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A Layman's Guide to Models of the Tidal Waters of Virginia

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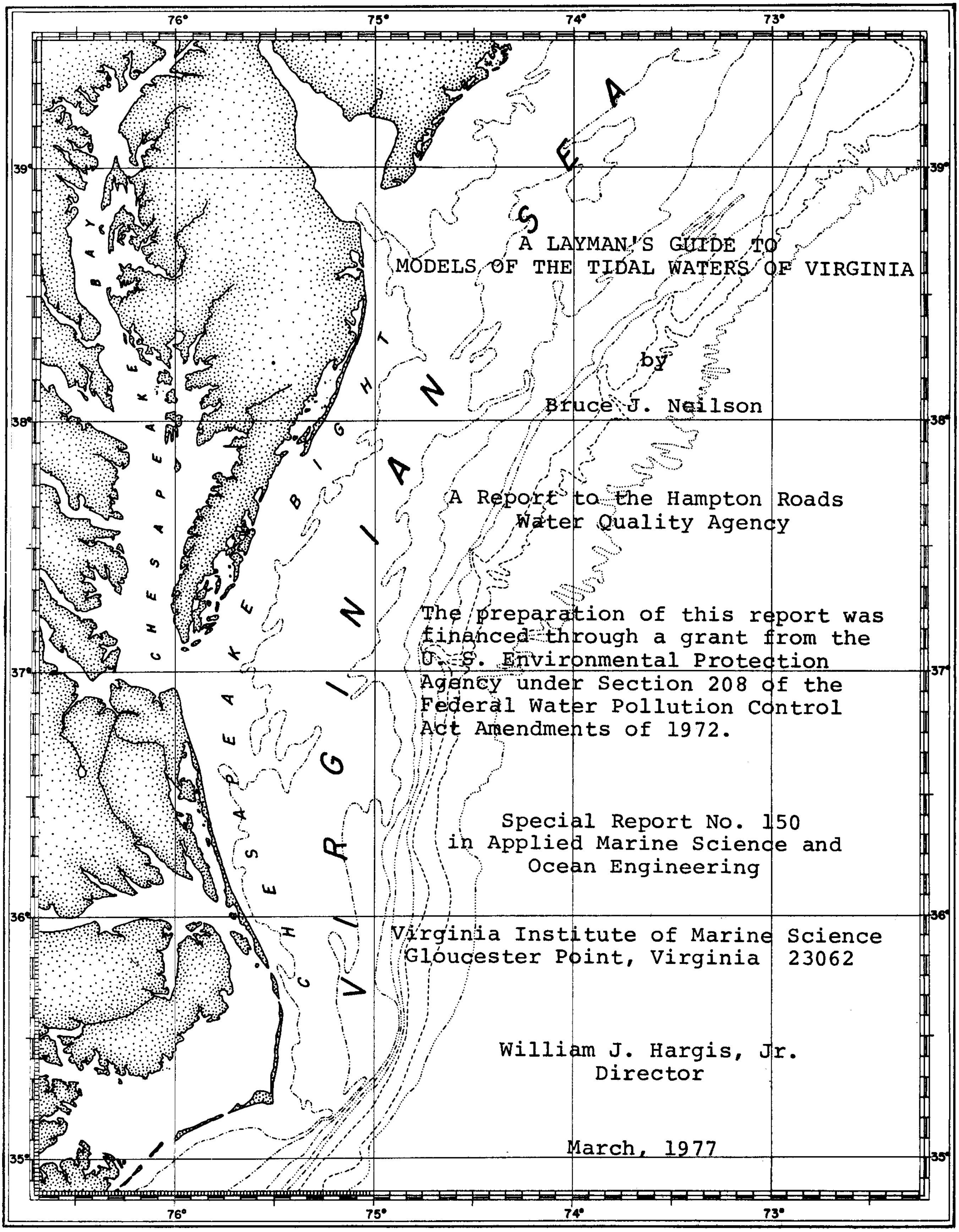

A LAYMAN'S GUIDE TO MODELS OF THE TIDAL WATERS OF VIRGINIA

by

Bruce J. Neilson

A Report to the Hampton Roads
Water Quality Agency

The preparation of this report was financed through a grant from the U. S. Environmental Protection Agency under Section 208 of the Federal Water Pollution Control Act Amendments of 1972.

