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Evaluating the effects of cohesive processes on sediment distribution in an idealized, partially-mixed estuary using a numerical model

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Cohesive Properties

- Surface charge on clay particles leads to:
  - **Flocculation** and variations in settling velocity.
  - **Consolidation** on the seabed and reduced erodibility (Fig. 2)
- At elevated suspended concentrations, **sediment-induced stratification** can limit sediment entrainment.
- Sediment transport models often neglect these processes.

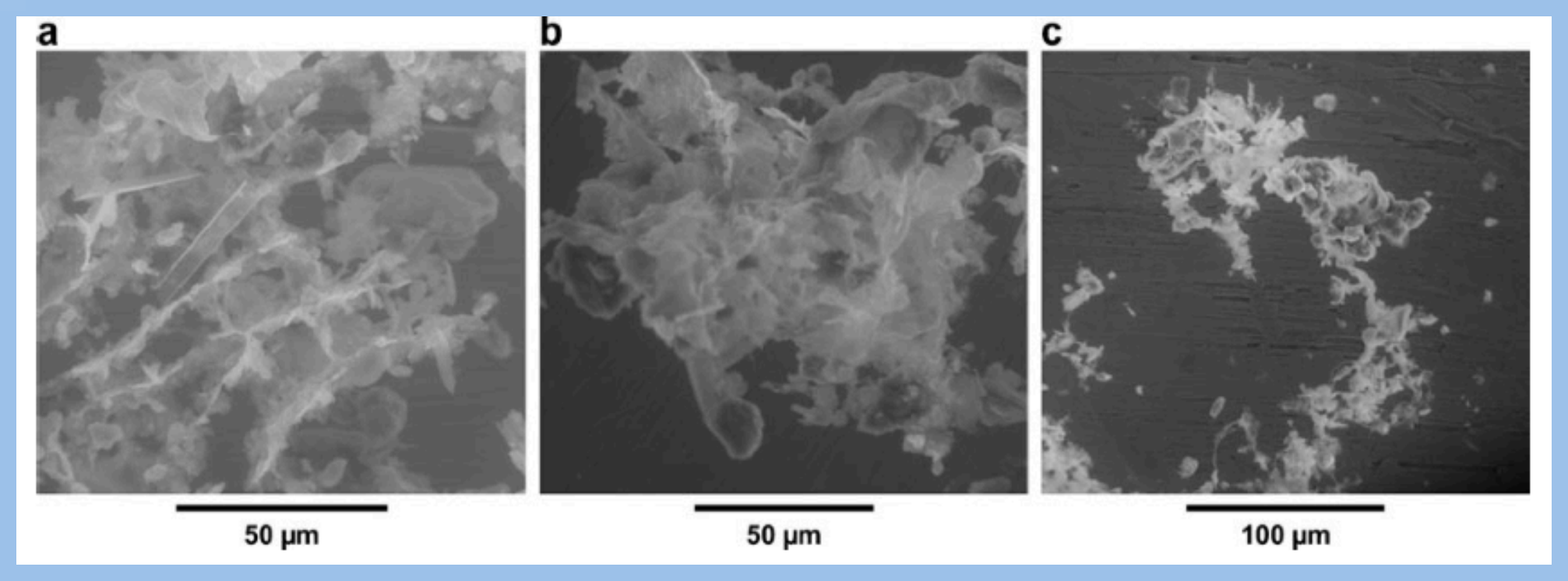

Figure 1: Representative images of flocculated particles using Environmental Scanning Electron Microscopy (ESEM) techniques (Garcia-Aragon et al., 2011).

