Observations and best-fit modeling of settling and suspension of multiple sediment particle types: York River, Virginia

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Observations and best-fit modeling of settling and suspension of multiple sediment particle types: York River, Virginia

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Motivation: Suspended particle settling velocity is one of the largest unknowns which limits accurate prediction of sediment transport in muddy coastal environments.

Physical-Biological Gradient found along the York estuary:

-- In the middle to upper York River estuary, disturbance by sediment transport reduces macrobenthic activity and sediment layering is often preserved. (e.g., Clay Bank – “Intermediate Site”)

-- In the lower York and neighboring Chesapeake Bay, layering is often destroyed by bioturbation. (e.g., Gloucester Point – “Biological Site”)

-- NSF Multi-Disciplinary Benthic Exchange Dynamics (MUBED) ADV tripods provide observations along gradient.

Schaffner et al., 2001; Friedrichs, 2009; Cartwright et al., 2009; Dickhudt et al. 2009; and Cartwright et al., 2011
Advantages of using Acoustic Doppler Velocimeters (ADVs) for continual observations in fine sediment environments:

-- Acoustics often survive long-term biofouling.

-- Provides estimates for:
  • Suspended Sediment Concentration (c): from Acoustic Backscatter
  • Effective Settling Velocity ($w_{seff}$): $<w'c'>/c_{set}$
  • Bed Stress ($\tau_b$): $\rho*<u'w'>$
Example Settling Velocity from ADV Data at Clay Bank ("Intermediate") site

\( \langle w'C' \rangle \) vs. \( \langle C \rangle \)

Plot \( \langle C \rangle \) (mg/liter) on x-axis and \( \langle w'C' \rangle \) (mm/s times mg/l) on y-axis, and slope gives \( w_s \)

\[ w' = \text{vertical turbulent velocity}, \quad C' = \text{turbulent concentration fluctuation} \]

\[ < > = \text{burst average}, \quad w_s = \text{sediment settling velocity}, \quad \langle C \rangle = \text{burst-average TSS} \]

During Feb to May 2007, flocs appeared to dominate, with \( w_{sf} \approx 0.5 \text{ mm/s} \)
3-day Mean $w_s$ Determined from Fits to $<w'C'> = w_s<C>$ using ADVs

-- Although noisy, mean $w_s$ at **biological** site is generally higher, ~ 1 mm/s.

-- At **intermediate** site, mean $w_s$ is bimodal and varies seasonally, from ~ 0.5 mm/s to ~ 1 mm/s.

Less bioturbated layer present at surface in May.
**Conceptual Model:**

- After HIGH river flow
  - Stratified lower estuary
  - Transport convergence
  - Mid-estuary ETM
  - Trapping of flocs
  - Dilution of pellets
  - LOW settling velocity

- After LOW river flow
  - Little or no stratification
  - Transport divergence
  - No mid-estuary ETM
  - Winnowing of fines
  - Concentration of pellets
  - HIGH settling velocity

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(Friedrichs, 2009), (Cartwright et al., 2009), (Dickhudt et al. 2008), and (Schaffner et al., 2001)
Rapid Sediment Analyzer (RSA)

Typically used to analyze coarse grain material based on particle settling velocities. Used here to determine settling velocities for Pellet-Silt-Sand Mixtures.

- Balance connected to computer
- Sediment drop and start button
- Thermometer to measure water temp.
- Settling tube filled with water
- Computer records weight and settling time
- Metal plate connected to balance (~150 cm from sediment top)
1) Gentle sieve method for down to 45 µm (by L. Kraatz) applied to sediment samples collected from 1-2 cm in the seabed during slack tide following both neap and spring tides in May 2010:

<table>
<thead>
<tr>
<th>Tide</th>
<th>%Pellets (dry wgt.)</th>
<th>% Sand + Coarse Silt (dry wgt.)</th>
<th>% Mud &lt; 45 µm (dry wgt.)</th>
<th>%water (by vol.)</th>
<th>%organic (dry wgt.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neap</td>
<td>8%</td>
<td>23%</td>
<td>69%</td>
<td>65%</td>
<td>10%</td>
</tr>
<tr>
<td>Spring</td>
<td>15%</td>
<td>23%</td>
<td>62%</td>
<td>66%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table from work by L. Kraatz