Special Report No. 150
in Applied Marine Science and
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Gloucester Point, Virginia 23062

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INTRODUCTION

In recent years, modelling studies have become a common component of engineering projects, especially environmental assessment and impact studies. Although there are many kinds of models which perform a myriad of tasks, the type of model, its capabilities, and often more importantly its limitations, are left unstated during typical modelling discussions. This report is an attempt to list the major types of models and, insofar as possible, explain them in a straightforward fashion. In so doing, it is hoped that some of the mystery and mystique of models can be dissipated. This report is intended for persons having little familiarity with mathematics, but a modest understanding of the physical, chemical and biological processes which occur in the estuaries and tidal rivers of the Chesapeake Bay system.

What is a Model?

A model can be many different things - a mannequin, a pattern, an imitation, an analogy or a mathematical description, to list a few. Most of these definitions, however, are not appropriate for biological and a physical systems such as exist in an estuary. A general definition for the kinds of models we will be discussing is simply "an accounting system for events which take place". There is very little difference between these models and the way we keep track of our checking account. Drawing from this analogy, the paragraphs below elaborate on the elements of modelling.

The first requirement, no matter whether we are looking at our checking account or some highly complicated environmental system, is a general understanding of the events which take place and how they are inter-related. This understanding, which we will call the "conceptual model", helps us to visualize the system we are studying. For example, we intuitively understand a checking account to be a sum of money that increases when we make a deposit and decreases when we write a check. We might have a visual image of a tank with water becoming more full or nearly empty, or a picture of a piggy bank being filled and emptied. The point is that each of us has an idea of how a checking account works. This conceptualization is very important since it provides an ordered way of thinking, and allows us to watch the flow of money into and out of our account. After we observe the system for some time, we also gain a feeling for those items which impact our account most (our paycheck, for example) and those which are less significant (expenses for small items such as the daily newspaper). We can also see ways that events are inter-related. For example, often there will be a charge for writing a check, so that our balance goes down not only the amount of the check, but also the extra charge for writing a check.

It probably will not be enough to have a qualitative feeling for where the money goes. Although it is useful to know that more money is spent on the house than the car, we still want to know if there is any money left for entertainment. If, for some reason, we are certain that we can never do math, we might use beans or poker chips to keep track of our money. That is, we would have a bag of beans and a pot. Each time we made a deposit, an appropriate number of beans would be added to the pot, and each time we wrote a check, some beans would be taken from the pot and put back in the bag. Thus, we would know approximately how many dollars was in the checking account by counting the number of beans in the pot. The point that we are trying to make is that you don't have to use mathematics to keep track of your money, but rather you can see an "analog", which behaves just like your account. One special kind of analog model is the "scale model" or reduced version of the real system. For the case of the checking account, a scale model would use pennies to represent dollars.

In the end, it is very likely that we will need to use mathematics to keep track of things, no matter how difficult balancing the check book may be. In fact, the running tally of the balance in your account is a simple mathematical model. We could write equations to represent our entries, which would say something to the effect that the new balance equals the old balance, plus deposits, and minus checks and other charges. The problem we all encounter when the bank statement arrives is that some checks get cashed very quickly while others take months, and there is a devil of a time figuring out which is which. In other words, a checking account is a <u>dynamic</u> system and it is hard to capture or picture the entire system at any single moment. Similar difficulties occur with real world systems since substances are added by effluent discharges, overland runoff, and brought in from upstream while at the same time some substances are leaving the system by flowing downstream.

The first step in the modelling process is to organize our thoughts into a conceptual model of the way things behave. After that we can simulate or reproduce the behavior using either an analog, or a mathematical representation of the real world system. Although the models being used in the HRWQA 208 project may seem exotic and extremely complicated (often the manipulations are quite complex), in essence they are not much different from our checking accounts. The following section of this report will discuss scale models and list those that have been constructed for the tidal waters of Virginia. The latter sections will review some of the different kinds of mathematical models, and how these have been applied to the estuaries of the Chesapeake Bay system.

ANALOG AND SCALE MODELS

An analog model behaves like the real world responding to changes in the same way as the prototype system. Usually an analog model is chosen because measurements are simple and cheap to make, whereas in the real world, measurements are very difficult or costly to obtain. Certain types of analog models have been built to simulate the behavior of rivers and other systems, but in general, they have not been especially useful since they cannot efficiently reproduce the many facets of real world systems. One special type of analog which has been used extensively, is a scale model, or reduced version. A scale model is to a river as a doll house is to our home. In both cases, the degree of similarity built into the miniature is dependent primarily on the time and money we are willing to invest in creating it.

