York River Physical Oceanography and Sediment Transport

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ABSTRACT

The York River is a partially-mixed, microtidal estuary with tidal currents in the mid- to upper estuary approaching 1 m/s. The upper York near West Point is generally less stratified than the lower York near Gloucester Point because of the shallower depths and stronger currents found upstream. Fluctuations in salinity stratification in the York River at tidal, fortnightly and seasonal time-scales are associated with tidal straining, the spring-neap cycle, and variations in freshwater discharge, respectively. Estuarine circulation in the York River, which averages ~5 to 7 cm/s, is often modulated by moderate winds. Waves are usually insignificant, although occasional severe storms have a major impact. The York River channel bed is predominantly mud, while the shoals tend to be sandier, and the mid- to upper York is marked by seasonally persistent regions of high turbidity. Fine sediment is trapped in high turbidity regions in response to tidal asymmetries and local variations in stratification and estuarine circulation. More work is needed to better understand the linkages between physical oceanography, sediment transport and turbidity in the York River system, especially during high-energy events and in response to ongoing climate change.

PHYSICAL FEATURES

The York River extends from its mouth near the Goodwin Islands to its head approximately 50 km upstream at West Point (at the confluence of the Mattaponi and Pamunkey Rivers). Along most of its length, the York is characterized by a main channel bordered by well-developed shoals. Depths along the axis of the main channel of the York River vary from about 20 m near Gloucester Point to about 6 m near West Point, with a tendency towards decreasing depth with distance upstream (Figure 1). Along the central third of its length, the York also contains a secondary channel about 6 m deep, separated from the main channel by along-axis shallows that rise to about 4-m depth. The average depth of the York River downstream of West Point, including shoals, is 4.9 m (Cronin, 1971), and its average width is 3.8 km (Nichols *et al.*, 1991). Upstream of West Point, the channels of the Mattaponi and Pamunkey are much narrower, measuring only several hundreds of meters wide.

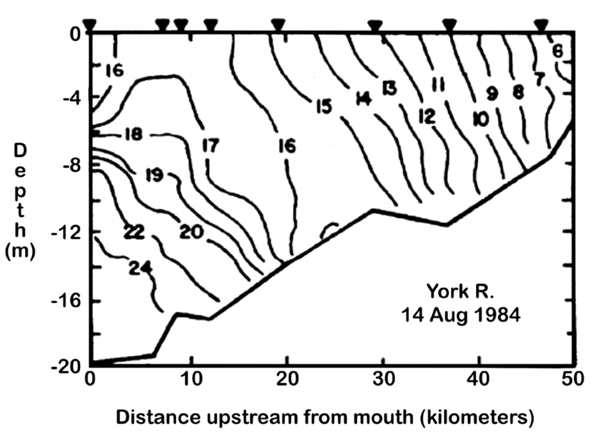

Figure 1. Typical salinity distribution along the York River (Figure 2 from Kuo and Neilson, 1987).

TIDES

The York River is a microtidal estuary with a mean tidal range at its mouth of 0.70 m, increasing to 0.85 m at West Point (Figure 2). After decreasing back to 0.75 m in the region of Sweet Hall, the range increases once more until approaching 1 m in the upper Pamunkey (Sisson *et al.*, 1997). Despite

