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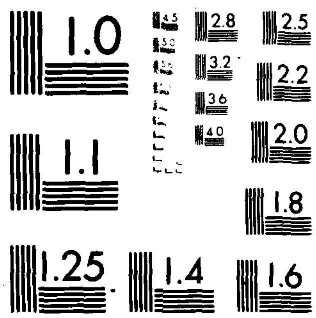

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LITERATURE REVIEW OF MARINE WETLAND AND ESTUARINE WATER QUALITY AND ECOSYSTEM MODELS

by

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This literature review surveys published models of hydrodynamics, sediment transport, water quality, and ecosystems in estuaries and intertidal wetlands. The review was based on the needs and problems of the U. S. Army Corps of Engineers (CE) in the coastal zone as revealed by a survey of CE Field Offices with coastal responsibility. In addition, a workshop, conducted in New Orleans in June 1979, assessing the state of the art in understanding and modeling estuarine and wetland processes, served to define the scope of the literature review

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PREFACE

The literature review described in this report was performed under Contract No. DACW39-74-C-0024, entitled, "Survey of Existing Marsh/ Estuarine Water Quality and Ecological Modeling Techniques," between the U. S. Army Engineer Waterways Experiment Station (WES) and Science Applications, Inc. (SAI). The research was sponsored by the Office, Chief of Engineers, under the Environmental Impact Research Program.

This report was prepared by Dr. Peter Hamilton and Mr. Kenneth Fucik. Messrs. Ivan Show, Jr., and Keith B. Macdonald provided assistance to the authors.

The contract was monitored at WES by Mr. Ross W. Hall, Jr., under the direct supervision of Mr. Donald L. Robey and the general supervision of Dr. Rex L. Eley, Chief, Environmental Research and Simulation Division, and Dr. John Harrison, Chief, Environmental Laboratory.

Director of the WES during the preparation of this report was COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

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LITERATURE REVIEW OF MARINE WETLAND AND ESTUARINE WATER QUALITY AND ECOSYSTEM MODELS

PART I: INTRODUCTION

1. This literature review surveys published models of hydrodynamics, sediment transport, water quality, and ecosystems in estuaries and intertidal wetlands. This review was based on the needs and problems of the U. S. Army Corps of Engineers (CE) in the coastal zone as revealed by a survey of CE Field Offices with coastal responsibilities. In addition, a workshop, conducted in New Orleans in June 1979, assessing the state of the art in understanding and modeling estuarine and wetland processes, served to define the scope of the literature review. Both the workshop report and the report of the survey of CE Field Offices have been published (Hamilton 1979a, 1979b).

2. Activities of the CE primarily alter the physical system in estuaries and wetlands by altering freshwater inflow, dredging navigation channels, constructing harbors and shore protection structures, and creating intertidal marsh. Therefore, prediction of the effects of these activities on the physical regime is of primary importance; the hydrodynamic models that are the basis of the majority of predictive techniques are surveyed and discussed in Part II of this report. Alteration of the physical regime can also profoundly affect sediment transport, biological and chemical processes, and possibly fisheries. Thus, the difficult problem of modeling sediment transport in estuaries is reviewed in Part III. Part IV concerns the important problem of modeling water quality parameters in estuaries. The majority of models considered are based on mass conservation that requires the use of hydrodynamic submodels to predict dispersion and velocity fields. However, some water quality models based on population dynamics and/or energy flow are also considered because of possible application to toxicity effects on estuarine organisms. Some of the more sophisticated water quality models of estuaries are effectively applied

ecosystem models of the lower trophic levels. Ecosystem models of estuaries, which have usually developed from marine models, are reviewed in Part V. Finally, the much less developed field of marsh ecosystem modeling is discussed in Part VI.

3. This review has been written as a guide to the published literature on estuarine and wetland models and attempts to span the gap between a simple reference list and a comprehensive critical review. Important studies of the last five years are put in historical perspective, and there is some discussion of their major achievements and limitations.

4. The authors of this survey have attempted to highlight those model studies of estuaries and wetlands that are or have been important contributions of the state of the art. The authors take full responsibility for their views and prejudices and sincerely apologize if important models, which are relevant to this investigation, have been inadvertently overlooked.

PART II: HYDRODYNAMIC MODELS OF ESTUARIES

Introduction

5. The basis of all water quality models and many ecosystem models that use the principal of conservation of mass is a model of the circulation of the estuary or coastal bay. The investigation of hydrodynamics of estuaries by the means of models has a long history. Most of the earlier studies concerned the propagation of tidal waves in channels (Defant 1961, Dronkers 1964) and only recently has the internal depth dependent circulation been a subject of model studies.

6. The circulation in a partially mixed estuary or bay is mainly driven by the tide, river inflow, salinity gradient, and wind. The importance of wind has only recently been realized. Based on extensive field observations, particularly long-term current meter measurements in Chesapeake Bay (Wang 1980), it is now thought that in many estuaries all four forcing mechanisms are equally important in influencing the circulation and the transport of pollutants and sediments. Estuarine circulations are perhaps some of the most complex geophysical flows in existence. Besides the complexity of the driving forces, there is the difficult phenomena of turbulence in a stratified system and the influence of channel topography in inducing cross-channel circulations and hence cross-channel variability. A review of recent turbulence studies in highly stratified estuaries is given by Gardner et al. (1979) who show that significant mixing can arise from tidal-induced internal waves or bores as well as due to boundary layer or wind-induced turbulence. A more traditional review is given by Bowden (1977) who emphasizes the need for parameterizing the vertical eddy viscosity and diffusion coefficients in order to improve models of vertical circulation. Topographic effects have had little study. However, Dyer (1977) discusses possible secondary circulations induced by changes in channel topography and an extensive field experiment has been performed at a bend in the lower Potomac Estuary to investigate these effects (Boicourt 1979).

7. Physical oceanography of estuaries is the subject of a number

of texts by Dyer (1973), Officer (1976), and McDowell and O'Connor (1977) and also symposia edited by Kjerfve (1978) and Hamilton and Macdonald (1980). For a review of numerical models of estuaries and coastal bays, see Liu and Leendertse (1978).

One-Dimensional Models

8. Apart from tidal propagation, one of the earlier uses of one-dimensional models, which include an advection-diffusion equation for a solute, is the investigation of salinity intrusion in an estuary (Thatcher and Harleman 1972; Stigter and Siemons 1967; Williams and West 1973). Neglect of the variation with depth of current and salinity means that the important upstream flux of salt due to density currents as well as vertical phase differences in the tidal variations of current and salinity are all lumped into one parameter: the one-dimensional longitudinal dispersion coefficient. It is not surprising, therefore, that Williams and West (1973) found that the dispersion coefficient is highly dependent on riverflow and distance from the estuary mouth. These kinds of one-dimensional models are difficult to use in a predictive mode in some partially mixed estuaries. These models are also the hydrodynamic basis for the majority of water quality models of estuaries.

