MODELING OF THE CHESAPEAKE BAY

presented by

Chesapeake Bay Program
Scientific and Technical Advisory Committee

compiled and edited by

Elizabeth C. Krome
Cynthia A. Corlett

based on a paper by
Charles Schemm

with guidance from
Lewis Linker
Charles Schemm

February 1990

Chesapeake Research Consortium, Inc.
P.O. Box 1120
Gloucester Point, Virginia 23062

CRC Publication No. 131a

MODELING OF THE CHESAPEAKE BAY

prepared by

Chesapeake Bay Program
Scientific and Technical Advisory Committee

NOTES

This talk describes the computer models of Chesapeake Bay that are being developed to help scientists better understand the Bay's problems and to help managers decide on a strategy for cleaning up the Bay.

The modeling effort is being funded jointly by EPA and the Army Corps of Engineers as part of the overall Chesapeake Bay cleanup effort. The work is being coordinated by the Chesapeake Bay Program.

Outline

I. Eutrophication
- **Anoxia**
- **Nutrient Enrichment**

II. Chesapeake Bay Models
- **Watershed**
- **Hydrodynamic**
- **Water Quality**

III. Model Results

IV. Modeling Issues

NOTES

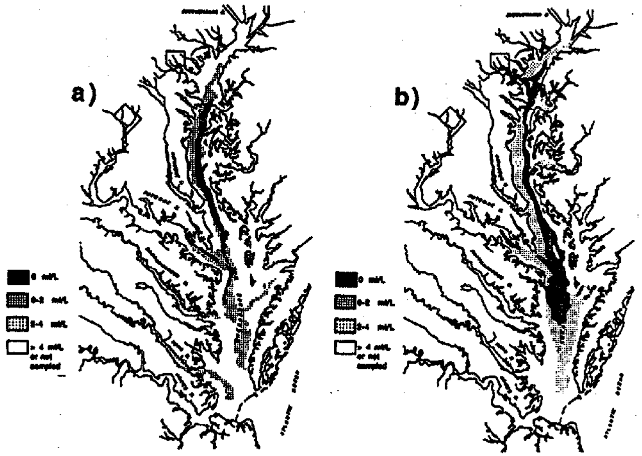
One of the major problems of the Bay is eutrophication, which is an excess of nutrients. We'll first discuss anoxia, or absence of oxygen, which is a symptom of eutrophication and a probable cause of the recent decline in stocks of finfish and shellfish in the Bay. Then we'll talk more about the relationship between eutrophication and anoxia and finally about the sources of nutrients in the Bay.

After some background material on the advantages of numerical modeling and what we hope to accomplish with the Chesapeake Bay models, we'll talk briefly about the three major components of the model system. These are the watershed model, the hydrodynamic model, and the water quality model. It is the latter that produces the outputs of interest to the community.

There are a couple of viewgraphs on model results that show how the models have been applied to the cleanup effort.

We'll conclude with a look at the modeling issues that we hope will be addressed in the generation of models now under development.

Dissolved Oxygen



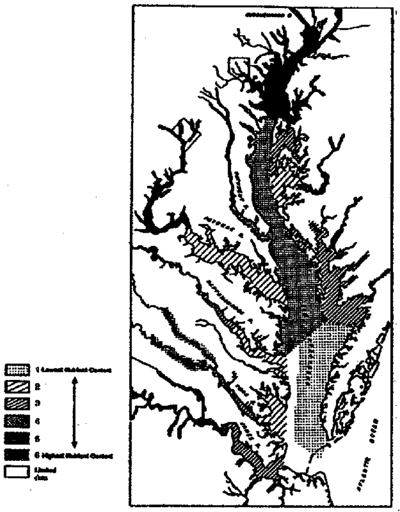
Comparison of dissolved oxygen levels in Chesapeake Bay in a) 1950 and b) 1980.

