Seasonal and spatial trends in biological versus physical influences on sediment settling velocity in the York River estuary

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Abstract

Scientists’ inability to reliably predict the settling velocity of suspended particles is critically limiting the accurate modeling of fine sediment transport and water quality in estuaries. Seasonal and spatial trends in the concentration and settling velocity of estuarine suspended aggregates were examined at two contrasting sites in the York River estuary between January and December 2007. The Gloucester Point site is characterized by generally higher biological activity while the Clay Bank site is characterized by generally more intense sediment transport. At times of relatively low concentration at each site, greater sediment concentration was associated with greater settling velocities. This relationship between concentration and settling velocity was reversed at higher concentrations at Clay Bank in the spring and early summer. This is most likely due to rapid deposition at Clay Bank in spring that amassed layers of light unconsolidated sediment, blanketing the biota residing upon the bed floor. This is believed to largely nullify the influence of pelletization and other biologic mechanisms that are normally prominent, allowing stress to drive up suspended sediment concentration with extremely light particles, which simultaneously lowers settling velocity.
Introduction

Overview
The proposed project is an examination of seasonal and spatial trends in biological versus physical influences on the concentration and settling velocity of muddy suspended sediment aggregates in estuaries. Biological processes tend to make suspended aggregates larger and stronger (and thus settle faster) due to the effects of (i) inclusion of sticky organic matter and (ii) mechanical compaction during feeding and excretion. In contrast, physical turbulence tends to tear suspended aggregates apart, making them smaller and settle more slowly. As well as being spatially variable, these processes undergo seasonal changes, with physical processes tending to dominate in the winter and biological processes tending to dominate in the summer.

This project hypothesizes that suspended sediment concentration will be lowest and settling velocity highest in muddy estuarine environments in the summer, when biological activity is the most intense, and the opposite in winter, when physical processes are relatively more important. Furthermore, suspended sediment settling velocity will tend to be larger overall at locations that are more biologically dominated and will tend to be smaller overall at more physically dominated locations.

Significance & Background
Estuarine water clarity is largely determined by suspended sediment. Suspended sediment blocks the light needed for sea grasses to survive, reducing the habitat available to fish larvae and to commercially important species such as the blue crab. Furthermore, fine sediment provides an avenue of transport for binding contaminants. Suspended sediment is also associated with the transport of organic carbon, which is crucial to understanding carbon sinks and the carbon cycle. Settling velocity of sediment particles
largely determines how high in the water sediment can be suspended and how far sediment can travel before being redeposited. Scientists’ inability to reliably predict the size and settling velocity of suspended particles is critically limiting the accurate modeling of fine sediment transport and water quality in estuaries.

Biologic activity heavily influences sediment transport. Suspended sediments in muddy estuaries with more biologically active benthic communities tend to have relatively greater settling velocities and lower suspended sediment concentrations. This is due in part to pelletization, which refers to the feeding and excretion processes of estuarine organisms. These processes compress, mold, and increase the cohesiveness of sediment particles. Pelletization increases the coagulation potential and density of suspended sediment, which contributes to the greater settling velocities and lower concentrations observed in these types of environments (Fugate and Friedrichs, 2003).

*The York River*

The York River is a subestuary that flows into the Chesapeake Bay, the largest estuary in the United States. The York River estuary is roughly 50 km long, flowing southeastward from its head at the union of the Mattaponi and Pamunkey Rivers at West Point to its mouth where it joins the Chesapeake Bay by the Goodwin Islands. For the majority of its length, the York River is defined by a main channel bounded by distinct shoals (Friedrichs, 2008). The depth along the main channel generally increases with distance downstream, spanning from about 6 m near the head of the river to about 20 m at the mouth (figure 1). The overall average depth of the river (including shoals) is fairly shallow at 4.9 m (Cronin, 1971). The average width of the York River is 3.8 km, compared to the relatively narrow hundreds of meters that upstream rivers and tributaries
extend across (Nichols et al. 1991).

The York River is classified as a microtidal system, meaning it has relatively low tidal ranges. The mean tidal range at the head of the estuary is 0.85 m, decreasing to 0.70 m at the entrance to the Chesapeake Bay (Friedrichs, 2008). Tidal current strength also differs across the width of the York, with deeper parts of the estuary experiencing greater tidal current strengths than shoals and other shallow areas. Although the tidal action of the York River estuary is considered moderate, the influence of tidal currents on the York are great, capable of causing significant sediment suspension in the middle and upper regions of the estuary (Schaffner et al., 2001). The sediments in the estuary are primarily muds.