Two-Dimensional Models

Longitudinal and vertical dimensions

9. The inclusion of the depth dimension makes possible the inclusion of the majority of the fundamental physical process that contributes to advection and diffusion of salt and pollutants. The first study which showed the importance of the depth variation of current and salinity was the steady-state analytical solution of Rattray and Hansen (1962). This was later expanded to include the horizontal salt balance explicitly by Hansen and Rattray (1965). A similar approach was also used for fjords by Rattray (1967) and Winter (1973). The same set of steady-state equations was solved numerically by Festa and Hansen (1976).

10. The time-dependent equations for a tidally driven partially mixed estuary were solved numerically by Hamilton (1975) and Blumberg (1975) and applied to the Rotterdam Waterway and the Potomac Estuary, respectively. Both numerical methods were explicit (i.e. time step limit by the gravitational wave speed--the Courant-Friedrich-Lewys condition) and had small steps of approximately 1 min. Semi-implicit extensions which enabled time steps of about one half hour to be used with little loss in accuracy have been developed by Hamilton (1976) and Wang and Kravitz (1980). This allows the important subtidal, wind-driven transients to be investigated efficiently (Wang 1980). These kinds of models have also been applied to branching estuaries (Elliott 1976).

11. The important parameters in these vertical circulation models are the vertical eddy coefficients. The effects of different formulations of these coefficients are shown in Bowden and Hamilton (1975), and the importance of the effects of stratification on vertical turbulent diffusion is stressed. The turbulent stresses may be calculated from the conservation equation for turbulent kinetic energy with some assumptions, and this approach has been used for an unstratified tidal channel by Johns (1978). This seems to be a promising approach to overcoming the limitations of first order K-theory to parameterize the eddy coefficients, but further complications are introduced such as very fine grids to resolve the boundary layers.

12. The models discussed above consider the depth coordinate to be continuous and in the numerical models this is approximated by a fixed grid. However, fjords such as Puget Sound and salt wedge estuaries such as the Mississippi are highly stratified and often more appropriately modeled by using layers. The displacement of the interfaces is a function of space and time. A time-dependent, two-layer model of a deep fjord (Alberni Inlet, British Columbia) has been developed by Hodgins (1979) and for a salt wedge estuary by Vreugdenhil (1970).

Horizontal dimension

13. The vertically integrated equations of motion have been used for storm surge modeling of coastal seas and estuarine bays for a number of years. Reviews of the different kinds of models are given by Hinwood

and Wallis (1975a, 1975b). The use of these models to predict water level and depth averaged current variations due to tides and wind is now quite sophisticated in that complex geometry using variable grids and imbedded subgrid scale features such as channels, barriers, and canopies can now be handled (Butler 1979; Reid et al. 1977a, 1977b). A good example of application of this type of model to tidal prediction in Chesapeake Bay is given by Blumberg (1977); however, there are many examples of similar applications to bays in the literature (Gordon and Spaulding 1974).

14. All the numerical models mentioned so far in this section employ finite difference methods. Models using finite element methods are based on the minimization of functions defined over elements (often triangular) subject to the constraints of the equations of motion. Formulation of these models is generally more complex than their finite difference counterparts and less is known of their stability and accuracy behavior. Examples are studies by Pearson and Winter (1977), Wang and Connor (1975), and Gray, Pinder, and Brebbia (1977).

15. The addition of a vertically integrated advection-diffusion equation for a salinity or water quality parameter has been the object of a few investigations. For example, Leendertse and Gritton (1971) hindcasted water quality parameters in Jamaica Bay, N. Y., and Hess and White (1977) modeled the dispersal of a marked fluid in Narragansett Bay from point sources within the bay.

Three-Dimensional Models

16. Three-dimensional models are very complex and only a few have been developed to a point where simulations are feasible. The primary ones are the model investigations by Leendertse and Liu (1975, 1977). This model uses explicit finite difference methods and consequently is very costly in computer time for any lengthly simulation. Horizontal grid dimensions are similar; therefore, narrow estuaries are difficult to model. Wang (1980) briefly mentions the use of simi-implicit methods and mode splitting as aids to efficiency for three-dimensional models.

Methods using vertical modes instead of a vertical grid have been developed by Heaps (1974) for shallow coastal seas. This model is linear and does not include the advection diffusion equation for salinity or density.

17. Caponi (1976) developed a complex time-dependent, three-dimensional model which used the complete three-dimensional Navier-Stokes equations instead of the Boussinesq approximation. It was applied to Chesapeake Bay, but the relatively coarse grid used seems to be responsible for some anomalous circulations.

Box Models

18. Officer (1980) has critically reviewed box models. The estuary is divided up into boxes or volumes of water and the fluxes between the boxes calculated from the equations of conservation of volume and salt. The resulting calculation is very simple and results in a steady-state distribution of fluxes. Elliott (1975) extended the box model by using an approximation to the horizontal momentum equation to calculate velocities. These kinds of models are sometimes used as a basis for water quality models (Barrett and Mollowney 1972). Numerical procedures are usually based on Pritchard (1969). Officer gives examples where two-dimensional box models give reasonable results when compared with two studies using steady-state numerical models. The investigations are the uptake of silica in San Francisco Bay (Peterson, Festa, and Conomos 1978) and the theoretical study of the turbidity maximum in an idealized estuary by Festa and Hansen (1978). A box model has also been used to assist the interpretation of nutrient distributions in Chesapeake Bay (Taft, Elliott, and Taylor 1978).

Summary

19. Table 1 summarizes important examples of the different kinds of models discussed above. It is not an exhaustive list of all the models known to the authors, but rather shows the variety of approaches to the numerical modeling of estuaries.

PART III: SEDIMENT TRANSPORT MODELS

20. Sediment transport and the interaction of sediment particles and turbulent estuarine flow is one of the most difficult problems in fluid mechanics. It is not surprising that there are relatively few sediment transport or turbidity models compared with hydrodynamic circulation models. Of course, a sediment transport model requires a hydrodynamic model as a basis. The greater complexity in the hydrodynamics over water quality models arises from the bottom boundary layer dynamics where important processes of deposition and resuspension take place.

