A TWENTY-YEAR HISTORY OF ENVIRONMENTAL MODELING IN CHESAPEAKE BAY

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Abstract: Environmental modeling in Chesapeake Bay has been in progress for more than 20 years. Modeling and management work in cycles. Model revisions are developed for periodic "re-evaluations" of management strategies for the Bay. Each re-evaluation produces new questions that lead to new models for use in the next re-evaluation. The Bay model has advanced from a steady-state representation of summer to time-variable continuous representation of decadal periods. Innovations developed as part of Chesapeake Bay modeling include coupling of three-dimensional hydrodynamic and eutrophication models, a predictive sediment diagenesis model, and living resource models of zooplankton, submerged aquatic vegetation and benthos. Advanced modeling of light attenuation and of suspended solids is underway.

INTRODUCTION

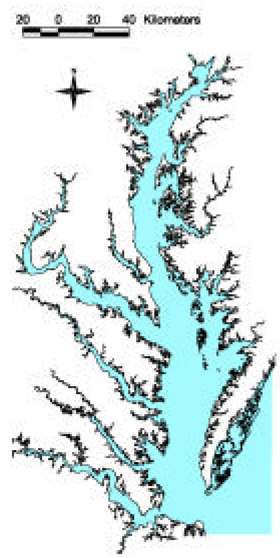

Figure 1. Chesapeake Bay

Chesapeake Bay (Fig. 1) is America's largest estuary. The bay is plagued with problems that accompany development and population growth along its shores and headwaters. Many problems, including bottom-water anoxia, decline in fisheries, and loss of submerged aquatic vegetation, are associated with cultural eutrophication. Predictive mathematical models have been employed to guide bay management and restoration since environmental degradation was widely publicized more than twenty years ago (Flemer et al. 1983). The earliest management effort (HydroQual 1987) coupled three-dimensional hydrodynamic and eutrophication models in a steady-state simulation of summer conditions. Despite the success of the initial effort, limitations were apparent. The chief limitation was absence of a predictive model of sediment-water interactions. The study indicated that sediment release was the dominant source of nitrogen and phosphorus during summer conditions. Sediment oxygen demand was a major dissolved oxygen sink. No means existed to predict how these sediment processes would respond to nutrient load reductions, however. Neither was the time scale for completion of the responses predictable. A second limitation was the steady-state nature of the analysis. The model allowed no influence of conditions in previous seasons or years on summer-average water quality. The model provided the basis for the 1987 Chesapeake Bay Agreement that called for a forty-percent reduction in the amounts of nitrogen and phosphorus entering the bay. In view of uncertainties associated with the model study, however, the agreement also specified a subsequent re-evaluation of the nutrient reduction goal.

THE CHESAPEAKE BAY ENVIRONMENTAL MODEL PACKAGE 1987-1992

The second round of modeling introduced the framework that still supports the Bay modeling efforts: A watershed model, a three-dimensional time-variable hydrodynamic model, and a three-dimensional eutrophication model coupled to a predictive sediment diagenesis model. The watershed model is a highly-refined version of the HSPF model (Bicknell 1996). Nutrient and solids loads are computed on a daily basis for the 166,000 km^2 watershed and routed to individual model cells based on local watershed characteristics and on drainage area contributing to the cell. Transport processes are modeled with the CH3D-WES hydrodynamic model (Johnson et al. 1993) that solves the three-dimensional equations of motion using a finite-difference numerical scheme. Loads from the watershed model and transport from the hydrodynamic model are input to the CE-QUAL-ICM eutrophication model (Cerco and Cole 1993). CE-QUAL-ICM was developed for the study and initially incorporated 22 state variables (Table 1). The model is based on the simulation of cycles including the carbon cycle, the nitrogen cycle, the phosphorus cycle, the dissolved oxygen cycle, and the silica cycle.

