosphorus and trophic state metrics
  * optics—Secchi depth, turbidity, remote sensing

a problem for ISPM in lakes
Particle size distributions (PSDs) of minerogenic assemblages from SAX
—natural polydispersed particle populations

- multiple sized particles observed
- broad size range(s) contribute
  * 1–14 μm in lake
  * 1–20 μm in stream
- behavior and impact reflect multiple sizes

- basis for four broad size classes

### Size classes:
1. < 2 μm
2. 2–5.6 μm
3. 5.6–11 μm
4. > 11 μm
### Advantages of $PAV_m$, disadvantages of ISPM, to represent minerogenic particles

<table>
<thead>
<tr>
<th>Feature</th>
<th>$PAV_m$ (SAX)</th>
<th>ISPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) analytical precision, lakes</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td>(2) representation of sizes of impacts</td>
<td>complete</td>
<td>none</td>
</tr>
<tr>
<td>(3) minerogenic particles successfully isolated</td>
<td>yes</td>
<td>no, variable contributions of diatoms</td>
</tr>
<tr>
<td>(4) resolve contributions of different sizes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>(5) resolve contributions of different geochemical types</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>(6) theoretical and demonstrated consistency with impacts</td>
<td>yes, projected area</td>
<td>no, mass</td>
</tr>
</tbody>
</table>
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Cayuga Lake 2013 water quality studies — phosphorus, clarity

- Intensive sampling: lake and major tributaries
- >400 SAX samples
- ~350 SAX samples, 1999–2006
SAX characterizations

Image analysis
– projected area (PA)
– size (area equivalent diameter, \(d\))

X-ray microanalysis
– elemental X-ray composition
– particle types: clay minerals, calcite, quartz

• Summary results
  - \(\text{PAV}_m\) (particle projected area conc.)
    - size and generic geochemical type distributions
    - related to turbidity, Secchi depth, \(\text{PP}_m\)
  - \(\text{PVV}_m\) (particle volume conc.; mm\(^3\)/L or ppm), clay platelets
    - mass loading, consistency testing
Sediment delivery to Cayuga Lake: Where and when?

1. reception from the watershed
2. localization at southern end—enters the shelf
3. mostly from runoff events — conspicuous visual signatures
4. estimates of external loads supported by focus on runoff events (NYSDEC)
Positive dependencies of minerogenic sediment metrics on stream flow ($Q_F$) for Cayuga tributaries

1. traditional gravimetric measurements
   • ISPM—mostly minerogenic
   • ISPM : SPM dominance, increasingly as $Q_F$ increased

2. SAX characterizations
   • composition and size
     • clay minerals dominate $PAV_m$

[Graphs and data points showing relationships between ISPM, SPM, clay minerals, and stream flow]
Increased minerogenic sediment input (i.e., $PAV_m$) from tributaries during runoff event

- example for Six Mile Creek
- also clearly manifested in $PAV_m$ dynamics

* flow event
* increases in $T_n$ (turbidity)
* increases in ISPM (inorganic sediment mass)
* increases in $PAV_m$
SAX–PAV$_m$ tributary dependencies with other particulate metrics of water quality (2013 observations) —driven by runoff event sampling (NYSDEC)

- $T_n$—turbidity
- strong dependencies
- linkage of PAV$_m$ to an optical metric of quality

<table>
<thead>
<tr>
<th>Creek</th>
<th>PAV$_m$ (m$^{-1}$)</th>
<th>PP (µg L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall Creek</td>
<td>$R^2 = 0.96$</td>
<td></td>
</tr>
<tr>
<td>Salmon Creek</td>
<td>$R^2 = 0.99$</td>
<td></td>
</tr>
</tbody>
</table>

- PP—particulate P (= TP – TDP)
- strong dependencies
- linkage to a trophic state metric
Sediment delivery to Cayuga Lake: Mass consistency of ISPM and SAX observations—Cayuga Lake tributaries