21. Suspended sediment is important for water quality models because it limits light penetration and thus photosynthesis. Also, many pollutants attach readily to sediment particles and, if deposition is taking place, may be removed from the water column. However, a large storm may resuspend large quantities of polluted sediments which could severely affect the water quality of the estuary.

22. Festa and Hansen (1978) used a steady-state, two-dimensional (longitudinal and depth) model for the circulation in an idealized estuary. They investigated the effect of settling velocities on the position of the turbidity maximum assuming no flux of sediment into the bed.

23. Odd and Owen (1972) have developed a two-layer model of the bed flow of fluid mud in the Thames Estuary (United Kingdom). This model is time dependent and solves equations for bulk flow in each layer.

24. Ariathurai and Krone (1976a) developed a two-dimensional (horizontal) finite element model for the depth-averaged advection diffusion equation. This model allows for deposition and resuspension; the bed is modeled as a number of thin layers, so consolidation of the bed can be accounted for (Ariathurai and Krone 1976b). The model has since been developed and used in breadth-averaged form so that the two dimensions are longitudinal and vertical. This model has been applied to the Savannah Estuary (Ariathurai, MacArthur, and Krone 1977).

25. Kuo, Nichols, and Lewis (1978) used a two-dimensional breadth-averaged hydrodynamic model similar to that of Blumberg (1975). The

deposition and resuspension are modeled by simple source and sink terms in the bottom layer of the model. The model is qualitatively compared with data from the Rappahannock Estuary.

PART IV: WATER QUALITY MODELS

Introduction

26. In Part II, hydrodynamic models of estuaries were discussed. These models are the basis of all water quality models which attempt to describe the distribution of constituents in an estuary. The majority of these models are based on the mass balance equations of continuity, momentum, and constitutent conversation, the later being affected by sources and sinks due to chemical and biological interactions. It is these source and sink terms that are the main subject of this section.

27. Nearly all water quality models are one dimensional and so use the constitutient equation:

$$\frac{\partial(AC_i)}{\partial t} = -\frac{\partial(AUC_i)}{\partial x} + \frac{\partial}{\partial x}\left(AE_x \frac{\partial C_i}{\partial x}\right) \pm A \sum_j S_{ij} \tag{1}$$

where

A = cross-sectional area

C_i = concentration of the ith constituent

t,x = time and the longitudinal dimension, respectively

U = cross-sectional mean velocity

E_x = longitudinal dispersion coefficient

S_{ij} = source and sinks of constituent i

The terms U and A are calculated from a one-dimensional tidal or steady-state model, and E_x is empirically determined by matching observed longitudinal distributions of salinity ($S_{ij} = 0$) using Equation 1.

Solution Techniques

28. Methods for the solution of Equation 1 usually involve finite differences. If the advection-diffusion equation is solved for a conservative substance ($S_{ij} = 0$), then stability criteria on the time step depend on U and E_x. The maximum allowable time step is often much greater than the usual explicit methods for solving the hydrodynamic

equations. Therefore, if Equation 1 is solved along with the hydrodynamic equations for U and A, it may not be necessary to calculate Equation 1 every time step. Alternatively, the model employing a set of equations may be solved independently of the hydrodynamics where U and A are the appropriately time-averaged output from the hydrodynamic model. In some cases, the hydrodynamic model is steady-state and the water quality model time dependent. Evidently U and A are then just constant coefficients in Equation 1.

29. When the two-dimensional (or possibly three-dimensional) version of Equation 1 is being employed, then spatial averaging of the hydrodynamic model output may be necessary if the water quality model uses large-scale volume elements. For example, in Kremer and Nixon's (1978) ecosystem model, initial studies of the hydrodynamics in Narragansett Bay were performed using the two-dimensional tidel model of Hess and White (1974). This hydrodynamic model uses 324 elements of 0.5 square nautical mile (1.72 sq km). The ecosystem model uses eight different-sized elements to represent the bay. The hydrodynamic model was used to study the exchange of material between the eight elements as a function of tide height, and linear regression equations were derived, which expressed the mass exchange between elements on a daily basis as a function of tide height. Thus, a years simulation of the exchanges could be run extremely efficiently compared with the full hydrodynamic model. The hydrodynamics were further refined by using a simple box model calculation (Pritchard 1969) to represent two-layer exchanges due to the gravitational circulation in the bay. Therefore, the hydrodynamics in the ecosystem model are made simple and efficient but are based solidly on investigations with a complex time-dependent, two-dimensional, vertically integrated hydrodynamic model.

30. When a complex set of source and sink terms are part of a set of equations describing a number of substances, then the stability of the set of the differential equations has to be analyzed before a solution technique for the source and sink terms can be determined. Since S_{ij} usually involves no spatial or time gradients and is usually linear or quasilinear, the spatial dependence of the left hand side (LHS)

of Equation 1 can be neglected and the stability or stiffness of a set of ordinary first-order differential equations can be determined. A set of stiff ordinary differential equations may require complex iterative techniques for successful solution. The more simple the technique for the source and sink terms, the more compatible it will be with finite difference techniques used for the LHS of Equation 1.

31. There is virtually no essential difference between finite element and finite difference techniques for one-dimensional problems. When two or more space dimensions are involved, the two types of techniques differ in their formulations. Finite difference techniques are more common, but finite element techniques have been used for the two-dimensional advection-diffusion equation (Ariathurai and Krone 1976a).

32. In some water quality studies a more sophisticated hydrodynamic model has been used as the base for the water quality calculations (Peterson, Festa, and Conomos 1978; Zitta, Shindala, and Corey 1977; Winter, Banse, and Anderson 1975; Leendertse and Gritton 1971; Pitbaldo and Prince 1977). For example, Zitta, Shindala, and Corey (1977) discuss a two-dimensional vertically well-mixed steady-state estuary model for describing the distribution of salinity, nitrogen, biochemical oxygen demand (BOD), and dissolved oxygen (DO) concentrations in a system of interconnected tributaries and bayous. The model was used to predict the effect of alternative wastewater management methods on the water quality of the estuary.

Water Quality and Ecosystem Models

33. Historically, the analysis of water quality in streams, estuaries, and lakes has concentrated on the DO and the BOD due to waste loads. The BOD is primarily responsible for the consumption of oxygen in an estuary. However, there are many other interactions that affect DO, which tend to make its distribution in the water rather complex. Against this, DO is a good index of the general health of the aquatic environment. A review of oxygen requirements of fish is given by Alabaster (1973) and Vernberg (1971).