It should be noted that problems often arise when discussing models because a word means different things to different people. The models we will be discussing in this chapter, are called scale models because the features of the real world are scaled down. Many people refer to these models as "physical models" since they are real, physical things which we can touch, walk around and see, as opposed to abstract or mathematical models. Others, unfortunately, use that term to mean any kind of model that simulates physical systems, as opposed to economics, animals and so on. Scale models are sometimes called "hydraulic models" because the main purpose is to simulate the flow of water. (This should not be confused with "hydrodynamic models" which are mathematical representations of the water flow.) The Corps of Engineers, which is probably the biggest builder of scale models in the country, uses the term hydraulic model. For this report, scale model, hydraulic model and physical model all refer to small replicas of rivers or estuaries.

Scaling Factors

There is no required ratio for reproducing the geometric features of an estuary. The Corps of Engineers often uses a 1,000/1 ratio, but 500/1 or 638/1 would be just as reasonable. The amount of reduction is dependent on the space available and the detail desired. On the other hand, there are instances when engineers have built a scale model that is larger than the real world prototype, in order to study a problem in greater detail, for example the flow of water through a valve. Geometric similarity normally is desired. That is, the model looks like the real estuary.

The time scales, ratios of forces and other comparisons between the model and the real world phenomenon normally will not be equal to the ratio of lengths. These ratios are determined from physical laws and by the characteristics of the system which are of greatest interest to us. If we are interested in tides, water currents and other features which are due to gravitational forces, we follow the "Froude scaling factors". If dispersion and mixing phenomena are our major concern, then the Reynolds scaling factor should be used. This may sound complicated, but all we are saying is that certain forces are dominant for each physical process, and the scaling should be done in such a fashion that these dominant forces can be measured in the model and related back to the real world.

If we return to the analogy of the checking account, one can observe that expenses vary from month to month. During December it is very likely that expenses for luxury items (Christmas gifts, entertainment, decorations, etc.) will be considerably higher than in almost any other month. Similarly, heating expenses are a major component of expenses during winter months. If we tried to characterize how we spend our money, different expenses would be important in each month. So, too, with estuaries. Sometimes we need to observe tides and tidal currents, and at other times we are most concerned about the dispersion and dilution of wastewater. The controlling factors for each situation will be different and ideally, there would be a model available for each case. In fact, however, most models are constructed according to the Froude scaling ratios and therefore do the best job, from a theoretical basis of reproducing tides and other gravitationally-induced phenomena. These models are used to investigate wastewater dispersion and transport and can provide great insight. But this use should be considered part of the "art" of modelling, since it is not founded on rigorous physical principles. In many respects, physical modelling is more art than science.

Hydraulic models are especially useful since they are full field models; that is, they reproduce the real world system in three dimensions and at all points and can simulate time variations as well. Modelling in general, though, implies a certain degree of simplification, which is necessary to render the problems tractable and reduce expenditures of time and money. Normally, an average tide, or perhaps a spring tide, will be reproduced over and over in the model. The diurnal inequality, variations between spring and neap tides, wind produced tides and other variations are not normally included. When the appropriate mathematical manipulations are done, flows may be scaled to a ratio of around a million to one. As a result, only large freshwater flows can be simulated with an accuracy, and hydraulic models are rarely used to simulate varying freshwater flows, such as occur during large storms and seasonal variations. Rather the model is operated with a constant freshwater inflow and a separate test is required for each flow rate. In other words the model predicts the conditions which would exist on the average and for a given set of hydrologic conditions.

Models must be calibrated and verified in order to give accurate predictions. Calibration is the process wherein the model is adjusted to reproduce the behavior of the prototype for some given set of conditions. Normally an extensive set of field data is collected and these are reproduced, as best as possible, in the model. Once this procedure had been completed, the model is then run to simulate a different set of conditions, say high freshwater flow versus low freshwater flow during calibration. If the model again reproduces the actual response, then it is said to have been verified. Normally, some minor adjustments are called for during the verification stage. Models can be verified for as many conditions as time, data and money allow. Two aspects of the calibration-verification process should be noted. First, the better the model reproduces the field data for both calibration and verification runs, the more likely it will be for the model to reproduce other conditions well. Secondly, the reliability of the simulation is ultimately dependent on the soundness of the field data. If the data used for calibration and verification cannot be trusted, it is unlikely that the model predictions will be any better. A good set of field data gives a far greater chance of success for the model to reproduce the behavior of the prototype.

