Manual of Water Quality Models for Virginia Estuaries

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MANUAL OF WATER QUALITY MODELS FOR VIRGINIA ESTUARIES

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I. INTRODUCTION

The planner who is faced with one of the myriad problems affecting water quality in an estuary will be forced to resort to modeling in order to find an answer to his query. There are many reasons for modeling. Among them are the needs to predict an expected future disturbance to a water body, to evaluate alternative methods for improving existing conditions and to determine the most economical method of avoiding or alleviating a problem. Models are relatively objective and models do require an explicit statement of the underlying assumptions. The planner himself, however, might be totally unversed in the art of modeling, even though he be an engineer familiar with the biochemistry of receiving waters. Lacking this expertise, he must either educate himself quickly or avail himself of other people's skill in this field.

Recognizing the need of interaction between the planners or managers and the modelers, SWCB (Virginia State Water Control Board) and VIMS (Virginia Institute of Marine Science) have, since 1969, jointly sponsored a Cooperative State Agency Program (CSA). Under this program, VIMS has developed several types of water quality models for Virginia estuaries. These models have been used by SWCB for water quality management. SWCB also constantly feeds back their management needs to VIMS for refining the existing models or developing new ones. A series of reports have been published for these models and their applications.
It is not the purpose of this manual to make a non-modeler able to develop a model by reading through it, since no manual of this nature can accomplish such a task. This manual is intended to increase the planner or manager's options by acquainting him with various types of models and informing him of the availability of currently working models. This manual contains the following:

1. A scheme indicating the types of water quality models which could be constructed, i.e. an overview of choices in models.

2. A brief description of each type of models developed under the Cooperative State Agencies program.

3. A list of empirical formulas or values for the rate constants used in the models.

4. A directory of water quality models which have been applied to Virginia estuaries.
II. OVERVIEW OF CHOICES IN MODELS

Water quality mathematical models for estuaries can be categorized in several different ways. The important subdivisions for the present purpose are: (1) what water quality components are modeled, (2) spatial dimension, (3) time scale, (4) kinematic or dynamic tidal calculation.

A. Water Quality Components

The degree of complexity depends on the nature of the water quality problem to be studied. The simplest models are dissolved oxygen (DO) models, which simultaneously calculate the concentration of dissolved oxygen and of the organic loading (expressed as a biochemical oxygen demand, BOD) tending to consume oxygen. On a higher modeling level, the oxygen demanding material is broken into a carbonaceous (CBOD) and a nitrogenous (NBOD) component. On the next level of complexity, the entire chain of nitrogenous compounds present in natural waters can be modeled. In certain situations, phytoplankton population becomes an important factor affecting water quality, as in eutrophication. This kind of model is called an ecosystem model. It is necessary to model the closed loops of nutrients (nitrogen and phosphorous) as well as chlorophyll, which is the standard indicator of phytoplankton population. (Dissolved oxygen and CBOD are of course included). It might become necessary in a few cases to include a model component for predatory zooplankton, or even to model species farther up the "food chain".
Besides this graduated progression of models there are specialized single-component models to study such problems as salinity intrusion, coliform count or toxic chemical dispersed in the water column.

B. Spatial Dimension

For most modeling purposes a one-dimensional model suffices. This means that cross-stream and vertical variances are relatively minor and that the cross-section average is meaningfully representative of the entire cross-section. Where this assumption is not so, models must be accordingly more complicated. If stratification is significant, there must be vertical segmentation in the model. If cross-stream variance is significant, lateral segmentation is advisable. In either case, a two-dimensional model is required. In cases both vertical and lateral variations are significant, a three-dimensional or quasi three-dimensional model is needed. However, the practical application of a three-dimensional model is often economical unfeasible at present.

Separate from the above considerations is the problem of branching. If a natural stream has prominent tributaries, the model also must obviously be branched. There is also a special case of zero-dimensional model in which an overall average concentration is used as representative of the entire water body. This simple approach is applicable to small coastal basins or semi-enclosed marinas.
C. Time Scale

Water quality components undergo transport as well as biochemical change. In estuaries, net transport represents a competition between advection and dispersion. Since motion occurs on all time scales, the question of time scale becomes very important in constructing a model. At the low-frequency limit there is net advection, consisting of mean net flow downstream and density induced circulation resulting in mean transport up-river near the bottom of the saline portion of the estuary. These are modeled as mean flow in the model. At the high-frequency end of the motion spectrum are turbulent fluctuations causing mixing. These are modeled as diffusion or dispersion in the model. Between these extremes there is tidal motion.

The effect of tides can be included as part of the dispersion, by effectively choosing a time scale longer than a tidal cycle and considering only the mixing that results from tidal action. This type of model is called a tidal-average or slack tide approximation model. Tides can also be modeled as an advective process, so that variations within a tidal cycle are computed. Although this approach requires a shorter time step of numerical computation and therefore increases the cost of operation, it has the advantage of showing instantaneous distributions and therefore is a more sensitive indicator of violations of minimum standards. In these 'tidal-time' or 'real-time' models the mixing action of tides results from the interaction of tidal motion with small scale turbulence.
D. Kinematic vs. Dynamic Tide

If tidal action is to be included in a model as advective transport, it can be done in one of two ways; either the tidal current can be calculated within the water quality model (kinematic tide) or a separate model can be run to predict the tides from the dynamic equations and the results fed into the water quality model (dynamic tide). This latter approach is more difficult but may be necessary in the case of two- or three-dimensional models where kinematic calculations cannot be done satisfactorily for every point.
III. TYPES OF MODELS

Mathematical models simulate water quality conditions by reproducing the system's essential variables on a computer. Every water quality parameter (dissolved oxygen, for example) obeys a physical law represented by the mass balance equation

\[
\frac{\partial c}{\partial t} = -u \frac{\partial c}{\partial x} - v \frac{\partial c}{\partial y} - w \frac{\partial c}{\partial z} + \frac{\partial}{\partial x} (e_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y} (e_y \frac{\partial c}{\partial y}) \\
+ \frac{\partial}{\partial z} (e_z \frac{\partial c}{\partial z}) + S_e + S_i
\]

where
- \( c \) is the concentration of water quality constituent,
- \( t \) is time,
- \( x, y, z \) are three spatial coordinates,
- \( u, v, w \) are velocity components in \( x, y \) and \( z \) direction respectively,
- \( e_x, e_y, e_z \) are diffusion coefficients in \( x, y \) and \( z \) direction respectively,
- \( S_e \) is the external addition or extraction of the water quality constituent,
- \( S_i \) is the internal biochemical transformation of the water quality constituent.

The advective terms, the first three terms on the right hand side of the equation, represent advection of mass by water movement; the diffusion terms, the next three terms of the equation, represent diffusion of mass by turbulent flow. These terms represent physical transport processes in the flow field and, are identical for all dissolved or suspended substances in the water. The last two terms, representing the external
additions and internal biochemical reactions, differ for different water quality components.

If it is known how much of a given constituent is injected into the system, and the strength of currents, how fast the diffusion is dispersing it and how the biochemical reactions transform it, a prediction of concentration up and down the estuary can be made. Each water quality constituent is represented in the model by its own mass balance equation. Each equation contains terms representing the rate at which the particular constituent is created or injected, terms for the rate of transport from one spot to another, and terms for the rate of dieoff or transformation. Due to the complexity involved, the mass-balance equations are simplified and their solution techniques are translated into a computer program. Numerical results are produced from the set of conditions which have been expressed in numerical form.

In general, the nature of water quality problem and the characteristics of estuary under study determine the type of model and degree of simplification. Models vary widely in sophistication. A greater degree of realism is achieved when additional water quality parameters or spatial dimensions are added. However, the cost and effort of model construction and operation increase with the number of parameters and spatial dimensions included. The planner must therefore find an optimum point in the tradeoff between realism and cost of operation. He must choose the simplest
model that will provide the necessary answers to a stated accuracy.

A. Spatial Dimensions

A water body is inherently a three-dimensional system. The complete description of water quality is concentration distributions of water quality constituents in three spatial dimensions and time. However, a solution with three spatial dimensions is economically unfeasible at the present state of art in water quality modeling. Approximation by reducing spatial dimensions is necessary.

1. Zero-Dimensional Model

A zero-dimensional model treats the water body as a homogenous system. Therefore, the model's results are average concentrations of water quality constituents over the entire water body. These models are most applicable to small embayments and boat basins, in which the overall average concentrations are reasonable representatives of water quality. The solution to zero-dimensional equation is simple enough that hand calculations may be easily carried out. No computer program has been written for this type of model under the CSA program.