The York River Watershed (figure 2) covers about seven percent of Virginia at just under 6880 square km of the coastal plain. The York, Mattaponi, and Pamunkey rivers and all their tributaries drain into the watershed. Despite its proximity to Richmond and Washington, D.C., the York River Watershed is primarily comprised of forested and rural areas. The basin is 72% forest, 18% cropland, and 10% urban or impermeable cover (Petrackis et al., 1995). The majority of the human population within the watershed resides in the towns of Ashland, Fredericksburg, West Point, and Williamsburg.

A salinity and turbidity gradient along the York River largely causes an increase in biologic diversity and activity downstream (figure 1). Greater salinity is often correlated with lower turbidity and higher dissolved oxygen content, leading to a significant gradient in biological diversity. The total number of species observed at
Figure 2

York River Watershed
various field stations along the York over an 11-year period revealed this biological
gradient, ranging from only 40 species near the head of the estuary to as many as 150
species at the mouth (Schaffner et al., 2001). Some of the dominant species observed in
the upper, middle, and lower regions of the estuary are displayed in figure 3. Salinity
distribution in the York River estuary is determined by the interchange between
freshwater and denser saltwater, tidal action, and winds. The salinity content along the
length of the York River estuary is always least at the head increasing downstream as the
water advances closer to the sea, with bottom salinities typically ranging from 5 to >25%.
(Schaffner et al, 2001). Vertical salinity gradients in the York are influenced by spring
and neap tidal cycles. Strongest mixing occurs during high spring tides and stratification
develops between these peak periods. Salinity levels change with the seasons as well,
with lowest salinity and greatest stratification occurring during periods of high freshwater
runoff.

**Study Sites**

Two sites varying in biologic and physical activity were chosen for this project;
Clay Bank, a relatively more physically dominated environment, and Gloucester Point, a
relatively more biologically dominated environment. The Clay Bank site is located
approximately 30 km upstream from the mouth of the river in a secondary channel 1 km
from the main channel at a depth of about 6 m. The Gloucester Point site is situated
about 10 km upstream from the mouth of the river at a depth of approximately 8 m
(figure 4). Due to less intense sediment transport, Gloucester Point is generally
characterized by greater biologic activity than Clay Bank throughout the year, although
there are annual fluctuations in activity at both sites.
Figure 3

(Schaffner et al., 2001)
Figure 4

(Dickhudt et al., 2008)
Methods

Since the end of 2006 to the present, instrumented tripods have been deployed intermittently in the York River estuary at two sites characterized by differing degrees of physical and biological dominance. Six separate data sets were collected during this time: four separate periods of instrumented tripod deployment at Clay Bank and two at Gloucester Point. This project is only concerned with the measurements of the Acoustic Doppler Velocimeters (ADVs). ADVs directly measure the concentration of suspended sediment and velocity of the water containing the sediment. ADVs achieve this by emitting sound waves that bounce off suspended solids and detect the reflected sound energy. The strength of the return reveals the amount of material off which the sound waves are reflecting, or the mass concentration of total suspended sediment. The Doppler frequency shift of the return gives the velocity of the particle, assumed to nearly equal that of the surrounding water.

The sampling volume of the ADVs used for this project is about 2 cm$^3$ and is located about 35 cm above the bed floor. All equipment was provided by Dr. Carl Friedrichs at the Virginia Institute of Marine Science (VIMS). From these values, settling velocity ($w_s$) may be calculated using the equations below (Fugate and Friedrichs, 2003):

\[
\text{Reynold’s flux: } \langle C \rangle w_s = \langle C'w' \rangle
\]

where $C$ is suspended sediment mass concentration, $w$ is vertical water velocity, $\langle \rangle$ indicate a time average over several minutes, and primes indicate fluctuations away from the burst average. Since the ADV can directly measure $C$ and $w$, including turbulent fluctuations, one can solve directly for burst averaged values of $w_s$ (settling velocity). A
second related relationship applied to the ADV data in this study is the Reynolds stress equation for bed stress:

\[
\text{Reynolds Stress: } \tau_0 = \rho_0 \langle \! u'w' \rangle
\]

Where \( \rho_0 \sim 1010 \text{ kg/m}^3 \) is estuarine water density and \( u' \) and \( w' \) are turbulent fluctuations in horizontal and vertical velocity.