34. Organic processes in estuaries are very complex, including primary production, respiration, and mineralization. These processes can cause significant changes to DO and carbon dioxide concentration and thus alter the speciation of many chemical constituents. An estuary is a complex interface of three quite separate and contrasting environments: seawater, fresh water, and land. The estuary is very dynamic and the turnover rates of material can be high. These processes are dependent on fluctuations of the marine, limnetic, and terrestrial influences. A good review of organic processes in estuaries is given by Head (1976).

35. Perhaps the most complete view of an aquatic system centered on DO-BOD is given by Beck (1978) which is reproduced in Figure 1. Of

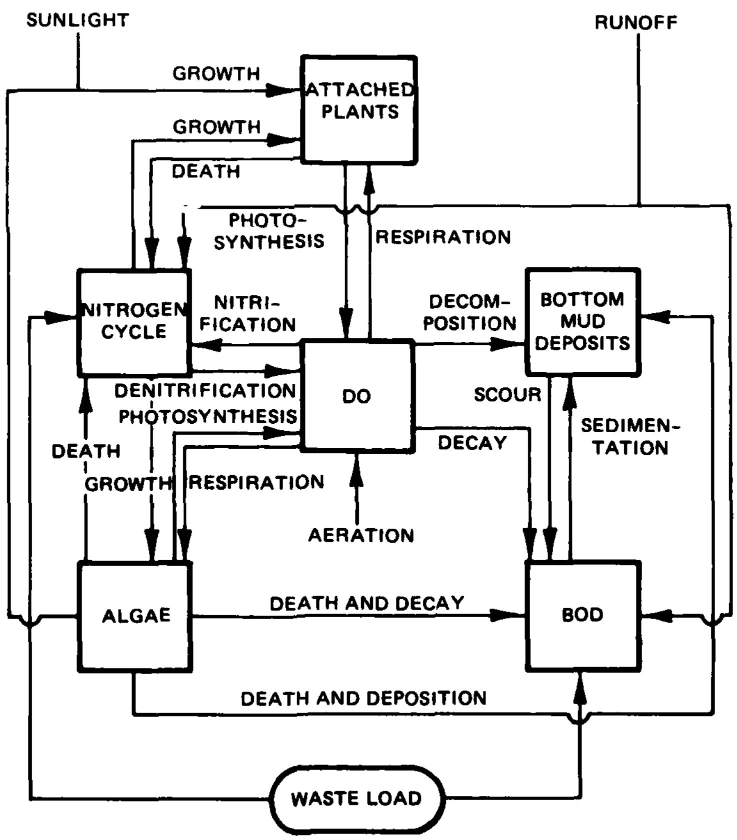

Figure 1. Factors affecting DO-BOD interaction (from Beck 1978, courtesy of John Wiley & Sons, Ltd. "Modeling of Dissolved Oxygen in a Non-Tidal Stream," by M. B. Beck (A. James, ed.), 1978, Wiley-Interscience, New York.

course, the degree of emphasis on the various constituents and the interactions included in the model vary among authors. The block diagram used to specify a zooplankton, phytoplankton, nutrients, and DO-BOD system is given by DiToro et al. (1977) and is reproduced in Figure 2. The

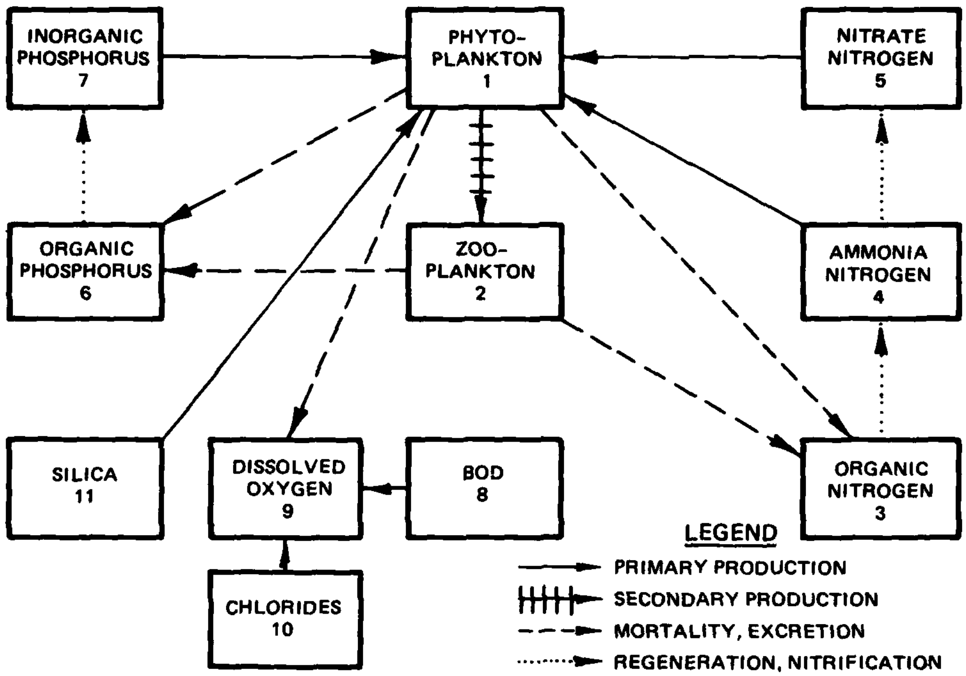

Figure 2. Kinetic interactions of the variables of an estuarine water quality model (from DiToro et al. 1977, courtesy of John Wiley & Sons, Ltd.)

nitrogen cycle is specified in more detail and the DO-BOD-nitrogen interactions is in less detail. The water quality models developed by the Water Quality Institute in Denmark, which are reviewed by Dahl-Madsen (1978), are also complex in that zooplankton, phytoplankton, detritus, nutrients, and DO are state variables. Processes such as mineralization of detritus and oxygen consumption by the sediment are included. The models also keep track of the uptake of nitrogen and phosphorus in the phytoplankton as well as total organic carbon. Fven though the DO-BOD cycle is included, the main interest in both DiToro et al. (1977) and Dahl-Madsen (1978) is in the problem of eutrophication due to excessive algal blooms in nutrient-rich waters. Another complex ecosystem model which includes DO-BOD is by Chen and Orlob (1972, 1975);

this model also includes some of the higher trophic levels such as fish and benthic animals. The model was applied to eutrophication problems in Lake Washington and San Francisco Bay. These models, DiToro et al. (1977), Dahl-Madsen (1978), and Chen and Orlob (1972), are effective ecosystem models which have been developed for water quality problems concerning DO and eutrophication. However, ecological models have also been developed as tools for investigating processes in the aquatic ecosystem per se. For example, Kremer and Nixon (1978), in their ecosystem model of Narragansett Bay, have a very complex zooplankton compartment and consider predation by the benthos; however, they do not use DO-BOD as part of the system. These differences reflect the goals and emphasis of the various models and the fact that there is no universal water quality or ecosystem model of an estuary.

