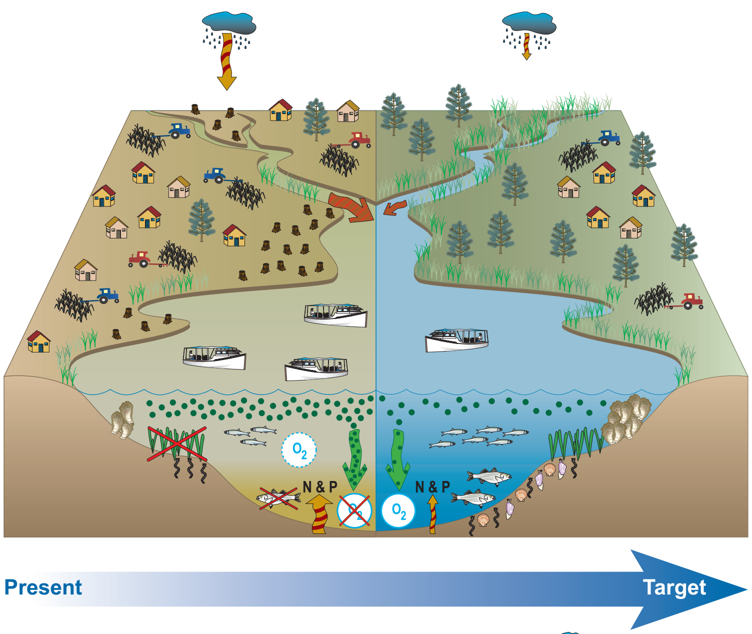
CHESAPEAKE BAY ENVIRONMENTAL MODELS

Prepared by the Chesapeake Bay Program and IAN, February 2005

Environmental models are essential for simulating ecosystems that are either too large or too complex to isolate to conduct real world experiments. Models allow scientists to simulate changes in an ecosystem due to changes in population, land use, or pollution management. These simulations, called scenarios, allow scientists to facilitate prediction of positive or negative changes in our ecosystem from management actions such as improved sewage treatment, reduced fertilizer or manure application on agricultural land, or controlling urban sprawl. Models use mathematical representations to simulate physical, chemical, and biological processes in the 'real' world to estimate the effects of complex and varying environmental events and conditions.

The Chesapeake Bay is one of the most productive estuaries in the world. Water quality problems, such as low summer dissolved oxygen, were identified to be primarily due to excess nutrient and sediment inputs from the 64,000 mi^2 (165,000 km^2) watershed. The *Chesapeake 1987 Agreement* called for a 40% reduction in nutrient loads to the Bay from the 1985 level, by the year 2000.[1] The *Chesapeake 2000 Agreement* set a further goal of correcting all nutrient and sediment related problems in order to remove the Bay from the list of impaired waters (under the Clean Water Act) by the year 2010.[2] The Chesapeake Bay Program has urged the development of computer models to predict responses of the Chesapeake Bay ecosystem to various types of nutrient and sediment management plans.



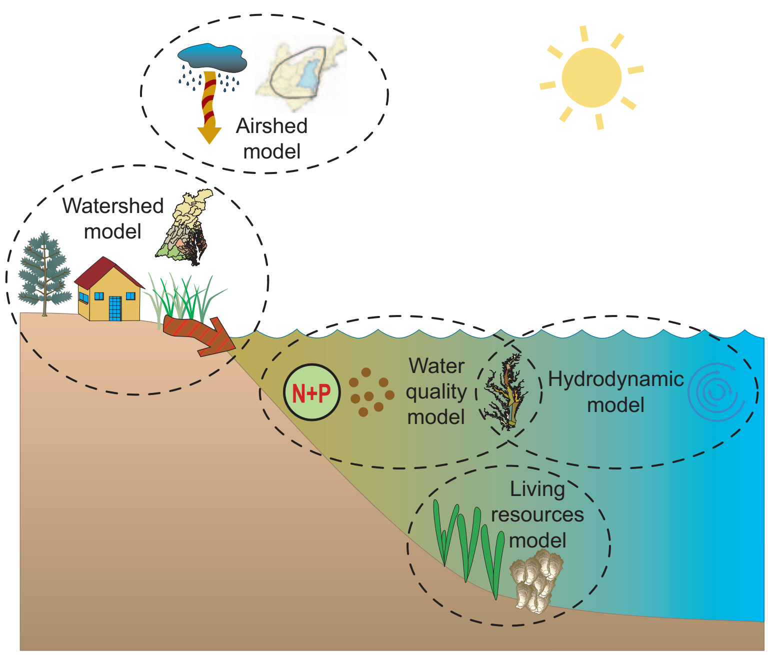
Nutrient inputs come from the atmosphere and from land uses such as deforestation, wetland loss, agriculture, and development. Combined with overharvesting of natural resources, this results in declining aquatic grasses, reduced oyster beds and benthic animals, and increased nutrient release from the sediments into the water. Algal blooms reduce water clarity and lower oxygen in deeper water, resulting in a restricted habitat for fish.