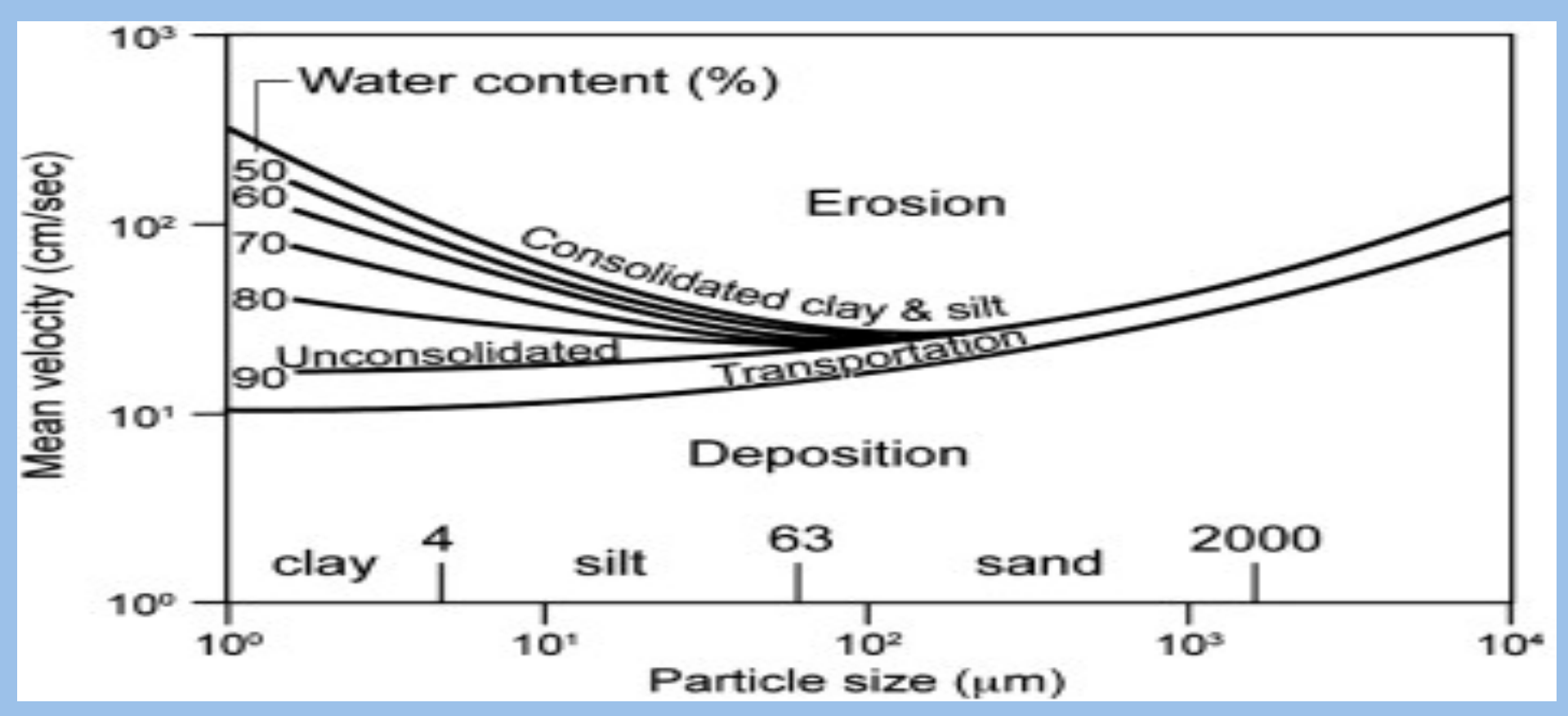

Figure 2: Postma diagrams of thresholds for erosion and deposition according to average particle size (Grabowski et al., 2011)

Objective & Questions

Objective:

Use a numerical model of an idealized, partially – mixed estuary to examine ETM dynamics.

Research Questions:

What are the relative roles of sediment – induced stratification and bed consolidation on:

1. **the location and magnitude of the ETM?**
2. **sequestering different size sediment classes in the ETM?**

Model Design

- Scaled similar to York River Estuary, VA.
  - 500 m along estuary
  - 120 m3 s-1 river discharge
  - 0 – 26 psu salinity range
  - Idealized, 12 hour tidal period
- Grid Resolution
  - 40 vertical layers
  - 10 bed layers

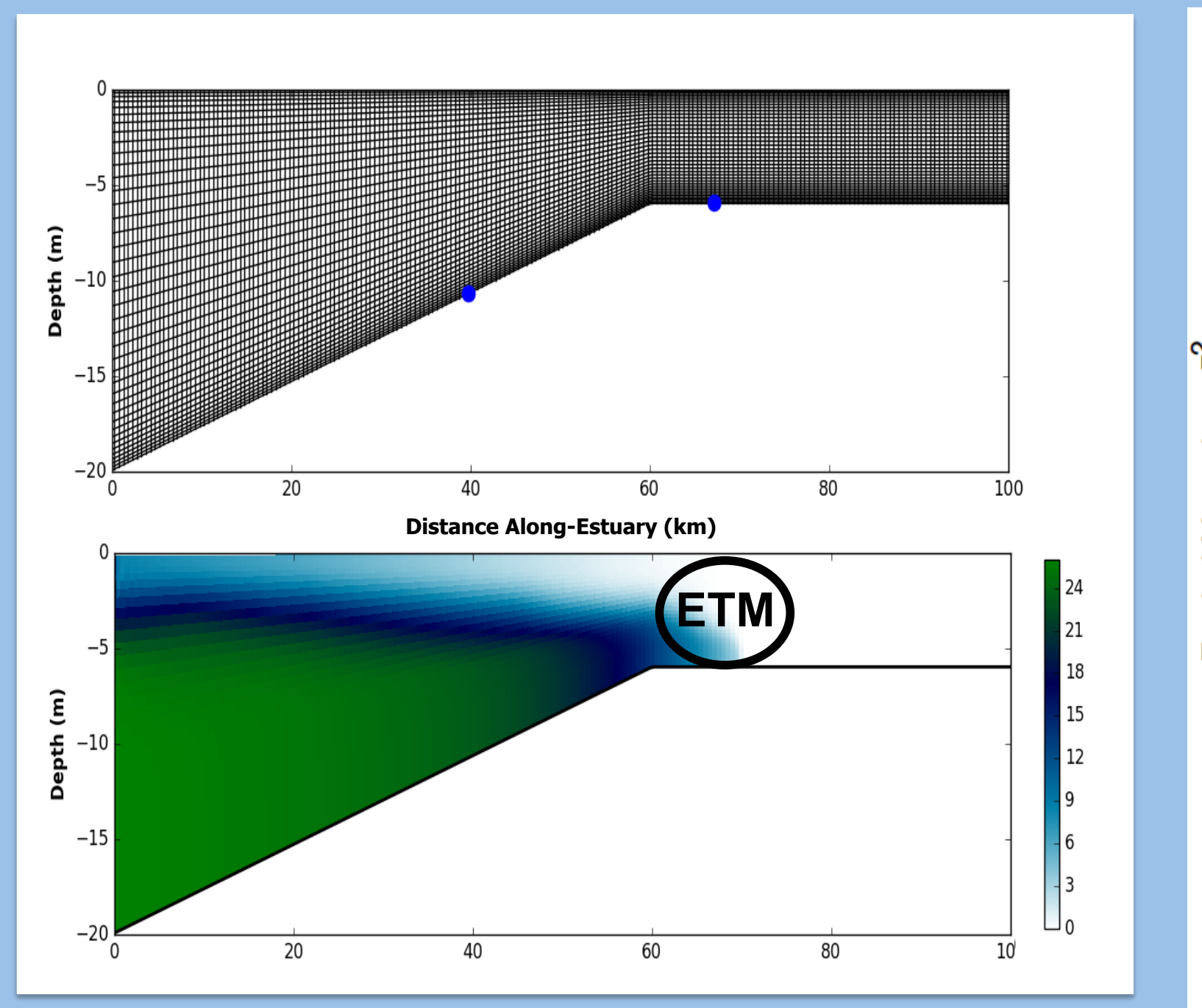

Figure 3:

Top: Grid for the idealized quasi 2-dimensional estuary. Blue dot represents the location of the model data used to calculate ETM estimates.