James River Hydraulic Model

The James River model is housed at the Corps of Engineers' Waterways Experiment Station in Vicksburg, Mississippi. It includes the portion of the river from Richmond to Old Point Comfort, and the Appomattox, Chickahominy, Nansemond and Elizabeth rivers. This is a distorted model; that is, the horizontal scale is 1:1000 while the vertical scale is only 1:100.

Studies which have been conducted in the James include channel modifications, point sources and thermal plumes. The original study for which the model was constructed was the proposed dredging of the navigation channel from the James River Bridge to the Richmond Deepwater Terminal.

York River Hydraulic Model

The model of the York River is located at the Alden Hydraulic Laboratories in Worcester, Massachusetts. This model was built for VEPCO in order to study the effects of a new (~1975) power station at Yorktown. Only the lower portion of the York River system is modelled. This model is also a distorted model.

Chesapeake Bay Hydraulic Model

A model of the entire Chesapeake Bay system has been constructed by the Corps of Engineers on Kent Island, Maryland. It, too, has a 1:1000 horizontal scale and 1:100 vertical scale. It provides a unique tool for the study of problems of a regional nature.

Lynnhaven Bay Model

In the 1950's, a model of the Lynnhaven Bay system was constructed by the Corps of Engineers at the WES in Vicksburg, Mississippi. Like several of the others, it had a horizontal scale of 1,000:1 and a vertical scale of 100:1. The model was built to determine changes in tidal currents and flushing resulting from several proposed dredging projects. Since that time, this model has been destroyed.

Lynnhaven Roads Model

At the same time that the previous model was built, a special model of a portion of Lynnhaven Roads and Lynnhaven Inlet was constructed to examine problems of shoaling at the entrance to the bay. Unlike the other models, this one did not have a concrete bottom or "fixed bed", but rather had a bottom of sediment particles. With this type of "movable bed" model, it is possible to follow changes in bottom topography and the movement of sediment. Several configurations for jetties were studied. This model also was destroyed at a later date.

Summary

Hydraulic models are useful tools for the study of certain problems in estuaries. The scaling factors for the existing models were chosen so that physical phenomena caused by gravitational forces are reproduced accurately. It is for this reason that tidal heights can be reproduced quite accurately and tidal currents are reproduced reasonably well. Mixing processes require a different set of scaling factors. Therefore, measurements of dispersion in the existing models cannot be justified on theoretical grounds, although these models have been used for this type of investigation with success in the past, e.g. the study of the thermal plume from the VEPCO Surry Nuclear Power Station. It must also be noted that only average tides can be reproduced, and it is extremely difficult to change freshwater flows during any given experiment.

The advantage of hydraulic models is that data for a large geographical area can be gathered with a modest expenditure of money once the model has been built, calibrated and verified. The existing models of the James and York could serve this purpose for local studies, while the Chesapeake Bay model will allow a comprehensive view of the entire study area.

MATHEMATICAL MODELS

A math model uses mathematical expressions and equations to represent the actions and processes which occur in a real world system. In this section, some of the more important differences will be presented so that the reader can differentiate between models and the capabilities and limitations inherent in each. The discussion will focus on numerical, as opposed to analytical, solutions. An analytical solution is one which is achieved by rigorous manipulations of the equations. It involves no approximation, but rather is exact. As a general rule, only simple problems or slightly more complex problems with very simple geometry will have analytical solutions. The estuarine environment tends to be extremely complex in its relationships and geometry, and there is a great deal of natural variability. Analytical solutions for estuaries are virtually unknown or else are achieved only by utilizing a long list of simplifying assumptions, so that the mathematics bears only a faint resemblance to the true situation. Numerical techniques, on the other hand, are approximate* and not exact, but they can be utilized to resolve complex systems of equations. Modern digital computers are able to make the calculations required

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* The word "approximate" may imply inaccurate to some persons, although this is not necessarily the case. The word is used here from a mathematical point of view to define methods which include some small amount of error, but otherwise give reliable and accurate results. To illustrate this approach to exactness, the following story is given: A boy and girl are seated at opposite ends of a sofa. As the boy becomes more certain of his desires, he moves one half the distance toward the girl. This process is repeated several times. From a mathematical point of view, the boy will never reach the girl no matter how many times he reduces the remaining distance by a half. In fact, however, he quickly gets close enough for all practical purposes. Similarly approximate solutions are not precise but are good enough for most practical needs.

for these numerical techniques in very small fractions of a second, duplicating many man-years of labor in a short span of time. As computer technology advances, our capability to model increasingly complex systems also grows.