NOTES

This slide illustrates the anoxia problem. The 1950 chart shows an area in the middle of the Bay where oxygen levels are in the <2 ml/L range, which is approaching anoxia; but there are no regions with absolutely no oxygen. Thirty years later the situation looks considerably worse. The medium grey area of low oxygen (or hypoxia) is extensive; and there is a black area, which indicates virtually zero oxygen. Fish can't survive in such an environment.

Although there are other, more obvious symptoms of the Bay's problems (e.g., decreasing catches of oysters, rockfish, and so on), we look at dissolved oxygen levels because they can be quantified, and anoxia is believed to be directly linked to declining fish stocks.

Nutrient Enrichment



NOTES

The chart on nutrient enrichment, which is reasonably current, shows regions of high nutrient content about where one might expect--in the Baltimore Harbor region, in the upper reaches of the Potomac River, and generally in the upper Bay. Note the correlation between regions of low oxygen content on the previous viewgraph and high nutrient content here.

(Both of these figures are from the EPA Report titled *Chesapeake Bay: A Framework for Action.*)

Effects of Nutrient Enrichment

Increased nutrient input

↓

More nutrients in water column

↓

Increased algal growth

↓

Decreased clarity, increased particulates

↓

Settling and decay of particulate organics

↓

Decreased oxygen in deep water

NOTES

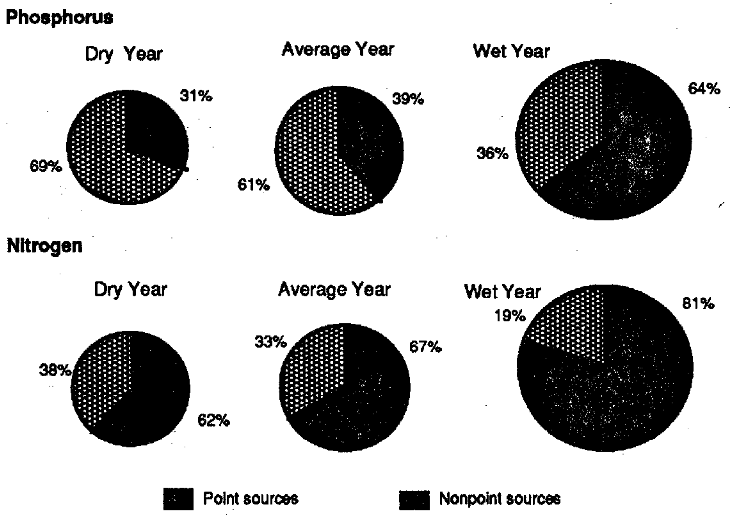
The fact that anoxia appears in regions of the Bay that are rich in nutrients suggests (but does not prove) a cause-and-effect relationship between the two phenomena.

One possible scenario linking excess nutrients to anoxia is illustrated on this viewgraph:

As more nutrients enter the Bay (largely in the form of phosphates and nitrates), more nutrients appear in the water column. These nutrients behave in the water exactly as they do on a suburban lawn--they increase growth, in this case the growth of algae. The result of this is a decrease in the clarity of the water and an increase in particulates. When these tiny organisms die, they settle and decay in the bottom waters; and as they decay, they consume the oxygen.

Numerical models can be used to confirm the above hypothesis and, thus, firmly establish a causal link between eutrophication and anoxia.

Relative Contributions of Point and Nonpoint Sources



NOTES

Here is some information on the sources of nutrients entering the Bay. The pie charts of nitrogen and phosphorous are sized according to the overall annual flow of the components. As you can see, in dry years the amounts entering the Bay are less than in wet years. In a wet year the phosphorus loading is about 23 million pounds, and the nitrogen loading is roughly an order of magnitude more.

What is interesting is how the ratio of point source (factories, sewage treatment plants, etc.) to nonpoint source (largely agricultural runoff) inputs changes from dry years to wet years. In a dry year point sources account for the majority of nutrients entering the Bay. In a wet year, although the absolute level of these point discharges does not decrease, their proportion decreases because there is more runoff.