Table 1. Original CE-QUAL-ICM State Variables

Water Temperature	Salinity
Iron and Manganese	Cyanobacteria
Spring Diatoms	Green Algae
Dissolved Organic Carbon	Labile Particulate Organic Carbon
Refractory Particulate Organic Carbon	Ammonium
Nitrate + Nitrite	Dissolved Organic Nitrogen
Labile Particulate Organic Nitrogen	Refractory Particulate Organic Nitrogen
Total Phosphate	Dissolved Organic Phosphorus
Labile Particulate Organic Phosphorus	Refractory Particulate Organic Phosphorus
Chemical Oxygen Demand	Dissolved Oxygen
Particulate Biogenic Silica	Dissolved Silica

The sediment diagenesis model (Figure 2) was also developed as part of the study (DiToro and Fitzpatrick 1993). Sediment diagenetic processes are fueled by net settling of organic matter from the water column to the sediments. In the sediments, organic matter diagenesis (decay) produces oxygen demand and inorganic nutrients. Oxygen demand, as sulfide (in saltwater) or methane (in freshwater), takes three paths out of the sediments: export to the water column as chemical oxygen demand, oxidation at the sediment-water interface as sediment oxygen demand, or burial to deep, inactive sediments. Inorganic nutrients produced by diagenesis take three paths out of the sediments: release to the water column, denitrification, or burial to deep, inactive sediments.

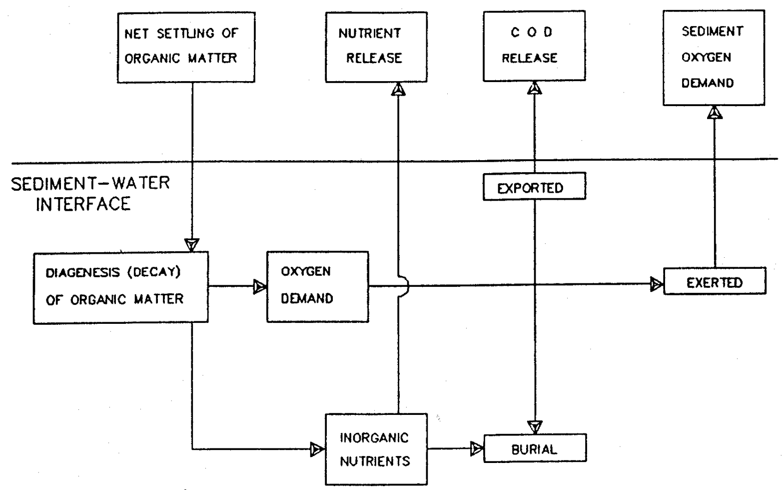

Figure 2. Schematic of Sediment Diagenesis Model

Three years, 1984-1986, were simulated. The model represented correctly the spatial distribution and seasonal cycling of key water quality constituents and processes. This model version was used in a 1992 re-evaluation of the original 1987 load reduction goals.

TRIBUTARY REFINEMENTS AND LIVING RESOURCES 1994-1999

Results from the 1992 model were well-accepted for the mainstem of the bay. Questions existed regarding model validity in the major western tributaries, however. Model performance in these regions was potentially compromised by coarse grid resolution. One aim of the "Tributary Refinements" phase of the model effort (Cerco and Meyers 2000) was improved resolution and model performance in the tributaries. A second goal was employment of newly-collected data through extension of the simulation period from 1985 to 1999. The most significant development was the direct simulation of living resources including zooplankton, submerged aquatic vegetation, and benthic invertebrates. Previously, benefits to living resources were inferred from modeled living resource indicators. Improvements in aquatic vegetation were inferred from computed reductions in light attenuation. Improvements in benthos were inferred from computed increases in dissolved oxygen. Simulation of living resources was intended to provide direct quantification of results of management actions.