Since the entire water body is treated as a single point, the physical transport processes will not transport water quality constituents from one spot to the other in the system, but only transport them in and out of the system.

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The transport processes may be represented with a flushing rate, \( r \), and eqn. (1) becomes

\[
\frac{\partial C}{\partial t} = -rC + S_e + S_i \tag{2}
\]

The flushing rate may be calculated as \( r = \frac{P}{V} \), in units of \( 1/\text{tidal cycle} \), where \( P \) is the intertidal volume and \( V \) is the high tide volume of the water body. In case some fraction of water, say \( a \), which leaves the system at ebb tide will return in the following flood tide, the flushing rate should be modified as \( r = (1 - a) \frac{P}{V} \).

The general expression for \( S_e \) and \( S_i \) of a water quality constituent may be written as

\[
S_e + S_i = M - kC \tag{3}
\]

where \( M \) is the combined source and sink per unit volume and \( k \) is rate constant for biochemical interaction. Substituting eqn. (3) into eqn. (2) and solving the resulting equation, one obtains:

\[
C(t) = \frac{M}{k+r} \left( 1 - e^{-(k+r)t} \right) + C_0 e^{-(k+r)t} \tag{4}
\]

where \( C_0 \) is the concentration at time \( t = 0 \). Equation (4) gives the general solution for concentration as function of time. The steady state solution is given with \( t \to \infty \), i.e.

\[
C(\infty) = \frac{M}{k+r} \tag{5}
\]
2. One-Dimensional Model

For most tidal estuaries in Virginia, a one-dimensional model is sufficient for water quality analysis. Most of the water quality models developed under the CSA program belong to this category. The models predict the cross-sectional average concentrations of water quality constituents. The basic framework of the model is derived from the cross-sectional integration of eqn. (1),

\[
\frac{\partial}{\partial t} (AC) = - \frac{\partial}{\partial x} (AUC) + \frac{\partial}{\partial x} (AE \frac{\partial C}{\partial x}) + A \cdot S_e + A \cdot S_i \tag{6}
\]

where \( C \) is the cross-sectional average concentration,
\( U \) is the cross-sectional average velocity,
\( A \) is cross-sectional area,
\( E \) is longitudinal dispersion coefficient.

The basin geometry of an estuarine river is usually so irregular that no mathematical expressions for the cross-sectional area \( A \) and velocity \( U \), as functions of distance \( x \), can be found. Therefore, unlike the zero-dimensional model, it is impossible to have an analytical solution of equation (6) in most cases. With the advance in high speed electronic computers, approximate solutions with numerical methods offer the most practical approach.

(1) One-Dimensional Non-Branched Model

This type of model is applicable to an estuarine river without significant branching. To facilitate the numerical computation, the river is divided into a number of volume
elements, called reaches, by a series of lateral transects perpendicular to its axis. The following sketch represents one of the reaches, the mth reach.

Equation (6) may be integrated with respect to x over the volume element to arrive at the equation describing the mass-balance of a substance within the reach.

\[
\frac{\partial}{\partial t} (C_m V_m) = Q_m C_m^* - Q_{m+1} C_{m+1}^* + (EA \frac{\partial C}{\partial x})_{m+1}
\]

\[
- (EA \frac{\partial C}{\partial x})_m + V_m S_e + V_m S_i
\]

(7)

where

- \(C_m\) is the volume average concentration of the mth reach,
- \(V_m\) is the volume of the mth reach,
- \(Q_m = U_mA_m\) is the flow rate of water through the mth transect,
- \(C_m^*\) is the concentration of the water flowing through the mth transect,
- \(E_m\) is dispersion coefficient at the mth transect.
To solve for the time varying concentration field, equation (7) is written in finite difference form

\[
\frac{C_m' - C_m}{\Delta t} = f(C_{m-1}', C_m, C_{m+1}', \ldots)
\]

where \( C_m \) and \( C_m' \) are the concentrations in the mth reach at the beginning and the end of time increment \( \Delta t \) respectively. The right hand side of equation (7) is represented by a general function, \( f \), which involves the concentrations in the adjacent reaches because of the advective and dispersive terms. Numerical computation is advanced with time over each successive time increment by calculating concentration \( C_m' \) based on the known concentrations at the beginning of the time step.

Two types of finite difference schemes are commonly used; the implicit and explicit schemes. To express the right hand side of equation (8), the explicit scheme will use only the concentrations at the beginning of time increment while the implicit scheme will use those at the end of time increment as well. By writing the finite difference equations for each of the volume elements of a river, the explicit scheme will result in a number of independent equations which may be solved individually for all \( C_m' \). The implicit scheme will result in a system of inter-dependent equations which have to be solved simultaneously for all \( C_m' \), because the equation for \( C_m' \) will involve the unknowns \( C_{m-1}' \) and \( C_{m+1}' \). Therefore, an implicit scheme is more complicated in computer programming, yet it is more stable for numerical calculation and requires less overall computer time.

For all the one-dimensional models developed under CSA program, an implicit scheme is used. The system of simultaneous
The one-dimensional non-branched models include those for the James, Rappahannock, Chickahominy, Nansemond, Pagan and Piankatank. Detail references of these models may be found in the Model Directory.

(2) One-Dimensional Branched Model

This type of model is applicable to an estuarine river with significant branching. The models include those for the York River System, Elizabeth River, Back River and Poquoson River. The structure of these models are almost the same as the non-branched models. The main river and tributary are treated independently, except at the volume element where the tributary joins the main river. Additional terms are included in the mass-balance equation for the junction reach to account for the advection and dispersion into and/or out of the tributary. This is equivalent to the sketch in the previous section, but with additional upstream transect bounding the volume element.

(3) One-Dimensional Two-Layered Model

In some estuaries, there exist significant variations of water quality from surface to bottom. A strategy to account for this situation is to divide each segment of the river into two layers. The models for the Cockrell Creek and the Great Wicomico River belong to this category.
The model essentially consists of two one-dimensional models, one for the upper layer and the other for the lower layer. The above sketch shows the vertical section of the mth segment and demonstrates the mass-balance relation between the upper and lower compartments. Equation (7) is applied to the upper layer and lower layer to form two inter-dependent one-dimensional models. Additional terms are added to the right hand side of equation to simulate the vertical advection and diffusion of mass between the two layers, i.e. for the upper layer,

$$\frac{\partial}{\partial t} \left( C_{1,m} V_{1,m} \right) = Q_{1,m} C_{1,m} - Q_{1,m+1} C_{1,m+1} + \left( E_{1} A_{1} \frac{\partial C_{1}}{\partial x} \right)_{m+1}$$

$$- \left( E_{1} A_{1} \frac{\partial C_{1}}{\partial x} \right)_{m} + 0.5 q_{m} \left( C_{1,m} + C_{2,m} \right) + EV_{m} \left( C_{2,m} - C_{1,m} \right) + V_{1,m} S_{1} + V_{2,m} S_{1}$$  \hspace{1cm} (9)

and for the lower layer,
\[
\frac{\partial}{\partial t} \left( C_{2,m} V_{2,m} \right) = Q_{2,m} C_{2,m}^* - Q_{2,m+1} C_{2,m+1}^* + \frac{\partial C_{2}}{\partial x} \bigg|_{m+1} - \frac{\partial C_{2}}{\partial x} \bigg|_{m} - 0.5 q_m (C_{1,m} + C_{2,m}) - EV_m (C_{2,m} - C_{1,m}) + V_{2,m} S_{e_2} + V_{2,m} S_{i_2}
\]

where the subscript 1 refers to the upper layer and subscript 2 refers to the lower layer; \( q_m \) is the flow rate in the vertical direction and \( EV_m \) is the vertical exchange coefficient.

In formulating the finite difference equations with respect to time, the vertical transport terms are treated explicitly, i.e., the concentrations in these terms are expressed in terms of those at the beginning of the time step. Therefore, no additional unknown is introduced into the finite difference equations. The solution technique of the one-dimensional, non-branched model may be used with little modification.

(4) Tidal Flushing Model

In equations (6) and (7), the physical transport in the longitudinal direction is simulated with advection and dispersion terms, which is applicable to both the tidal and fluvial streams. An alternative approach which is applicable only to tidal streams is to extend the concept of tidal flushing from zero-dimensional model to one-dimensional model. In fact, the tidal flushing model is most applicable to coastal creeks which have small freshwater inflow.
To construct a one-dimensional tidal flushing model, an estuary is divided into a series of volume elements with each having a length of one tidal excursion, i.e., the distance a water particle will travel over the flood tide. Complete mixing at high tide is assumed within each segment. The transport between adjacent segments is calculated from the tidal prism, i.e., the volume of water flowing through a transect over flood tide.