Numerical models must be designed to take into account both point source and nonpoint source inputs and their yearly and seasonal variations.

Rationale for Numerical Modeling

- **Chemical/biological processes are interdependent**
- **Depend on local availability of constituents**
- **Concentrations depend on currents and stratification**
- **Time scales vary from hours to decades**
- **Equations are too complex to be solved exactly**

NOTES

You may be asking why we need numerical models given the amount of data we have for the Chesapeake Bay. The first thing to remember is that chemical and biological processes are interdependent; in particular, they depend on the local availability of constituents. The concentration of these constituents at any given location and time depends on the Bay's circulation and on the extent to which it is vertically stratified.

The Bay is affected by processes with time scales that vary from hours to decades. The time scale of turbulent motions is typically less than an hour, but turbulence can affect motions at much larger scales. At the other extreme, climatological factors that drive the Bay's circulation may only change every 10 years or so.

Equations exist that describe all these motions, but they are too complex to be solved exactly, even in a relatively closed system such as the Chesapeake Bay. The role of the scientists is to determine an approximate set of equations that (1) retains all the essential physics and (2) can be solved numerically on present generation computers.

Advantages of Numerical Modeling

- **Less expensive than data collection or physical modeling**
- **Models are ideal laboratories**
- **Provide forecasting as well as analysis capability**

NOTES

The advantages of numerical modeling are several:

It is less expensive than massive data collection efforts or physical modeling. The physical model of Chesapeake Bay built by the Corps of Engineers was closed down in part because numerical models have advanced to the point where they are much more versatile and much less expensive to develop and operate.

Numerical models are ideal laboratories. A model's parameters can be changed rather easily, which makes it possible to examine the effects of changes such as increased runoff, or of decreased nutrient input such as might result from a new treatment plant coming on line.

The final advantage of numerical modeling is that it provides forecasting as well as analysis capability.

Potential Applications

- **Quantify the relationship between nutrient loading and anoxia**
- **Identify critical nutrients for control of eutrophication and anoxia**
- **Determine the relative merits of point-source and nonpoint-source controls**
- **Establish priorities**
- **Estimate the response time for improvement**

NOTES

The potential applications of numerical models are numerous; here are a few of them.

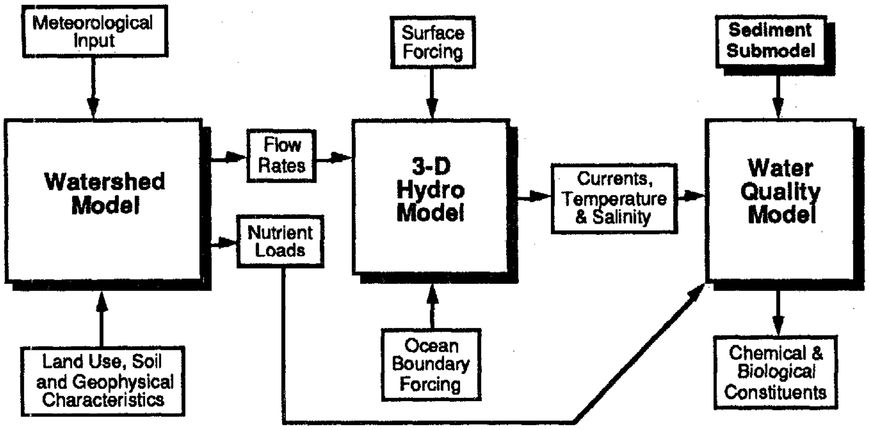
(1) The models can and, in fact, have been used to quantify the relationship between nutrient loading and anoxia. The two charts shown earlier indicated a possible relationship; numerical models can be used to prove the relationship.

(2) Models can be used to identify the critical nutrients for control of eutrophication and anoxia at specific times and locations.

(3) Models can be used to determine the relative merits of point- vs. nonpoint-source controls; for instance, is it a better use of political energy to get farmers to fertilize less, or to ban phosphate detergents that enter the Bay through the sewage system?