ADVs must be calibrated so that acoustic backscatter is accurately transformed to sediment concentration. The ADV calibrations for all data sets are displayed in figure 5. It is important to note that the ADV calibrations in January and August at Gloucester Point are pretty different from July at Clay Bank. This may be because of different amounts of suspended sand. Acoustic backscatter strength increases with sediment particle size. However, settling velocity calculations are relatively insensitive to this because concentration is on both sides of the Reynolds Flux equation and the absolute magnitude of \( C \) largely cancels the calculation of \( w_s \).

The initial goal of this project was to have constant monitoring of sediment dynamics throughout spring, summer, fall, and winter at the two project sites, Clay Bank and Gloucester Point. Unfortunately, technical problems prevented both tripods from being available for continual deployment. Nevertheless, a large amount of reliable data was still retrieved. A total of six reliable data sets, or time periods of instrumented tripod deployment, were collected; four from the more physically dominated Clay Bank site and two from the more biologically dominated Gloucester Point site. Reliable data at Clay Bank spans from 2/27/07-5/6/07 (“spring”), 6/12/07-9/4/07 (“summer”), 8/31/07-9/18/07 (a peek at “fall”), and 12/5/07-1/26/08 (“winter”), more or less representing all four seasons. The amount of reliable data from Gloucester Point is significantly smaller,
spanning from 12/4/06-2/1/07 (“winter”) and 9/1/07-10/1/07 (“fall”). There is no reliable ADV data from Gloucester Point for the spring or summer. The table below illustrates the reliable data that was retrieved:

<table>
<thead>
<tr>
<th>RELIABLE DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>'06</td>
</tr>
<tr>
<td>Dec</td>
</tr>
<tr>
<td>Blue = Gloucester Point</td>
</tr>
</tbody>
</table>


Results

**Expectations**

Six separate reliable data sets were collected from late 2006 to early 2008; four at Clay Bank and two at Gloucester Point. It was generally expected that total suspended sediment concentration would be larger in winter than in summer and consistently larger at the more physically dominated site (Clay Bank). In addition, it was predicted that greater bed stress at the biologically dominated site would tend to suspend increasingly larger, strongly bound pellets, therefore increasing settling velocity. Conversely, Fugate and Friedrichs (2003) described that in the absence of biology, aggregates are easily broken by greater turbulence. As such, it was believed that greater stress at the physically dominated site would decrease settling velocity (figure 6).

**General Data Yield**

Gloucester Point’s total average settling velocity was 1.33 mm/s, 0.43 mm/s greater than Clay Bank’s overall average of 0.90 mm/s. At Clay Bank, spring and early summer suspended sediment concentrations were far greater than other times of the year (figure 7). Overall, the concentrations at Clay Bank were much greater than (at least 2x) Gloucester Point’s concentrations (figure 8), which never reached above 100 mg/l, although reliable spring and summer data for Gloucester Point were not recorded. These patterns are similar to spatial and temporal trends in erodibility observed by Dickhudt et al. (2008). Erodibility was greatest at Clay Bank in spring and early summer, and Clay Bank had generally higher erodibility than Gloucester Point.

**Stress VS. Concentration/Settling Velocity:**

In general, the data indicate that both sediment concentration and settling velocity increase with stress (figs 9,10). This does not support the hypothesis that stress decreases sediment concentration (and therefore settling velocity) in physically dominated
Figure 6

**Biologically Dominated**

\[ \langle C \rangle = \text{Total suspended solids (mg/L)} \]

(Fugate & Friedrichs 2003)

\[ 0.3 \text{ meter} \quad 1 \text{ meter} \quad 5 \text{ meter} \]

**Physically Dominated**

\[ d = \text{Median particle size (mm)} \]

\[ \langle C \rangle = \text{Total suspended solids (mg/L)} \]
Figure 8

"Winter" (12/4/06-2/1/07)

"Fall" (9/1/07-10/1/07)
Figure 10
environments. However, when the data is averaged to produce daily mean stresses, concentrations, and settling velocities, more subtle relationships between the variables become apparent. The use of daily average calculations essentially smooths out the plots by erasing fluctuation in the variables over individual 12-hour tidal cycles.