36. The majority of recent sophisticated water quality models are based on three fundamental principles. The first and most fundamental is the conservation of mass as given by Equation 1. The second is the kinetic principle in which generally the rate of change of constituent is equal to the product of constituents that affect that reaction and a rate coefficient. Thus, the rate of utilization of oxygen by bacteria is linearly proportional to the BOD load. The third principle is the stoichiometry of chemical transformations. Whenever the conservation of more than one chemical species is considered in a model, then the stoichiometric relationships between the species during chemical transformations are specified. For example, if along with the conservation of oxygen, the conservation of carbon dioxide was modeled, then the ratio of oxygen consumed to carbon dioxide generated by the bacteria must be specified. In many models constant stoichiometric relationships are implicitly assumed (i.e., DiToro et al. 1977). However, when phenomena such as competitive uptake of nutrients by algae are to be modeled, then a variable stoichiometry is necessary.

Water quality models based on DO-BOD

37. The majority of BOD-DO models have evolved from the study of Streeter and Phelps (1925). They assumed that the balance between DO and BOD concentrations is the result of two processes only: the

reaeration of the stream and the consumption of DO in the oxidation or decay of BOD by first-order linear kinetics. This model still has utility, particularly in nontidal streams (Grantham, Schaake, and Pyatt 1971). Improvements in this scheme were made by Dobbins (1964) and Dresnack and Dobbins (1968) who added source and sink terms for DO due to plant photosynthesis and respiration or decomposition of bottom muds, and sink terms for BOD due to sedimentation and/or adsorbtion. These early models did not use the full time-dependent mass balance equation (Equation 1) and subsequent work corrected these deficiences (Whitehead and Young 1975; Beck 1973; Grantham, Schaake, and Pyatt 1971; O'Connor 1967). A further step in the development of DO-BOD models was made by O'Connor (1967) and O'Connor and DiToro (1970) where BOD and DO utilization were divided into nitrogenous and carbonaceous forms and rates. The two forms of BOD are associated with different types of sewage loading and different types of bacteria. The nitrogenous form is often associated with bottom sediments and benthic bacteria.

38. Further progress in model structure has been made by the introduction of nonlinear Monod (1942) or Michaelis-Menten kinetics. This hyperbolic growth rate has been used as a description of algae growth (Chen 1970; Steele 1974; Thomann, DiToro, and O'Connor 1974; Kremer and Nixon 1978) and for the growth of bacteria and protozoa in river sediments (Rutherford and O'Sullivan, 1974). One of the most comprehensive estuarine water quality models is that by Thomann, DiToro, and O'Connor (1974) and later developments by DiToro et al. (1977). In these models algae is a major compartment affecting both the nitrogen cycle and BOD-DO. It is noted that in all these models the rate constants of decay and growth, whether from linear kinetics or nonlinear Monod kinetics, are highly sensitive to temperature. Additionally, these models require forcings to be specified as functions of time. Forcings include temperature, light (for photosynthesis), wind (for reaeration), waste loading (for BOD), as well as the time-dependent tidal and nontidal estuarine flow.

39. Monod hyperbolic functions which relate growth to algae or bacteria to the substrate are almost universally used in water quality

and ecologic models. However, among biologists there are some doubts whether Monod kinetics are correct, particularly in multinutrient environments with hetrogeneous algal populations (Platt, Denman, and Jassby 1977). Models have been developed by Bierman et al. (1974) for phytoplankton species competition in a lake. Cell growth was treated as a two-step mechanism that involves separate nutrient uptake and cell synthesis processes and includes an intermediate storage capability. The mode of cell growth, i.e., assimilation and subsequent ingestion of nutrients, was thought to be more important in modeling growth dynamics than are the extremely complex chemical conversions within the cell.

40. It appears the more complex the model of DO-BOD, the more kinetic rate coefficients need to be determined; however, it is more likely that these rates can be determined independently through laboratory measurements of that process. For example, if algal respiration is included in the model structure, then measurements in the laboratory or in situ may be able to determine the range of values for the rate coefficient for which the model must produce reasonable results. If a number of processes are lumped into one coefficient as in the Streeter and Phelps (1925) model, then it is difficult to determine the decay coefficients independently of the simulation.

41. This point leads to the whole question of simulation and verification of water quality models. In almost all cases, it is necessary to determine some coefficients by fitting the model output to observations in the estuary or river. The determination of the longitudinal dispersion coefficient E_x has already been mentioned. This process is known as calibration. The hydrodynamic part and the kinetic parts of the model are regarded as being independent of each other. Once a model has been calibrated, then it must be verified against a completely independent set of data with no change in the parameters. Only then can the model be reliably used in a forecast mode. For example, DiToro et al. (1977) calibrated their phytoplankton model for the Potomac Estuary by using 1968 data. They verified it against 1969 data making only the required changes in the forcing functions, riverflows, light, waste-loading, etc. They achieved satisfactory agreement which

allowed confidence that the major physical, chemical, and biological processes were satisfactorily included in the model structure.

42. The models discussed so far are deterministic and parameterize the internal structure of the system. The alternative approach is the black box approach which is often used in rivers where time series of water quality variables measured at an upstream site are used to predict variables at a downstream site. This is often useful when combined with system analysis as advocated by Thomann (1972). It allows the use of various modeling hypotheses, within the black box, to be applied to a reach of a river and evaluated against data. A case study on the river Cam in England is given by Beck (1978). This stochastic modeling approach would be difficult to apply to an estuary with its reversing tidal flows.

43. A further question that arises in the use of models for managing aquatic systems concerns time dependency. Often steady-state models are used as a forecast of the long-term state the estuary or river will reach under various loadings. The time-dependent models are often used to study more short-term variability of the estuary. Of course, the latter require a great deal more computer resources than the former, and, therefore, the former are often a cheap way of investigating many different scenarios. There is a trend at present towards using time-dependent models for all situations, particularly for estuaries which are highly dynamic. Harlemann (1977) has pointed out that use of steady-state models of complex systems can lead to serious errors when compared to time-dependent models.

44. Reviews of water quality modeling may be found in the books edited by James (1978); Canale (1976); Biswas (1976); and Hatzinger, Vanlelgveld, and Zoeteman (1978); and in review articles by DiToro et al. (1977); Hahn and Schreiner (1978); and O'Connor, Thomann, and DiToro (1977). Perhaps one of the most successful uses of a simple kinetic model to assist in the clean up of an estuary is the study of the Water Pollution Research Laboratory in England on the Thames. This is assessed by Barrett, Mollowney, and Casapieri (1978).