(4) And finally, model results can be used to help establish priorities in the cleanup effort, to estimate the response time for improvements, and to estimate the degree to which the Bay's condition will worsen if no corrective action is taken.

Chesapeake Bay Modeling Strategy



Meteorological Input

Surface Forcing

Sediment Submodel

Watershed Model

Flow Rates

Nutrient Loads

3-D Hydro Model

Currents, Temperature & Salinity

Water Quality Model

Land Use, Soil and Geophysical Characteristics

Ocean Boundary Forcing

Chemical & Biological Constituents

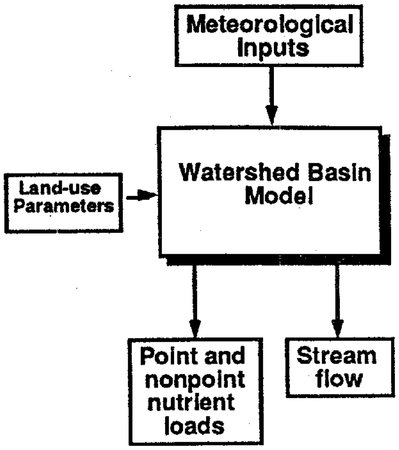
NOTES

The Chesapeake Bay Model is actually a system of three models—a watershed model, a hydrodynamic model, and a water-quality model—shown here by the three large shadowed boxes.

The three models are run sequentially, with output from the Watershed Model being fed to both the Hydrodynamic and Water Quality Models, and output from the Hydro Model being fed to the Water Quality Model.

It is the Water Quality Model that produces the output of primary interest to the community—concentrations of nutrients, dissolved oxygen, etc.

Watershed Basin Model



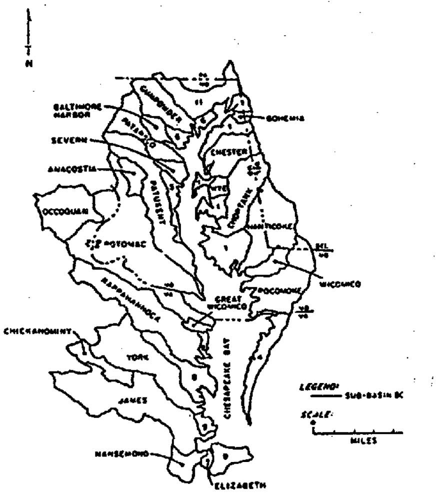
Meteorological Inputs

Watershed Basin Model

Land-use Parameters

Point and nonpoint nutrient loads

Stream flow



NOTES

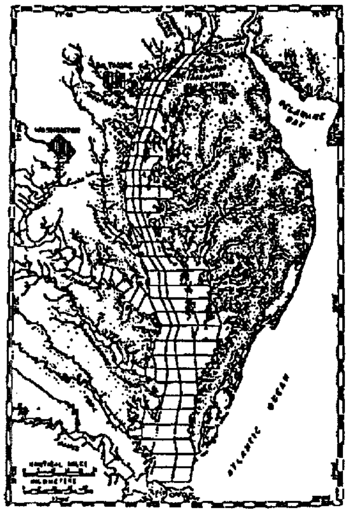
A few words about the components of the system.

First, the Watershed Model. On the right of the viewgraph is the region covered by the watershed model. As you can see, it is a fairly broad area, including a large percentage of Virginia, Pennsylvania, Maryland and DC, and smaller areas of Delaware and West Virginia.

The watershed model is driven mostly by meteorological inputs, i.e., rainfall. Other factors are land use and soil characteristics.

The model computes flow rates at the fall lines of the Bay's tributaries and provides concentrations of nutrients and other constituents in those flows. The flow rates are input to the Hydrodynamic Model, and the nutrient concentrations are held out and used later as point-source inputs in the Water Quality Model.