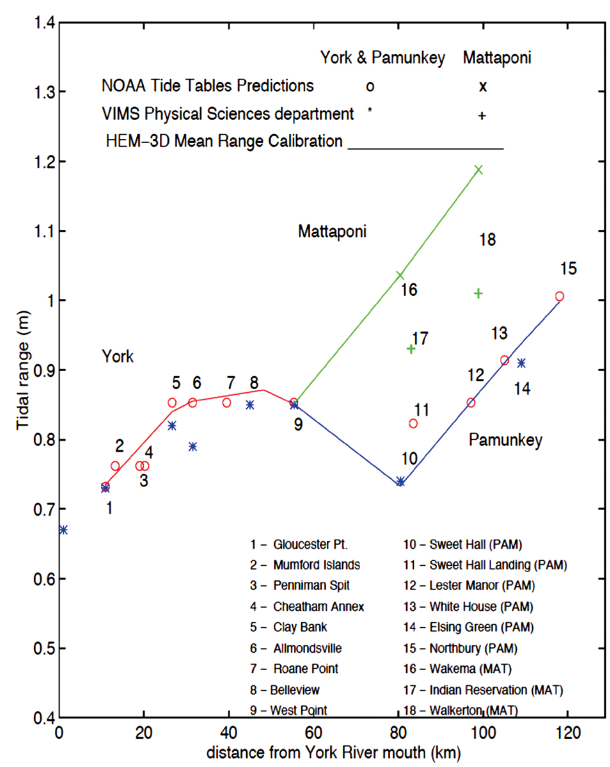

Figure 2. Comparison of tide range along the York, Pamunkey and Mattaponi from VIMS HEM-3D model output, VIMS gauge data, and NOAA tide table data (Figure 9 from Sisson *et al.*, 1999).

being classified as a microtidal system, tidal currents in the mid- to upper-York are strong enough to cause significant sediment suspension (Schaffner *et al.*, 2001). Figure 3 displays estimates of tidal current magnitude at spring tide as a function of distance up the York and Pamunkey. These estimates of tidal current strength are based on the methods of Friedrichs (1995) using cross-sectional areas and tidal volumes for the York and Pamunkey as presented by Cronin (1971). The magnitude of tidal currents increases with distance up the York River such that tidal currents in the mid- to upper-York are stronger than those typically found in microtidal estuaries. Tidal current strength also varies across the width of the estuary. For example, tidal currents are about twice as strong in the 10-m deep main channel of the York than at 3-m depths over the adjacent shoals (Huzzey and Brubaker, 1998). Tidal fronts often form for periods of a few hours over the tidal cycle at the channel-shoal transition due to differential along-channel advection of salinity by the tide.

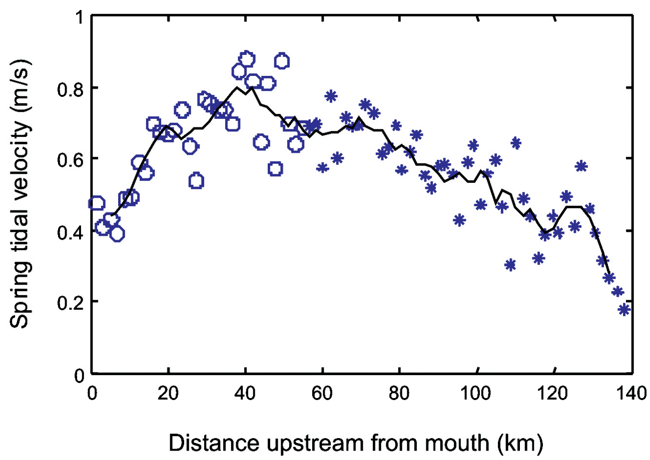

Figure 3. Spring tidal velocity amplitude as a function of distance up the York (o) and Pamunkey (*) rivers estimated from data presented by Cronin (1971). Solid line is a five-point running average.

RIVER INFLOW

Because of the relatively small watershed of the York River, the freshwater flow into the river is normally modest. Mean river discharge in the Pamunkey and Mattaponi at the USGS stream gauges near the heads of the tide are 28.7 m^3s^{-1} and 14.4 m^3s^{-1}, respectively (Shen and Haas, 2004), and the mean total discharge into the York from all sources is estimated to be 71 m^3/s (Nichols *et al.*, 1991). The 90th percentile high flow between 1942 and 2001 gauged for the Pamunkey plus Mattaponi totaled 107 m^3s^{-1}, whereas the 20th percentile low flow was just 9.2 m^3/s (Shen and Haas, 2004). One of the highest discharges on record is associated with Tropical Cyclone Isabel, when the Pamunkey plus Mattaponi gauged flow reached 421 m^3s^{-1} (Gong *et al.*, 2007). Despite the low mean freshwater discharge into the York relative to its cross-section, the influence of river flow on the dynamics of the estuary as a whole is still extremely important due to its effect on the salinity distribution. The location of head the salt intrusion, the overall degree of stratification, and the location and intensity of the estuarine turbidity maximum are all ultimately dependent on river inflow.