The vast majority of environmental models are deterministic, meaning that they are based on physical, chemical and biological laws and principles. One result of this approach is that the model responses are consistent. If the same input conditions are used, the resulting predictions will always be the same. Stochastic models, on the other hand, employ statistical relationships of one type or another. Some of these models are quite similar to the deterministic models but include estimates of the anticipated variability of the predictions. Other stochastic models achieve predictions through a series of "random events" that are appropriately structured. For the most part, the remaining discussion will deal with deterministic, numerical models only.

Dimensions of Space and Time, and Mathematical Approaches

The estuaries of the Chesapeake Bay system are variable both in space and in time. For example, if we began taking water samples from one end of the James River Bridge and proceeded to the opposite shore, one would observe that the characteristics of the water varied considerably over that distance. In addition, there would be differences with depth and time of the tidal cycle, as well as day to day variations. These variations can be observed throughout the tidal portions of the rivers, although the differences are usually most pronounced in the saline reaches. If we desire to characterize the river, either for our own understanding or for modelling purposes, it is necessary to observe the variations which occur in the three dimensions of space and over time. Over the years, our understanding of estuarine circulation has been developed by examining first those cases which are somewhat simpler. During late summer and early fall, the freshwater river flow is often quite small and constant, and as a result tidal mixing reduces vertical stratification and lateral variations. For this case, a steady state (does not change with time), one-dimensional model of the river may be justified. The dimension that is modelled is the longitudinal one, since salinity, for example, will still vary from something close to seawater near the mouth to freshwater in the uppermost reaches. Lateral and vertical variations are not directly included, since the average values for the cross-section will be used. Early models of estuaries were of this type. At a later date, it was possible to include more dimensions. Some scientists chose to have two-dimensional, steady state models while others chose one-dimensional, time-varying models. The important point to note is that the added dimension could be either time or space, but the increase in complexity of the mathematics and the added computer time were roughly equal.

At present, three-dimensional, time-varying models are feasible from a technological point of view, but are extremely expensive. Even two-dimensional, time-varying models pose significant problems and require large amounts of money, but they are being used in many applications. Longitudinal variations are nearly always included, but the second dimension can be either vertical (where stratification is strong) or lateral (where the estuary is very broad).

The equations used to describe the system are for a continuum, namely the length of the river to be modelled. Since numerical techniques are employed, it is necessary to divide the river into segments, each of which is assumed to have uniform characteristics throughout its volume. The equations then describe the exchanges which occur between segments and the transformations which occur within each segment. Two techniques for segmenting the river and modifying the equations are called the Finite Element and the Finite Difference techniques. In many instances they may have equal usefulness, but in other applications one will be superior to the other.

Once the equations have been written in the format appropriate to the segmented river scheme, a variety of numerical methods can be used to solve the set of equations, such as the explicit and the implicit schemes. These methods also will have characteristics which make them desirable (rapid solutions) or undesirable (instability) for any given application. The choice of the mathematical approach is very important for technical reasons, but from a managerial point of view, it is not since one must assume that the scientist will use methods which are appropriate and sound. Therefore, no further discussion of mathematical techniques will be presented.

Hydrodynamic Models

Hydrodynamic models are those which use the equations describing the forces acting on water parcels to predict the water movement. These models are useful for studies of circulation, sediment transport, erosion, and water quality. In particular, hydrodynamic models have been developed to provide input data to math models of water quality, since the current patterns determine how wastewaters and other substances are transported and dispersed through an estuary. The alternate route is simply to measure water currents at the same time that water quality is determined, but the resultant description of circulation is applicable only to those hydrological and meteorological conditions which existed during the field study. If, on the other hand, the data are used to calibrate a hydrodynamic model, the model can be used to predict currents for other freshwater flows.

At present, hydrodynamic models have been developed for the James River and the Chincoteague/Sinepuxent/Assawoman Bay system as indicated in Figure 1. A one-dimensional model, applied to the James River from around the James River Bridge to Richmond, was calibrated for low freshwater flows, but also duplicated the flood following Tropical Storm Agnes with rather good accuracy. A two-dimensional model (both horizontal dimensions) also has been applied to the estuarine portion of the river from the mouth of Hampton Roads (Old Point Comfort-Fort Wool) to the mouth of the Chickahominy River, as part of the Hampton Roads 208 study.