Steady-State Model Grid



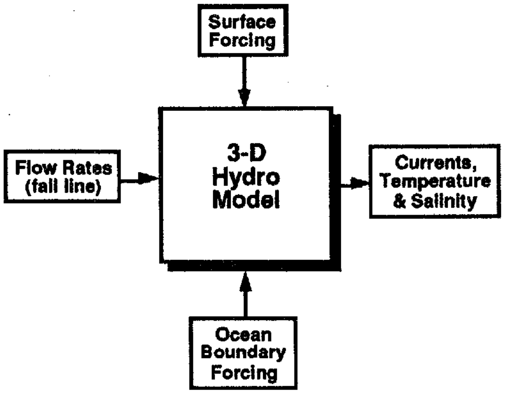
NOTES

This viewgraph shows the computational grid on which the equations of the existing steady-state hydrodynamic and water quality models are solved. The models contain between 5 and 10 vertical levels.

Although the grid cells are longer than they are wide, they are of adequate size to resolve important features along the length of the Bay. In the cross-bay direction, however, there are only three cells on average, and the spatial resolution is not sufficient to properly represent the Bay's general circulation.

This and other problems with the existing models will be corrected in the fully 3-D, time-variable hydrodynamic and water quality models now under development by the Army Corps of Engineers. The new models will have about three times the resolution of the steady-state models in the main stem of the Bay and will also resolve the tributaries better.

Hydrodynamic Model



Surface Forcing

Flow Rates (fall line)

3-D Hydro Model

Currents, Temperature & Salinity

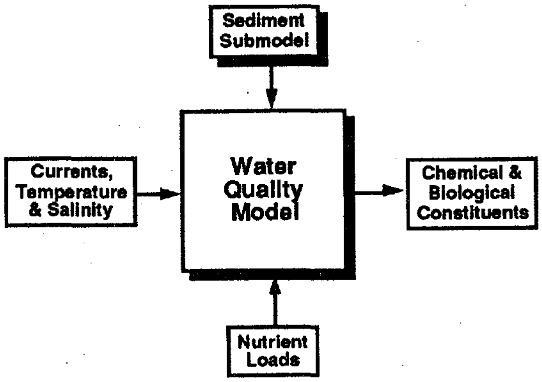
Ocean Boundary Forcing

NOTES

The Hydrodynamic Model solves differential equations for temperature, salinity, and the horizontal components of velocity at each point on the computational grid shown in the previous slide. Pressure, density and vertical velocity are obtained from algebraic balance equations.

The model is driven at the surface by thermal heating and wind forcing, and at the fall line of each tributary by the flow rates computed from the Watershed Model. Values of surface height (from the tides) and salinity are provided at the ocean boundary. There is also a no-slip boundary condition applied at the bottom of the estuary.

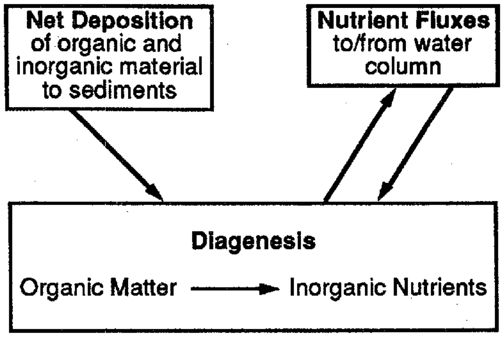
Water Quality Model



NOTES

Currents predicted by the Hydrodynamic Model and nutrient loads obtained from the Watershed Model are input to the Water Quality Model, which solves kinetic equations for the primary state variables (temperature and salinity) and the chemical and biological constituents of interest. Included among the latter are nitrogen and phosphorus in their various forms, dissolved oxygen, and phytoplankton.

Sediment Submodel



Net Deposition of organic and inorganic material to sediments

Nutrient Fluxes to/from water column

Diagenesis

Organic Matter ⟶ Inorganic Nutrients

NOTES

It turns out that the sediments play a far more important role in the Bay than was thought even a few years ago. Chemicals are trapped in the sediments and may ultimately reenter the water column; but depending on conditions at the sediment/water-column interface, a chemical may reenter the water in a different form than it had when it left. The time scale over which the sediments flush themselves out is largely unknown.