Nutrient inputs can be reduced in part by controlling land use, including guiding development and agriculture, and restoring forests and wetlands. Along with sustainable fisheries yields, ecosystem benefits include restored aquatic grasses, improved oyster beds, diverse and well-distributed benthic animals, and decreased nutrient release. Improved algal levels result in adequate oxygen and an expanded fish habitat.

Conceptual diagram outlining some of the key issues facing Chesapeake Bay, and how these issues can be addressed in the future.

Long term monitoring data were used to calibrate the models, so they are able to represent the observed data. Monitoring data only provides observations in the past or the present, at discrete times and at isolated locations. Modeling scenarios can be used to represent the environment under different management regimes in different temporal and spatial scales.

The Chesapeake Bay environmental model includes the linked Airshed Model, Watershed Model, Estuarine Hydrodynamic Model, Estuarine Water Quality Model, and Living Resources Model. For example, the Watershed Model estimates the delivery of nutrients and sediments to the Bay by simulating hydrologic and nutrient cycles. The Estuarine Hydrodynamic and Water Quality Models simulate the movement of the Bay's water due to freshwater runoff, tide and wind, and models water quality changes (such as algal blooms and dissolved oxygen) due to nutrient inputs and cycling.



The Chesapeake Bay environmental model is made up of five linked models—the Airshed Model, Watershed Model, Estuarine Hydrodynamic and Water Quality Models, and Living Resources Model.

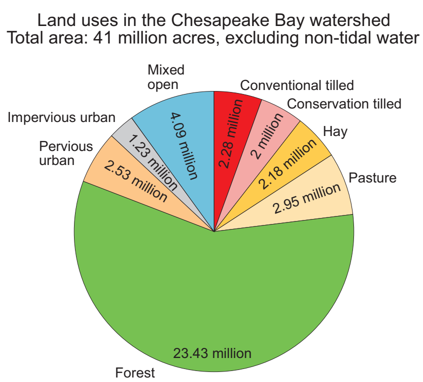
WATERSHED MODEL

The Chesapeake Bay watershed has an area about 12-13 times the size of the Bay. Nutrient and sediment loads from the watershed are the main cause of the Bay's water quality decline.

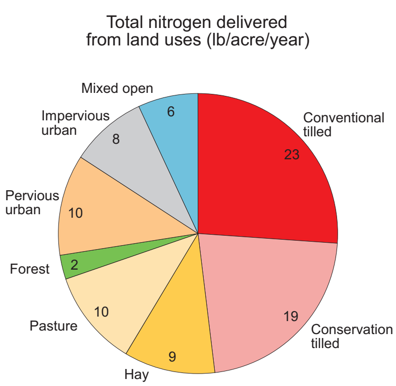
The Chesapeake Bay Watershed Model was developed to estimate flow, nutrient, and sediment loads to the Bay. The Watershed Model provides input to the Estuarine Water Quality Model. The Chesapeake Bay Program uses the Hydrological Simulation Program—Fortran (HSPF)[3], which is supported by the US Environmental Protection Agency, US Geological Survey and US Army Corps of Engineers. There have been many upgrades since the first phase of the Watershed Model in 1982. The current Phase 4.3 Watershed Model, completed in year 2000, consists of 94 segments simulating the nine major basins (figure, right).