SALINITY - ALONG-CHANNEL DISTRIBUTION

Between its mouth and West Point, the York River encompasses the majority of the range of salinities characteristic of temperate estuaries. Bottom salinities along this gradient typically range from about 6 psu to 25 psu (see Figure 1). The transition to fresh water (≤ 1 psu) is normally found within the Mattaponi and Pamunkey between 60 and 90 km from the mouth of the York (Lin and Kuo, 2001; Shen and Haas, 2004). Although the precise location of the transition to fresh water varies with river discharge, the transition to fresh water along the Pamunkey commonly occurs near the Sweet Hall Marsh CBNERR site. Because of the relatively small watershed feeding the York River and much larger watershed feeding the neighboring Chesapeake Bay, regionally wet years can result in relatively fresher water being advected into mouth of the York from the lower Bay, resulting in a local reversal of the salinity gradient within the York River and a local maximum in salinity being found within the lower York itself (Haywood *et al.*, 1982).

SALINITY STRATIFICATION

The lower York is generally more stratified than the upper York (see Figure 1). This is because shallower depths and stronger tidal currents with distance upstream both favor greater mixing of the water column. Superimposed on the spatial gradient is a strong time-variation in stratification associated with the 14-day spring-neap tidal cycle. In the lower York, top-to-bottom stratification regularly exceeds 7 psu around neap tide and commonly is reduced to less than 2 psu around spring tide (Haas, 1977). In the middle York, the cycle in stratification is typically on the order of 3 psu at neap, decreasing to less than 1 psu around spring (Sharples *et al.*, 1994). In the middle and upper York, this stratification cycle is due to a competition between the tendency of gravitational circulation to increase stratification and the tendency of strong spring tidal currents to mix stratification away (Sharples *et al.*, 1994). Near the mouth of the York, advection of relatively fresh water in from the lower Chesapeake Bay may also play a role in enhancing destratification around spring tide (Hayward *et al.*, 1982).

Salinity stratification in the York River tends to increase over the course of the ebb and decrease over flood through a process known as tidal straining (Scully and Friedrichs, 2003, 2007a, b; Simpson *et al.*, 2005). Because tidal currents are stronger at the surface than at depth, ebb tides in the York River advect fresher surface water seaward over underlying saltier water, increasing stratification during ebb. Conversely, flood tides transport saltier surface water landward over relatively fresher water, decreasing stratification. Less stratification on flood results in more turbulence and sediment suspension on flood (i.e., tidal asymmetry), favoring up-estuary transport of sediment (Scully and Friedrichs, 2003). The presence of shoals on either side of the river and the relatively shallow secondary channel lead to strong variations in stratification across the width of the estuary as well. The shoals and secondary channel tend to be more well-mixed than the main channel, and along-channel fronts often form along steep lateral changes in bathymetry (Huzzey and Brubaker, 1988; Scully and Friedrichs, 2007a).

CIRCULATION AND RESIDENCE TIME

In the absence of wind or major discharge events, the mean estuarine circulation along the York River is relatively weak. Three-dimensional modeling suggests that time-averaged landward flow in the lower layer of the main channel of the York halfway to West Point under normal conditions is about 5 to 7 cm s^{-1} (Gong *et al.*, 2007). Relatively weak upstream flow in the main channel may be due in part to the presence of the neighboring shallower secondary channel. Increased stratification in the main channel during ebb tends to delay the turn to flood, enhancing seaward transport in the main channel (Scully and Friedrichs, 2007a).

Because of the low fresh water inflow and relatively weak mean circulation in the York River, residence times for dissolved materials such as fresh water or pollutants are relatively long. Based on numerical model simulations, Shen and Haas (2004) found that under mean flow it takes about 60 days for such material to be transported from the head of the tributaries to West Point, 85 days to be transported to the middle of the York, and 100 days to be transport out of the York River entirely. The residence times are cut nearly in half under high flow and more than doubled under low flow (Shen and Haas, 2004).