Treatment of sediments in the present steady-state model is somewhat primitive, but the time-variable model now under development will include a separate submodel to handle sediment processes. Its major components are illustrated in the figure.

A program is under way to collect data on sediments and sediment/water-column interactions. The information so obtained will be used to support the model development effort.

Steady-State Model Results: Sediments

- **Decrease in dissolved oxygen in 1965-1985 was due primarily to increases in SOD and sediment nutrient fluxes**
- **Sediments were the largest source of dissolved inorganic phosphorus and ammonia in 1984-1985**
- **Dissolved oxygen and algae are controlled largely by SOD, nutrient fluxes and the degree of vertical stratification**
- **Reducing SOD and nutrient fluxes 30% will result in a 2 ppm increase in DO in the bottom layers**

NOTES

The need for improved sediment modeling was demonstrated by early results from the steady-state model. Those results are summarized as follows:

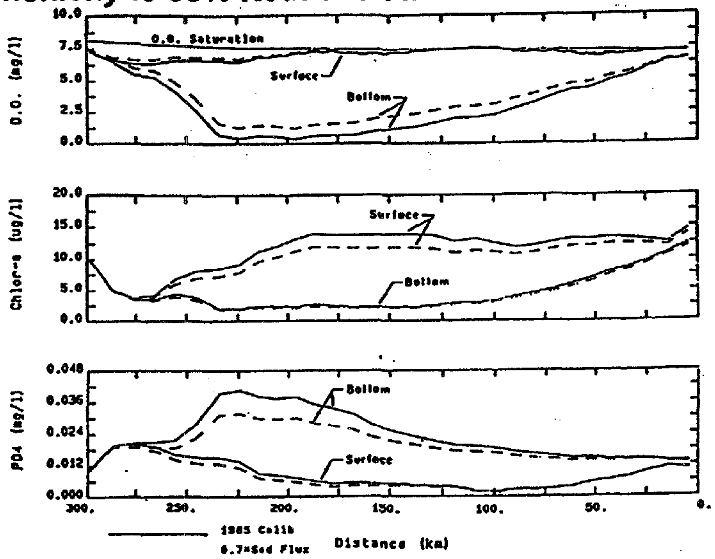
First, the decrease in dissolved oxygen between 1965 and 1985 appears to have been due primarily to increases in sediment oxygen demand and sediment nutrient fluxes.

Sediments appear to have been the largest source of dissolved inorganic phosphorus and ammonia in 1984-85, which were the calibration years for the steady-state model. One of these was a wet year and the other a drier-than-average year.

Dissolved oxygen and algae are controlled largely by sediment oxygen demand, nutrient fluxes, and most importantly, the degree of vertical stratification. The Chesapeake Bay is a partially-mixed estuary, which means it is well mixed near the top but stratified in the lower layers. The stratification also changes seasonally. Estuaries that are well mixed all the time are much easier to model.

As for concrete numbers, the models have led us to believe that reducing the sediment oxygen demand and the nutrient fluxes by 30% will result in a 2 ppm increase in dissolved oxygen in the bottom layers. This would leave the Bay with virtually no anoxic water; so the result, if correct, is significant.

Sensitivity to 30% Reduction in Sediment Flux Rates



NOTES

The next slide provides an example of the type of output we get from the steady-state models. The predicted effects of the aforementioned 30% reduction in sediment flux rates can be seen by comparing solid and dashed lines in the three panels.

In the first panel, the uppermost pair of lines shows dissolved oxygen concentrations in the surface layer. (There are five layers in the water quality model.) The predicted effects of a 30% reduction in sediment fluxes are minimal. In the bottom layer, however, there was virtually no oxygen in the middle Bay in 1985; but the model predicts that reducing sediment flux rates will raise dissolved oxygen levels to between 1.5 to 2 ppm, which is a significant increase.