Bottom: Salinity structure for idealized two-dimensional estuary with the location of the estuarine turbidity maximum (ETM) marked.

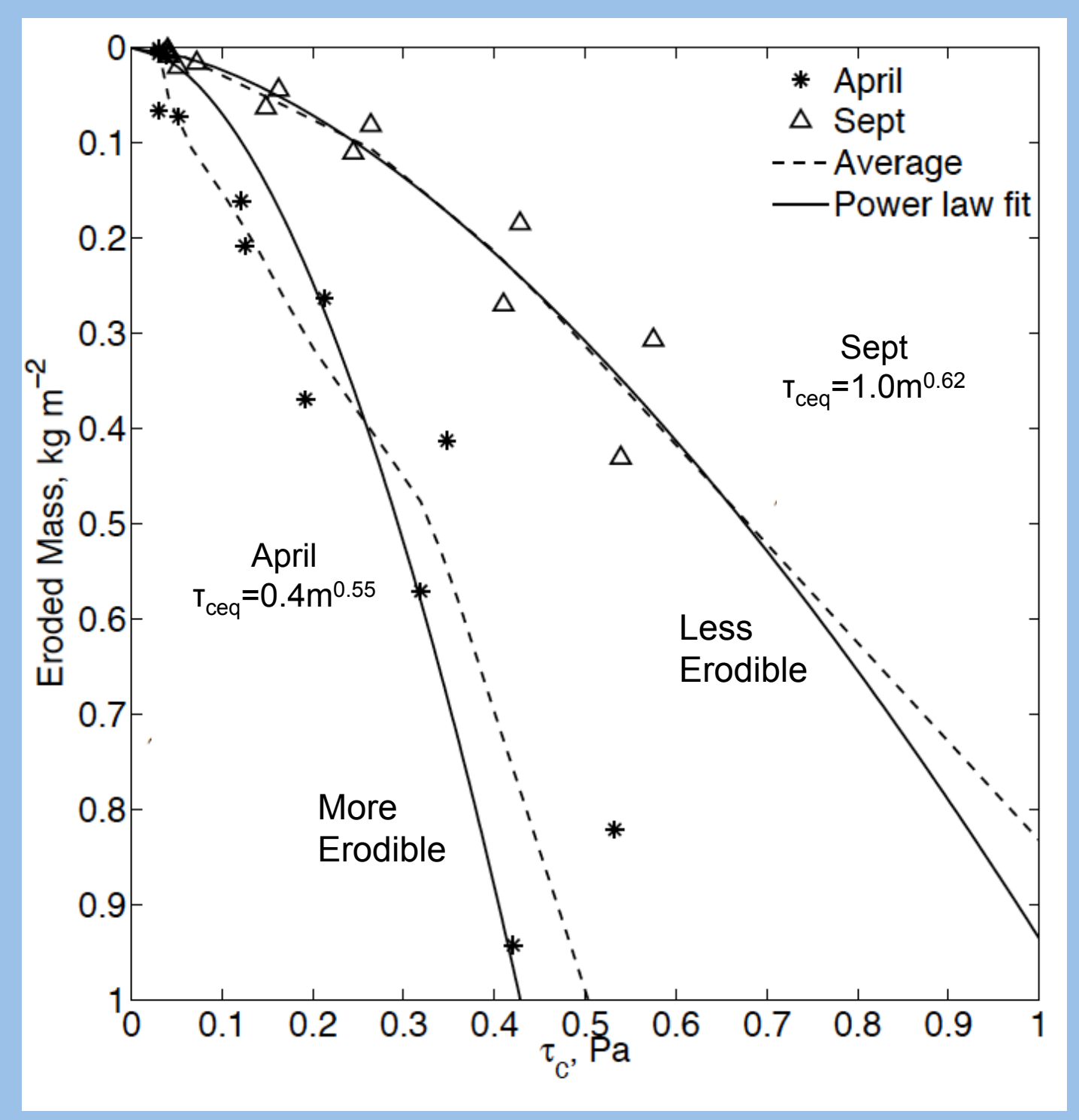

Figure 4: Average (dashed lines) and assumed equilibrium (solid lines) critical stress profiles for April and September, 2007. Equilibrium profiles obtained by a power-law fit to the observed values (Rinehimer, 2008). Symbols show observed erodibility data for the York River from Dickhudt et al. (2009).

- Sediment Specifications
  - Settling velocities: 0.1, 0.8, 2.4, 6.0 mm s^{-1}
  - Density: 2650 kg m^{-3}
  - Porosity: 90%
- Erosion Formula

$$E = M(\tau_b - \tau_{cr}(z))$$

- Where critical shear stress $\tau_{cr}(z)$ varies with depth in the bed, and time, following Sanford (2008):

$$\frac{\partial \tau_{cr}(m)}{\partial t} = \begin{cases} \frac{1}{T_c}(\tau_{ceq}(m) - \tau_{cr}(m)) & \tau_{cr}(m) < \tau_{ceq}(m) \\ 0 & \tau_{cr}(m) = \tau_{ceq}(m) \\ -\frac{1}{T_s}(\tau_{ceq}(m) - \tau_{cr}(m)) & \tau_{cr}(m) > \tau_{ceq}(m) \end{cases}$$

Results

Using Standard (Std.) run as the reference:

Table 1: Description of the parameters changed between each simulation compared in this stud.