Two zooplankton groups, microzooplankton and mesozooplankton, were added to the model carbon cycle which consisted previously of three algal groups, and three organic carbon variables. An SAV submodel (Fig. 3), which interacted with the model of the water column and with the sediment diagenesis submodel, was created (Cerco and Moore 2001). Three state variables were modeled: shoots (above-ground biomass), roots (below-ground biomass), and epiphytes (attached growth). Three dominant SAV communities were identified in the bay based largely on salinity regimes. Within each community, a target species was selected: *Vallisneria* *americana*, *Ruppia maritima*, or *Zostera marina*. Each community was modeled using the same relationships but with parameter values selected for the target species. Benthos were included in the model because they are an important food source for crabs, finfish, and other economically and ecologically significant biota. In addition, benthos can exert a substantial influence on water quality through their filtering of overlying water. Benthos within the model were divided into two groups: deposit feeders and filter feeders (Fig. 4). The deposit-feeding group represents benthos that live within bottom sediments and feed on deposited material. The filter-feeding group represents benthos that live at the sediment surface and feed by filtering overlying water.

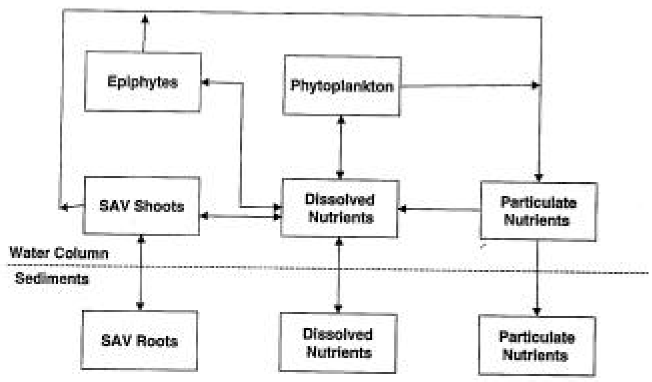

Figure 3. Schematic of Submerged Aquatic Vegetation Model

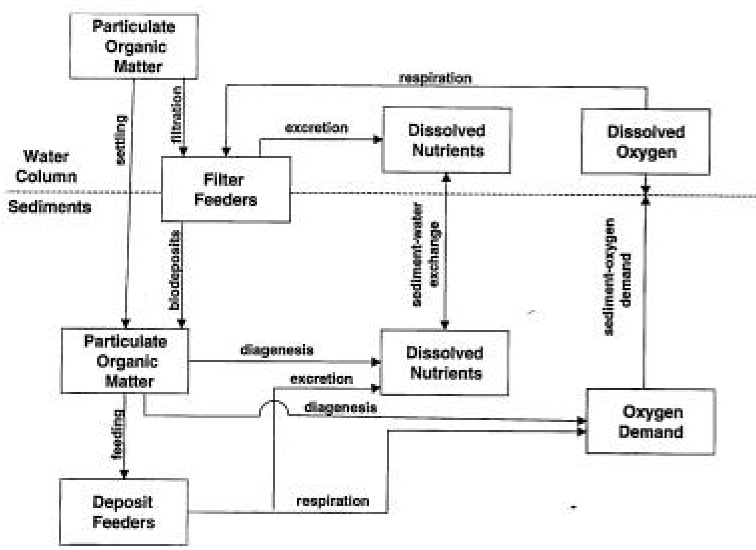

Figure 4. Schematic of Benthos Model

Comparison of computed and observed living resources was more difficult than comparison of the model with precisely monitored substances such as dissolved oxygen. Periodic cycling was obscured in the zooplankton observations but prominent in the model (Figure 5). Order-of-magnitude variations in benthos rendered comparisons difficult to judge (Figure 6). Annual vegetation cycles were apparent in both observations and model although the model performed better at representing the spatial distribution of vegetation rather than the inter-annual variations (Figure 7).