The steady-state model calculations led to two important results: (1) a number (30%) that can perhaps be used to help plan the cleanup effort and (2) an understanding of how sensitive the model predictions are to sediment-related processes. This latter result demonstrated the need for improved sediment modeling in the time-variable model.

Another variable of interest is phosphorus. The bottom panel shows that reducing sediment flux rates by 30% will result in a significant decrease in the concentration of phosphates in the bottom layer of the Bay.

Steady-State Model Results: Nutrients

- **A 40% reduction in point-source and controllable NPS nutrient loadings will eliminate anoxia and maintain minimum DO levels (>2.0).**

NOTES

A final result from the steady-state model predictions is that a 40% reduction in point-source and controllable nonpoint-source nutrients entering the Bay would eliminate anoxia and maintain minimum DO levels (>2.0). The 40% target for nutrient reduction was arrived at by running the model repeatedly with various control strategies until predicted dissolved oxygen levels reached the desired levels.

You may have seen this 40% target figure in the newspapers last year in connection with the so-called Chesapeake Bay Agreement. In December 1987 the governors of Virginia, Maryland, Pennsylvania, the mayor of Washington, the chairman of the Chesapeake Bay Commission, and the administrator of EPA signed an agreement which attached some specific goals and deadlines to the Chesapeake Bay cleanup effort. The number 40% actually appeared in that document as a target for nutrient reduction. This proves, if nothing else, that the models are valued by those managing the cleanup effort and are being used for their intended purpose—to provide input to the decision making process.

Limitations of Steady-State Models

- **Coarse lateral resolution (about 10 km)**
- **Temperature treated diagnostically**
- **Water quality model uses tuned diffusion coefficients**
- **Ad hoc representation of sediment fluxes**
- **Predict seasonally averaged quantities**

NOTES

Despite these successes, present-generation models are limited in certain respects:

First of all, the models' coarse lateral resolution precludes realistic predictions of the Bay's circulation patterns. The time-variable models will have about 3 times the number of grid points in each direction.

Second, temperature is treated as a diagnostic rather than a prognostic variable. This means that temperature is not determined from the solution of a differential equation but instead is held constant (in time) throughout the calculation at values determined from seasonally-averaged data. This treatment is adequate for seasonally-averaged calculations, which is what we have been doing to this point, but not for long-term predictions, where seasonal variations in temperature must be taken into account. The next generation of models will allow more flexibility in dealing with temperature.

The water quality model uses "tuned" diffusion coefficients, which were determined solely on the basis of agreement between model predictions and the 1984-85 data. The original intent had been to compute diffusion coefficients using output from the hydro model; but for a number of reasons, this proved unworkable.

These models use a very ad hoc representation of sediment processes, which is unsatisfactory in light of the models' proven sensitivity to changes in sediment flux rates.

Finally, the steady-state models predict steady-state quantities, in this case seasonally-averaged quantities. One cannot expect to predict long-term trends with models such as these.

Features of Planned Time-Variable Models

- **Boundary-fitted coordinates with improved lateral resolution (about 3 km)**
  - **Improved circulation estimates**
- **More vertical levels in both the hydrodynamic and water quality models**
- **Hydro model predicts both temperature and salinity**
- **25 water-quality variables**
- **Sediment submodel**
- **Capable of short- and long-term (30 yr) simulations**

NOTES

A five-year effort is under way to replace this generation of models. Like the present system, the new system will consist of separate hydrodynamic and water-quality models designed to be run sequentially; but the models will be time-variable as opposed to steady-state. Other improvements include:

- Boundary-fitted coordinates, which will give improved predictions near coastlines, and improved cross-Bay resolution (about 3 km), which will allow predictions of the Bay's general circulation.
- More vertical levels in both the hydrodynamic and water quality models, which will yield improved predictions of stratification and mixing events.
- The hydro model will predict temperature as well as salinity.
- The water-quality model will predict approximately 25 chemical and biological quantities of interest, which represents about a 50% increase over the present model. The model variables have been chosen after much discussion of which are most needed and what processes can be represented with our present state of knowledge.
- A separate sediment submodel is under development and will be included.
- Finally, the time-variable models should be capable of predicting both short-term and long-term trends. The goal is 30 years. Our first priority will be to start with the 1965 data and run the models out to 1985 to see if they can predict changes that have already occurred.