	Stratification	Critical shear stress
Std.	No	Constant @ 0.1 Pa
Run 1	Yes	Constant @ 0.1 Pa
Run 2	No	Depth varying
Run 3	Yes	Depth varying

Bed thickness (Fig. 5A):

- Stratification decreases the deposit (89%);
- Consolidation alone increases the deposit (49%);
- Combination decreases the deposit (97%).

Applied bed stress (Fig. 5B):

- Reduced significantly by sediment stratification.

Suspended mass (Fig. 5C):

- Stratification - decrease 72%
- Consolidation - increase 88%
- Combination - decrease 36%

Erodibility:

- ETM is most erodible (Fig. 6)
- Including stratification reduced the calculated erodibility (Fig.8).

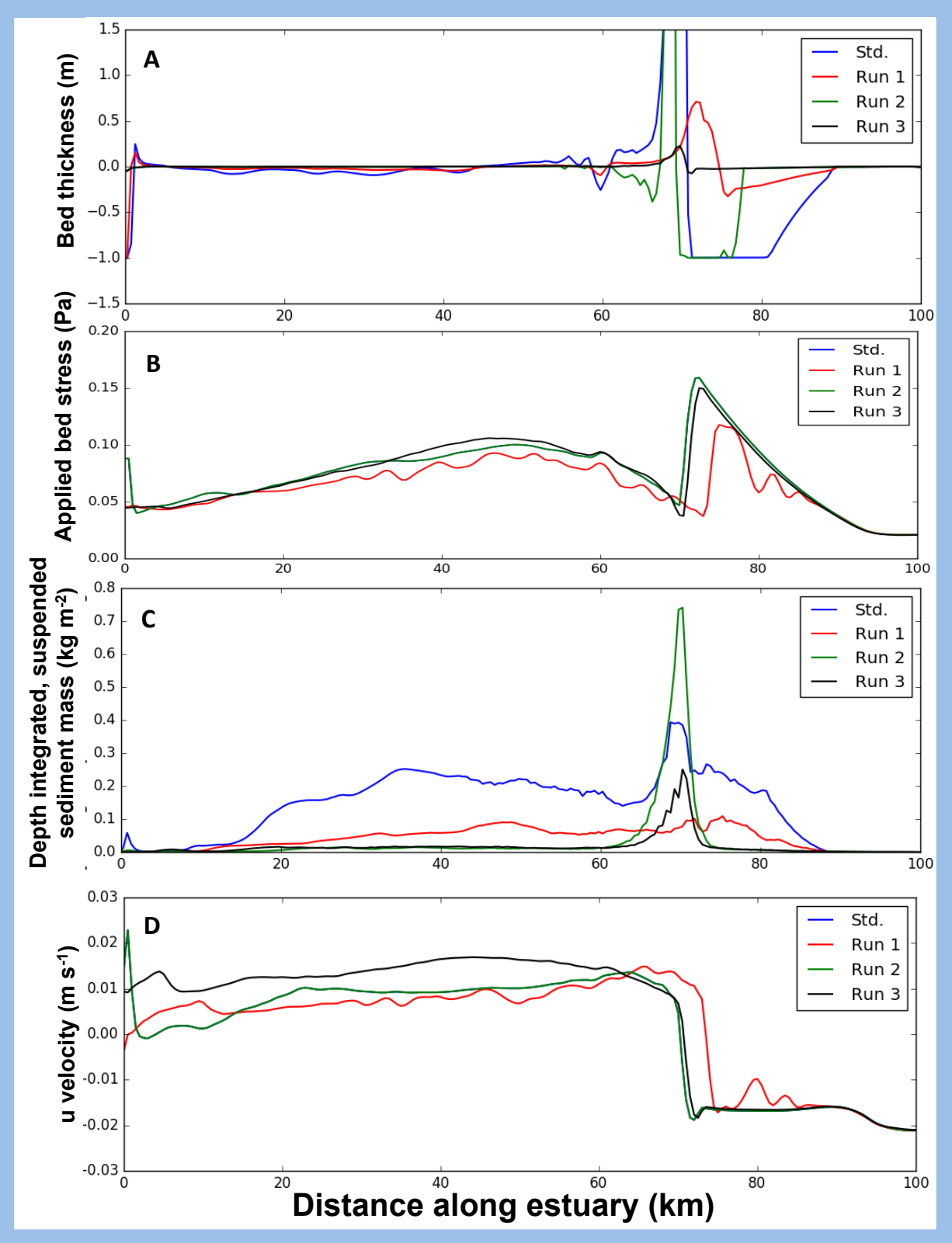

Figure 5: Longitudinal section of idealized estuary: (A) bed thickness (m) day 365; (B) daily average bed stress (Pa); (C) daily averaged, depth-integrated total suspended mass (kg m⁻²); (D) daily averaged, along estuary near-bed velocity (m s⁻¹).