Water quality models
not involving DO-BOD

45. Some modeling studies have been performed on estuaries where the primary interest is not DO-BOD or the higher trophic levels, but the distribution of silica. Silica is utilized by algae in the estuary and constant uptake rates are assumed which may vary with depth. A more complex depth-dependent, steady-state, two-dimensional circulation model is used (Festa and Hansen 1976), and the relations between advection, mixing, and uptake are more completely characterized (Peterson, Festa, and Conomos 1978). Recently, Rattray and Officer (1979) showed that very similar results could be obtained for San Francisco Bay by using a variation on the box model approach to characterize the circulation and mixing. This approach is considerably less costly than using the full numerical model. Silica uptake has also been studied for the Scheldt Estuary (The Netherlands) by Wollast (1977) using a simple model.

46. An interesting approach to water quality modeling in a highly polluted estuary, where nutrient limitation is not a factor, is taken by Nihoul et al. (1979) and Billen and Smitz (1977). Each chemical is considered in oxidized and reduced form through reversible reactions. Thus, the two forms together are conservative. The estuary is considered to be in thermodynamic equilibrium and redox potentials are involved as part of the solution. The final relationship between the eight separate reactions is made by considering the global oxygen budget. This makes the solution technique particularly elegant since the redox potentials which control the reactions are known from laboratory experiments. The authors admit, however, that thermodynamic equilibrium is not necessarily fulfilled throughout the estuary.

47. In contrast to models of BOD and nitrogen loading of estuaries, there have been few models of the fate and effects of heavy metals. One such model is that by Jorgensen (1979) which is based on the concept of trophic length levels recently introduced by Thomann (1979) where a length scale is introduced into the equations as an independent variable which represents the length of time a substance spends in a particular

trophic level. The fate of metals in an estuarine environment is very complicated, involving precipitation of metals by seawater, adsorbtion by suspended sediment, and biological uptake by algae and benthic organisms. The geochemistry of estuarine trace metals is discussed by Turekian (1977). A study, using a model based on population dynamics, of the uptake of heavy metals by benthic algae has been performed by Seip (1979) and Seip et al. (1979). This study compares the differences found between a polluted and nonpolluted Norwegian fjords.

Time and Length Scales

48. All water quality and ecologic models are forced systems. An important part of the construction of models is the question of resolution of the important time and length scales. To a large degree, the system will be governed by the scales of the hydrodynamics. Important scales range from the turbulent, on the order of a few centimetres and a few seconds; tidal, 12 to 25 hr and a few kilometres; wind, a few days and a few tens of kilometres; to riverflow, one to several months (flushing times) and tens to hundreds of kilometres. Of course, these scales are functions of the characteristic geometry (longitudinal, width, and depth) of the estuary. Modern time-dependent hydrodynamic models normally have time steps on the order of a few minutes to 1 hr and so should be able to resolve all the above scales except the turbulent, which is parameterized by eddy viscosity and diffusion coefficients. The degree to which they do so depends on the sophistication of the model and the number of space dimensions considered.

49. Biological and chemical processes also have characteristic length and time scales, some of which may be different from the physical scales. The main additional forcing mechanism is that of light which has diurnal and seasonal variability and also a depth scale associated with extinction by the water. If point and nonpoint sources for material (such as BOD waste) are separate from the freshwater flow, then their characteristic time and length scales also need to be considered. Ford and Thornton (1979) have reviewed time and length scales as they

affect ecological modeling of lakes. Patchiness of plankton in the marine environment has received some study because the nature of the variance is important for predators such as fish larvae. An example is the investigation by Steele and Henderson (1977) which confirms that important scales appear to be on the order of kilometres and days for the lower trophic levels in the North Sea. At horizontal scales less than 100 m, chlorophyll spectra were similar to the turbulent spectra of temperature. The 1-day time step is very common for ecological models (DiToro et al. 1977; Chen and Orlob 1972); however, Jamart et al. (1977) show that, for a depth- and time-dependent model of phytoplankton growth in the northeastern Pacific, due to the nonlinear nature of the light forcing, time steps of 6 min are required during times of rapid light changes. In some systems (i.e. Puget Sound) plankton cells may double in number in a few hours.

50. An example of the increasing sophistication of ecological models in taking account of the time scales of the physical medium is given by Kemp and Mitsch (1979). They suggest that the natural time variability, due to advection and turbulence, of the euphotic layer of a water body modifies interactive pressures between plankton populations. The growth and distribution of a plankton population are to some extent controlled by the water movements; for turbulent frequencies, which are of the same order as growth rates, heterogeneous populations are shown to coexist in the model. Without the turbulence, one population would out compete the others and completely and unrealistically dominate the water body.

51. The chemical and biological equations of water quality models have their own characteristic time scales determined by the kinetic rate coefficients. These time scales are usually on the order of 1 to 10 days; however, the linear kinetics of the model are the result of quasi-reversible chemical reactions that may take place very rapidly. DiToro (1976) has given some theoretical basis by which relatively slow linear kinetics are satisfactory. The thermodynamic equilibrium argument used by Nihoul et al. (1979) that employs redox potentials is very similar to that of DiToro (1976).

Summary

52. Table 2 summarizes examples of different kinds of models used for water quality in estuaries that have been discussed above. Again, this is a list of important models that are representative of different approaches and is not meant to be exhaustive.

PART V: ESTUARINE ECOSYSTEM MODELS

53. In the previous section, a number of water quality models, which were effectively applied estuarine ecosystem models, were discussed. In this section, estuarine ecosystem models are surveyed which attempt to further the knowledge of the interactions between the lower trophic levels and the various forcing mechanisms. A major difference between these models and water quality models is their historical line of development from marine ecologic studies.