In this model, it is the mass transport over the entire period of flood tide, or ebb tide, that is quantified, but not the instantaneous mass transport which varies with tidal current throughout the tidal cycle. Therefore, the mass-balance equation is written as the change of mass within a segment from tidal cycle to tidal cycle. Referring to the sketch of the one-dimensional non-branched model, the equation describing the mass-balance of a substance in the mth reach is written as

$$\frac{3}{3t} (C_m V_m) = P_m C_{m-1} - P_{m+1} C_m + P_{m+1} C_{m+1}^* - P_m C_m^*$$

$$+ V_m S_e + V_m S_i$$

(11)

where

- $C_m$ is the concentration at high tide,
- $V_m$ is the high tide volume of the mth reach,
- $P_m$ is the tidal prism upstream of the mth transect,
- $C_m^* = (1-\alpha)C_m + \alpha C_{m-1}$, with $\alpha$ as the returning ratio.

The first two terms on the right hand side of the equation represent the mass transport in and out of the mth reach over
ebb tide, and the next two terms represent those over the flood tide. The time rate of change on the left hand side of equation should be interpreted as the change over one tidal cycle. Equation (11) is presented to demonstrate the formulation of transport by tidal flushing, and it is applicable to the case in which freshwater flow is negligible compared to tidal prism. In case the freshwater inflow is significant, the modification of tidal prism by freshwater inflow is required.

As with the one-dimensional non-branched model, equation (11) is written into an implicit finite difference form for each segment of the estuary, resulting in a system of simultaneous algebraic equations. The equations are solved by the technique of successive substitution.

This model is easier to develop because it requires the tidal prisms through the transects, not the time varying flow rates which fluctuate throughout the tidal cycle. However, the model predicts only the water quality condition at high tide, and gives no temporal variation within a tidal cycle. This type of model has been developed for the Little Creek and the Lynnhaven Bay systems.

3. Two-Dimensional Model

A two-dimensional vertically averaged model was developed for the lower James estuary and Hampton Roads. This water body is so wide that a one-dimensional model could not account for the significant lateral variations of water quality condition.
The model is based on the depth integrated equation of eqn. (1).

\[
\frac{\partial}{\partial t} (H C) = - \frac{\partial}{\partial x} (H U C) - \frac{\partial}{\partial y} (H V C) + \frac{\partial}{\partial x} (E_x H \frac{\partial C}{\partial x}) \\
+ \frac{\partial}{\partial y} (E_y H \frac{\partial C}{\partial y}) + H \cdot S_e + H \cdot S_i
\]

(12)

where \( C \) is the depth average concentration,

\( H \) is the depth,

\( U \) and \( V \) are depth average velocity components in the \( x \) and \( y \) directions respectively,

\( E_x \) and \( E_y \) are dispersion coefficients in the \( x \) and \( y \) directions respectively.

Because there is no way to measure the velocity at each of the two-dimensional grid points of the model, a two-dimensional water quality model has to include a hydrodynamic submodel. The submodel is based on the depth integrated equations of continuity and momentum. The equations are solved numerically for the time varying velocity components, \( U \) and \( V \), and water depth \( H \). This information is substituted into equation (12) to solve for the concentration field, \( C \), of water quality components.

The model is a real-time model simulating all water quality components of an ecosystem model, as well as the hydrodynamics of the flow field. The biochemical interaction among the water quality components will be discussed in the next section. The model uses Galerkins Weighted residual finite element numerical scheme for solution. Triangular element with linear shape function is employed. This model has been
applied to the portion of the James River from the confluence with the Chickahominy River to Old Point Comfort. This is so far the most sophisticated model developed under the CSA program, and the operation of the model requires some degree of training.

4. Three-Dimensional Model

A three-dimensional model requires the solution of the mass-balance equation, eqn. (1), in three spatial coordinates $x$, $y$ and $z$. The numerical method of solving such a partial differential equation for a domain of natural body of water requires substantial computer capacity and computation time. Furthermore, the model needs an enormous amount of field data for calibration and verification. The cost of collecting these data is often beyond the reach of practical application. Therefore, a truly three-dimensional model is still beyond the current state-of-art in water quality modeling.

However, there are cases that, because of basin geometry or spatial variation in water quality parameters, a three-dimensional description of water quality conditions are necessary. The lower York River is one of them. A quasi three-dimensional model was developed for the York River from West Point to the mouth. The model is essentially the extension of the one-dimensional two-layered model. In addition to the two-layered longitudinal segments along the channel, there are two parallel chains of two-layered segments along each side of the channel. Therefore, each longitudinal section of the river is divided
into two vertical layers and three lateral compartments. The river may be visualized as a composite of six one-dimensional bodies of water parallel to each other. The one-dimensional mass-balance equation, eqn. (6), is applied to each one of them, with additional terms accounting for the mass exchange in the vertical and lateral directions. Concentrations of water quality constituents are predicted for each segment in each layer and lateral compartment. However, to reduce the computation time, the model is formulated as a tidal average model in which all the results represent tidal average conditions.

B. Water Quality Components

The existing or anticipated water quality problem of an estuary should determine what water quality components are to be included in a model. All significant water quality parameters relating to that problem should be considered. Traditionally, dissolved oxygen content is the most important water quality parameter of a natural water body. It is not only an essential element for aquatic life but also a water quality indicator commonly used for water quality management and for the enforcement of water quality standard. Therefore, the water quality model development under the CSA program has been centering around the prediction of dissolved oxygen and relating components.

1. DO-BOD Model

In these earlier models, the kinetics of waste assimilation described by Streeter and Phelps (1925) was adopted. Oxygen demanding pollutants were treated as a single component -
biochemical oxygen demand (BOD) - and its deoxygenation rate is assumed to be proportional to the amount of BOD remaining. The source/sink and biochemical reaction terms of eqn. (1) are described as follows:

(1) Biochemical Oxygen Demand, BOD in mg/l
\[ S_e = W_b - k_s \cdot BOD \]
\[ S_i = -k_1 \cdot BOD \]
where \( W_b \) is the wasteload from point and non-point sources, \( k_s \) is the settling rate and \( k_1 \) is the oxidation rate.

(2) Dissolved Oxygen, DO in mg/l
\[ S_e = k_2 \cdot (D_O - DO) - BEN \]
\[ S_i = -k_1 \cdot BOD + Ph \]
where \( k_2 \) is the reaeration rate, \( D_O \) is the saturated oxygen content, \( BEN \) is the benthic oxygen demand and \( Ph \) is the net oxygen production by photosynthesis and respiration of phytoplankton.

(3) Salinity, S, in parts per thousand
\[ S_e = 0 \]
\[ S_i = 0 \]
Salinity is included in the model because it is one of the parameters determining the saturated oxygen content of water. Furthermore, salinity by itself is an important water quality parameter in the saline portion of estuaries.
2. DO-CBOD-NBOD Model

In order to meet 1977 water quality standards most municipal waste treatment systems have been or are being upgraded from primary to secondary treatment levels. The increased treatment level removes a large portion of carbonaceous BOD but only a small portion of the nitrogenous BOD thus altering the relationship between these two components of waste loads. To better accommodate these modifications, CSA models were refined by treating carbonaceous BOD and nitrogenous BOD separately. The model parameters were thus increased from three (DO, BOD, salinity) to four (DO, CBOD, NBOD, salinity).

(1) Carbonaceous Biochemical Oxygen Demand,

\[
\text{CBOD in mg/l} \\
\text{Se} = W_b - k_s \cdot \text{CBOD} \\
\text{Si} = - k_1 \cdot \text{CBOD}
\]

(2) Nitrogenous Biochemical Oxygen Demand,

\[
\text{NBOD in mg/l} \\
\text{Se} = W_n - k_{sn} \cdot \text{NBOD} \\
\text{Si} = - k_{ln} \cdot \text{NBOD}
\]

where \( W_n \) is the wasteload from point and non-point sources, \( k_{sn} \) is the settling rate, \( k_{ln} \) is the deoxygenation rate.