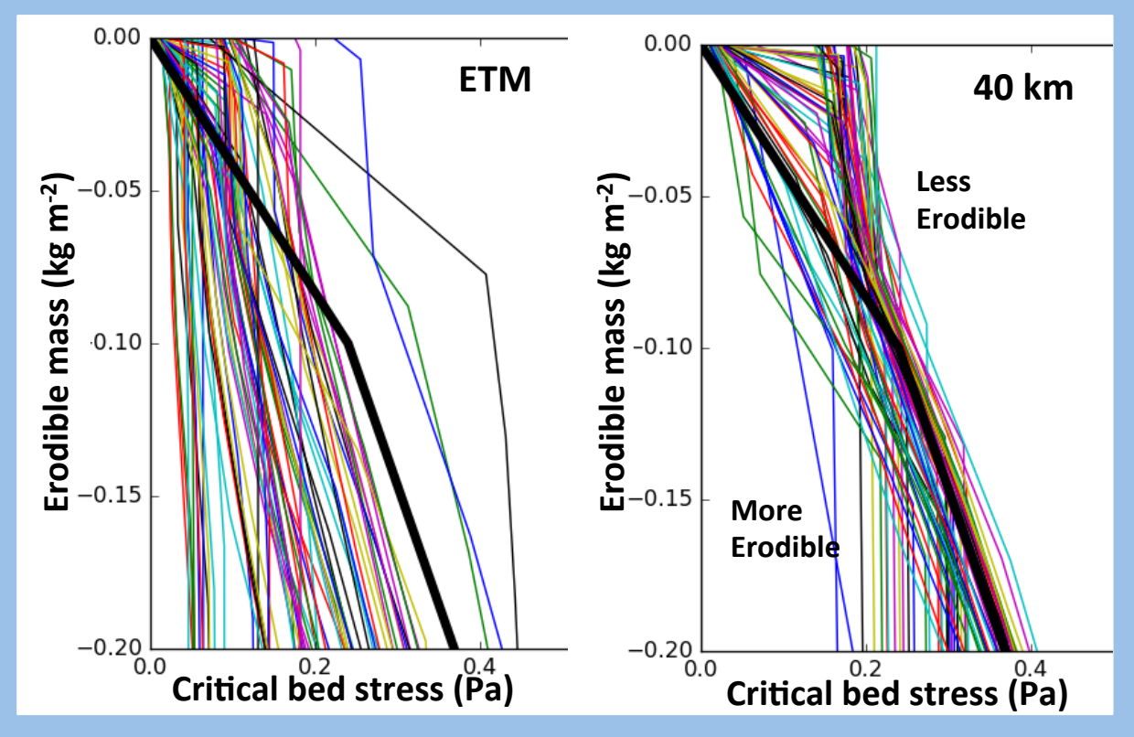

Figure 6: Critical bed stress for erosion profiles in the ETM (left) and at 40 km from the mouth (right) throughout the year for Run 3.

Animation

Animation 1: Modeled suspended sediment concentration (color), along channel velocities (arrows) along the idealized estuary and salinity (black contours) for the Standard run (top) and Run 3 (bottom).

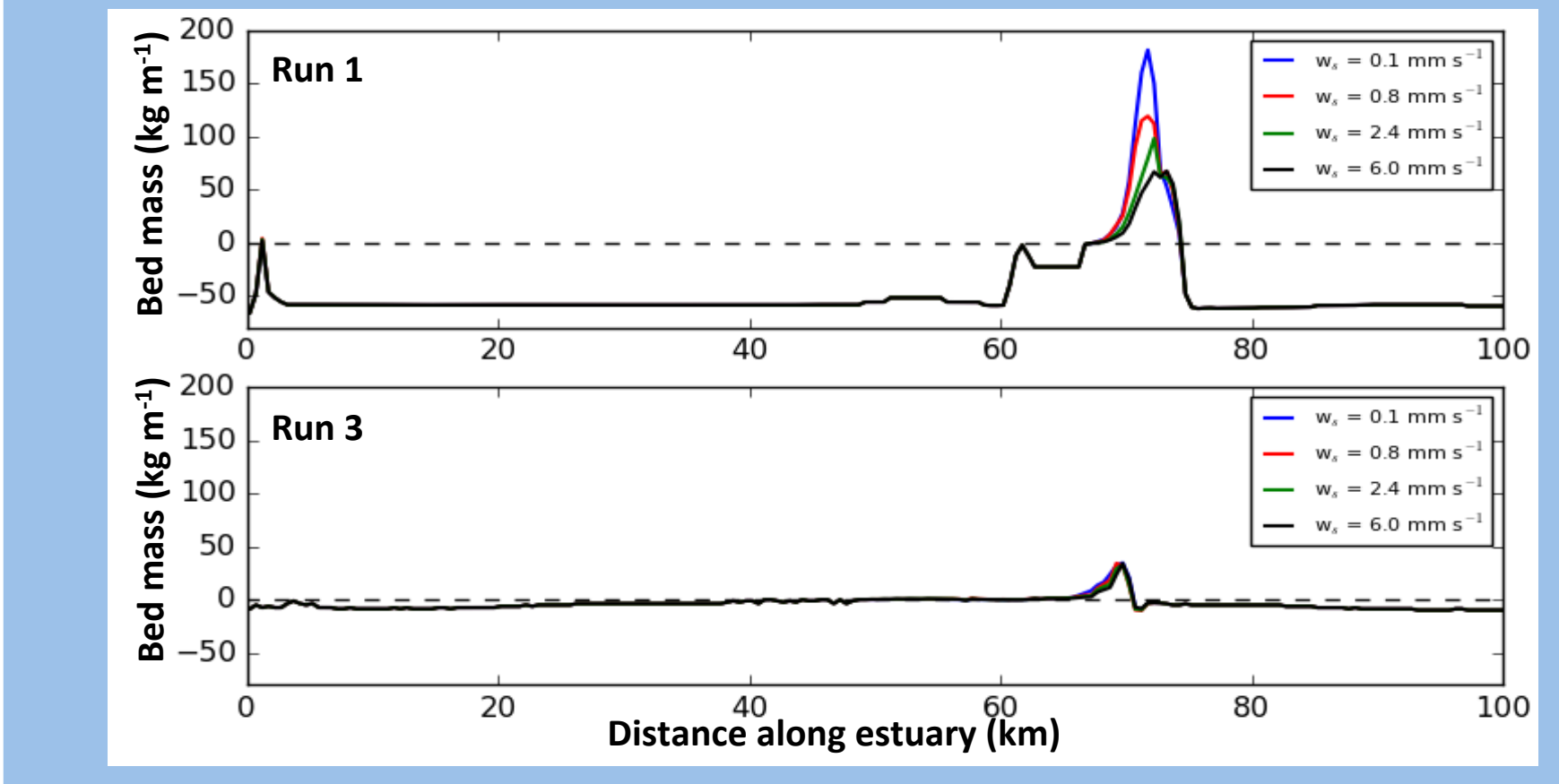

Figure 7: Longitudinal transect of bed mass (kg m^{-2}) for each size class (defined above) on day 365 for model runs 1 and 3 (Table 1).

