Including Fine-Grained Sediment Processes Within Numerical Representations of a Partially-Mixed Estuary, the York River, Virginia, USA

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York River

- Partially mixed estuary
- Seasonal secondary turbidity maximum (STM)
- ETM near West Point
- Multidisciplinary Benthic Exchange Dynamics (MUDBED) focus site, since 2006.

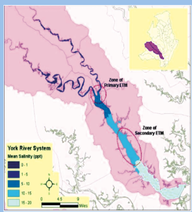


Figure 1 (above): Map of mean salinity for the York River estuary based on monthly (April-October) cruises of 2003, 2004, and 2005. Also, shows general locations of primary and secondary ETM (Reay, 2009).

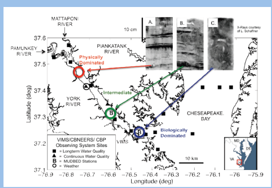
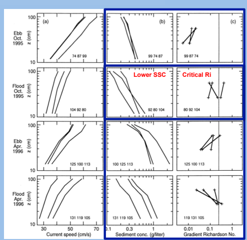


Figure 2 (left): York River Estuary, VA from Cartwright et al., 2009. The location of the MUDBED Intermediate site is in green. X-radiographs for (a) upper estuary, (b) middle estuary, and (c) lower estuary are courtesy of L. Schaffner (Fall, 2012).

Motivation



- Sediment-induced stratification impacts mixing in the York River, even at relatively low sediment concentrations.
- At the Clay Bank Site in the York River:
  - Seasonal STM with highly erodible bed
  - Occurs with high river discharge.

Figure 3 (above): Examples of: (a) velocity profiles, (b) suspended-sediment concentration profiles, (c) Gradient Richardson number (ratio between the buoyancy frequency and the change in velocity with depth) profiles observed during ebb and flood in the York River estuary in October 1995 and April 1996. Burst numbers (sample number) are listed in order of increasing parameter value at the lowest elevation (Friedrichs et al., 2000).

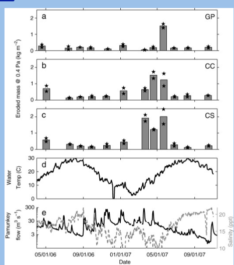


Figure 4 (right): Time-series of erodibility at (a) Gloucester Point (GP), the (b) Clay Bank channel (CC) site and (c) Clay Bank secondary channel (CS). Bars indicate the mean value, stars the range. (d) Time-series of water temperature in the York River estuary near Clay Bank. Data from Virginia Estuarine and Coastal Observing System (VECOS). (e) Time-series of river flow (solid black line) measured at Hanover, VA. Data from USGS Water Data. Time-series of York River salinity (dashed grey line) near Clay Bank. Data from VECOS (Dickhudt et al., 2009).

Research Questions

- Can an idealized two-dimensional estuarine model represent an ETM similar to that seen in the York River estuary?
- Will sediment-induced stratification reduce SSC in the water column?
- What vertical resolution is needed to represent processes in the ETM?

ETM Processes

ETM: Estuarine Turbidity Maximum:

- Location: head of the salt front
- Defined by: high suspended sediment concentrations (SSC)
  - Sediment trapping
- Development of a "mud reach"
  - Easily erodible bed
  - Landward of salt front (Geyer, 1993; Fig. 5).
- Additional processes influence ETM sediment concentrations
  - Sediment-induced stratification
  - Flocculation and breakup of aggregated particles

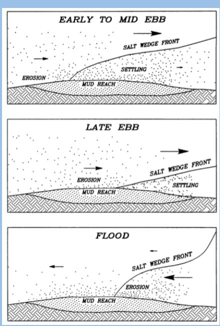


Figure 5: Schematic of the variation of the estuarine regime through the tidal cycle (Geyer, 1993).

2-D Estuary

Idealized Model Configuration

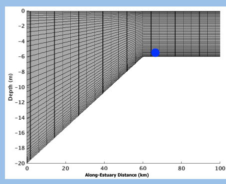


Figure 6: Grid for an idealized quasi 2-dimensional estuary. Blue dot represents the location of depth-integrated SSC time series and SSC profile figures below.

