Biological versus physical controls on seabed erodibility in a muddy, partially mixed estuary
ABSTRACT

Sediment erodibility has important implications for pollutant transport and burial, benthic communities, nutrient cycling, channel stability, and various other processes and systems within estuaries. We examined several characteristics of the York River seabed, which is a subestuary of the Chesapeake Bay, at a biologically dominated and a physically dominated site in order to better understand which factors most influence sediment erodibility in a muddy estuarine environment. Physical factors affecting erodibility that we observed include physical grain properties, water content, depositional history and compaction of sediment, and recent erosion or disturbance. Biological effects include extracellular polymeric substances (EPS) that are secreted by certain benthic invertebrates as well as microbial organisms and bioturbation by macrobenthic organisms. Multiple box cores were taken in the York River estuary offshore Gloucester Point (a more biologically dominated site) and at the Clay Bank channel and shoal (more physically dominated sites). We analyzed these cores for Eh, porosity, total % organics, 7-Be, and grain size for June 2006 samples and Eh, porosity and colloidal carbohydrate concentration for July 2006 samples. Also, digital X-rayographs for each site allowed us to observe whether bioturbation or preserved physical layering of the sediment is more prominent. A Gust Erosion microcosm was used to directly measure a critical stress profile at each site with stresses similar to average tidal resuspension. In this presentation, the results of the erosion rate tests are compared with the porosity, Eh, X-rays and colloidal carbohydrate concentration to see which properties correlate most with the critical shear stress for each site. Volume clay fraction appears to have a significant impact on sediment erodibility as does consolidation. Colloidal carbohydrate concentration does not show significant range between sites, which did not give us a clear understanding of its actual affects on sediment erodibility, more studies need to be done.

INTRODUCTION

The York River, a subestuary of the Chesapeake Bay, is a prime example of a muddy, tidally energetic estuary in which there is a gradient between physically and biologically dominated regions, thus providing an opportunity to test for corresponding differences in erosion potential of the sediment (Figure 1). In the upper York River estuary, the Clay Bank channel and shoal are two of the study sites chosen for their more prominent physical domination, as bed roughness is dominated by physical processes that often eliminate macrobenthos from the upper sediment layers, which was observed by Schaffner et al. in preliminary studies (Schaffner et al., 2001. Friedrichs et al., 2005). Also, upper estuarine channels, such as the Clay Bank channel and shoal, are often net sediment traps (Pethick, 1984), thus supporting the physical dominance at these sites. The lower estuary, nearer the mouth of the Chesapeake Bay, which is the Gloucester Point site used in this study is more biologically dominated, as bed roughness is attributable to mounds of epifauna in the sediment, and macrobenthos are more abundant. Therefore, the purpose of this study is to observe several characteristics of the seabed at each location and compare the data from each
site to understand which factors are impacting the erosion potential for physically dominated and biologically dominated systems.

Physical properties of the seabed itself, such as grain size and composition, water content (porosity), volume fraction of mud (the rest being sand and water), as well as chemical properties of the water column influence erodibility. Benthic communities, thus biological factors, can also increase or decrease the erosion potential of the seabed by either bioturbation or biostabilization respectively (Black, et al., 2002). Macrobenthic organisms can significantly increase the erodibility of the seabed through their diurnal activities such as burrowing. Biostabilization results from extracellular polymeric substances (EPS) and other carbohydrates in the sediment which secreted by microphytobenthic flora and microbial organisms, as well as certain benthic fauna, and serve various functions such as motility, desiccation resistance, mediation of extracellular exchange and also as photosynthetic overflow (Bellinger et al., 2005). These substances can also significantly reduce sediment erodibility by increasing cohesion between particles. EPS related to photosynthesizing organisms tends to be concentrated in the upper 0.3mm of sediment where light is readily available and diatom populations can thrive; therefore, this very surface layer is crucial for understanding erodibility of the seabed. The critical entrainment condition of the seabed correlates to the entrainment of the very surface sediment layers, which may be slightly different than the actual measurement we found for erodibility, but the point being that the surface of the sediment is more crucial for erodibility (Black, et al., 2002).