- PVV$_m$—minerogenic particle volume per unit volume of water (i.e., volume conc.)
  - from SAX
  - calculated from PAV$_m$/PVV$_m$ ratios (priori) or individual particle volumes
- slope value $\rightarrow$ density (2.6$\times$10$^3$ kg m$^{-3}$)

- apparent densities ($\rho$) consistent with clay mineral values (e.g., kaolinite 2.60$\times$10$^3$ kg m$^{-3}$)
  * Peng and Effler (2015)—Cayuga tributaries
  * Peng and Effler (2012)—NYC reservoir and tributary
SAX–$PAV_m$ tributary dependencies on flow (2013 observations): Support for tributary load estimates

—benefits of runoff event sampling

• positive, reasonably strong (power law, $PAV_m = A \times Q_F^B$) dependencies

• associated loads would increase with increased runoff events and severity of the events

• however, noteworthy variance in relationships, as with other particulate constituents—consider origins
SAX–PAV$_m$ tributary dependencies on flow
(2003 Schoharie Cr., NYC Reservoir System)

NYC Reservoir System, Catskill region:
Stream bank erosion—a problem
Aerial photo of Ashokan Reservoir, NY
SAX–PAV_m tributary dependencies on flow (Fall Creek 2013)

Fall Creek: Stream bank erosion

- importance of stream bank erosion for sediment inputs from certain Cayuga streams, and sources of variance

Expectations for lake $PAV_m$ magnitudes and patterns

- tributary impacts concentrated on shelf during runoff events

- great spatial $PAV_m$ gradient along the lake’s major axis observed
### Selected SAX–PAV<sub>m</sub> results for 2013

Table 4. Minerogenic particle population characteristics, in terms of contributions to PAV<sub>m</sub> by geochemical and size classes, for Cayuga Lake tributaries and lake sites in 2013 (Peng and Effler 2015)

<table>
<thead>
<tr>
<th>Stream or Lake Site</th>
<th>Avg. PAV&lt;sub&gt;m&lt;/sub&gt;</th>
<th>% Contributions by Particle Types to PAV&lt;sub&gt;m&lt;/sub&gt;</th>
<th>% Contributions by Size (µm) Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Clay</td>
<td>% Quartz</td>
</tr>
<tr>
<td>Fall Creek</td>
<td>23.94</td>
<td>86.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Cayuga Inlet Cr.</td>
<td>129.3</td>
<td>83.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Salmon Creek</td>
<td>19.68</td>
<td>82.2</td>
<td>5.7</td>
</tr>
<tr>
<td>Six Mile Creek</td>
<td>26.30</td>
<td>84.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Site 1</td>
<td>2.74</td>
<td>83.2</td>
<td>6.6</td>
</tr>
<tr>
<td>Site 2</td>
<td>0.35</td>
<td>82.5</td>
<td>6.4</td>
</tr>
<tr>
<td>Site 3</td>
<td>0.071</td>
<td>74.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Site 5</td>
<td>0.053</td>
<td>70.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Site 7</td>
<td>0.058</td>
<td>67.1</td>
<td>5.5</td>
</tr>
</tbody>
</table>

**Key features:**

1. **PAV<sub>m</sub> gradient:** southern trib→shelf→pelagic
2. Clay dominance, calcite secondary for pelagic
3. Shift in PSD from trib to lake—larger to smaller particles
Example distributions of $\text{PAV}_m$ observations in 2013

- runoff event driven dynamics
- the general south–north gradient

### Site 1
- Fall Creek
- $Q_F$ (m$^3$ s$^{-1}$)

### Site 2
- $\text{PAV}_m$ (m$^{-1}$)

### Site 3
- $\text{PAV}_m$ (m$^{-1}$)

### Fall Creek
- $\text{PAV}_m$ (m$^{-1}$)

### Site 1
- $\text{PAV}_m$ (m$^{-1}$)

### Site 2
- $\text{PAV}_m$ (m$^{-1}$)

### Pelagic
- $\text{PAV}_m$ (m$^{-1}$)
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Impacts of minerogenic particles on water quality: \( \text{PAV}_m \)-based, optics