Down-estuary winds in the York River can strongly enhance the typical pattern of estuarine circulation, whereas up-estuary winds reduce and can even reverse the two-layer flow (Scully *et al.*, 2005, Figure 4). Down-estuary winds blowing at 5 m/s for a day or two can double the typical strength of the estuarine circulation. The enhanced circulation associated with down-estuary winds in turn increases estuarine stratification because fresher water from upstream is advected down-estuary over saltier water. Conversely, winds directed up-estuary reduce stratification and rapidly mix the water column. Because of this wind-induced straining of the salinity field,

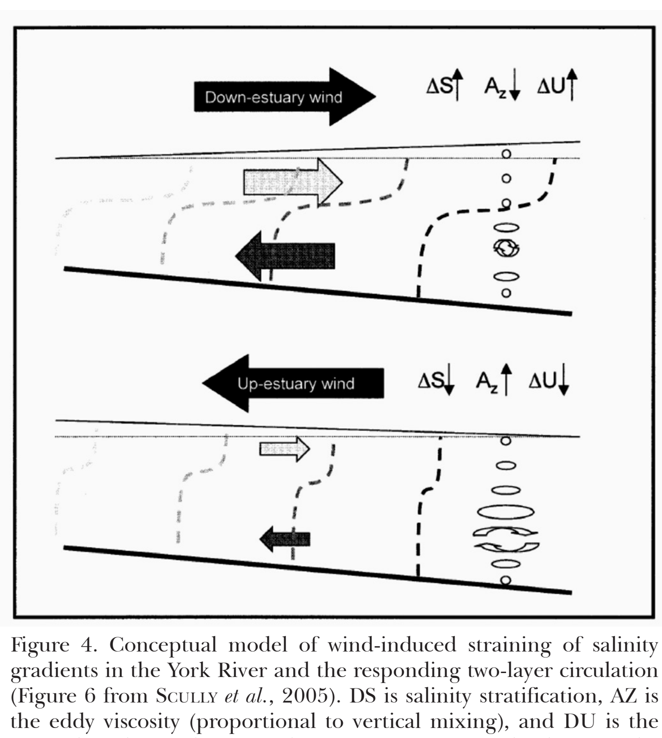

Figure 4. Conceptual model of wind-induced straining of salinity gradients in the York River and the responding two-layer circulation (Figure 6 from Scully *et al.*, 2005). DS is salinity stratification, AZ is the eddy viscosity (proportional to vertical mixing), and DU is the strength of the two-layer circulation. Arrows point in the direction the wind is blowing toward.

increased wind strength (up to a point) does not necessarily result in increased vertical mixing if winds are directed down-estuary. The degree of stratification present also affects the ability of the winds to mix the water column, with greater stratification being more difficult to mix away. If the water is only weakly stratified, 10 m s^{-1} winds in any direction will mix the water column. But if the water is already stratified, 10 m s^{-1} down-estuary winds may simply induce more straining and further stratify the water (Scully *et al.*, 2005).

EFFECTS OF WAVES AND STORMS

Except during occasional storms when strong winds line up with the axis of the estuary, waves are generally quite small in the York River. An analysis of the wind climate in the lower York estuary indicated that conditions favorable for wind wave growth exist only 3 to 4% of the time (Vandever, 2007). Observations of wave height over the course of 2006 found that significant wave height exceeded 0.30 m off Gloucester Point and 0.57 m off Goodwin Islands 1% of the time. A wave gage placed in 2-m water depth off the Catlett Islands CBNERR site from February to May 1996 documented only two events when significant wave height briefly exceeded 0.4 m, each with wave periods of 2 to 3 sec (Boon, 1996). Nonetheless, large waves can occur during extreme events. During Tropical Depression Ernesto in September 2006, significant wave height reached 1.7 m off Goodwin Islands and during Tropical Cyclone Isabel in September 2003, significant wave height reached 1.6 m at Gloucester Point (Vandever, 2007).