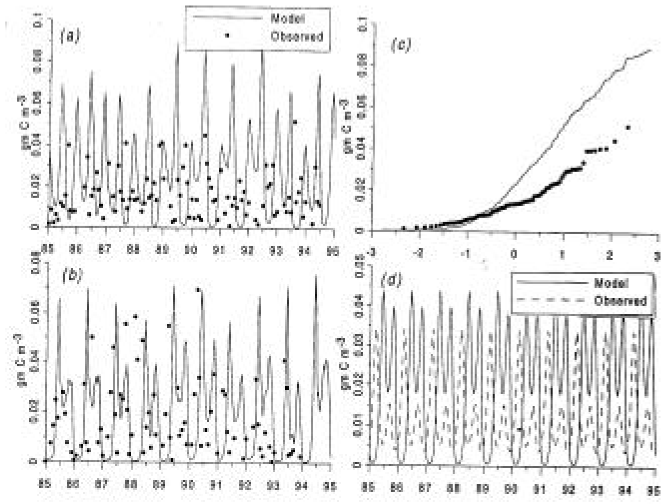

Figure 5. Computed and observed zooplankton: a) Mesozooplankton time series, b) microzooplankton time series, c) Cumulative microzooplankton distribution, d) Harmonic analysis of mesozooplankton.

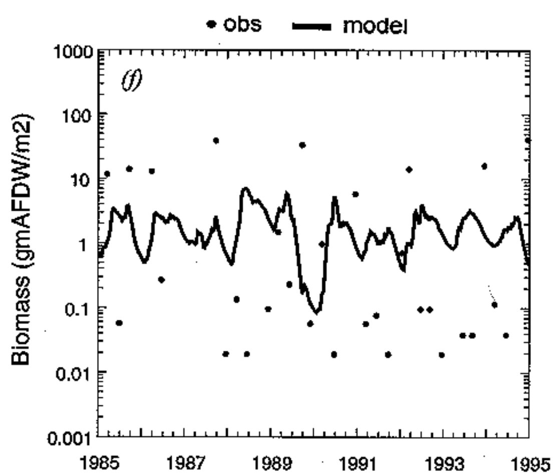

Figure 6. Computed and observed filter feeders in central James estuary

The Tributary Refinements phase highlighted the significant role of inorganic solids in light attenuation. In portions of the bay, SAV restoration is impossible without reductions in inorganic solids. The model also indicated that nutrient reductions are not entirely beneficial to higher trophic levels such as zooplankton and benthos. The increase in habitat, due to improved dissolved oxygen, can be countered by diminished availability of food in the form of phytoplankton. Both of these indications were preliminary and indicated the need for additional study.

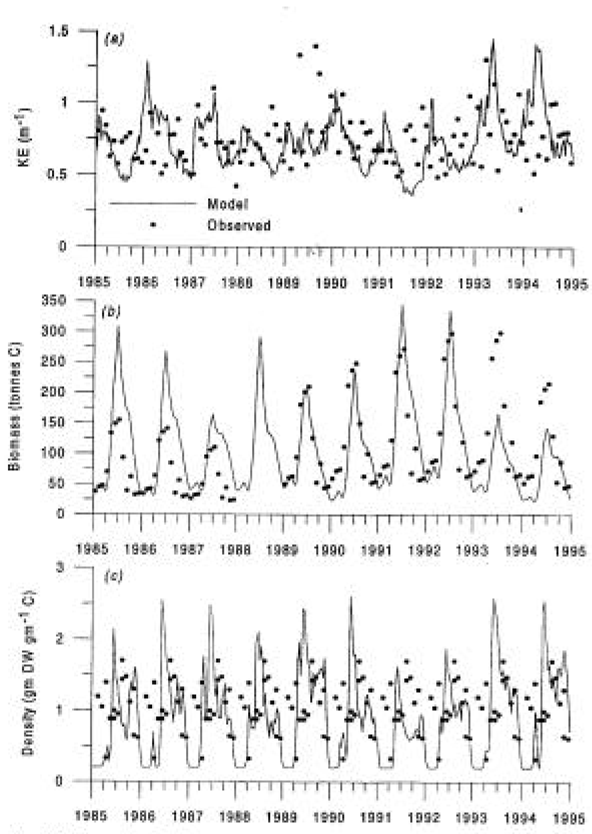

Figure 7. Computed and observed a) light attenuation, b) submerged aquatic vegetation, c) epiphytes in lower Chesapeake Bay