- optical metrics—regulated through light scattering
  
  (1) Secchi depth (SD)
  
  \[
  \text{SD}^{-1} \propto b_p \quad (b_p: \text{particulate scattering coeff.}, \text{ m}^{-1})
  \]
  
  \[
  b_p = b_m + b_o \quad (\text{minerogenic and organic components})
  \]
  
  \[
  b_m = \langle Q_{b,m} \rangle \times \text{PAV}_m
  \]

  scattering efficiency factor = 2.3 (±5%)

  \[
  b_o \quad \text{estimated from chlorophyll-}a \text{ or POC-based empirical models}
  \]

  (2) turbidity \( T_n; \) side-scattering

  (3) backscattering \( b_b \)

- conceptually sound; well documented
  
  – see \( \text{PAV}_m \)-themed reference list

- ISPM is not a legitimate alternative
Impact assessments of minerogenic particles on water quality metrics in Cayuga Lake, 2013: Secchi depth (SD) predictions

- based on empirical system-specific relationships

  \[ \frac{1}{SD} \propto b_p \]

  \[ b_p = b_m + b_o \]

  - Minerogenic component: \( b_m = 2.3 \times PAV_m \)
  - Organic component: \( b_o = f(\text{Chl-a}) \)

- Temporal patterns of SD for

  - \( b_o \) only, and for \((b_o + b_m)\)
    - \( b_m \) (i.e., \( PAV_m \)) caused lower SD compared with \( b_o \) (phyto) only cases, from contributions to \( b_p \)
    - Effect greater on shelf than pelagic waters
      † 27% greater on shelf without minerogenic particles
      † 15% greater in pelagic waters
Impact assessments of minerogenic particles on water quality metrics in Cayuga Lake, 2013: Turbidity ($T_n$) predictions

- based on two component partitioning (Effler et al. 2014, Inland Waters)—Chl-$\alpha$ and $PAV_m$ as drivers
- temporal patterns of $T_n$
  - ‘org’ contribution only
  - ‘org’ + ‘min’ contributions
- higher $T_n$ values because of added $T_{n/m}$; larger effect than on SD
- effect greater on shelf than in pelagic waters
  † log- vs. linear scale
  † $T_{n/o}$ max. on shelf <1 NTU (negligible)
  † $T_{n/m}$ 48% of $T_n$ on average at Site 3

Organic: $T_{n/o}$ : Chl-$\alpha$ = 0.08
Minerogenic: $T_{n/m}$ : $PAV_m$ = 4.80
Impacts of minerogenic particles on water quality: PAV\textsubscript{m}-based

- associated phosphorus, a particulate form—PP\textsubscript{m}
- published for the Cayuga Lake case in the peer-reviewed literature
- first presented on this project (TAC meeting, Jan 2014, Ithaca), reviewed here
  - \(PP = (PP_o : \text{Chl-}a) \times \text{Chl-}a + (PP_m : PAV_m) \times PAV_m\)

  unavailable fraction of PPM (PP\textsubscript{m/u}) dominates, subsequently

- ISPM is not a legitimate alternative to support this analysis
Impact assessments of minerogenic particles on water quality metrics in Cayuga Lake, 2013: Particulate phosphorus (PP)

- based on empirical system-specific model of Effler et al. (2014); paired measurements of PP, $PAV_m$, and Chl-$\alpha$

$$PP = (PP_o : Chl-\alpha) \times Chl-\alpha + (PP_m : PAV_m) \times PAV_m$$

- $PP_m$ and $PP_o$ are the minerogenic and organic (phyto) particle components

- summer avg. TP (and PP) concentrations partitioned

- 20 $\mu g/L$ NYS guidance value
- higher $PP_m$ concentrations primarily cause of higher shelf TP levels
- negative implications for listing and application of guidance value
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A conceptual model for minerogenic particles in a lake