Modeling Issues

1) **Long-term simulations**
   - **Parameterization of small-scale effects**
     - **Tides**
     - **Internal waves**
   - **Data for forcing and verification**

NOTES

Four remaining issues have been identified as crucial to the model development effort:

First, there are questions about the feasibility of long-term simulations. All models neglect or parameterize some small-scale effects. In a 30-year simulation, effects like tidal oscillations are small-scale and must be averaged out in order to obtain equations that are solvable on today's computers. Tides, however, are important because they cause mixing, which affects the Bay's large-scale dynamics. They must be parameterized in a way that accounts for their effects on the larger-scale motions.

Other small-scale phenomena not included in today's models are internal waves. Recent experiments in Chesapeake Bay have revealed the presence of large-amplitude internal waves at certain times and locations. These, too, can cause mixing at larger scales.

Another problem for long-term simulations is the absence of reliable data for use in forcing the models—population estimates, land-use estimates, estimates of what will happen as sewage treatment plants are added or upgraded.

We also need data for model validation. Properly verifying a model requires reliable data at both the beginning and the end of the forecast period. A 30-year simulation ending today would have to be initialized with pre-1960 data. Data sets obtained prior to 1965 are not thought to be particularly useful.

Modeling Issues (continued)

2) Sediments

- **Physical understanding of processes**
- **Time scales**
- **Hydrodynamic transports**

NOTES

A second issue is sediments.

It became obvious early in the model-development process that we simply did not know enough about what takes place within the sediments and at the sediment/water-column interface to intelligently model sediment processes. In 1988 a program was initiated to collect core samples and analyze data in an effort to improve our understanding of sediment processes. Results are being used to guide the model development effort.

The time scale is a big issue. If the sediments are a significant source of pollutants entering the water column and if the time scale for the sediments to flush out is 30 years, then it would take approximately 30 years for improvements in water quality to be seen if all input of pollutants to the Bay were stopped today. If this is the case, then for numerical models to be of any use, they would have to be validated over at least a 30-year period. We simply do not have reliable sediment data that far back in time. An encouraging note, however, is that very preliminary results from the time-variable model indicate that the characteristic time scale for the sediments may be much shorter than expected—perhaps as little as 5 to 10 years.

And finally, there is the question of hydrodynamic sediment transport, which is not included in either model and which may be important.

Modeling Issues (concluded)

3) Influx of chemicals from the atmosphere

- **Acid rain**

4) Toxics

- **Identification**
- **Approach to modeling**

NOTES

A third issue concerns the influx of chemicals from the atmosphere. In particular, questions have been raised about the possible effects of acid rain on the Bay. At present the model does not allow for the input of nitrogen and sulfur--the primary constituents of acid rain--at the surface boundary, although this provision could be added later if necessary. We don't know if acid rain contributes enough nitrogen to the Bay to warrant such a modification to the model, and we have very little data.

Toxics will become a more important issue over the next few years as more data become available. So far, the cleanup effort (and, hence, the modeling effort) has focused on nutrients because they were perceived to be the major problem. The difficulty with including toxins in the models is that there are so many potential compounds to consider and little is known about which are harmful to marine life. The scientific community needs to start identifying and categorizing them.

And finally, there is the question of how to model toxins once they have been identified as being important. Assuming they are non-reactive, individual compounds could be included in the water quality model without extensive modifications; however, computer limitations would likely preclude the inclusion of more than one or two additional scalar variables in any one simulation.