(3) Dissolved Oxygen, DO in mg/l

\[
\text{Se} = k_2 \cdot (DOS - DO) - \text{BEN} \\
\text{Si} = - k_1 \cdot \text{CBOD} - k_{ln} \cdot \text{NBOD} + \text{Ph}
\]

(4) Salinity, S in parts per thousand

\[
\text{Se} = 0 \\
\text{Si} = 0
\]
3. Phytoplankton Ecosystem Model

As the more stringent 1983 water quality requirements are implemented, the emphasis of waste treatment will shift from BOD control to nutrient control. Water quality models will need to take account of the transfer and transformation of the organic nutrients to inorganic forms and the utilization of them by plants. These are called ecosystem models. Many chemical, biological and physical processes involved in the nutrient cycle must be included, to the extent possible. An ecosystem model was developed under the CSA program. The model parameters include salinity, DO, CBOD, organic nitrogen, ammonia nitrogen, nitrite-nitrate nitrogen, organic phosphorus, inorganic phosphorus, chlorophyll 'a' as phytoplankton, and coliform bacteria. Among these components, salinity and coliform bacteria are treated as two independent systems, the others are simulated as an interacting system of eight components. The schematic diagram shows the interaction of these components. Each rectangular box represents one component being simulated by the model. The arrows between components represent the biochemical transformation of one substance to the other. The arrows with one end not attached to any component represent the external sources (or sinks) or the internal sources (or sinks) due to biochemical reactions.
The mathematical representations of the terms $Se$ and $Si$ of eqn. (1) for each component are listed as follows:

1. Phytoplankton concentration, $C$, measured as $\mu g/l$ of chlorophyll 'a'

$$Se = -k_{cs} \cdot C$$

where $k_{cs}$ is the settling rate of phytoplankton.

$$Si = (g-d-kg)C$$

where $g$ and $d$ are the growth and endogenous respiration rates of phytoplankton respectively, $kg$ is the grazing of phytoplankton by zooplankton.

2. Organic Nitrogen, $N_l$ in mg/l

$$Se = W_{nl} - k_{nll} \cdot N_l$$

where $W_{nl}$ is the wasteload from point and non-point sources and $k_{nll}$ is the settling rate.

$$Si = -k_{n12} \cdot N_l + a_n \cdot (d + 0.4 \text{ kg})C$$

where $k_{n12}$ is the hydrolysis rate of organic nitrogen to ammonia nitrogen and $a_n$ is the ratio of nitrogen to chlorophyll 'a' in mg-N/$\mu g$-C. The term $0.4 \text{ kg} \cdot C$ accounts for the fact that about 40% of organic material is secreted for each unit of phytoplankton grazed by zooplankton.

3. Ammonia Nitrogen, $N_2$ in mg/l

$$Se = W_{n2}$$

where $W_{n2}$ is the wasteload from point and non-point sources.
Si = \( k_{n12} \cdot N1 - k_{n23} \cdot N2 - a_n \cdot g \cdot C \cdot P_r \)

where \( k_{n23} \) is the \( NH_3 \) to \( NO_3 \) nitrification rate, \( P_r \) is ammonia preference by phytoplankton given by

\[
P_r = \frac{N2}{N2 + K_{mn}}
\]

\( K_{mn} \) is the Michaelis constant.

(4) Nitrite - Nitrate Nitrogen, \( N3 \) in mg/l

\( Se = w_{n3} - k_{n33} \cdot N3 \)

where \( w_{n3} \) is wasteload from point and non-point sources, \( k_{n33} \) is the nitrate escape rate.

\( Si = k_{n23} \cdot N2 - (1 - P_r) \cdot a_n \cdot g \cdot C \)

where the first term represents the nitrification of ammonia nitrogen and the second term represents the uptake by phytoplankton.

(5) Organic Phosphorus, \( P1 \) in mg/l

\( Se = w_{p1} - k_{p11} \cdot P1 \)

where \( w_{p1} \) is wasteload from point and non-point sources, \( k_{p11} \) is the settling rate.

\( Si = -k_{p12} \cdot P1 + a_p \cdot (d + 0.4 \text{ kg}) \cdot C \)

where \( k_{p12} \) is the organic \( P \) to inorganic \( P \) conversion rate, \( a_p \) is the phosphorus to chlorophyll ratio, in mg - \( P/\mu g\cdot C \).

(6) Inorganic Phosphorus, \( P2 \) in mg/l

\( Se = w_{p2} - k_{p22} \cdot P2 \)

where \( w_{p2} \) is wasteload from point and non-point sources, \( k_{p22} \) is settling rate.
\[ \text{Si} = k_{p1} \cdot P1 - a_p \cdot g \cdot C \]

where the first term represents the conversion of organic phosphorus to inorganic phosphorus, the second term represents the uptake by phytoplankton.

(7) Carbonaceous Biochemical Oxygen Demand, CBOD in mg/L

\[ \text{Se} = W_b - k_s \cdot \text{CBOD} \]

where \( W_b \) is the wasteload from point and non-point sources, \( k_s \) is the settling rate.

\[ \text{Si} = -k_1 \cdot \text{CBOD} + 2.67 \cdot a_c \cdot 0.4 \text{ kg} \cdot C \]

where \( k_1 \) is the oxidation rate of CBOD, \( a_c \) is the carbon-chlorophyll ratio.

(8) Dissolved Oxygen, DO in mg/L

\[ \text{Se} = k_2 \cdot (\text{DOS} - \text{DO}) - \text{BEN} \]

where \( k_2 \) is reaeration rate, \( \text{DOS} \) is the saturated oxygen concentration, \( \text{BEN} \) is the benthic oxygen demand.

\[ \text{Si} = -k_1 \cdot \text{CBOD} - 4.57 \cdot k_{n23} \cdot N2 + a_d \cdot g \cdot C - a_r \cdot d \cdot C \]

where the first two terms represent the oxygen demands by oxidation of CBOD and by nitrification of ammonia nitrogen, the last two terms represent the source and sink due to photosynthesis and respiration of phytoplankton, \( a_d \) (or \( a_r \)) is the amount of oxygen produced...
(or consumed) per unit chlorophyll synthesized
(or respired) in the photosynthesis (or
respiration) process.

(9) Salinity, $S$ in parts per thousand
$S_e = 0$
$S_i = 0$

(10) Coliform Bacteria, $BAC$ in MPN/100 ml
$S_e = W_{bac}$
where $W_{bac}$ is the loading from point and non-
point sources.
$S_i = -k_b \cdot BAC$
where $k_b$ is the die-off rate.

4. Salt Intrusion Model

In the saline portion of estuaries, salinity is an
important water quality parameter. Therefore, salt intrusion
models were developed for the major Virginia estuaries - the
James, York and Rappahannock. These models are tidal average
models which are more suitable to simulate the long-term
variation of salinity distribution in response to freshwater
input. In these models
$S_e = 0$
$S_i = 0$
and the advective velocity is the tidal average value which
equals to the freshwater inflow divided by cross-sectional area.
5. There are other water quality components which need to be modeled for particular water quality problems. These components include, but are not limited to, suspended sediment, heavy metal, insecticide, herbicide. The kinematics of the bio- and geo-chemical transfer and transformation of these water quality components in an ecosystem are often not clearly understood. Therefore, substantial research is often required before a practically applicable model can be developed. An example of these special models is the model of kepone transport in the James Estuary, which is currently being developed.

The following table is a brief summary of water quality components which are most commonly included in a water quality model.

C. Time Scale of the Model

Among the models mentioned in the two preceding sections, the tidal prism model and the salt intrusion model are tidal-average or 'slack tide approximation' models. The model calculates the change of water quality from tidal cycle to tidal cycle, without looking into the intra-tidal variation. In this type of model, the time step of numerical calculation is a multiple integral of tidal cycle. Therefore, the models are more suitable in simulating long-term variation of water quality. The advective velocity is the average current over tidal cycles, and the transport by time varying tidal current is simulated as dispersion or flushing.
TABLE 1
LIST OF WATER QUALITY COMPONENTS