Summary: SAX–$\text{PAV}_m$ and Cayuga Lake


- SAX was applied to characterize minerogenic particles of Cayuga Lake and primary tributaries
- SAX–$\text{PAV}_m$ applied to quantify their effects on common metrics of water quality
- $\text{PAV}_m$ the primary summary metric
- $\text{PAV}_m$ is linearly related to the minerogenic particle components of PP ($\text{PP}_m$), $T_n$ ($T_{n/m}$), light-scattering coefficient, and inversely related to SD
**Summary: SAX–PAV$_m$ and Cayuga Lake**

- SAX supports partitioning PAV$_m$ into multiple particle size (i.e., polydispersed populations) and composition classes.
- PAV$_m$ was higher on shelf than in pelagic areas following runoff events because of elevated inputs from local tributaries.
- Coupled degradations in water quality included higher PP$_m$, $T_{n/m}$, and lower SD, on the shelf; though diminished quality in pelagic waters was also resolved for the largest events.
- PAV$_m$ information is superior to ISPM for this important particle group, particularly in lacustrine systems.
- A conceptual model for PAV$_m$ behavior in the lake was presented.
Mass-balance type model for sediment input, transport, and fate — PAV$_m$ based

Part II: Outline

1. $\text{PAV}_m$ 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 $\text{PAV}_m$ model

- Model state variables—multiple size classes of $\text{PAV}_m$, $\text{PAV}_{m,n}$, $n = 4$
- Sources and sinks
- Parsimonious approach
  - Complex feature, $\text{PAV}_{m,n}$, but necessary
  - Simplifying, number of sink processes and size classes

Sources and sinks include:
- External loads from tributaries
- Stokes settling
- Filtration mussels
- Augmented by coagulation

Size class contributions:

$$\sum_{i=1}^{n} \text{PAV}_{m,i} = \text{PAV}_m$$
Post runoff event: Shelf
Parsimonious choices for $PAV_m$ model structure: An appropriate approach

<table>
<thead>
<tr>
<th>Model structural features</th>
<th>model complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>simple</td>
</tr>
<tr>
<td>(1) particle size classes ($n$)</td>
<td>1</td>
</tr>
<tr>
<td>(2) dimensions, transport submodel</td>
<td>1D</td>
</tr>
<tr>
<td>(3) aggregation</td>
<td>no</td>
</tr>
<tr>
<td>(4) filtration loss(es)</td>
<td>no</td>
</tr>
<tr>
<td>(5) internal production CaCO$_3$</td>
<td>no</td>
</tr>
</tbody>
</table>

* intermediate choices made

**model values:**
- performance, management
- utility, credibility
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Model loss processes for PAVₘ: Three represented (1)–(3)

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

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

• setting loss of PAVₘ,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 \( i^{th} \) size class
- \( c_i \) —PAVₘ of the \( i^{th} \) size class
- \( z \) —vertical dimension

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

- \( \alpha \) —shape factor (platelet) = 0.5
- \( g \) —gravitational constant
- \( \rho_p \) and \( \rho_w \) —densities, particles and water
- \( d_i \) —particle diameter for \( i^{th} \) size
- \( \mu \) —water viscosity
The 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 $i = \text{classes } 1, 2, 3$,

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

For class 4,

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

$k_{c,i} = 0.5 \text{ m} \cdot \text{d}^{-1}$, aggregation rate constant for the $i^{th}$ PAV$_m$ size class ($i = 1, 2$ and $3$)

$K = 0.05 \text{ m}^{-1}$, 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
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

(a) Fall Creek
(b) 2013

<table>
<thead>
<tr>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q$_F$ (m$^3$ s$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>80</td>
<td>120</td>
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</tr>
</tbody>
</table>

| DF$_{ISPM}$ (kg m$^{-2}$ d$^{-1}$) |
| 0   | 20  | 40  | 60  | 80  |

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·m⁻²), diminished on shelf (~9 gDW·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$^3$·m$^{-2}$·h$^{-1}$)
  
  $$k_f = f_r M_a \theta^{(T-20)}$$

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

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

- **sink term** for $PA_m$, for $i^{th}$ size class ($S_{i,\text{grazing}}$, m·s$^{-1}$)
  