In each model segment, the Phase 4.3 Watershed Model simulates physical, chemical, and biological processes for eight land uses: conventional tilled cropland, conservation tilled cropland, hay, pasture, forest, pervious urban, impervious urban, and mixed open (non-agriculture grass land). Forest is a major land use throughout the watershed (58% of the watershed area), followed by agricultural lands (23%) and urban areas (9%) (figure, below). The Watershed Model nutrient inputs are fertilizer and manure application, point sources, septic, and atmospheric deposition. The major processes simulated include rain precipitation, infiltration, evapotranspiration, plant uptake, water and material movement by surface runoff or groundwater, and discharge into rivers or tidal waters.

The input of nutrients is highest on croplands due to fertilizer and manure applications. The input to forest is low and mainly from atmospheric deposition. Croplands deliver the most nutrients to the Bay (figure, bottom).

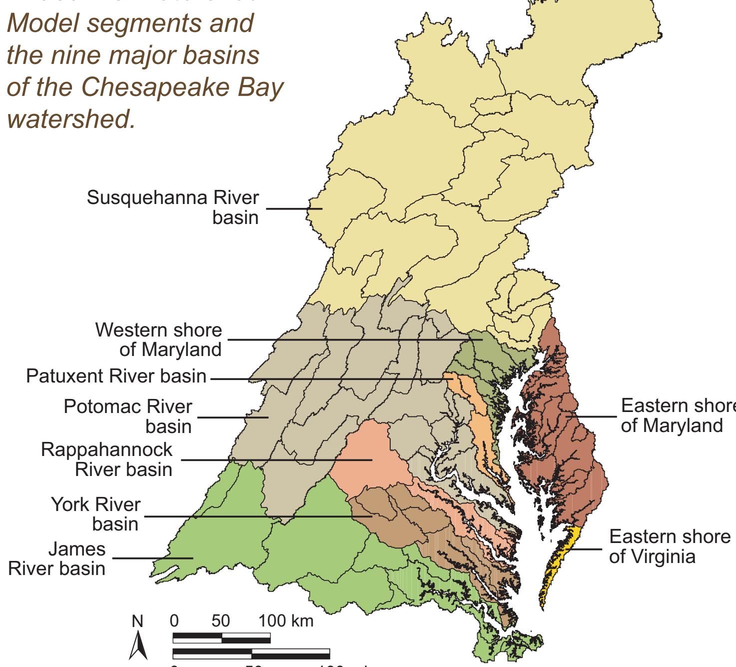


The eight land uses simulated in the Watershed Model.



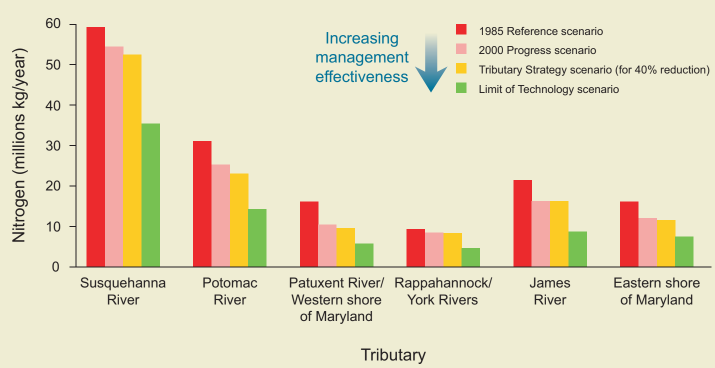
Nitrogen delivery to the Bay from different land uses.

Phase 4.3 Watershed Model segments and the nine major basins of the Chesapeake Bay watershed.



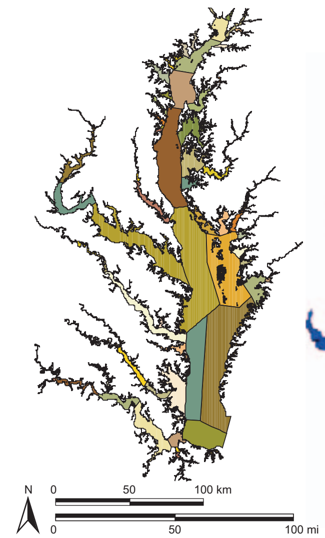
Besides providing input for the Estuarine Water Quality Model, the Watershed Model itself provides useful management information. Early in the 1980s, after scientific findings determined that excess nutrient loads were the cause of water quality degradation in the Bay, the Watershed Model was used to estimate loads to the Bay from different basins. Model outputs were used to recommend reduction of non-point source loads to the Bay through best management practices and to regulate nutrient discharge from point sources. The Watershed Model has been in constant use since then.