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Symbol</th>
<th>Function</th>
<th>Critical Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved Oxygen</td>
<td>O₂</td>
<td>Oxygen needed for self-purification. Oxygen is therefore the most fundamental.</td>
<td>Water quality standards require DO above 4 ppm &amp; daily average above 5 ppm</td>
</tr>
<tr>
<td>Carbonaceous Biochemical Oxygen Demand</td>
<td>CBOD</td>
<td>Organic food for microbial population; oxygen consumed as it is metabolized. Put into the river by municipal &amp; industrial wastes; also by nonpoint sources.</td>
<td></td>
</tr>
<tr>
<td>Nitrogenous Biochemical Oxygen Demand</td>
<td>NBOD</td>
<td>Certain specialized bacteria consume ammonia &amp; produce nitrite; others produce nitrate from nitrite.</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>S</td>
<td>Salt works part way upstream from the ocean. Salt marginally affects saturation concentration of oxygen but its chief significance is for potability of water.</td>
<td>water with chlorinity 250 ppb (salinity 0.45 ppt) classified as undrinkable</td>
</tr>
<tr>
<td>Chlorophyll 'a'</td>
<td>Cl'a'</td>
<td>Critical ingredient of phytoplankton for photosynthesis. Used therefore as index of phytoplankton population. Since phytoplankton respire and die as well as photosynthesize, high phytoplankton levels lead to low oxygen levels as food supplies are exhausted or the sun does down.</td>
<td>40 µg/l of chlorophyll 'a' is considered the onset of nuisance conditions.</td>
</tr>
<tr>
<td>Constituent</td>
<td>Symbol</td>
<td>Function</td>
<td>Critical Levels</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>Z</td>
<td>Zooplankton feed on phytoplankton and form the basis of the food chain for higher animals. Modeled only in scientific studies, not in engineering applications.</td>
<td></td>
</tr>
<tr>
<td>Organic Nitrogen</td>
<td>N&lt;sub&gt;org&lt;/sub&gt;</td>
<td>Complex organic compounds such as amino acids; released from dead cells and feces. Decompose to ammonia.</td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Decay product of organic nitrogen compounds. Exerts oxygen demand as it is metabolized. Can also be taken up by phytoplankton as nutrient.</td>
<td></td>
</tr>
<tr>
<td>Nitrite</td>
<td>NO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Metabolically transformed from ammonia. Can be transformed to nitrate or taken up directly by phytoplankton.</td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>NO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Final nitrogen compound on reaction chain. Utilized as nutrient by phytoplankton. Often nitrate and nitrite are lumped together owing to rapid rate of transformation from nitrite to nitrate.</td>
<td></td>
</tr>
<tr>
<td>Organic Phosphorus</td>
<td>P&lt;sub&gt;org&lt;/sub&gt;</td>
<td>Complex phosphorus compounds released from dead cells and/or feces. Decay to simple phosphates.</td>
<td></td>
</tr>
<tr>
<td>Soluble Reactive Phosphorus</td>
<td>SRP</td>
<td>Dissociated phosphorus radicals and simple phosphates. Taken up by phytoplankton.</td>
<td></td>
</tr>
<tr>
<td>Constituent</td>
<td>Symbol</td>
<td>Function</td>
<td>Critical Levels</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Coliform Bacteria           | BAC    | Although not pathogenic themselves, these bacteria indicate possible contamination by pathogenic organisms. Tests for coliform bacteria are more simple and reliable than specific tests for pathogens. Fecal coliform constitute a subset of coliform. Fecal coliform are those that have actually originated in a digestive track and so are considered a more reliable indicator than coliforms as a whole. | For secondary contact recreation (e.g. fishing): 1000 MPN (most probable number) of fecal coliform per 100 ml.  
For primary contact recreation (e.g. swimming): 200 MPN of fecal coliform/100 ml.  
For shellfish growing: 14 MPN fecal coliform/100 ml |
| Suspended Sediment          | SS     | Creates problems if present in excess amounts in water supplies; will flocculate under certain conditions to cause filling of channels. |                                                                                                       |
| Heavy Metals & Chlorinated Hydrocarbons | Cu,Zn,Cd, Kepone, etc. | Present in water column and adsorbed on sediments; capable of bioconcentration in shellfish. |                                                                                                       |
The Do-BOD model and ecosystem model are real-time (or tidal-time) models. The time step of numerical calculation is much smaller than a tidal cycle, and thus, the intra-tidal variation of water quality may be calculated. The time varying tidal current is simulated in the advective transport term of the equation. This type of model is more suitable for simulating a system which will reach equilibrium state in a month or sooner.

D. Kinematics vs. Dynamics

In a real-time model, the tidal current is modeled as advective velocity which is a function of space and time. The velocity field may be calculated with a hydrodynamic sub-model which solves the equations of motion and continuity. The results of the dynamic tidal calculation are fed into the water quality model. This approach requires substantial efforts in the development, calibration and verification of the hydrodynamic sub-model. However, there are cases for which this approach is necessary. They include two- and three-dimensional models, and one-dimensional model applied to the high freshwater inflow condition. The model of the lower James estuary and Hampton Roads developed under the CSA program adopted this approach of dynamic tidal calculation.

For most of the one-dimensional water quality models developed under the CSA program, the approach of kinematic tide was used. The models were designed for use in low freshwater
inflow condition under which the tidal current is rather insensitive to the change of freshwater flow. The cross-sectional average tidal current may be calculated through field measurement coupled with one-dimensional continuity condition, and modeled as a periodic function of time with phase varying with space. The following equation is used to calculate the advective velocity in the water quality model:

\[ u(x,t) = u_t(x)\sin\left(\frac{2\pi}{T} t + \phi(x)\right) + u_f(x) \]

where \( u_t \) is the amplitude of tidal current, \( T \) is tidal period, \( \phi \) is phase and \( u_f \) is freshwater flow. \( u_t \) and \( \phi \) are obtained from field measurements and continuity condition. \( u_f \) is calculated by

\[ u_f(x) = \frac{Q(x)}{A(x)} \]

where \( Q \) is the freshwater inflow from the drainage area upstream of the transect at distance \( x \) and \( A \) is the cross-sectional area. Since the tidal rivers are ungauged, freshwater inflow is estimated from the gauging station upstream of fall line by linear extrapolation with drainage area.
IV. MODEL FORMULATION, CALIBRATION AND VERIFICATION

It is necessary to choose an appropriate model for a given study from the menu of available models. This choice depends on the characteristics of water body and the external demands of water control management. Once a model is chosen, data must be collected and analyzed. From these data, the model is first constructed, then calibrated and verified.

A. Data Requirements

There are some data needs common to all models; others are specific to a particular model. Concerning particular requirements, there should be adequate sampling of each constituent (and loadings thereof) to enable calibration and verification. The data requirements common to all models are:

(1) Basin geometry
(2) Water temperature
(3) Tidal velocity and tidal height
(4) Fresh water inflow
(5) Salinity

(1) Basin geometry. The geometric data defining the boundary of a water body are necessary for any model. To obtain the data, bottom profiles along predetermined transects must be taken. The transects are usually taken perpendicular to the estuary axis, if such an axis may be defined (e.g. one-dimensional model). The spacing between these transects should be no greater than half a tidal excursion, and only half as much in the vicinity of a significant point source. Bottom profile measurements are taken with a fathometer connected to a strip-chart recorder, both on a vessel travelling along the
transect. In using these data, care must be taken to correct the depth from water level at time of measurement to mean tide level.

(2) Water temperature. All biochemical processes are temperature-dependent. Temperature is therefore listed here as a general requirement for all models. Temperature has a wide seasonal variability (0°C to 32°C), but varies spatially by only 2°C to 4°C at any given time. On a diurnal basis, water temperature is quite stable. Therefore it is important to determine temperature on the same day as calibration or verification data are collected, but high spatial sampling density is not greatly important, except perhaps near a heated effluent.

(3) Tidal velocity and tidal height. The tidal current affects tidal mixing and atmospheric reaeration. Thus it must be known even for tidal-average or tidal-prism models. The ideal way to determine tidal current is by placing arrays of current meters in selected transects (for one-dimensional model) or strings of meters at selected locations (for two-dimensional model) to measure current velocity as function of time, and thus deduce a tidal velocity curve. The data measured at different points may be averaged to arrive at the cross-sectional average or depth average current depending on needs of the model. However, where this procedure is not warranted owing to time or money constraints, tidal current for one-dimensional model can be computed adequately from the tidal
range as measured or as listed in the NOS publication *Tide Tables*, using the tidal prism concept.

(4) Fresh water inflow. Larger drainage basins usually have one or more flow gauges in their fluvial portions. Using these records and assuming hydrologic homogeneity (i.e. equal runoff for equal drainage area) one can compute the fresh water inflow into the upstream boundary of the model. This inflow is normally time-averaged over two weeks to a month preceding the simulation period. Model results are not very sensitive to the averaging period. For ungauged systems, runoff records from nearby gauged streams are used to calculate fresh water inflow.

(5) Salinity. The distribution of salinity in an estuary is an index of the mixing taking place. In fact, calibration begins with an attempt to reproduce the salinity distribution. Salinity should be sampled along with the specific water quality components.

Data for specific water quality components must meet the requirements for calibration and verification. To say that a model is calibrated means that one set of observed data has been adequately reproduced by the model. The second step, verification, improves a model greatly, and is generally considered necessary before a model can be accepted for application. The reason that verification is so important is that all models are over-determined in the sense that there are so many (unmeasured) parameters to be adjusted. While one set of parameters
might reproduce the calibration data, others sets of parameters may be that would also serve to calibrate the model. The verification step eliminates or greatly reduces this non-uniqueness and greatly improves the utility of the model.