The response of the York River to Tropical Cyclone Isabel is particularly well documented (Brasseur *et al.*, 2005; Gong *et al.*, 2007). During Isabel, gauged river discharge into the York reached 412 m^3/s, winds at Gloucester Point reached over 40 m/s, and the local storm surge exceeded 2.0 m. The nearly coincident times of high tide, the storm surge and maximum wave heights resulted in more severe coastal damage locally than in either Tropical Storm Agnes or the hurricane of 1933. At the peak of the storm, water velocity near the mouth of the river was dominated by up-estuary wind driven flow, and normal ebb tides were not seen for over 12 hours. As a result of the high fresh water discharge, the York estuary changed from its typical partially-mixed state to a highly stratified system (Figure 5). The strength of seaward, tidally-averaged surface flow two days after the storm exceeded 20 cm/s. It took approximately four months for the salinity field in the estuary to completely recover to pre-Isabel conditions.

SEDIMENT DISTRIBUTION AND SUSPENSION

The beds of the main and secondary channel of the York River are predominantly mud, with the percentage of mud generally exceeding 80% (Nichols *et al.*, 1991; Figure 6). The shoals of the main channel and the Pamunkey and Mattaponi Rivers in general tend to be sandier, with the percentage of sand on the bed in these regions often exceeding 50%. In relatively open areas, waves routinely play a role in suspending sediment in water depths less than about a meter. But even in depths as shallow as two meters, tidal currents tend to dominate suspension in the York River (Boon, 1996). Suspended sediment concentrations in the lower water column are closely tied to the strength of the tidal current and the availability of easily suspended sediment on the bed. In the muddy reaches of the York secondary chan-

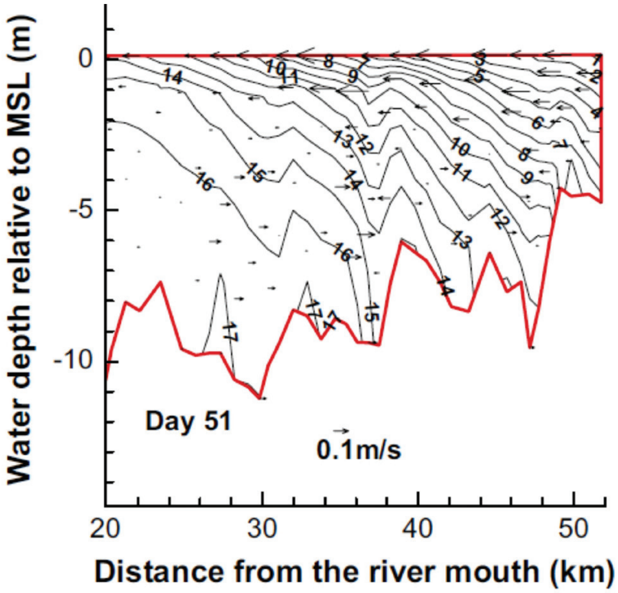

Figure 5. A 3D numerical simulation of the longitudinal distribution of tidally averaged salinity and velocity along the York River two days after the passage of Tropical Cyclone Isabel (Figure 13 from GONG *et al.*, 2007).

nel, Friedrichs *et al*. (2000) documented near-bed tidal suspensions regularly exceeding 1 gram/liter at peak tidal flow.

Persistent spatial patterns of fine sediment suspension are seen both across and along the York River. Because shallower areas tend to be more well-mixed, surface waters in shoal areas tend to be more turbid than is the case in deeper areas (Figure 7). There are also persistent along-estuary peaks in turbidity along the York River known as estuarine turbidity maxima (ETMs). The main ETM in the York River is typically located near the head of the salt intrusion. A secondary ETM is often found about 20 to 40 km from the mouth of the York where there tends to be an upstream decrease in stratification (LIN and KUO, 2001). At slack water, sediment concentrations at the main ETM can reach 250 mg/liter near the bed and 50 mg/liter near the surface (Figure 8). Concentrations often exceed 100 mg/liter near the bed at the secondary ETM as well, but stratification usually prevents high concentrations from reaching the surface.