Figure 11 displays plots of daily average stresses versus the daily average suspended sediment concentrations for all data sets. The daily averaged Clay Bank data for the spring and summer cases seem to display two separate relationships within each of the plots. These most likely represent different events during which the sediment being acted upon differed, perhaps in type and/or size. There are likely unknown outside variables that influenced these relationships. The data collected in the fall and winter at Gloucester Point and Clay Bank, respectively, also exhibit significant scatter, but distinct multiple events are not as evident. Most interestingly, the winter data from Gloucester Point initially shows an increase in concentration with increased stress followed by a decline once stress reaches about 0.13 Pascals (figure 11). This may imply that there is a certain point where most of the available sediment had already been suspended, and further increases in stress simply spread the sediment upwards and away from the ADV. More data would have to be collected to determine whether this is an accurate representation of the mechanisms at play.

The daily mean stresses versus the daily mean suspended sediment settling velocities for all data sets are presented in figure 12. Although it was expected that increased stress at the physically dominated site (Clay Bank) would lead to a decrease in settling velocity, this was not the case. The plots for all data sets comparing stress and settling velocity show a positive relationship at low stresses. Winter and fall daily mean
data from Clay Bank and Gloucester Point, respectively, contain some scatter, but still show a generally positive relationship between bed stress and suspended sediment settling velocity. Fall and winter data from Clay Bank and Gloucester Point, respectively, display extremely significant scatter and thus the relationships are largely unclear. The most intriguing results comparing stress and settling velocity are the spring and summer daily mean plots for Clay Bank (figure 12). Both plots seem to show two separate events marked by declines of varying steepness in settling velocity as bed stress increased. These data are likely related to sizable sediment deposition events. When bed erodibility increases, the settling velocity of suspended sediment likely decreases due to the new, unconsolidated, light sediment. These distinct declines may represent separate deposition events of different sediment type and/or size.

*Concentration VS. Settling Velocity:*

Plotting concentration versus settling velocity times concentration (wpr*Cpr) allows a new perspective on the data, with the slope (m) of the trend representing sediment settling velocity. All of the data sets are displayed in this manner in figure 13. Clay Bank average settling velocities in the spring, summer, fall and winter were 0.40, 0.93, 1.35, and 0.92 mm/s respectively. Gloucester Point recorded an average settling velocity of 1.15 mm/s in the fall and 1.51 mm/s in the winter. All but two of the data sets displayed a fairly consistent positive relationship between suspended sediment concentration and settling velocity. Figure 14 displays all data sets on concentration versus settling velocity axes and figure 15 plots the daily averages. A positive relationship between concentration and settling velocity is intuitive; as sediment is kicked up into the water column particles coalesce and gain mass, therefore increasing in settling velocity. The data that did not agree with this relationship are the spring and summer
Figure 14
data sets for Clay Bank. In both the overall and daily average instances, settling velocity seems to rise sharply with concentration at some variable rate and then steadily decline.

**Conclusions**

As expected, the more biologically dominated site experienced the greatest peak and average settling velocities. The data signify that both sediment concentration and settling velocity increase with stress, which does not support the hypothesis that stress generally decreases settling velocity in physically dominated environments. Perhaps Clay Bank still has enough biologic activity to often counter the effects of stress, or there could be an unknown mechanism compacting and strengthening the sediment.

The weakening of the relationship between concentration and settling velocity in the spring and summer is most likely due to the interaction of newly deposited sediment and bed stress. Stress plays two roles that affect the settling velocity of suspended sediment in different manners. 1) Stress disturbs the bed floor, kicking up sediment into the water column, increasing suspended sediment concentration and therefore settling velocity and 2) stress causes turbulence, which acts upon the concentrated suspended sediment and can break it up into smaller particles, thus decreasing settling velocity.

The reversal of the relationship between concentration and settling velocity in the spring and summer at Clay Bank is most likely related to high erodibility caused by rapid deposition episodes. Research by Dickhudt et al. (2008) indicates that spring and early summer are times defined by an easily erodable bed at Clay Bank (figure 16). This high erodibility is believed to exist because of the rapid deposition of very light, poorly consolidated sediment layers. While biologic activity (pelletization) drives low bed
erodibility and higher settling velocities for most of the year, the effect disappears during these episodes of high erodibility. One hypothesis is that the rapid deposition of sediment is significant enough to cover the biologically active bed and nullify the influence of pelletization that is normally prominent. Settling velocity is inversely related to erodibility so these episodes of rapid deposition would be conducive to decreasing settling velocity, which may explain the reversal of the relationship between suspended sediment concentration and settling velocity in the spring and summer.
Figure 16

(Dickhudt et al., 2008)
References

Dickhudt, P.J., Friedrichs, C.T., and Sanford, L.P., 2008. Mud matrix solids fraction and bed erodibility in the York River, USA, and other muddy environments. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA

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