Management Modeling of Suspended Solids and Living Resource Interactions

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Chesapeake Bay

- America’s largest estuary.
- 300 km long, 15 to 50 km wide, largely shallow ($\approx 2$ m) but with a deep trench (up to 30m) along the center.
- Classic symptoms of eutrophication:
  - Bottom-water anoxia
  - Poor water clarity leading to diminished aquatic vegetation
  - Diminished fisheries and other living resources
Regional Atmospheric Deposition Model

Watershed Model

Hydrodynamic Model

Eutrophication Model

SAV Component

Benthos Component

The CBEMP
Submerged Aquatic Vegetation

• SAV is limited to shallow water (< 2 m) and littoral zones.
• SAV distribution and abundance are determined by numerous factors. Light is the foremost of these.
• Restoration of SAV to its 1950’s level is a goal of the Chesapeake Bay Program.
• Image courtesy of Virginia Institute of Marine Science.
SAV Sub-Model

Schematic of SAV Model Components

SAV Model Sub-Grid
Reflection  
Surface Irradiance  
Attenuation by Colored Dissolved Organic Matter  
Attenuation by Particulate Organic Matter  
Attenuation by Inorganic Solids  
Attenuation by Attached Epiphytes  
20% of Surface Irradiance Required by SAV
Sources of Light Attenuation

Graph showing light attenuation in various samples labeled CB1TF to CB8PH. The bars are color-coded to represent different sources of attenuation: Fixed Solids, Organic Matter, and CDOM.

Arrows indicate comparisons between Freshwater and Saltwater samples.
Suspended Solids Model

- Transport from CH3D Hydrodynamic Model
- Current-Generated Shear Stress
- Wave Stress from Wind-Wave Model
- Filter Feeders, Submerged Aquatic Vegetation
- CE-QUAL-ICM Eutrophication Model
- Regional Ocean Modeling System Bed Model
- Bank Erosion
- Loads from Watershed

Connections:
- Deposition
- Resuspension
Bottom Shear Stress, Bank Erosion

Percent of time that bed shear stress is dominated by currents. (After Harris et al. 2010)

Long-term average shoreline erosion in the Chesapeake Bay system (From Halka and Hopkins 2006).
The Suspended Solids Model

- The model considers four classes of inorganic solids:
  - Sand
  - Silt
  - Clay
  - Fine Clay

Mass Conservation for 3-D Finite Volume Model

The equation is the mass conservation equation for a control volume which represents all ICM state variables:

\[ \frac{\delta V_j}{\delta t} \frac{C_j}{C_j} = \sum_{k=1}^{n} Q_k \frac{C_k}{C_k} + \sum_{k=1}^{n} A_k \frac{\delta C}{\delta x^k} + \sum S_j \]  

(1)

- \( V_j \) = volume of jth control volume (m³)
- \( C_j \) = concentration in jth control volume (g m⁻³)
- \( Q_k \) = volumetric flow across flow face k of jth control volume (m³ s⁻¹)
- \( C_k \) = concentration in flow across flow face k (g m⁻³)
- \( A_k \) = area of flow face k (m²)
- \( D_k \) = diffusion coefficient at flow face k (m² s⁻¹)
- \( n \) = number of flow faces attached to jth control volume
- \( S_j \) = external loads and kinetic sources and sinks in ith control volume (g s⁻¹)
- \( t, x \) = temporal and spatial coordinates
Suspended Solids Model

Continuous Deposition through Water Column

Deposition is modeled as a continuous process utilizing the settling velocity through the water column, as outlined by Sanford and Halka (1993):

\[ D_i = Ws_i \cdot C_i \]  \hspace{1cm} (4)

Erosion and Deposition at Sediment-Water Interface

For model cells which interface with the sediment bed, the settling term is modified to incorporate erosion and deposition as well as settling, if any, from above:

\[ S_j = Ws_j \cdot \frac{Cu_{p_i}}{\Delta z} + \frac{E_i}{\Delta z} - \frac{D_i}{\Delta z} \]  \hspace{1cm} (3)

- \( Cu_{p_i} \) = concentration of solids size class \( i \) in the cell overlying the cell which interfaces with the bottom (\( g \ m^3 \))
- \( \Delta z \) = thickness of cell which interfaces with the bottom (m)
- \( E_i \) = erosion rate of solids size class \( i \) (\( g \ m^2 \ s^{-1} \))
- \( D_i \) = deposition rate of solids size class \( i \) (\( g \ m^2 \ s^{-1} \))
Suspended Solids Model

Erosion of Clays and Silt

The formulation for clay and silt is adopted from Sanford and Maa (2001):

\[ E(z, t) = M(z) \cdot [\tau_b(t) - \tau_c(z)] \]  \hspace{1cm} (5)

\( M = \text{erosion rate per unit of excess shear stress (kg m}^{-2} \text{ s}^{-2} \text{ P}^{-1}) \)
\( \tau_b = \text{applied shear stress (P)} \)
\( \tau_c = \text{critical shear stress for erosion (P)} \)
\( z = \text{depth into sediments (m)} \)
\( t = \text{time coordinate (s)} \)

Erosion of Sand

The model considers that sand erosion is the product of a near-bed reference concentration, \( C_a \), and settling velocity (Harris and Wiberg, 2001):

\[ E = C_a \cdot W_s \]  \hspace{1cm} (6)
Light Attenuation Model Based on Inherent Optical Properties

Albert and Mobley (2003) used a simplified expression to relate Ke to absorption and backscattering:

\[ Ke = \kappa_0 \cdot \frac{a_t + b_p}{\mu_0} \]

\( \kappa_0 \) = empirical constant (= 1.0546)

In this study, \( \kappa_0 \) is considered to be a variable which depends on backscatter probability (B), \( \mu_0 \), the ratio of \( b_p \) to \( a_t \), and optical depth \((a_t + b_p) \cdot Z\)

Field program to measure optical properties.
Computed and observed total suspended solids along bay axis during SAV growing season for years of varying hydrology.
Computed and observed light attenuation along bay axis during SAV growing season for years of varying hydrology.
Ten-year time series of computed and observed total suspended solids at three locations along bay axis.
Ten-year time series of computed and observed total suspended solids at three locations along bay axis.
The goal of the Bay Program is to restore SAV to the 2m depth contour.

This roughly represents the distribution circa 1950.

Watershed loads of nutrients and solids were much lower than. As an approximation we use 10% of present levels.

We examine the individual and combined response to 90% reductions in nutrient and solids loads.
Percent Improvement in Area of SAV Beds

90% Nutrient Reduction

90% Solids Reduction

Nutrient and Solids Reduction

Improvements in middle to lower portions of systems.

Improvements near watershed inputs.

Management has little effect on the extreme lower bay.
Conclusions

Model

- The model reproduces the basic solids distribution and the major processes that affect solids.
- We have moved in the right direction by incorporating solids in the eutrophication model.
- The model is “ahead” of the data in terms of biological feedbacks, observations of solids, and solids processes.

Aquatic Vegetation

- The largest fraction of light attenuation originates in high inorganic solids concentrations.
- Inorganic solids respond to load controls primarily near local loading sources from the watershed.
- SAV in the mid-bay and lower tributaries responds to reduction of organic solids and epiphytes achieved via nutrient controls.