2) RSA measured settling velocity for gently sieved particles captured on 45 µm sieve

Effective settling velocity of ~1 mm/sec for pellets + coarse silt + fine sand when integrated over the skewed distribution

$$W_{sp} \approx \sim 1 \text{ mm/s}$$

Table from work by L. Kraatz
3-day Mean $w_s$ Determined from Fits to $<w'C'> = w_s<C>$ using ADVs

Now look at transition period at intermediate site when $w_{sf} \sim 0.5 \text{ mm/s} \rightarrow 1 \text{ mm/s}$

-- Although noisy, mean $w_s$ at **biological** site is generally higher, $\sim 1 \text{ mm/s}$.

-- At **intermediate** site, mean $w_s$ is bimodal and varies seasonally, from $\sim 0.5 \text{ mm/s}$ to $\sim 1 \text{ mm/s}$.

Less bioturbated layer present at surface in May.

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12 cm

Less bioturbated layer present at surface in May.
Using RSA settling velocities in very simple model

Assume: Effective settling velocity composed of Pellets+Silt/Sand and Flocs: \( W_s = W_{sp} \cdot C_p + W_{sf} \cdot C_f \)

From RSA: \( W_{sp} \approx 1 \text{ mm/s} \); From ADV: \( W_{sf} \approx 0.5 \text{ mm/s} \); Assume \( C \) at slack is washload

\( W_s \) = effective settling velocity (from ADV), \( W_{sp} \) = settling velocity of Pellets+Sand, \( W_{sf} \) = settling velocity of flocs, \( C_p \) = Conc. Pellets+Sand, \( C_f \) = Conc. Flocs

From ADV: Settling Velocity (\( W_s \))

\( mm/s \)

0 0.5 1 1.5

06/17 06/24 07/01 07/08 07/15 07/22 07/29 08/05 08/12 08/19 08/26

From Model: Concentration

\( C_{floc} > C_{pellet} \)

\( C_{pellet} > C_{floc} \)

\( mg/L \)

0 20 40 60 80 100

06/17 06/24 07/01 07/08 07/15 07/22 07/29 08/05 08/12 08/19 08/26

From ADV: Bed Stress (\( \tau_b \))

\( Pa \)

0 0.05 0.1 0.15 0.2

06/17 06/24 07/01 07/08 07/15 07/22 07/29 08/05 08/12 08/19 08/26

June 12, 2007-August 31, 2007

Dyer, 1999; Friedrichs et al., 2008; Cartwright et al., 2011
-- Flocs and pellets have distinct relationships between stress and suspended sediment concentration.
-- Flocs appear easier to resuspend than pellets (i.e., floc erodibility is higher than pellet erodibility).
-- Pellets have a critical threshold stress for resuspension, flocs do not (i.e., floc line intersects zero).
Conclusions and future work:

• In estuaries, ADVs allow continual, long-term observation of bed stress, fine sediment concentration, and total effective settling velocity ($w_s$), all while resisting biofouling.

• In the middle York River estuary, stratification traps flocs ($w_{sf} \sim 0.5$ mm/s), whereas mixed conditions disperse flocs, leaving behind a pellitized lag ($w_{sp} \sim 1$ mm/s).

• A very simple model assuming (i) wash load + (ii) flocs + (iii) pellets/silt/sand can be applied to ADV data to estimate the time-varying concentration of each particle class.

• The ADV-based model indicates flocs are much easier to suspend than pellets (i.e., floc erodibility is higher than pellet erodibility).

• The ADV-based model also indicates that pellets have a critical threshold stress for resuspension ($\tau_{crit} > 0$), whereas flocs have no significant critical erosion stress ($\tau_{crit} \approx 0$).

• Our future work will include (i) fine-tuning the RSA method, (ii) using vertically stacked ADVs, (iii) deploying a new particle settling camera, and (iv) using adjoint data assimilation to allow more sophisticated best-fit models.
Questions?

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