SEDIMENT TRAPPING

Trapping of fine sediment in these ETM regions is due in large part to local decreases in the strength of near-bed estuarine circulation. Estuarine circulation decreases with distance upstream if (i) the along-channel salinity gradient decreases, (ii) vertical stratification decreases, and/or (iii) water depth decreases. All three mechanisms contribute to sediment trapping at the main ETM, whereas (ii) and (iii) are more important at the secondary ETM (LIN and KUO, 2001). Another mechanism that contributes to sediment trapping at the ETMs is tidal asymmetry. Because of interactions with gravitational circulation and stratification, the flood tide tends to be stronger and more turbulent than the ebb tide, and more sediment is suspended and moved landward on flood (SCULLY and FRIEDRICHS, 2003, 2007b). This asymmetry becomes weaker as stratification and estuarine circulation decrease, leading to additional transport convergence and sediment trapping at the ETMs.

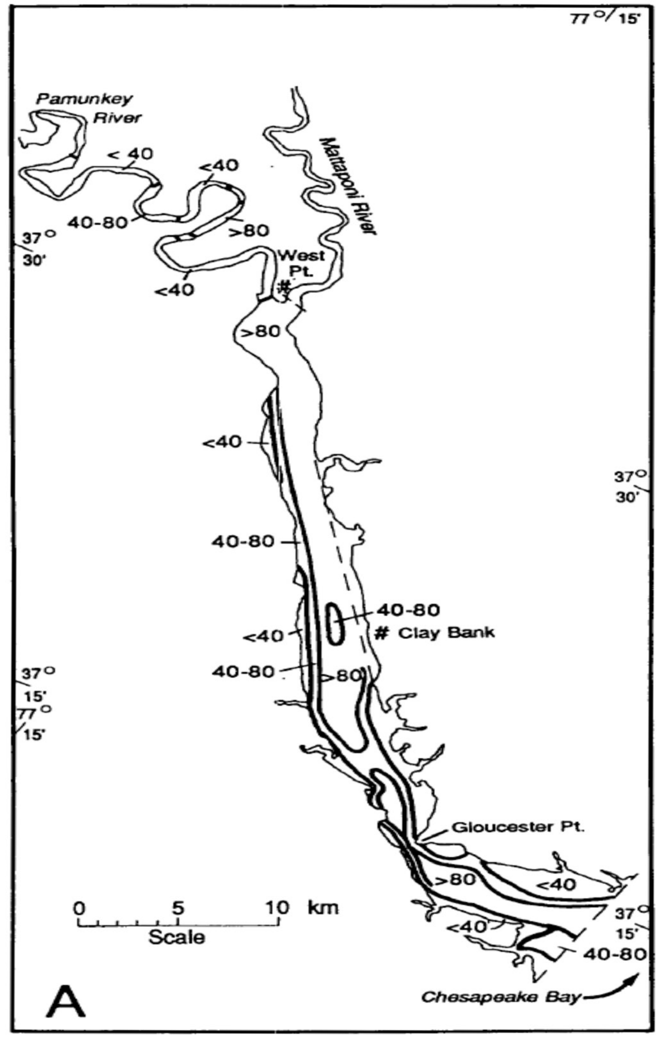

Figure 6. The spatial distribution of percent mud in the bed of the York River (Figure 6 from NICHOLS *et al.*, 1991).

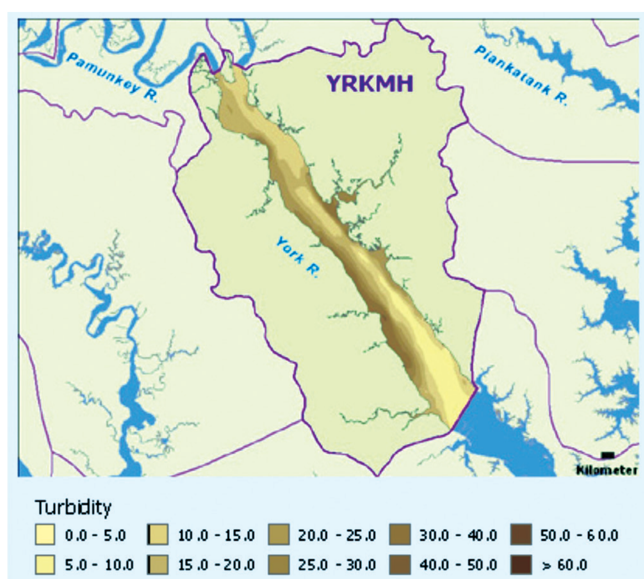

Figure 7. Surface turbidity measured on July 6, 2005 by CBNEERVA in units of NTU (http://www.vecos.org).