B. Survey Methods

Calibration data are normally collected in an intensive survey. This survey is designed to sample cross-sectionally, vertically and temporally as well as longitudinally. Hence the suitability of the one-dimension or two-layer approximation can be demonstrated from the data and the model can be checked for diurnal variation as well as time average. In an intensive survey, small vessels are deployed simultaneously. Each occupies several stations on one or two transects. Samples are taken at several depths from these vessels on an hourly or bi-hourly basis. Most stations are occupied for daylight hours only for two days, but some stations are occupied for thirty-seven hours continuously. Measurements are made of salinity, temperature and the specific water quality components which are to be modeled. Sometimes a component can be modeled without actually being measured. This is done if and when the component is known not to affect other components significantly, and is done to avoid the complication of re-encoding the model to eliminate the irrelevant component. Meanwhile current meters and tide gauges are operating at the selected stations, collecting the necessary tidal current and tidal height data.
For verification, another set of intensive survey data collected at different hydrographical and/or water quality conditions from those of calibration data would be ideal. However, in view of the large manpower and expenditure requirements for an intensive survey, a slack water survey data is often used and considered as an adequate alternative. A slack water survey is conducted at stations located several miles apart (depending on size of the river) along the main channel of the river. Water temperatures are measured and samples for salinity, dissolved oxygen, and other water quality components are collected at several depths at each station. Each survey starts at slack water (slack before flood tide or slack before ebb tide) at the downstream station and progresses upstream at a rate equal to the upstream progression of the slack water phase of the tide. Thus each station is sampled at the same tidal current condition (slack water or no current), hence the same slack survey.

In the freshwater portion of a tidal river, there is no salinity distribution to serve the purpose of calibrating the dispersion coefficient of a model. A dye study is often conducted as a substitute. Dye is dumped into the river as an instantaneous batch release at the upstream location shortly before an intensive survey begins. In addition to the samples collected at the intensive survey stations, the longitudinal dye distributions are also measured along river axis at the same slack tides. This same slack survey of dye distributions are conducted every couple of tidal cycles until most of the dye is flushed out of the study area.
C. Model Parameters

The simulation of a natural phenomenon with a mathematical relationship is, to some degree, a kind of approximation with various assumptions. Model calibration requires a modeler to have sound knowledge of the mathematical relationship and the underlying assumptions. The adjustment of the numerous model constants to reproduce calibration data is a tedious process. However, there is range of value or semi-empirical formula for each particular model constant which may be used as a guide in calibration process. The following are those used for the calibration of the CSA model:

(1) Reaeration coefficient, $k_2$

There are numerous empirical or semi-empirical formulas expressing reaeration rate in terms of stream characteristics. A review of these formulas was given by Rathbun (1977). O'Conner-Dobbins' (1956) formula was adopted for the CSA water quality models with satisfactory result. The formula may be written as:

$$(k_2)_{20} = \frac{12.9 \ u^{0.5}}{h^{1.5}}$$

where the velocity $u$ is in the unit of feet per second, depth $h$ is in feet and the reaeration rate at $20^\circ C$, $(k_2)_{20}$, is in 1/day.
To adjust \( k_2 \) for temperature other than 20\(^\circ\)C, Elmore and West's (1961) formula was used

\[
k_2 = (k_2)_{20} \cdot 1.024^{T-20}
\]

where \( T \) is the water temperature in centigrade degrees.

(2) CBOD oxidation rate, \( k_1 \)

The oxidation rate of CBOD (carbonaceous biochemical oxygen demand) normally ranges from 0.1 to 0.6 per day. The rate also depends on water temperature; the following formula is used for this temperature dependence.

\[
k_1 = (k_1)_{20} \cdot A^{(T-20)}
\]

The value of \((k_1)_{20}\) is obtained by model calibration and \( A \) is usually assigned a value of 1.047.

(3) CBOD settling rate, \( k_s \)

The net settling rate \( k_s \) is usually assumed to be negligible unless evidence shows the contrary.

(4) NBOD oxidation rate, \( k_{1n} \)

The oxidation rate of NBOD (nitrogenous oxygen demand) normally ranges from 0.05 to 0.3 per day. The following formula is used for temperature dependence.

\[
k_{1n} = (k_{1n})_{20} \cdot A^{(T-20)}
\]

where \( A \) is usually assigned a value of 1.017.
(5) NBOD settling rate, $k_{sn}$

$k_{sn}$ is obtained through model calibration.

(6) Saturated oxygen content, $DO_s$

The saturation concentration of dissolved oxygen depends on temperature and salinity. From tables of saturation concentration (Carritt and Green, 1967) a polynomial equation was determined by a least-squares method.

$$DO_s = 14.6244 - 0.367134T + 0.0044972T^2$$

$$- 0.0966S + 0.00205TS + 0.0002739S^2$$

where $S$ is salinity in parts per thousand and $DO_s$ is in mg/liter.

(7) Benthic oxygen demand, $BEN$

The bottom sediment of an estuary may vary from deep deposits of sewage or industrial waste origin to relatively shallow deposits of natural material of plant origin and finally to clean rock and sand. The oxygen consumption rate of the bottom deposits must be determined with field measurement. Field data were used wherever they are available. A value of 1.0 gm/m²/day at $20^\circ$C is typical average for most estuaries. The temperature effect was simulated by Thomann (1972),

$$BEN = (BEN)_{20} \cdot 1.065(T-20)$$

where $(BEN)_{20}$ is the benthic demand at $20^\circ$C.
(8) Coliform bacteria dieoff rate, \( k_b \)

\[ k_b = (k_b)_{20} \cdot 1.040(T-20) \]

where \((k_b)_{20}\) is the dieoff rate at 20°C. The normal range of \((k_b)_{20}\) is 0.5-4.0/day.

(9) Settling rate of organic nitrogen, \( k_{n11} \)

\( k_{n11} \) is of order of 0.1/day.

(10) Organic N to NH\(_3\) hydrolysis rate, \( k_{n12} \)

\[ k_{n12} = aT \]

where \( a \) is of order of 0.007/day/degree

(11) NH\(_3\) to NO\(_3\) nitrification rate, \( k_{n23} \)

\[ k_{n23} = aT \]

where \( a \) is of order of 0.01/day/degree

(12) NO\(_3\) escaping rate, \( k_{n33} \)

\( k_{n33} \) is usually negligible.

(13) Organic phosphorus settling rate, \( k_{p11} \)

\( k_{p11} \) is of order of 0.1/day.

(14) Organic P to inorganic P conversion rate, \( k_{p12} \)

\[ k_{p12} = aT \]

where \( a \) is of order of 0.007/day/degree

(15) Inorganic phosphorus settling rate, \( k_{p22} \)

\( k_{p22} \) is of order of 0.1/day.

(16) Nitrogen-chlorophyll ratio, \( a_n \)

\( a_n \) is of order of 0.01 mg N/µg C

(17) Phosphorus-chlorophyll ratio, \( a_p \)

\( a_p \) is of order of 0.001 mg P/µg C
(18) Carbon-chlorophyll ratio, $a_c$

$$a_c \text{ is of order of } 0.05 \text{ mg carbon/µg C}$$

(19) Oxygen produced per unit of chlorophyll growth, $a_d$

$$a_d = 2.67 \cdot a_c \cdot PQ$$

where PQ is photosynthesis quotient, PQ = 1-1.4.

(20) Oxygen consumed per unit of chlorophyll respired, $a_r$

$$a_r = 2.67 \cdot a_c / RQ$$

where RQ is respiration ratio, RQ = 1.0

(21) Phytoplankton settling rate, $k_{cs}$

$$k_{cs} = S_\ell / h$$

where $S_\ell$ is settling velocity, whose normal range is 15 to 150 cm/day (0.5 to 5 ft/day), h is water depth.

(22) Zooplankton grazing, kg

In reality, kg should depend solely on the concentration of herbivorous zooplankton biomass. However, the settling rate has been assumed to be zero and its effect has been included in the grazing rate. kg was determined by model calibration.

(23) Endogenous respiration rate, $R_s$

$$R_s = aT$$

where $a$ is of order of 0.005/day/degree.