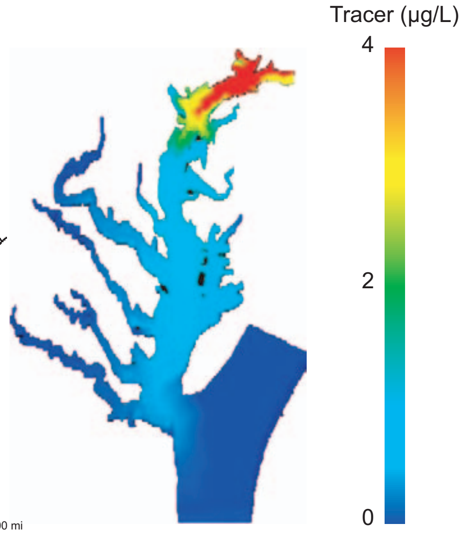
Watershed Model Management Scenarios. Nutrient loads from the watershed to the Bay can be reduced by implementation of best management practices, such as optimal use of fertilizer, manure management, storm water control, shoreline protection, and upgrades of wastewater treatment technologies. Management scenarios were run to estimate the effectiveness of best management practices and the amount of nutrients delivered to the Bay. Based on the goal or cap of total nutrient load, the estimated loads for different areas are used for load reduction allocation.



Different management scenarios can be run on the Watershed Model to evaluate the effectiveness of Best Management Practices.

ESTUARINE MODELS





The 78 Chesapeake Bay segments used in the Estuarine Hydrodynamic and Water Quality Models.

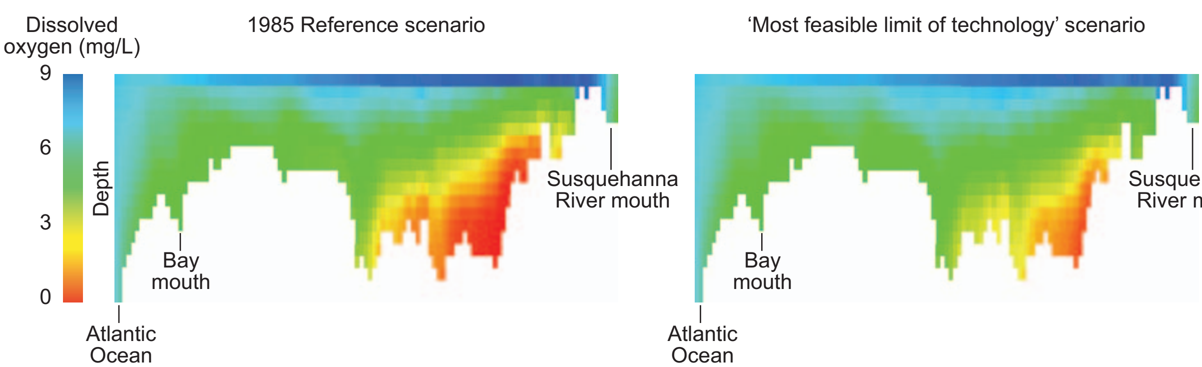
A tracer simulation showing the substantial influence of Susquehanna River loads on the whole Bay.

The model of Chesapeake Bay is a coupled Hydrodynamic Model[4] and Water Quality Model[5]. They are three-dimensional models, simulating the mainstem Bay and tidal tributaries. Both the Hydrodynamic Model and the Water Quality Model share the same computational grid, consisting of 12,961 model cells (representing more than 78 segments; figure, far left) in the current version.

The Hydrodynamic Model simulates hydrodynamics for water movement in the estuary, that is used as forcing for the Water Quality Model, for example, the delivery of particles from the Susquehanna River (figure, left).