- ❑ Sediment Specifications
  - Settling velocities: 0.2, 0.8, 2.4 mm s^{-1}
  - Density: 2650 kg m^{-3}
  - Erosion rate: 0.03 kg m^{-2} s^{-1}
  - Critical shear stress for erosion: 0.1 Pa
- ❑ Open Boundary Conditions
  - Free surface:
    - No Gradient at head
    - Chapman at mouth.
  - 2D Momentum: Clamped
  - 3D Momentum: No Gradient
  - Tracers: Clamped
- ❑ Advection Scheme
  - 3D: 3rd Order upstream
  - 2D: 4th Order centered difference
  - Tracers: MPData
- ❑ Grid Resolution
  - 500 m cells along-estuary.
  - 40 vertical layers
  - 200 × 3 grid cells
- ❑ Salinity: 0 – 26 psu
- ❑ Tides: 12 hour tidal period
- ❑ River discharge: 120 m^3 s^{-1}

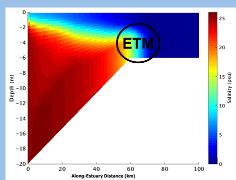


Figure 7: Salinity structure for idealized two-dimensional estuary. Black circle marks the approximate location of the modeled estuarine turbidity maximum (ETM).

Results

ETM

- Animation 1:
  - Typical estuarine circulation
  - ETM at the salt front
  - Higher SSC during flood tide.
- Sediment trapping
  - Deposition occurred seaward of the ETM
    - ▪Lower bed stress
    - ▪Velocities converge.
  - Erosion throughout the rest of the estuary

Animation

Animation 1: Modeled SSC and along channel velocities (arrows) along the idealized estuary.

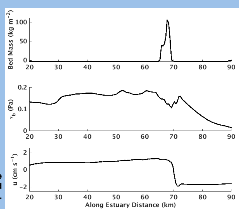


Figure 8 (right): Cumulative net deposition (top) along the estuary, peak bed stress (middle), and tidally averaged along estuary velocity (bottom) (model day 141).

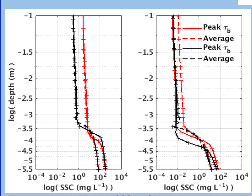


Figure 9 (above): Modeled SSC profiles during peak bed stress in a 24 hour period (solid lines), and 24 hour SSC average (dashed lines; model day 141) with the Shchepetkin (2010) verticalstretched grid (red lines) and the Geyer stretched grid (black lines). Also, without (left) and with (right) sediment-induced stratification .

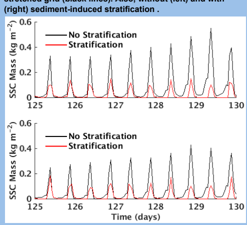


Figure 10 (above): Modeled depth-integrated SSC time-series with and without the influence of sediment-induced stratification for the Shchepetkin (2010) vertical stretched grid (top) and the Geyer vertical stretching scheme (bottom).

Sediment-Induced Stratification

- Modification of the density equation of state

$$\rho = \rho_{water} + \sum_{m=1}^{Nsed} \frac{C_m}{\rho_{s,m}} \left(\rho_{s,m} - \rho_{water} \right)$$

- Influence of sediment – induced stratification:
  - Reduces SSC mass and concentrations (Fig. 9 & 10)
  - Similar location of luctocline (Fig. 9)

Vertical Resolution

- Compared two vertical resolution schemes
- Both show a reduction in SSC mass with stratification (Fig. 10)
- Differing SSC magnitudes (Fig. 10)

Conclusions

- An idealized 2-dimensional estuarine model can represent the processes that create an ETM.
  - Suspension of fine grained sediment in the salt front.
  - Sediment trapping in the salt frontal zone.
  - Higher suspended sediment during the flood tide.
- Sediment-induced stratification reduces suspended sediment concentrations.
- Observational data is useful to guide the processes necessary to incorporate into numerical models.

Future Work

Expand the capabilities of the model to better compare with observations.

- Three-dimensional model of York River estuary (Rinehimer, 2008; Fig. 10).
  - Incorporates bed consolidation and swelling.
  - Observational data drives the salinity, winds and river discharge.
- Track sediment resuspension
  - Use Beryllium-7 as a tracer (Fig. 11)

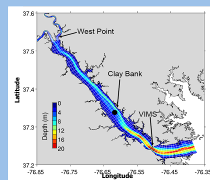


Figure 11: The three-dimensional York River estuary model grid, each square represents 5 model grid cells.

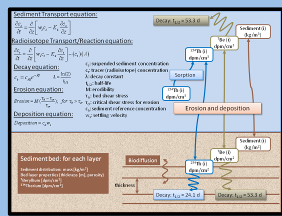
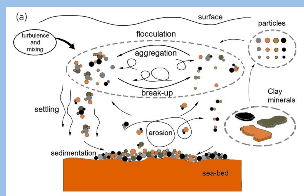


Figure 12: Schematic of the combined Community Sediment Transport Modeling System (CSTMS) and the geochronology model (Birchler, 2014).



- Aggregation and breakup of flocculated particles with a size class based population model
  - FLOCMOD (Verney et al., 2011)

Figure 13: Cycle of deposition and resuspension of cohesive sediment involved in particle aggregation and breakup (Maggi, 2005).

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