(24) Growth rate, $G_C$

The growth rate expression is that developed by Di-Toro, O'Connor and Thomann (1971) and as used in this model is given by
\[ G_c = k_{gr} T \cdot I (I_a, I_s, k_e, C, h) \cdot N (N2, N3, P2) \]

where \( k_{gr} \) is the optimum growth rate of the order 0.1/day/degree. The functional form, \( I \), for the light effect incorporates vertical extinction of solar radiation and self-shading effect. The form is

\[ I = \frac{2.718}{k_e h} \left( e^{-\alpha_1} - e^{-\alpha_0} \right) \]

\[ k_e = k_e' + 0.0088 \cdot C + 0.054 \cdot C^{0.66} \]

\[ \alpha_1 = \frac{I_a}{I_s} \exp(-k_e \cdot h) \]

\[ \alpha_0 = \frac{I_a}{I_s} \]

where \( k_e' \) is the light extinction coefficient at zero chlorophyll concentration, \( k_e \) is the overall light extinction coefficient, \( I_a \) is the incoming solar radiation and \( I_s \) is the optimum light intensity, about 300 langleys per day. The nutrient effect makes use of product Michaelis - Menton kinetics and is given by

\[ N = \frac{N2 + N3}{K_{mn} + N2 + N3} \cdot \frac{P2}{K_{mp} + P2} \]

where \( K_{mn} \) is the half saturation concentration for total inorganic nitrogen and \( K_{mp} \) is the half saturation concentration for phosphorus. \( K_{mn} \) and \( K_{mp} \) have been reported to be about 0.2-0.4 and 0.03 - 0.05 mg/l respectively, although \( K_{mn} \) has been reported as low as 0.008 mg/l and \( K_{mp} \) has been reported as low as 0.005 mg/l.
V. DIRECTORY OF WATER QUALITY MODELS FOR VIRGINIA ESTUARIES

This section presents a directory of water quality models developed for Virginia estuaries, including those for the Potomac River and Chesapeake Bay. Table 2 is a brief index arranged in alphabetical order of the estuaries. The main directory contains detail descriptions of each model in light of the discussions in previous sections.
<table>
<thead>
<tr>
<th>Estuary</th>
<th>Institution</th>
<th>Type of Model</th>
<th>Page</th>
<th>(Ref. No.)</th>
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</table>
Estuary: Back River

Area Covered by Model: Mouth to navigation limit

Time Scale: Tidal

Dimensions: Branched one-dimensional

Hydrodynamics: Kinematic tide

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus

References: VIMS SRAMSOE 144, June, 1977

Calibration: Intensive survey data, July, 1975

Verification: Slack water run data, Sept. 1975

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230 or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Virginia 23062

Estuary: Chesapeake Bay

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: Two-dimensional, longitudinal & vertical

Hydrodynamics: Tidal hydrodynamics & wind stress

Water Quality Components: Salinity


Calibration: Incomplete

Verification: None

Contact: Chesapeake Bay Institute, Baltimore, Md.

Comments: Chesapeake Bay & Potomac were treated as a combined system. Primary purpose of study was to assess effects of wind stress on haline structure. Vertical exchange coefficients were formulated in relation to Richardson's number.
**Estuary**: Chesapeake Bay

**Area Covered by Model**: Mouth to fall line

**Time Scale**: Tidal

**Dimensions**: Two-dimensional horizontal

**Hydrodynamics**: Dynamic tidal calculations plus density-driven circulation, coriolis force & wind stress

**Water Quality Components**: None


**Calibration**: Calibrated against tidal phase & amplitude published in tide tables.

**Verification**: None

**Contact**: Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Md.

**Comments**: Basic research in numerical modeling of estuaries.
Estuary: Chesapeake Bay

Area Covered by Model: Bay mouth to fall line

Time Scale: Tidal

Dimensions: Three-dimensional

Hydrodynamics: Tidal hydraulics with coriolis force & bottom friction, driven by tidal forcing and wind stress

Water Quality Components: Salinity & temperature


Calibration: None

Verification: None

Contact: Rand, Santa Monica, Cal. 90406

Comments: Model application to the Chesapeake Bay was basically a demonstration of capabilities of Leendertse 3-D model. Report contains predictions of tidal current and salinity, but no comparison with observation.
Estuary: Chesapeake Bay

Area Covered by Model: Mouth to Havre de Grace

Time Scale: Tidal

Dimensions: Three-dimensional

Hydrodynamics: Dynamic equations, including wind stress, barometric effects, Coriolis force, density-driven circulation, salinity effect on density

Water Quality Components: Salinity (other components possible)


Calibration: Salinity observations (source or time of collection not given)

Verification: None

Contact: Department of Meteorology, University of Maryland, College Park, Md.

Comments: Capable of generating hydrodynamic input for water quality models. Also a research tool for experimenting with formulations of subgrid-scale processes.
Estuary: Chesapeake Bay

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: Dissolved oxygen, salinity, CBOD, NBOD, Total N, Total P


Calibration: CBI slack water run data, 1968

Verification: CBI slack water run data, 1969

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Virginia 23062

Comments: Calibrated and verified for salinity only. Not suitable for other water quality components without further calibration.
Estuary: Chickahominy

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, NBOD

References: VIMS SRAMSOE 141, March, 1977

Calibration: Intensive survey data, June, 1975

Verification: None

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Virginia 23230, Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, VA 23062

Comments: Intended for engineering application. Capable of assessing point source impacts, although not employed to date. Calibrated with dye data as well as water quality data.
Estuary: Cockrell Creek

Area Covered by Model: Mouth to fall line

Time Scale: Tidal average

Dimensions: Branched one-dimensional

Hydrodynamics: Tidal prism

Water Quality Components: Fecal coliform, salinity


Calibration: Calibrated for salinity only

Verification: None

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt, Va. 23062

Comments: Applied to problem of fecal coliforms from proposed STP. Incapable of modeling multiple components.
Estuary: Cockrell Creek

Area Covered by Model: Navigation limit to mouth

Time Scale: Tidal

Dimensions: Two-layer, one-dimensional

Hydrodynamics: Kinematic tide plus gravitational circulation

Water Quality Components: DO, CBOD, NBOD, salinity

References: VIMS SRAMSOE 120, Sept., 1976

Calibration: Intensive survey data, July, 1974

Verification: Slack water run data, June, 1975

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Virginia 23230, Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt., VA 23062

Comments: Model intended for engineering study of point discharges. Used for assessing impact of industrial discharges into Cockrell Creek.
Estuary: Elizabeth River

Area Covered by Model: Mouth to navigation limits or intra-coastal waterway

Time Scale: Tidal time

Dimensions: Branched, one dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus


Calibration: Intensive survey, July 1976 data

Verification: Slack water runs Aug. 1976 data

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, VA 23230; Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, VA 23062

Estuary: Great Wicomico River

Area Covered by Model: Navigation limit to mouth

Time Scale: Tidal

Dimensions: Two-layer, one-dimensional

Hydrodynamics: Kinematic tide plus gravitational circulation

Water Quality Components: DO, CBOD, NBOD, salinity

References: VIMS SRAMSOE 120, Sept., 1976

Calibration: Intensive survey data, July, 1974

Verification: Slack water run data, June, 1975

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, VA 23230; Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, VA 23062

Comments: Model suitable for engineering study of point discharges, although not actually applied to date.
Estuary: James River

Area Covered by Model: Fall line to confluence with the Chickahominy River

Time Scale: Tidal average

Dimensions: One-dimensional

Hydrodynamics: Mean flow plus dispersion to simulate tidal mixing

Water Quality Components: DO, CBOD, NBOD

References: No document published to date

Calibration: None

Verification: None

Contact: Engineering Science, Inc.

**Estuary:** James River

**Area Covered by Model:** Fall line to the confluence with the Chickahominy River

**Time Scale:** Tidal time

**Dimensions:** One-dimensional

**Hydrodynamics:** Dynamic calculation of current and tidal height

**Water Quality Components:** DO, CBOD, NBOD

**References:** None

**Calibration:** None

**Verification:** None

**Contact:** GKY Associates

**Comments:** Receive II model. No official publication of model to date; intend to be applied to Richmond area 208 study.
Estuary: James River

Area Covered by Model: Mouth to fall line (at Richmond)

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, BOD, salinity

References: VIMS SRAMSOE 41, Sept., 1973

Calibration: Intensive survey data, July, 1971

Verification: None

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, VA 23230 or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, VA 23062

Comments: Model intended for engineering application. All BOD lumped together in a single model parameter. This model will be superseded for Richmond-Hopewell reach by CBOD-NBOD model now in progress.
Estuary: James River

Area Covered by Model: Mouth to fall line (at Richmond)

Time Scale: Tidal average

Dimensions: One-dimensional

Hydrodynamics: Mean flow plus dispersion

Water Quality Components: Salinity

References: VIMS SRAMSOE 41, Sept., 1973

Calibration: Slack water run data, Sept., 1971

Verification: April - Nov. 1963 data

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt., Va. 23062

Comments: Long-term salinity intrusion model. Suitable for engineering studies of salinity intrusion in response to dry periods or water impoundments.
Estuary: James River

Area Covered by Model: James River Bridge to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Dynamic calculation of currents & tidal height