Seabed erosion is a major vector for nutrient transport and cycling, contaminant transport, settling, resuspension, which in turn affect the health and sustainability of benthic communities (Schaffner et al., 2001). Erodibility of the seabed can be characterized as the product of a shear stress and the surface area of the bed exposed to this stress, which was measured for this project (Black et al., 2002). Basic particle properties working against shear stress include the submerged weight of the particle, frictional interlocking of the grain aggregates, and cohesion. The critical shear stress of a seabed is a force great enough to exceed these physical counteracting properties (Black et al., 2002). Various physical and biological properties of the seabed significantly affect the erodibility of the sediment at a given location by either reducing or increasing the frictional and cohesive properties of the sediment. This paper attempts to describe certain quantified seabed properties and correlate them to the erodibility of the seabed at various locations in the York River.

METHODS

Grain Size and Eh

Core samples were taken using a Smith-Mac grabber for each of the sites. A total of 30 samples were taken, 10 from each site, and 10 total were extruded directly upon return and cut into 1cm increments and placed in labeled plastic containers. The other 10 samples were used to take digital X-radiographs (and then extruded and cut into 1cm slices) and for Eh analysis. In order to find Eh, a pH probe with an Eh attachment was used to take Eh readings at every centimeter to determine the redox of each sample. Grain size analysis was conducted using the standard pipette analysis protocol in which a dispersant is used to separate particles and grain sizes for each cm depth are measured. Sand was separated with a 63-micron sieve and placed in the oven to remove water. Next, 4phi and 8phi particles were
removed after a given lapsed time and given depth and placed in a metal tray, placed in the oven, and measured for dry weights. Percent of each grain size was then calculated based on dry weights of sediment.

Water Content and Organics

Water content and organic content were found by weighing a series of metal trays then placing about 20g of sediment in each tray and reweighing the trays. The samples were then placed in an oven where moisture in the soil was removed. The trays were then reweighed for dry sediment weight. The same trays with dry sediment were then placed in a 550°C oven for several hours and then reweighed to measure sediment weight minus organic matter.

EPS

Colloidal carbohydrates were measured as an index of EPS (Underwood et al, 1995). EPS is actually 20-30% of colloidal carbohydrate concentration (Smith and Underwood, 2000). This was determined by collecting 24 samples for each site at increments of 5mm using a 5mL syringe marked every 5 to 20mm and cutting cores at each interval depth. Samples were placed in the -80° freezer overnight and then lyophilized for at least 48 hours. EDTA was added to about .1g of lyophilized sediment from each sample and they were vortexed and let sit for 15 minutes. Next samples were treated with a phenol-sulfuric acid assay and then centrifuged for 15 minutes (Underwood et al., 1995). 2mL of supernatant were used to run assay. Liquid from the centrifuged samples was extracted via pipette and dilutions with DI water were made to make a total 4000mL of liquid. The samples were run through a spectrophotometer to find a calculated concentration, which was used to find the colloidal carbohydrate concentration in the sediment.

Digital X-Radiographs

Sediment cores taken in special flat panels were placed into the X-radiographer and scanned with a resulting image of a cross-sectional view of the sediment. These X-rays were taken digitally so the image was readily accessible to enhance as needed. The images manifest evidence of bioturbation or lack thereof if there is obvious physically intact bedding. Patterns of X-ray attenuation in the digital images were also correlated with calculated porosity for each site. Data was then analyzed using Matlab image analysis toolbox.

Gust Erosion Microcosm

Pristine cores were collected and analyzed soon after for the purpose of quantifying the critical shear stress of the seabed at each site. The erosion microcosm applies a sequence of increasing shear stress to the intact cores. The eroded sediment is transported through a turbidimeter and collected. Once run, we filtered and weighed the eroded sediment to
determine an actual mass from each step of shear stress application. The data was then analyzed using the erosion formulation of Sanford and Maa, which produces profiles of critical stress (2001).

RESULTS

We determined the Eh, porosity, colloidal carbohydrate concentration, and took digital X-rays and ran the erosion microcosm for each site in July 2006. We also quantified ⁷Be, grain size and percent organics for all sites in June 2006 for the purpose of site comparison over time. Based on the grain size data from June 2006 and July 2006 it is evident that there is widespread temporal and spatial variability for each site and therefore data from a previous collection is inconsequential for the purpose of this study. Pending data includes grain size and ⁷Be for July 2006 sampling. The results from the erosion microcosm indicate that the Clay Bank shoal has the highest erodibility based on eroded mass versus applied shear stress (Figure 2). Therefore, we compared the properties of the seabed at the Clay Bank shoal with those of the other two sites.