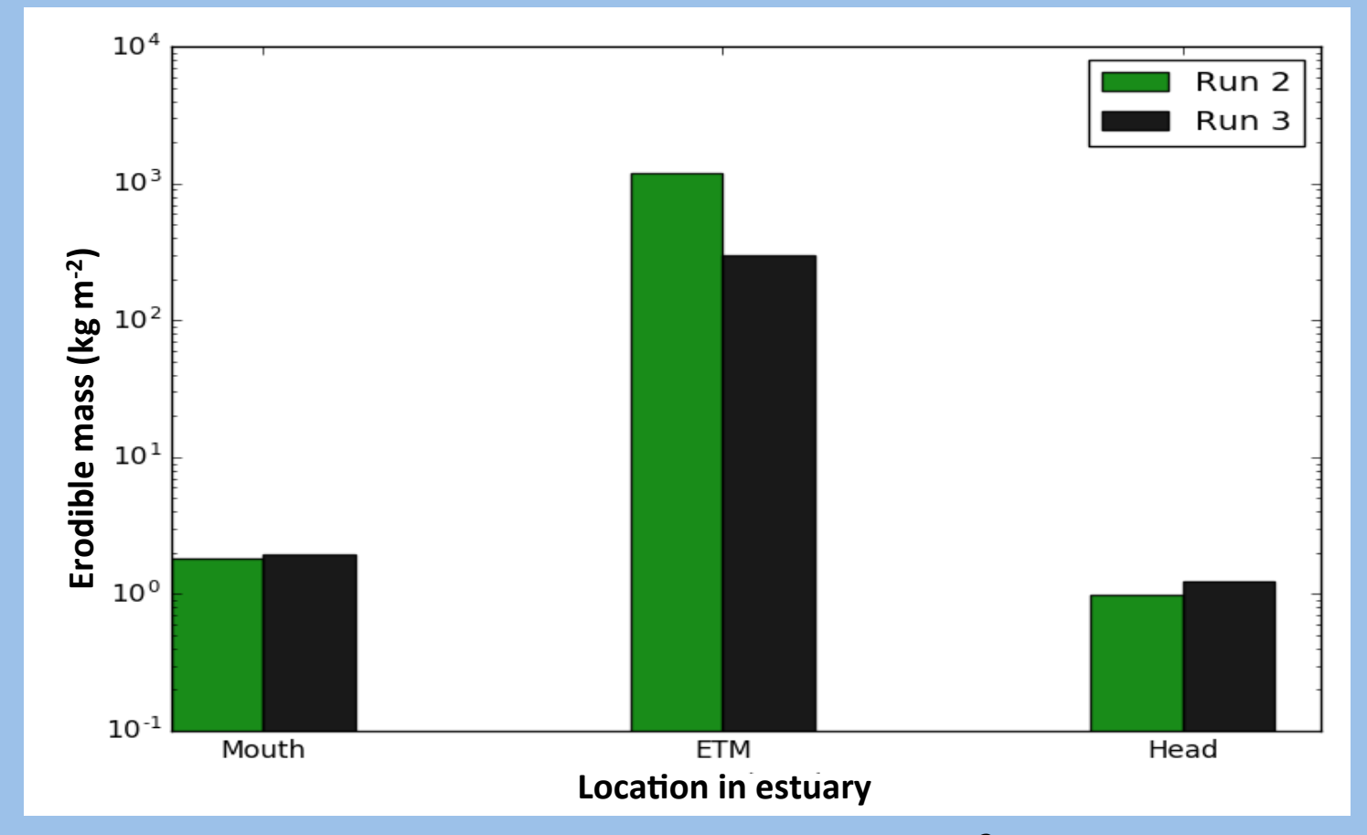

Figure 8: The estimated erodible bed mass (kg m^{-2}) at 0.4 Pa (see Dickhudt et al., 2009) for Run 2 and 3 at the mouth, ETM, and estuary head.