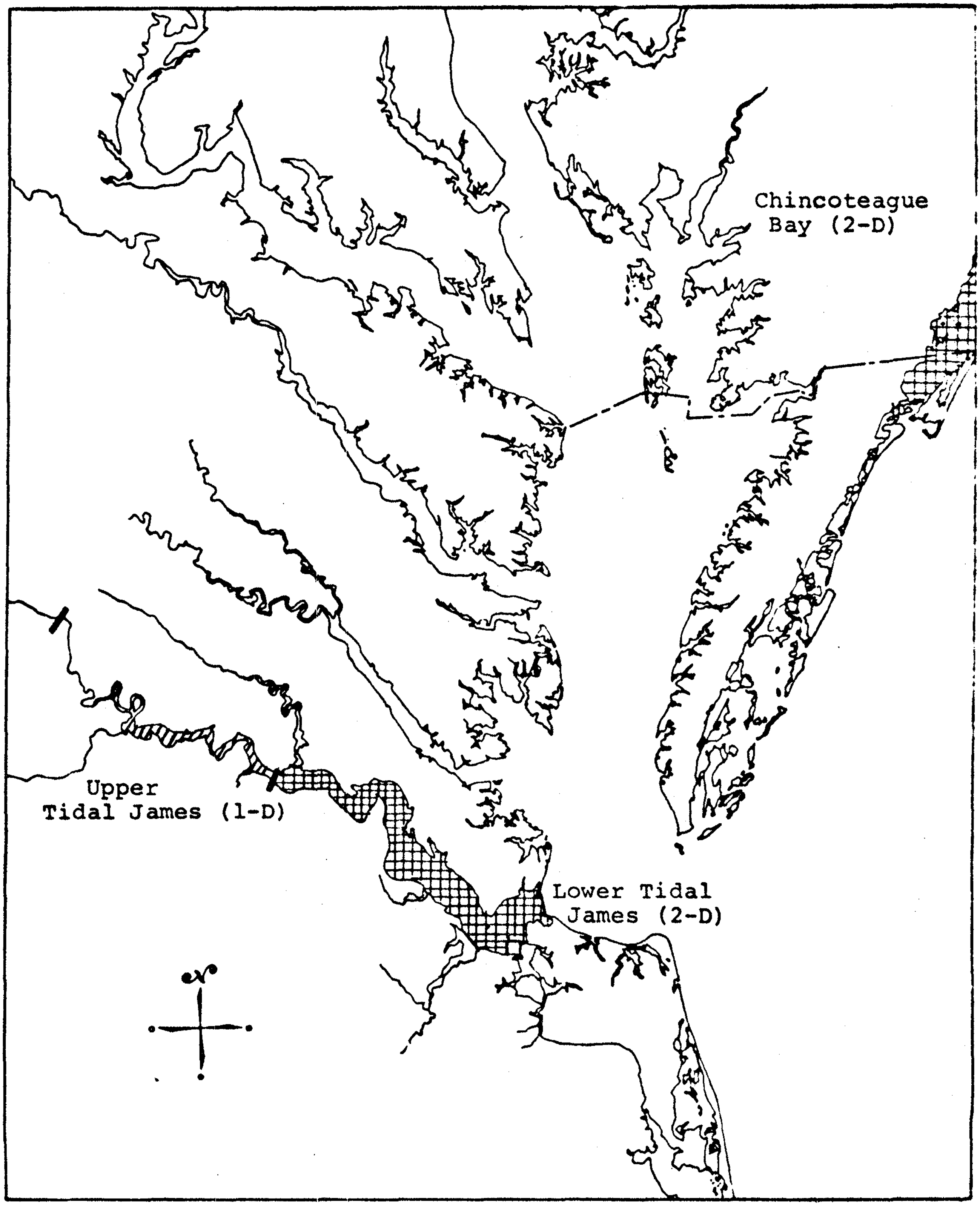

Figure 1. Hydrodynamic Models.

A similar two-dimensional (both horizontal dimensions) model applied to the Chincoteague Bay system incorporates wind effects, since the astronomical tide is weak and wind induced tides can become quite large.

Salinity Intrusion Models

Freshwater flowing down an estuary tends to push salt water toward the ocean. When freshwater flows are large, the saline portion of the river is reduced in length, and when freshwater flows are small, the salt water intrudes further upriver. For example, the limit of salt water intrusion on the James is normally about Jamestown Island, but during a drought in the mid-1960's brackish water is reported to have reached nearly to Hopewell, about 30 miles further upriver. Had the salt water intrusion proceeded much further, the drinking water supply for the nearby towns would have been jeopardized. These changes in salinity also have important ramifications for the organisms in the river and the plants growing along the banks. For these and other reasons, scientists have questioned the impact of various projects on the salt water intrusion.