Porosity is frequently cited as the most influential property on seabed erodibility, therefore we calculated the porosity of the sediment at each site based on the water content for each site (Figure 3). The porosity of the seabed at the Clay Bank shoal is significantly lower than the other two sites, about 80% water per compared to about 90% water per total volume at the channel and Gloucester Point site. This data varies from much of the previous work on seabed erodibility, which has shown that overall lower porosity often yields less erodible sediment, and as porosity decreases with depth there is a corresponding decrease in erodibility with depth (Williamson and Ockenden, 1996). The digital X-radiographs taken of sediment for each site manifest a distinctly thicker near-surface non-bioturbated layer at the Gloucester, with similar results for the Clay Bank channel, yet the Clay Bank shoal appears to have bioturbation nearer the surface and a clear, denser, sandy top layer (Figure 4). The Eh values, which represent an intensity factor of oxidation and reduction in the sediment at each site, are less negative at the Clay Bank shoal, which may indicate or relate to more recent disturbance of the seabed from bioturbating activities. The channel and Gloucester Point sites have significantly more negative Eh values, perhaps indicating higher consolidation at these sites (Figure 5). The average colloidal carbohydrate concentration for all sites fell into a narrow range of values, from about 20-30 mg of glucose equivalent/grams of dry weight sediment (Figure 6).

DISCUSSION

According to Black et al., 2002, there are three major concepts related to the erodibility of cohesive sediments: 1) erosion rates are lower when there is increased cohesion of particles due to microbial binding (a form of biostabilization), 2) macrofaunal bioturbation increases erosion rates by destabilizing surface sediments (Black, et al., 2002) and 3) erosion rates temporarily increase with physically-induced deposition that greatly increases water
content in the sediment. According to Stevens et al., porosity in cohesive sediments tends to decrease with depth, decreasing the water content and hence decreasing erodibility with time and depth (2005). Our data shows a different trend with porosity, with lower values of porosity yielding more erodible sediment overall between sites. Decrease in porosity with depth for each site corresponds with a decrease in erodibility with depth, which is a commonly cited occurrence. However, another way to consider porosity is by looking at the volume fraction of solids, which is $1 - \text{porosity}$ and measure the sand and clay per volume. From data previously collected by Patrick Dickhudt in May 2006 for the Clay Bank channel and shoal, it is evident that differences in porosity can be explained by the volume fraction of clay compared to volume fraction of all solids (Figure 7). In May 2006 these two sites have similar erodibility, though different porosity, which can likely be explained by the similar volume fraction of clay. The shoal site in May 2006 had a much higher volume fraction of sand than the Clay Bank channel, which can detract from the natural cohesiveness of clay and thus reduce erodibility. Therefore, the higher erodibility of the sediment at the Clay Bank shoal in July 2006 may be attributed to a higher volume fraction of sand than clay.

Perkins et al., 2004, found that higher EPS content and binding effects balanced the water content effects to reduce erodibility, and that the best way to observe this is through natural intact sediment samples. Studies by Widdows and Brinsley, 2002 also support this notion. According to their studies, there are strong relationships between critical erosion thresholds and microphytobenthos density. We observed little difference between the colloidal carbohydrate concentration values and therefore could not conclude that this parameter was significantly affecting the erodibility of the sediment, though it may decrease erodibility for each site. Perkins et al., 2004 also found, however, that the erosion threshold of sediment itself, without polymer, varies, therefore our observations of physical seabed properties aside from EPS indices are still telling. EPS can be quantified through various methods and carbohydrate forms, such as the colloidal. Many authors cite measurements of chlorophyll a as proxies for EPS, which may be an important quantified property to address in future studies, which may require sample sites in shallower water where light can penetrate and allow for microphytobenthos growth.

Increased bioturbation may also increase the erodibility at the Clay Bank shoal, which is seen in the digital X-radiographs (Figure 4). The bioturbation activity also appears to be closer to the surface. According to Black et al., 2002, bioturbation activities influence porosity and permeability over a greater scale relative to EPS influence. Bioturbation can also greatly modify the bed roughness and hence the friction experience between the bed and the water column. A study by the same group found that during one particularly cold winter a population of benthic amphipods was decimated which reduced grazing pressure on sediment-stabilizing benthic diatoms. In late spring, the amphipod population began to recover and the result was an increased suspended sediment concentration in the channel (Black et al., 2002). Such an example addresses the myriad complexities between sediment erodibility and biological interactions with the seabed. Widdows and Brinsley concluded that the erosion rate and sediment mass eroded is significantly enhanced by the activities of the clam *Macoma balthica*, and is density dependent (2002). In terms of our study, if the effect of bioturbation activities is indeed stronger near the surface at the Clay Bank shoal then its reflection in the higher erodibility of the sediment is supported. Macrobenthos counts for each of our study sites are expected to be completed in the near future, which may give
insight into population density and therefore into degree of bioturbation activities at each site.