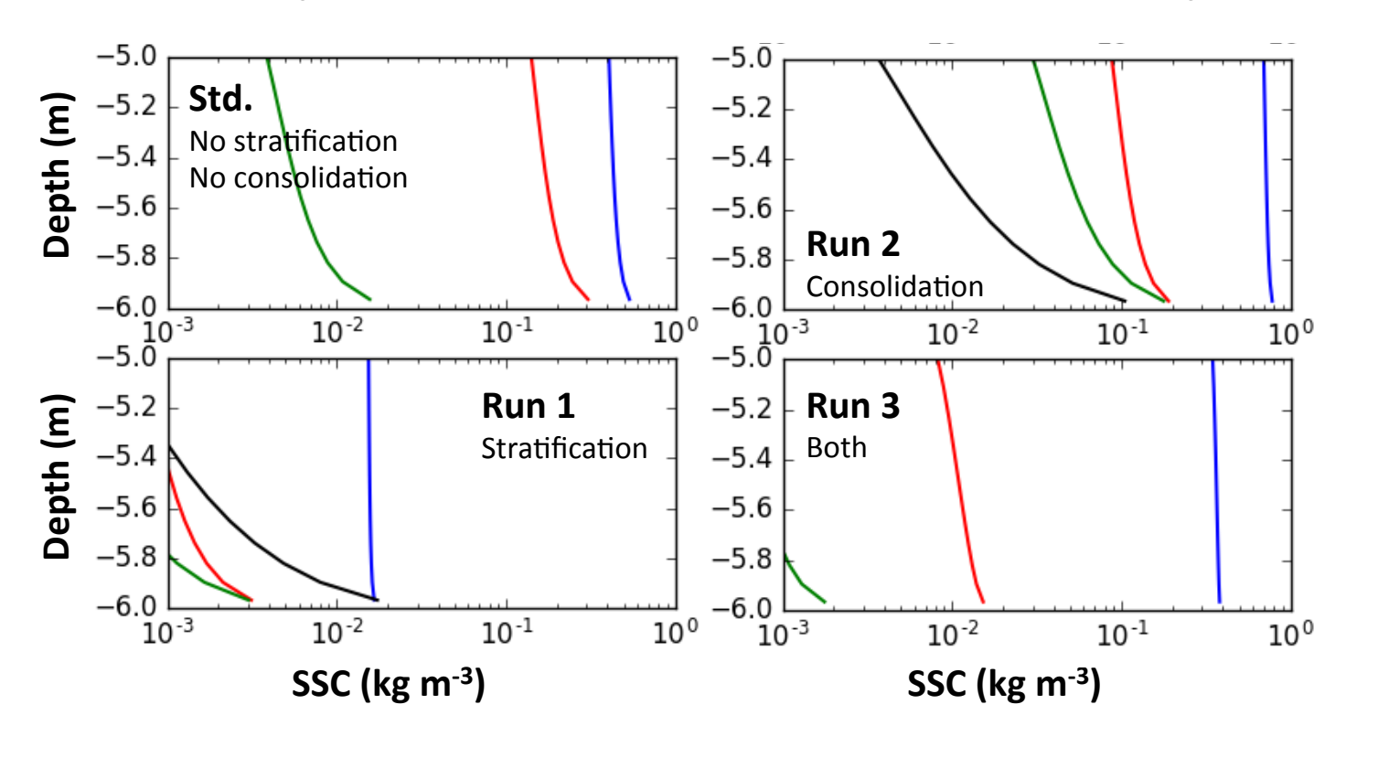

Figure 9: Vertical profiles of suspended sediment concentration (SSC; kg m^{-3}) for each size class in the bottom meter of the ETM during peak tidal velocity at day 365. SSC less than 10^{-3} kg m^{-3} not shown.

Sediment Trapping in the ETM:

- Standard run (no stratification or consolidation): preferentially trapped slow settling material (Fig. 7A).
- ETM trapped all sediments equally when stratification or consolidation limited erosion (example, Fig. 7B).
- Stratification provided more of a limit to sediment entrainment than bed consolidation at the ETM (Fig. 9).
- When both consolidation and stratification were included, suspended concentrations were very limited (Fig. 9): bed armoring?

Conclusions

- An idealized estuarine model developed to scale with the York River Estuary, Virginia, produces an Estuarine Turbidity Maximum (ETM).
- In the ETM:
  - Neglecting stratification effects and bed consolidation overestimates suspended sediment concentrations (SSCs), fluxes, and net deposition.
  - Including suspended sediment stratification reduces the bed stresses, SSCs, and net deposition.
  - Bed consolidation limits erosion downstream, but unreasonable erosion upstream remained.
- Stratification governs the vertical suspension of the differing size classes and consolidation confines sediment to the bed. The combination produces a reasonable ETM location and magnitude, and allows all size classes to converge in the ETM.

Future Work

- Include aggregation and breakup of flocculated particles (Fig. 10)
  - FLOCMOD: population size class model.