The time scale for salt water intrusion is on the order of months, and it is necessary to consider long records of freshwater inflows. Day to day changes will be small and only after several weeks of low inflow will the movement of the salt water be readily apparent. Models to simulate salt water intrusion must duplicate these flow records. In order to minimize computer expenses, specialized math models are used which do not simulate the short term variations, but rather consider tidal averages. Models of this type have been developed to evaluate proposed dams and other engineering projects on the Rappahannock River (Salem Church Dam), North Anna River (York system) and the James River.

Water Quality Models

The Virginia Institute of Marine Science and the Virginia State Water Control Board jointly have been developing models of water quality for Virginia's estuaries under the Cooperative State Agencies (CSA) program since around 1970. Initially, efforts were focused on the three major estuaries, and the model simulated dissolved oxygen (DO) levels in the rivers, the major features being the decay of oxygen demanding material (BOD), the uptake of oxygen by this process and natural reaeration from the atmosphere. Since then the models have been upgraded to include nutrient cycling and fecal coliform die-off. The nutrient cycling component includes the growth and eventual decay of phytoplankton with concomitant uptake and release of nitrogen and phosphorus. The production of dissolved oxygen as a by-product of photosynthesis and the consumption of DO for respiration are included in the DO regime.

The water quality models have been applied to many of the smaller estuaries, and additional model development is underway for VIMS portion of the Hampton Roads "208 Study". Many of the models are one-dimensional and time varying, but a few are steady state, and others include more spatial dimensions. A list of models for which reports are available or will be available during 1977 is given in Table 1. Stochastic models of water quality in the James River have been developed at VPI & SU, and special purpose models have been applied to portions of estuaries during environmental impact studies for major projects.

TABLE 1. Math Models of Water Quality

One Dimensional/Steady State

Little Creek Harbor	July, 1977
Lynnhaven Bay System	July, 1977
Great Wicomico/Cockrell Creek	April, 1976

One Dimensional/Time Varying

Back River	June, 1977
Poquoson River	June, 1977
Pagan River	Dec., 1975 & August, 1977
Chickahominy River	May, 1977
Nansemond River	June, 1977
Elizabeth River	September, 1977
Piankitank River	May, 1977
Rappahannock River	1972, 1975
York/Mattaponi/Pamunkey	1971, 1975
James River	1973
Chesapeake Bay	1975