Marine Models

54. Modeling primary production in the sea has a long history, which has been reviewed by Cushing (1975) in his book on marine ecology and fisheries. He stresses the abandonment of the agricultural model based on limiting nutrients for the predator-prey model and the regeneration of nutrients through rapid recycling of detritus. The majority of marine ecosystem models have concentrated on the nutrient-phytoplankton-zooplankton interactions where often there is only one compartment for each trophic level, but transfers between compartments are complex (Steele 1974). The reason for this is that the upper layers of the ocean are relatively homogeneous (compared with terrestrial systems) and phytoplankton species show only minor differences in basic chemical composition. It seems reasonable to lump all phytoplankton species into one compartment. These kinds of investigations do not involve any explicit spatial variation of state variables; however, this basic approach, which has been developed from the pioneering studies of Fleming (1939), Riley (1946, 1947), and Riley, Stommel, and Bumpus (1949), has been adapted to allow spatial as well as time variability in systems which have large physical gradients such as upwelling regions (Walsh 1971; O'Brien and Wroblewski 1973) and estuaries (Winter, Banse, and Anderson 1975; Kremer and Nixon 1978). The alternative approach advocated by Patten (1968) uses very complex model structures involving all critical components, which may involve many species, but the transfers between

components are generally simple, linear, and empirical. This kind of model tends to be very theoretical because data are not available for calibration of the transfers and has, therefore, been little used for aquatic systems.

55. The higher trophic levels, such as fish or shellfish, have been very rarely coupled to ecosystem models of the lower trophic levels. Green (1975) was among the first to model an entire ecosystem with her model of the Ross Sea. Models of population dynamics of fisheries are used for fishery management (Beverton and Holt 1957); examples of this approach applied to estuaries are given by Wyatt and Quasim (1973) and Seip et al. (1979).

Estuarine Models

56. Models of estuarine systems have tended to lag behind those of the marine system. Many of the more recent modeling efforts in the estuarine system have been theoretical in nature, i.e., have attempted to further the understanding of nature. One of the earliest estuarine ecological models was that of Pomeroy et al. (1972). This model was designed to simulate phosphorus flux in several Georgia estuaries. Bahr (1974) developed both linear and nonlinear models of energy flux in Georgia oyster beds. A similar model by Dame, Vernbert, and Bonnell (1977) on South Carolina oyster beds emphasized sensitivity analysis, i.e., critical components in the system. Show (1979) developed a hydrological-biological model to explain zooplankton distributions in a small lagoon on the Texas coast. Ferguson and Adams (1979) simulated the trophic dynamics of epifauna and juvenile fish of an eelgrass community in order to test their response to temperature.

57. Probably the two most important ecosystem models of the lower trophic levels of estuaries are by Winter, Banse, and Anderson (1975) and Kremer and Nixon (1978). The ecosystems are contrasted primarily by their physical dimensions and hydrodynamics. Winter, Banse, and Anderson (1975) constructed a model of primary production for the central basin of Puget Sound, which is a deep fjord with strong surface layer

stratification. The Kremer and Nixon (1978) model is for Narragansett Bay, which is a shallow, wide, and partially mixed estuary. It is noteworthy that both models are based on extensive investigations of the ecosystems carried out by many different investigators over many years.

58. The hydrodynamic basis of Winter, Banse, and Anderson (1975) is an analytical, steady-state, longitudinal, and depth-dependent model of the circulation and stratification as it is influenced by tidal mixing, river discharge, and wind. The primary production model was forced by observed nitrate and zooplankton concentration and solar insolation. Phytoplankton concentrations were simulated for April-June 1966 and April-May 1967. It was found that estuarine circulation with its associated upwelling from depth supplies the euphotic zone with algal seed stock and replenishes exhausted supplies of essential nutrients so that nutrient limitation is rarely a factor in algal growth rates. It was also found from the model that herbivore grazing and algal sinking were of secondary importance. The investigation is a good example of how a model can assist the quantitative analysis of the dynamics of phytoplankton blooms. New relationships between system components, such as the strong influence of physical environmental factors on phytoplankton growth, are often perceived, and experimental priorities are classified.

59. The state of the art in estuarine ecosystem modeling is probably represented by the Kremer and Nixon (1978) model of Narragansett Bay. A detailed energy flow model of the bay was developed based on information taken from various sources over a 20-year period. This conceptual model was much more simple than nature, yet too complicated to simulate. The model eventually chosen for simulation emphasized the plankton-nutrient components of this system (Figures 3 and 4). The six primary state variables included phytoplankton; smaller, primarily herbivorous zooplankton; ammonia; nitrate and nitrite; phosphate; and silicate. In contrast to Winter, Banse, and Anderson (1975), the nutrient cycle and zooplankton are included in the model and the strong interactions and feedback between the three major compartments are very important in the model formulation. Secondary compartments that were