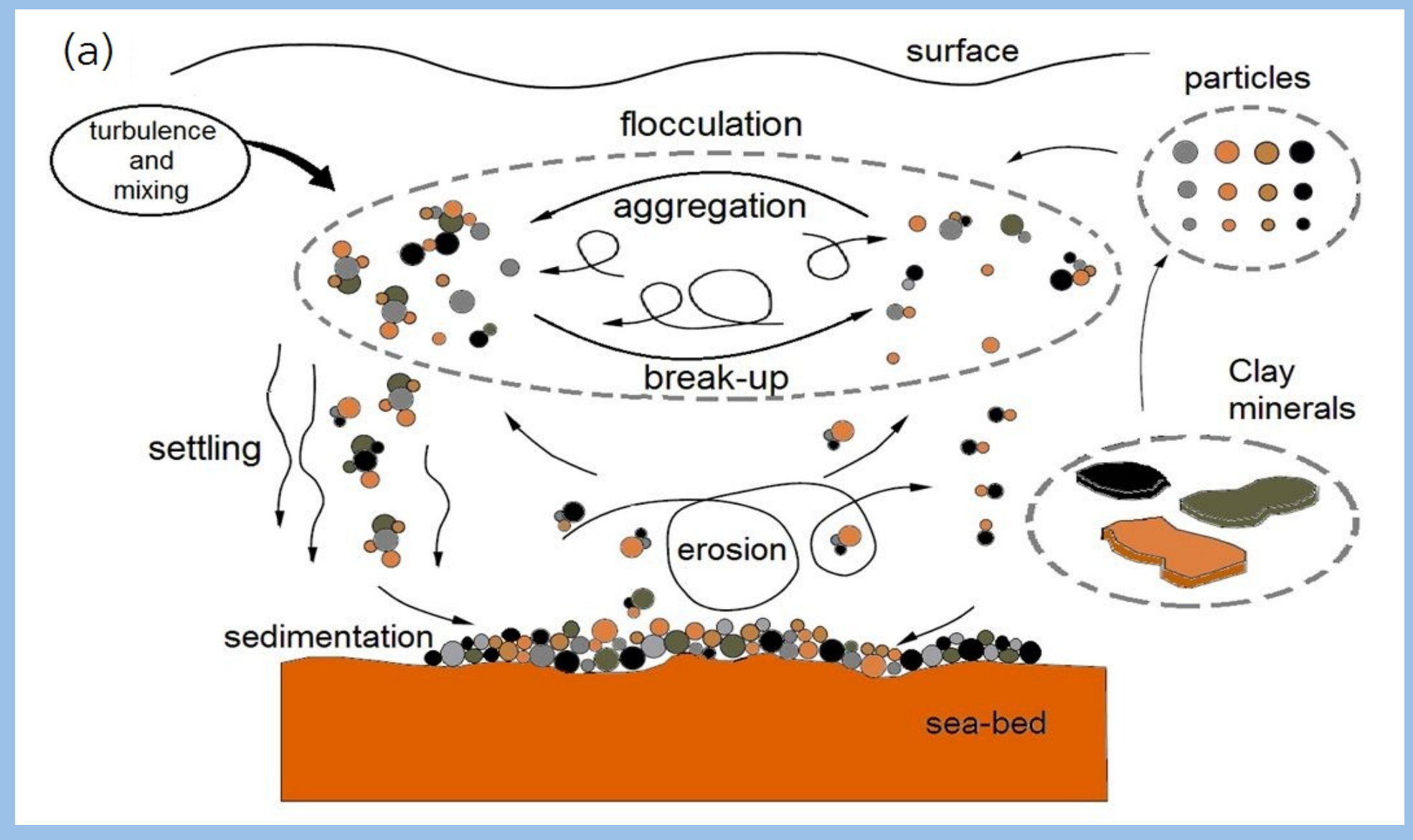

Figure 10: Cycle of deposition and resuspension of cohesive sediment involved in particle aggregation and breakup (Maggi, 2005).

- Capture the dynamics of the Secondary Turbidity Maximum (STM)
  - Full 3-dimensional model of the York River estuary (Rinehimer, 2008; Fall et al., 2014; Fig. 11)

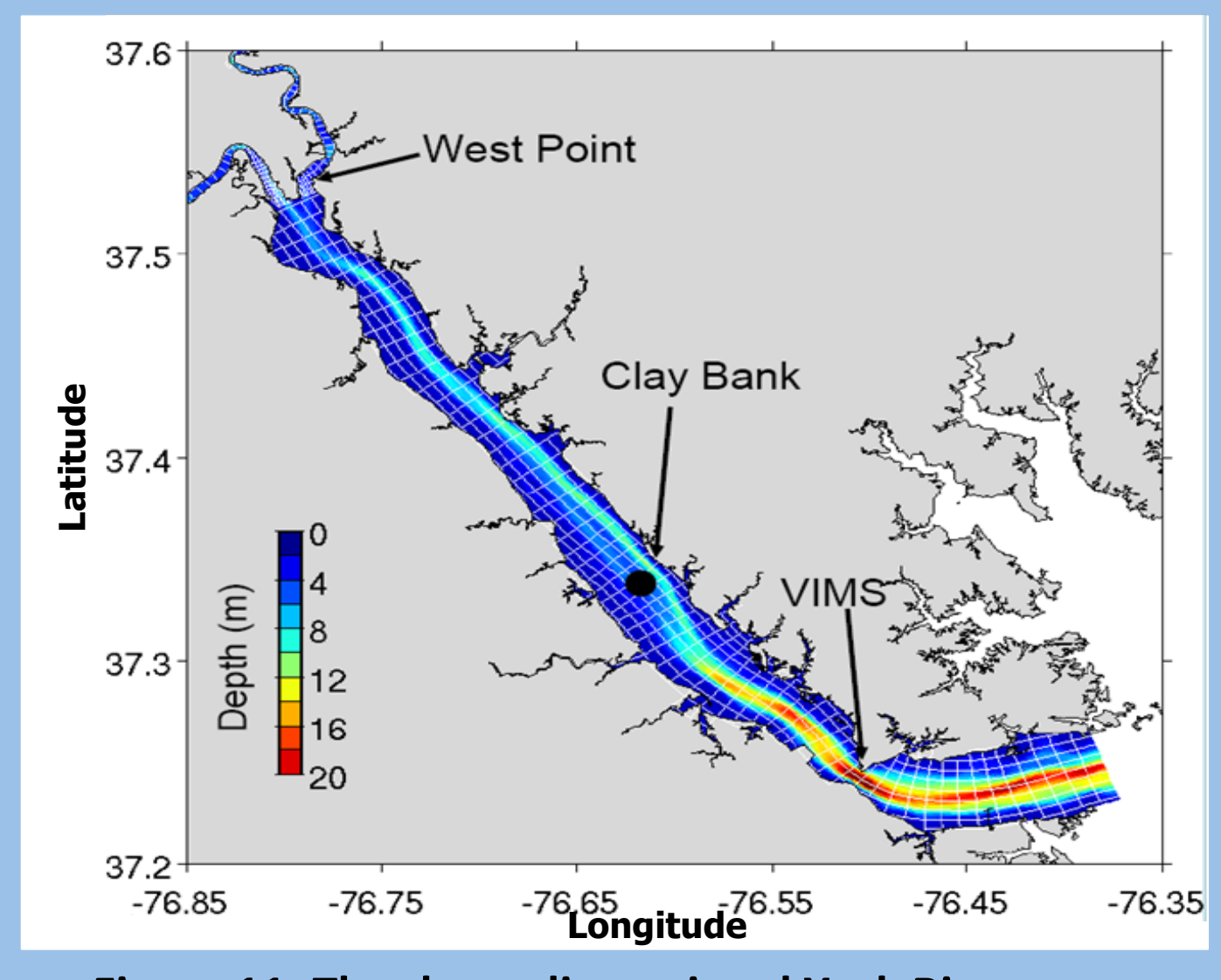

Figure 11: The three-dimensional York River estuary model grid, each square represents 5 model grid cells.

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Acknowledgments

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