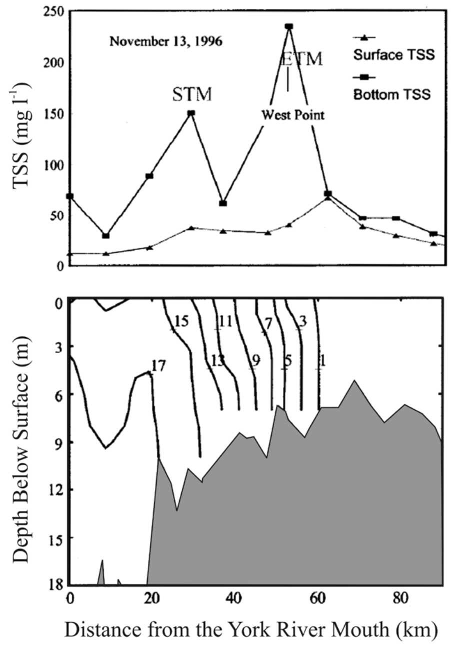

Figure 8. Total suspended sediment (TSS) concentrations collected 1 m above the bed and 1 m below the surface along with vertical salinity distributions at slack water along the York and Pamunkey Rivers (Figure 5 from Lin and Kuo, 2001).

The rate at which sediment is trapped within the York River is not entirely resolved. Nichols *et al*. (1991) estimated an influx of 0.22 x 10^6 tons $year^{-1}$ of sediment into the York from the Pamunkey and Mattaponi, 0.05 x 10^6 tons $year^{-1}$ from shoreline erosion, and 0.13 x 10^6 tons/year from the Chesapeake Bay. The input rate from the Bay was estimated by assuming transport rates to be similar to those better documented in the neighboring James and Rappahannock Rivers. Herman (2001) combined a decade of suspended sediment concentration measurements from water quality monitoring in the York with predicted tidal currents and estuarine circulation to estimate contributions to net sediment flux. Based on monitoring data, Herman (2001) calculated a larger net flux of 0.7 x 10^6 tons/year into the York from the Bay and concluded that this up-estuary flux was dominated by tidal asymmetries. However, Herman (2001) noted that this larger value may be biased by the relatively calm conditions associated with monitoring cruises, and net seaward transport of sediment may occur during storms.

FUTURE RESEARCH DIRECTIONS

More work is needed to better understand the linkages between physical oceanography, sediment transport and turbidity in the York River system, especially during high energy events. The potential effects of climate change, especially its effects on the frequency and intensity of storms in this region are not well known. The dynamics of mean circulation and the estuarine turbidity maxima in the York are reasonably well understood during calm conditions. However, preliminary results suggest the distribution of turbidity and net transport may be quite different under the influence of strong winds. Analysis of data from fair weather monitoring cruises suggests very high rates of landward sediment transport during fair weather, supporting speculation that major downstream sediment transport occurs during storms. Because fresh water discharge is still minor during most storms relative to the large cross-sectional area of the York, the specific processes that drive sediment downstream are still not clear. Other potential areas for research include the mechanisms that maintain sandy shoals versus muddy channels. Waves are too small in the York to regularly suspend sediment, even in areas as shallow at 2 m. Since tidal currents are stronger in deeper water, one might expect tidal suspension to eventually disperse fine sediment back toward the shoals. Are waves and wind-driven currents during major storms extremely important for removing mud from shoals? Or could tidal suspensions laden with fine sediment possibly be driven directly into deeper areas by down-slope gravity currents? Finally, recent work has highlighted the role of tidal asymmetries in controlling stratification and sediment transport in the York River. Additional work is needed to evaluate the importance of tidal asymmetry relative to more classical, density- driven estuarine circulation.

ACKNOWLEDGEMENTS

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