  $$S_{i,\text{grazing}} = -k_f c_i \frac{A_{\text{sed}}}{V}$$

  $A_{\text{sed}}$ — 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

- 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

Lake gradient

(a) Fall Cr.
(b) Site 1
(c) Site 2
(d) Pelagic
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>
<thead>
<tr>
<th>Event No.</th>
<th>Sampling Date</th>
<th>Peak Q&lt;sub&gt;f&lt;/sub&gt; (m&lt;sup&gt;3&lt;/sup&gt;/s)</th>
<th>Δt (hr)</th>
<th>PAV&lt;sub&gt;m&lt;/sub&gt; (m&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>T&lt;sub&gt;n&lt;/sub&gt; (NTU)</th>
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<tr>
<td>1</td>
<td>15-Jun-2000</td>
<td>41.6</td>
<td>74</td>
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<td>2</td>
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<td>0.98</td>
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<tr>
<td>3</td>
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<td>4</td>
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<td>5</td>
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<td>9</td>
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<td>11</td>
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<td>7</td>
<td>0.08</td>
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<td>2.03</td>
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<tr>
<td>13</td>
<td>27-Apr-2011</td>
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<tr>
<td>14</td>
<td>03-Jul-2013</td>
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<td>1.98</td>
<td>46.1</td>
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<td>09-Aug-2013</td>
<td>113</td>
<td>12</td>
<td>86.02</td>
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<td>16</td>
<td>12-Aug-2013</td>
<td>113</td>
<td>86</td>
<td>2.67</td>
<td>9.1</td>
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</table>
Part II: Outline

1. $\text{PAV}_m$ model concepts
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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**

<table>
<thead>
<tr>
<th>Fig. ID</th>
<th>n</th>
<th>med.</th>
<th>$med_p$</th>
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<td>(a)</td>
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<td>3.8</td>
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<td>(b)</td>
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<td>(c)</td>
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<td>0.08</td>
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<tr>
<td>(d)</td>
<td>102</td>
<td>0.04</td>
<td>0.05</td>
</tr>
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</table>

![Graph showing PAVm model performance and distributions for Sites 1, 2, and 3, and pelagic conditions.](image-url)
Good performance of $\text{PAV}_m$ 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

![Relationship between predicted and observed $\text{PAV}_m$ values](image)

- $\text{PAV}_m$ pred. vs $\text{PAV}_m$ obs.
- Event numbers, see Table 2

- $\text{int} = 0.10$
- $S = 1.15$
- $R^2 = 0.86$
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

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Application of the $\text{PAV}_m$ model: Dependence of shelf response on runoff event magnitude

- Fall Creek peak $Q_F$ for the earlier runoff events
- corresponding predicted peak $\text{PAV}_m$ 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

![Graph showing relationship between Fall Cr. $Q_F$ Peak and Site 2 Peak $\text{PAV}_m$ with $R^2 = 0.59$]
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

![Graph showing cumulative PA loss over time for Fall Creek](image)

(a) Shelf (model seg. 2–7)
- Settling: with agg.
- Settling: no agg.
- Filtering

(b) Pelagic (model seg. 8–33)

Legend:
- Pink: settling: with agg.
- Yellow: settling: no agg.
- Blue: filtering

Graphs show cumulative $PA_m$ loss $(10^9 \text{ m}^2)$ over time from July to August.
Application of the PAVₘ model: Predictions of related water quality attributes, PAVₘ and Chl-α 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 PAVₘ-based minerogenic vs. Chl-α-based organic particles to bulk water quality metrics in Cayuga Lake, NY, 2013.

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

\[ PP (\mu g/L) \]

- Site 1
- Site 2
- Site 3

\[ 'm' — \text{minerogenic}; 'o' — \text{organic} \]

max. 106
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

**Graphical Representation:**
- 'm' — minerogenic; 'o' — organic
- $T_n$ (NTU) and PP ($\mu$g/L) for Sites 1, 2, 3
  - Max. values: 72 for Site 1, 106 for Site 2, 72 for Site 3

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

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