The Water Quality Model simulates the fate of nutrients and sediments in the Bay, and the response of water quality through chemical and biological processes for 24 state variables: water temperature, salinity, algae (diatoms, cyanobacteria and green algae), dissolved oxygen, micro- and meso-zooplankton, dissolved organic carbon (C), labile and refractory particulate C, ammonium, nitrate-nitrite, dissolved organic nitrogen (N), labile and refractory particulate N, dissolved organic phosphorus (P), labile and refractory particulate P, phosphates, chemical oxygen demand, dissolved and particulate silica, and inorganic solids. It also simulates submerged aquatic vegetation (SAV), and benthic suspension and deposit feeders.

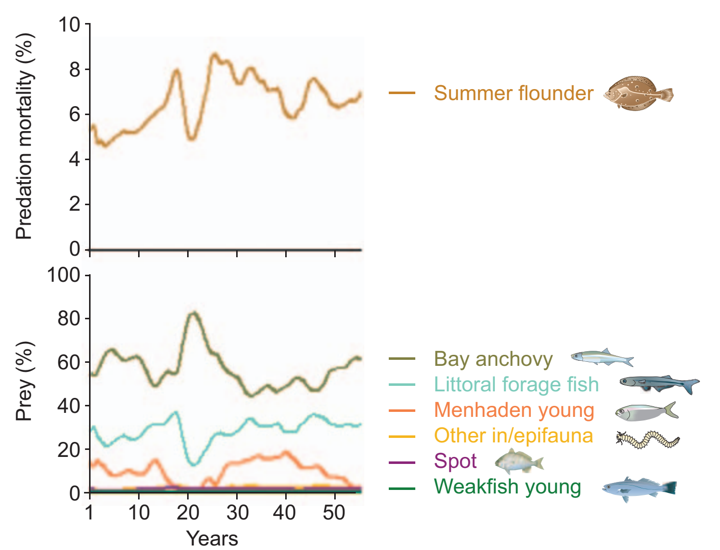
These figures (right) show the improvement of summer dissolved oxygen in the mainstem Bay by nutrient reduction through a most feasible limit of technology program over the 1985 Reference case.



LIVING RESOURCES MODEL

The Chesapeake Bay Living Resources Model (using Ecopath with Ecosim[6]) is under development, and simulates major aquatic animals and plants in the Bay, such as algae, SAV, blue crabs, oysters, other in/epi fauna (such as mud worms), and various fishes, and considers food-chain and prey-predation relationships.

Currently only a few key living resources of lower trophic levels are simulated as fully interactive with the Water Quality Model. One example is the simulation of SAV, coupled to the Water Quality Model so that at each time step, water quality, particularly water clarity, affects the growth of SAV in shallow water. The presence of simulated SAV beds affects water clarity by increasing particle settling rates and reducing resuspension. An oyster simulation is also coupled to the water quality simulation and is fully interactive at each time step. Water quality affects oyster filtering rates and biomass through temperature, suspended solids, salinity, and dissolved oxygen, while the simulated oyster biomass removes particulate organic and inorganic material from the water column through filtration and subsequent biogeochemical processes. Future efforts are underway to relate higher trophic levels through linkages between the Water Quality and Living Resources Models.