Two Dimensional (horizontal), Time Varying

James River (Hampton Roads to Chickahominy River mouth)	September, 1977

Quasi-Three Dimensional, Time Varying

York River (Two horizontal dimensions & two vertical layers)	September, 1977

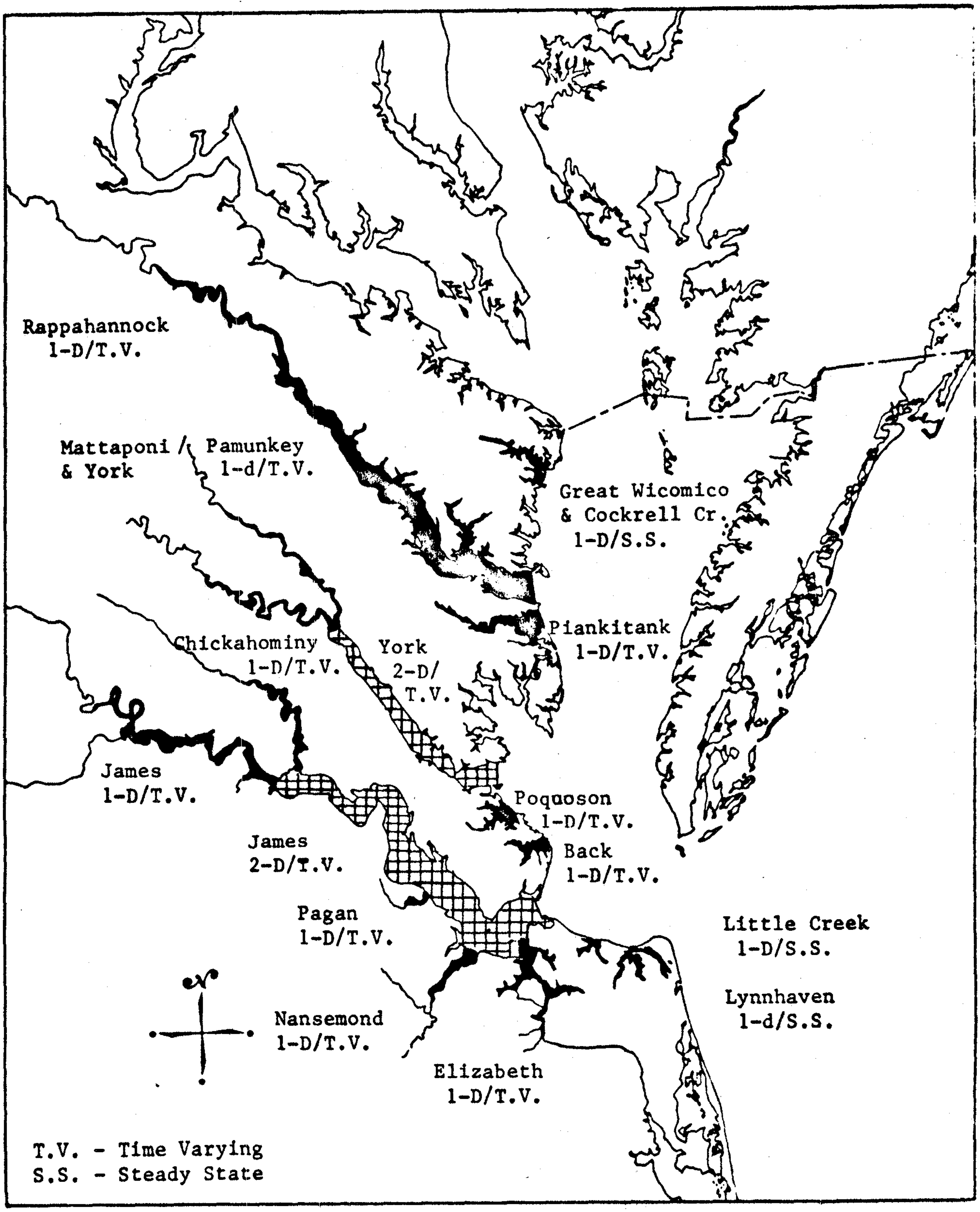

Figure 2. Water Quality Models.

MODEL SELECTION

Models are extremely useful tools for both engineering studies and scientific investigations. Scale models of rivers have the advantage that they reproduce the prototype system entirely so that measurements can be made at any point within the system as well as at the desired times. Furthermore, many of us are best able to understand a system if we can see it in operation. Since a tidal cycle in the model may last only ten minutes or so, it is possible to see a patch of dye spread out and travel downstream or to observe the currents at some point repeatedly, but all within reasonably short periods of time. The major disadvantage of a physical model is that once the model has been constructed, it is there until one decides (and spends money) to have it destroyed. The models and their housing often require large amounts of space.

Mathematical models come in a variety of types and styles. Because of the variety it is possible to select a math model that simulates the processes under study both accurately and efficiently, so that costs to operate the model are small.

All models require a comprehensive set of field data for the purposes of calibration and verification. The reliability of the models is directly dependent on the extent and quality of these data sets, which often are extremely expensive to obtain. Ideally, there would be an interactive process between a modeler and a field observer. The field data are necessary to calibrate the model, but once that is accomplished, the model can be operated to simulate a variety of test conditions. This then allows one to more fully grasp how the system responds to various forces and to better understand the workings of the system. For subsequent field studies this increased knowledge should be utilized to derive the greatest amount of information from the field program.

Choice of a model can be difficult, since many are available. The manager should focus his efforts on defining the kinds of questions that are important to him and the degree of accuracy he would desire in the model predictions. If the manager can delineate the problem with reasonable clarity, the model experts should have little difficulty suggesting the type of model and characteristics of the model that best suits his needs. Sometimes it is best to select an all-purpose model that can provide answers for a variety of questions, such as hydraulic models, but the generality may come at the expense of efficieny or accuracy. Therefore, for other circumstances it would be most appropriate to have one or more highly specialized models, each of which is able to do a specific type of operation rapidly and accurately.

The final point is that models are tools and not answers. The problems must be outlined and the questions posed by managers, scientists and engineers. The results of the model studies must be interpreted by these same persons, including some analysis of the faith we should place in the predictions. Models will not answer questions or resolve problems unless those persons utilizing them are aware of the capabilities and limitations inherent in the modelling process. They also should understand the real world system that is being simulated. In short, man must still employ every bit of intelligence he can muster. Models will reduce the labor and tedium of testing alternate solutions, but to do so effectively, they require skilled and competent modelers and knowledgeable managers.

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