CONCLUSIONS

Of the three study sites, the Clay Bank shoal seabed was the most erodible in July 2006 based on the results from the Gust Cosm. The seabed properties most likely attributable to this include a lower total clay fraction and higher sand, though the porosity was lower than the other sites. We concluded that volume of clay relative to sand and water may play a more influential role on seabed erodibility than porosity, as clay has higher electrostatic binding, which actually naturally increases cohesion between clay particles (Perkins et al., 2004). Also, based on the Eh test and the X-radiographs, we inferred that perhaps the surface layers of the sediment at the Clay Bank shoal were either recently deposited or disturbed, which means the sediment is less consolidated and would therefore support the fact that the seabed here is more erodible. The colloidal carbohydrate concentration was slightly lower at the Clay Bank shoal, which also supports the lower erodibility here; however, due to the remarkably small range of concentrations, we concluded that more testing of various types of EPS need to be performed to better understand the natural range of EPS and colloidal carbohydrates in the sediment and chlorophyll a testing also needs to be done. As a continuation of this study, sampling at the same sites should be done following episodic events as well as during different seasons in order to observe changes in seabed properties and how that influences changes in seabed erodibility. During the winter, there may be much lower concentrations of carbohydrates in the sediment, which would greatly influence the erodibility. Also, there is great spatial and temporal variation among individual sites due to variations in sedimentation and local channel dynamics so even at sites considered physically dominated, such as the Clay Bank shoal, there might be localized regions of higher biological activity. The contrary is possible to for the Gloucester Point site, where they may be localized regions with physical laminations in the sediment. Finally, certain seabed properties that were quantified for the June 2006 samples were not used to characterize the seabed in July 2006, which was what this project focused on; therefore, grain size analysis and $^{7}$Be quantification can be run on the most recent samples, though time was not sufficient to do so for this particular study.
Figure 1: Map of study sites in the York River, Lower Chesapeake Bay. Top left Clay Bank sites are the physically dominated sites and lower right Gloucester Point is biologically dominated. CS refers to Clay Bank shoal, CB Clay Bank channel and GP Gloucester Point. Ensuing number indicates approximate water depth at each location.

Figure 2: Erodibility increases downward and to the right on this graph. The graph shows eroded mass relative to the critical stress applied at each step. The Clay Bank shoal site had the most eroded mass at the lowest critical stress compared to the other sites, meaning the sediment is more erodible at this site. The critical stress profile decreases with depth.
Figure 3: Figure shows volume of water per total volume of sediment and water versus depth. The Clay Bank shoal has an overall lower average porosity than the other two sites.

Figure 4: Digital x-radiographs from Gloucester Point site (left) and Clay Bank shoal (right). The Gloucester Point x-ray shows a thicker non-bioturbated layer, which could imply either recent deposition or consolidation. Evident lighter laminations at the surface may indicate higher sand content, as light cannot penetrate through the higher density of the sandier sediment.
Figure 5: More positive Eh values can indicate less consolidation and thus more recent deposition, whereas more negative values indicate greater consolidation. The Clay Bank shoal has the least negative Eh values with depth.

Figure 6: Average colloidal carbohydrate concentration in the sediment is a proxy for EPS with EPS accounting for 20-30% of this measure. There is little variability between sites, which makes it difficult to interpret the influence of EPS on sediment erodibility. The Clay Bank shoal has slightly lower colloidal carb concentration.
Figure 7: Top figure shows volume fraction solids for samples taken in May 2006. The porosity and solids fraction for these two sites is significantly different. The Clay Bank shoal has a higher solids fraction. However, to explain this the volume fraction of clay, or mud, is shown on bottom. The clay fractions are very similar. The difference between the solids and clay fractions is the sand fraction and the Clay Bank shoal then has a much higher sand fraction, which means it has a much lower clay fraction. The Clay Bank channel is almost completely clay, which would explain its lower erodibility. $v_f s = 1 - \text{porosity}$