Water Quality Components: Salinity


Calibration: Tide & current observations & salinity data, June, 1971

Verification: None

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt., VA 23062

Comments: Model written for Master's thesis: academic in orientation. Model used to simulate flood wave from Hurricane Agnes as case study. Model capable of generating hydraulic input to water quality model.
Estuary: James River

Area Covered by Model: Mouth up to Chickahominy mouth

Time Scale: Tidal

Dimensions: Two horizontal dimensions

Hydrodynamics: Dynamic calculation of current & tidal height using finite element method


References: Chen, H. S., 1978 "Hydrodynamic & biogeochemical water quality models of Hampton Roads", VIMS SRAMSOE No. 147

Calibration: Intensive survey, summer, 1976

Verification: Slack water runs, summer, 1976

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt., Va. 23062

Comments: Phytoplankton ecosystem model, intended for engineering study of point and nonpoint sources. Hydrodynamic sub-model runs independently to produce hydraulic inputs to water quality model. Model used for Hampton Roads area 208 study.
Estuary: James River

Area Covered by Model: Fall line to the confluence with the Chickahominy River

Time Scale: Tidal time

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, NBOD

References: Report in preparation by VIMS

Calibration: Intensive survey data, July 1976

Verification: Intensive survey data, Aug., 1975
Slack water run data, July, 1977

Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062; or Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230

Comments: Model intended for engineering application
Estuary: James River

Area Covered by Model: Fall line to the confluence with the Chickahominy River

Time Scale: Tidal time

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus, coliform

References: Report in preparation by VIMS

Calibration: Intensive survey data, July 1976


Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062; or Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230

Comments: Model intended for engineering application
Estuary: James River

Area Covered by Model: Richmond to 60 mi. downstream limit of freshwater regime

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow. Variation of cross-section area tidal cycle is included in model

Water Quality Components: Organic carbon, inorganic carbon, organic nitrogen, ammonia, nitrate plus nitrite, phosphorus, oxygen deficit, algae, protozoa, zooplankton, higher predator & bacteria

References: Bard, H. & R. G. Krutchkoff, 1974 "Predicting Pollution in the James River Estuary - a stochastic model" Bulletin No. 70, Virginia Water Resources Research Center, VPI

Calibration: None

Verification: None

Contact: Virginia Water Resources Research Center, VPI&SU, Blacksburg, Va.

Comments: Spatial limits chosen to stay within vertically homogeneous regime; hence fresh-water regime only extensive sensitivity study. Identification made of the most useful indicators of water quality. No calibration.
Estuary: Little Creek

Area Covered by Model: Mouth to navigation limit

Time Scale: Tidal average

Dimensions: Branched one-dimensional

Hydrodynamics: Tidal prism model

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus

References: VIMS SRAMSOE 145, June 1977

Calibration: Intensive survey data, Sept. 1975

Verification: Slack water data, 1976

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Estuary: Lynnhaven Bay

Area Covered by Model: Mouth to navigation limit

Time Scale: Tidal average

Dimensions: Branched one-dimensional

Hydrodynamics: Tidal prism model

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus

References: VIMS SRAMSOE 145, June 1977

Calibration: Intensive survey data, Sept. 1977

Verification: Slack water data, 1976

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Estuary: Nansemond River

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, NBOD, salinity

References: VIMS SRAMSOE 133, Dec., 1977

Calibration: Intensive survey data, Aug., 1974

Verification: Slack water run data, Aug., 1976

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Estuary: Pagan River

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, NBOD, Salinity

References: VIMS SRAMSOE 107, Jan., 1976

Calibration: Intensive survey data, Aug., 1974

Verification: Slack water run data, July, 1975

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Comments: Employed by Water Control Board for assessing impact of point discharges
Estuary: Pagan River

Area Covered by Model: Mouth to fall line

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrite plus nitrate N, organic phosphorus, soluble reactive phosphorus

References: VIMS SRAMSOE 148, October, 1977

Calibration: Intensive survey, July 1976 data

Verification: Slack water runs, Aug. 1976 data

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230 or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

**Estuary:** Piankatank River

**Area Covered by Model:** Mouth to 16 miles upstream

**Time Scale:** Tidal

**Dimensions:** One-dimensional

**Hydrodynamics:** Kinematic tide plus mean flow

**Water Quality Components:** DO, CBOD, NBOD, salinity

**References:** VIMS SRAMSOE 124, Jan., 1977

**Calibration:** Intensive survey data, July, 1975

**Verification:** None

**Contact:** Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Virginia 23230 or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Pt., Va. 23062

**Comments:** Calibrated with dye dispersion data as well as water quality data. Intended for engineering application. Capable of assessing point source impacts, although not employed to date.
Estuary: Poquoson River

Area Covered by Model: Mouth to navigation limit

Time Scale: Tidal

Dimensions: Branched one-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: Salinity, coliform, DO, CBOD, chlorophyll, organic N, ammonia N, nitrate plus nitrite N, organic phosphorus, soluble reactive phosphorus

References: VIMS SRAMSOE 144, June 1977

Calibration: Intensive survey data, July 1975

Verification: Slack water run data, Aug. 1975

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Virginia 23062, or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Estuary: Rappahannock River

Area Covered by Model: Tappahannock to fall line at Fredericksburg

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, BOD, salinity

References: VIMS SRAMSOE 25, June 1972

Calibration: Intensive survey data, July, 1970

Verification: None

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Comments: Model intended for engineering application. Model later extended to include entire Rappahannock (Ref. SRAMSOE 102).
Estuary: Rappahannock River

Area Covered by Model: Mouth to fall line at Fredericksburg

Time Scale: Tidal

Dimensions: One-dimensional

Hydrodynamics: Kinematic tide plus mean flow

Water Quality Components: DO, CBOD, NBOD, salinity

References: VIMS SRAMSOE 102, Aug., 1975

Calibration: Intensive survey data, July, 1973

Verification: None

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Va. 23230; or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Va. 23062

Comments: Employed by SWCB for assessing impact of point discharges.
Estuary: Rappahannock River

Area Covered by Model: Mouth to fall line (at Fredericksburg)

Time Scale: Tidal average

Dimensions: One-dimensional

Hydrodynamics: Meanflow plus dispersion

Water Quality Components: Salinity

References: VIMS, SRAMSOE 102, August, 1975

Calibration: Intensive survey data, July, 1973


Contact: Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Virginia, 23062

Comments: Long-term salinity intrusion model, intended for engineering study of dry periods or water impoundments.
Estuary: York River

**Area Covered by Model:** Mouth of York to fresh water region of Mattaponi and Pamunkey

**Time Scale:** Tidal

**Dimensions:** Branched one-dimensional

**Hydrodynamics:** Kinematic tide plus mean flow

**Water Quality Components:** DO, BOD, Salinity

**References:** VIMS, SRAMSOE 104, October, 1975

**Calibration:** Intensive survey data, August, 1973

**Verification:** Slack water run data, October, 1970

**Contact:** Bureau of Water Control Management, State Water Control Board, P. O. Box 11143, Richmond, Virginia, 23230, or Virginia Institute of Marine Science, Gloucester Point, Virginia, 23062

**Comments:** Employed by consultant to SWCB for assessing impact of point discharges. Calibrated with dye dispersion data as well as water quality data.
**Estuary:** York River

**Area Covered by Model:** Mouth of York to fresh water region of Mattaponi and Pamunkey

**Time Scale:** Tidal average

**Dimensions:** Branched one-dimensional

**Hydrodynamics:** Mean flow plus dispersion

**Water Quality Components:** Salinity


**Calibration:** Slack water run data, September - November, 1970

**Verification:** Slack water run data, April - May, 1971

**Contact:** Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Virginia, 23062

**Comments:** Long-term salinity intrusion model intended for engineering studies of dry periods or water impoundments. Coastal Engineering Conference report concerns earlier version of model extending to four miles downstream of West Point.
Estuary: York

Area Covered by Model: Mouth to 48 km upstream

Time Scale: Daily radiation cycle

Dimensions: Two layer, three lateral segments

Hydrodynamics: Meanflow including gravitational circulation

Water Quality Components: Salinity, Coliform, DO, CBOD, Chlorophyll, Organic N, Ammonia N, Nitrite plus Nitrate N, Organic Phosphorus, Soluble Reactive Phosphorus

References: VIMS, SRAMSOE 146, November, 1977

Calibration: Intensive survey data, June-July, 1976

Verification: Slack water run data, September, 1976

Contact: Bureau of Water Control Management, State Water Control Board, P. O. Box 1143, Richmond, Virginia, 23230, or Department of Physical Oceanography & Hydraulics, Virginia Institute of Marine Science, Gloucester Point, Virginia, 23062

REFERENCES