IMPROVED STANDARDS AND ADDITIONAL CALIBRATION 1999-2004

Living resources are not only influenced by their environment, they influence their environment. The ability of bivalve filter feeders to clarify their surrounding water column is well known, for example. The potential for management of water quality through management of living resources was the impetus for plans to add oysters and menhaden to the model package. At the same time, regulatory forces were shaping the direction of management efforts. Portions of Chesapeake Bay were listed as "impaired." Impairments were defined as low dissolved oxygen, excessive chlorophyll, and diminished water clarity. Management emphasis shifted from living resources back to living-resource indicators: dissolved oxygen, chlorophyll, and clarity. A model recalibration for the period 1985 – 1999 was undertaken, with emphasis on improved accuracy in the computation of the three key indicators.

The model representation of suspended solids was adapted from the Tributary Refinements phase. One inorganic solids class was considered along with the sum of modeled particulate organic matter. Solids settling to the bottom was represented by a net settling velocity with no resuspension. Light attenuation was represented by a partial attenuation model that summed contributions from organic solids, inorganic solids, and color (Cerco et al. 2004). This modeling approach was largely successful (Figure 8) but indicated lagging technology relative to more advanced portions of the eutrophication model. The study recommended significant improvements in monitoring and modeling including: rigorous mechanistic sediment transport modeling, improved quantification of bank loads, and optical modeling based on direct measurement of optical properties of water and solids.

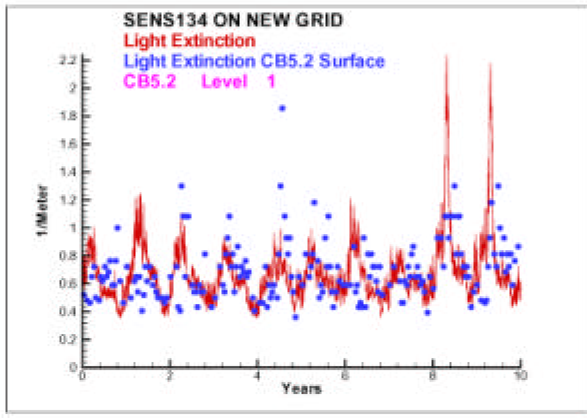

Figure 8. Computed and observed light attenuation in central Chesapeake Bay.

SUSPENDED SOLIDS AND LIVING RESOURCES 2004-2007

The present phase of Chesapeake Bay modeling addresses the issues raised at the completion of the two previous efforts. Chief among them is a mechanistic suspended solids model that is fully coupled to the eutrophication model. Physical processes (e.g. resuspension) are represented as well as interactions with living resources (e.g. bivalve solids filtration). Sampling is underway to provide data for application of an advanced optical model (Gallegos et al. 1990). The application period is being extended to the year 2000. The possibilities for coupling to a fisheries model of organism populations at higher trophic levels (Christensen et al. 2000) are being explored. This improved model package is scheduled for use in a 2007 re-evaluation of the Chesapeake Bay management plan.

SUMMARY

The Chesapeake Bay Environmental Model Package has evolved over a period of 18 years. A model that incorporated no living resources evolved into a model that included them. Feedback effects in which organisms influence their environment are being modeled and coupling with fisheries management models is anticipated. These improvements acknowledge that environmental improvements may not be achieved solely with load reductions. Direct management of living resources accompanied by load reductions may accomplish more than can be accomplished by load reductions alone.

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