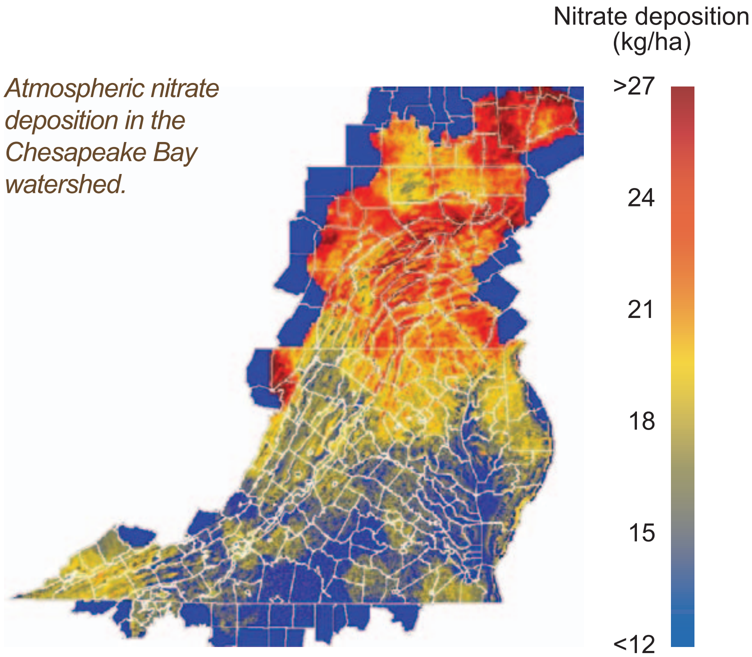


Prey and predation relationships for fishes in the Chesapeake Bay, simulated by Ecopath with Ecosim.[6]

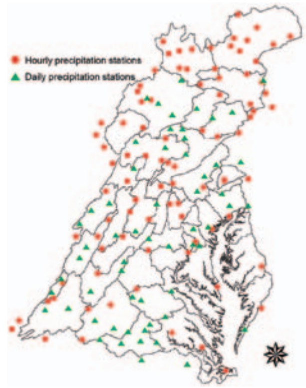
AIRSHED MODEL

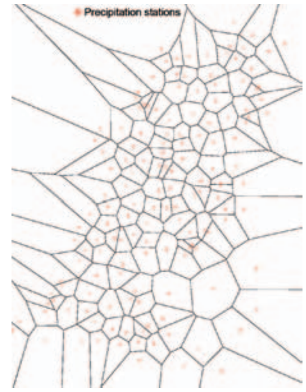
The Chesapeake Bay Airshed Model simulates atmospheric nutrient deposition to the watershed and the Bay, which is required input for the Watershed Model and the Water Quality Model. The current Airshed Model uses a combination of the Regional Acid Deposition Model (RADM) and a regression model.

The RADM estimates nitrogen deposition through regional air circulation from sources including the Chesapeake region and the Ohio valley[7], and predicts the results from changes in emissions due to management actions or growth, such as the Clean Air Act and ozone control technology. This model considers the reactions of different types of nitrogen (such as nitrate and ammonium) in clouds, eddy diffusion, movement velocity, source of emission or loss, and dry deposition.



Atmospheric nitrate deposition in the Chesapeake Bay watershed.





Precipitation stations used in the Phase 4.3 model (left), and the Thiessen polygon which estimates precipitation in each model segment (right).

Regression model. Although the RADM provides good estimates of changes in atmospheric deposition due to different management actions, for more accurate estimates of wet deposition used in the Watershed Model and Water Quality Model calibration (1985-1994), a regression method is used. This is based on eight years (1985-1992) of observed precipitation and wet deposition data from 15 National Air Deposition Program stations in the Chesapeake region.[8] The regression considers the concentrations of nitrate and ammonium in rainfall, the intensity of precipitation, season, and latitude. Atmospheric deposition is different among Watershed Model segments partly due to differences in precipitation. About 150 hourly and daily precipitation stations were used in the current Phase 4.3 model. The Thiessen polygon method is used to estimate the spatial distribution of precipitation to model segments (figures, above). In the Phase 5 Watershed Model, there are 680 precipitation stations and it uses the USGS *xyz* (latitude, longitude, and elevation) regression method with a 5 km grid to distribute the precipitation data spatially.

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Acknowledgements

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A Watershed Partnership

*The **I**ntegration and **A**pplication **N**etwork (IAN) is a collection of scientists interested in **solving**, not just studying environmental problems. The intent of IAN is to inspire, manage and produce timely syntheses and assessments on key environmental issues, with a special emphasis on Chesapeake Bay and its watershed. IAN is an initiative of the faculty of the University of Maryland Center for Environmental Science, but will link with other academic institutions, various resource management agencies and non-governmental organizations.*

Primary objectives for IAN

- **Foster** problem-solving using integration of scientific data and information
- **Support** the application of scientific understanding to forecast consequences of environmental policy options
- **Provide** a rich training ground in complex problem solving and science application
- **Facilitate** a productive interaction between scientists and the broader community

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