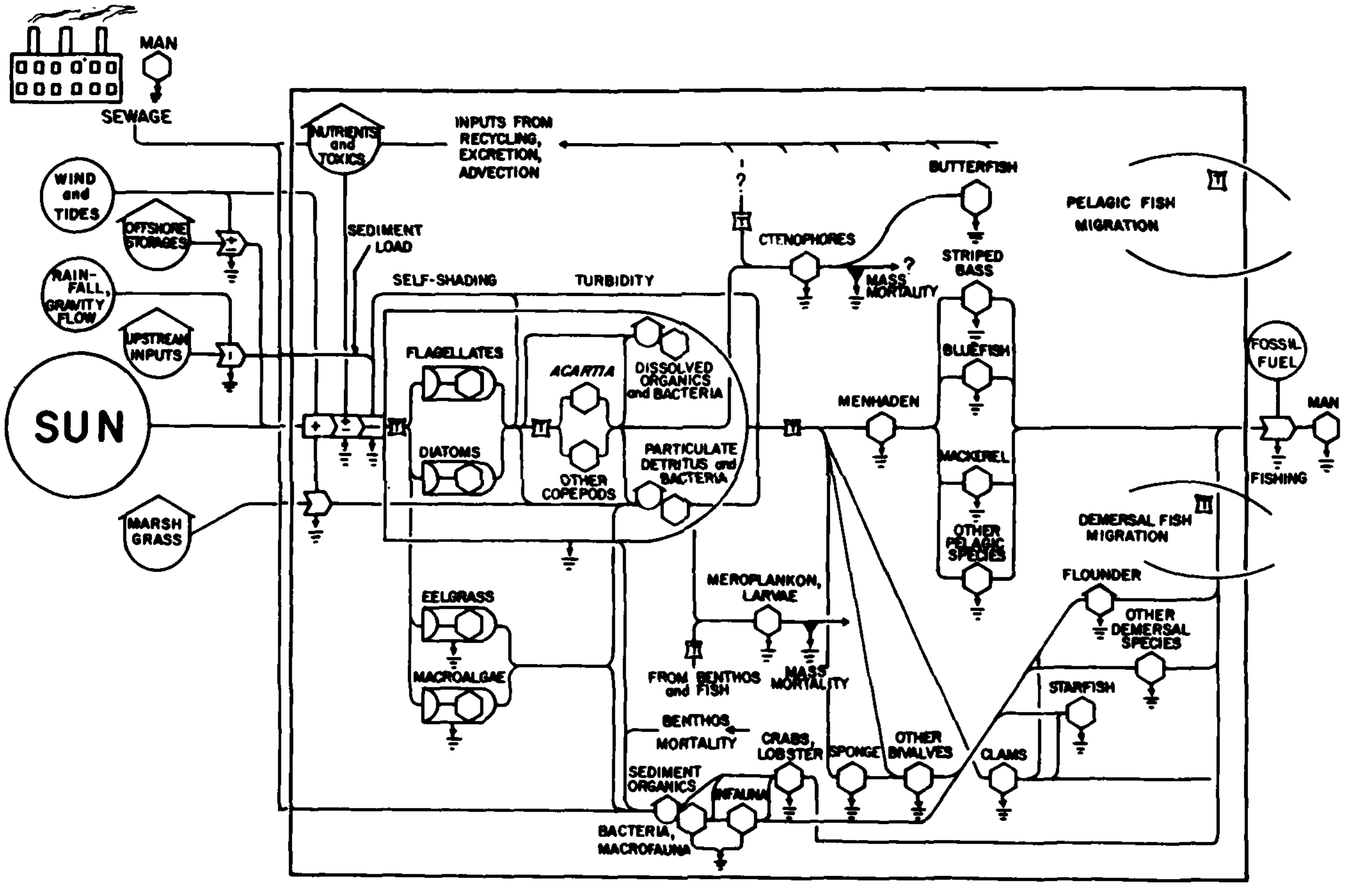

Figure 3. A complex, but still greatly simplified, energy flow diagram for the Narragansett Bay ecosystem on a summer day. This conceptual model was a first step in the process of abstraction that led to development of the numerical model (from Kremer and Nixon 1978, courtesy of Springer-Verlag, Inc.)

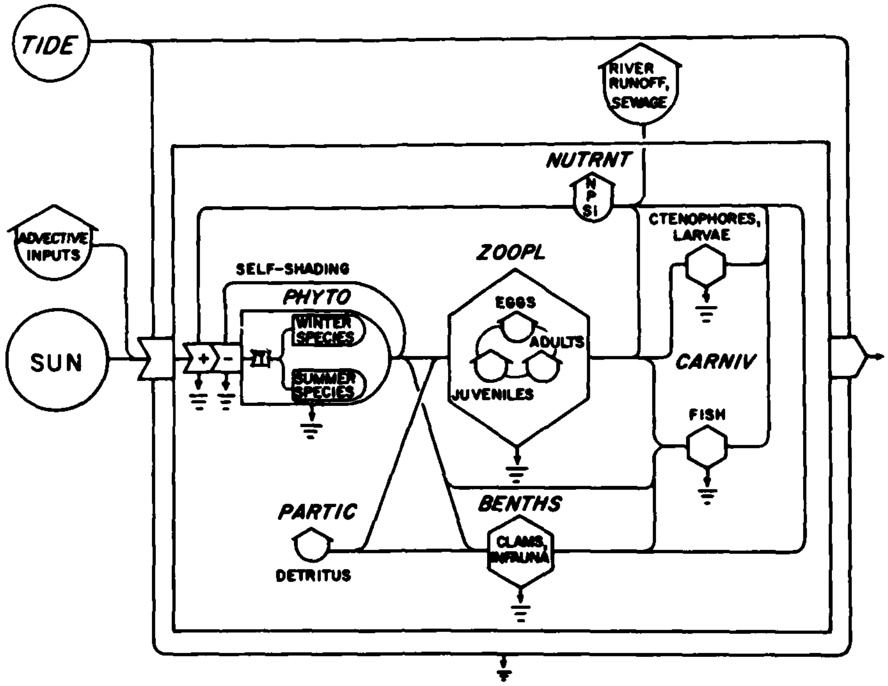

Figure 4. Final energy flow diagram and the conceptual framework for the numerical model of the Narragansett Bay ecosystem. While much of the complexity of Figure 3 has been omitted, some detail has been added in the zooplankton compartment. Only the phytoplankton, zooplankton, and nutrient compartments are fully simulated with mechanistic detail. This same conceptual model is used in each of the eight elements of the bay, with appropriate values for each compartment and forcing function (from Kremer and Nixon 1978, courtesy of Springer-Verlag, Inc.)

thought to be important influences on the plankton-nutrient system were included by forcing appropriate patterns when necessary to express feedbacks and internal controls. The primary control exerted by the higher trophic levels was predation by the benthos. Narragansett Bay was divided into eight areas, and the coupling to the hydrodynamics is described in Part IV. Simulations done in each area account for relatively large-scale spatial heterogeneity within the bay.

60. The model had various limitations that were discussed by Kremer and Nixon (1978). The model, at best, represents the current understanding of the Narragansett Bay system. In its present design,

the model cannot change to different system states that may result from large increases in inorganic inputs, drastic changes in salinity, etc. Hence, the model is limited as a management tool to those responses of the system due to small changes in parameters and processes that are specifically included in the formulation of the model. However, the model is essentially a complex tool designed to assist in the analysis of a complex estuarine ecosystem process and to integrate the data into an overall perspective and framework. As the authors point out, a model, no matter how realistic, cannot offer escape from value judgments and long links of supposition for the decisionmakers. An important point was that, if a management tool is contemplated, then the management objectives and related questions to be posed to the model should be specified from the outset.

Estuarine Management Models

61. Empirical models are often used in management-related studies and were discussed in Part IV. The models of O'Connor, DiToro and Mancine (1972); O'Connor, DiToro, and Thomann (1975); and Chen and Orlob (1972, 1975) have been applied to water quality problems in various aquatic systems around the country. O'Connor and his associates overcome the lack of data inherent in model building by adapting their models to the existing data base, whatever it may be, rather than the reverse (Orlob 1975). This tends to lead to aggregation (i.e., temporal and spatial averaging); however, the model tends to be amplified consistent with the data base and the level of detail required by decisionmakers. Kelly (1975) and Kelly and Spafford (1977) developed their ecological model of the Delaware River estuary specifically to answer management questions with regard to water quality problems. One of the goals of this exercise was to show how ecological models could be incorporated into wider scope management (optimization) models. The authors concluded, however, that a lack of appropriate data is the major limiting factor in constructing and validating ecological models used for management purposes.

Fishery Models

62. Another type of practical model widely used in the past is the fish population model. These models have generally emphasized single species and are not true ecological models in the sense that they do not show relationships between species. In view of the fact that most estuarine models have neglected the higher trophic levels except in a cursory way, applications of the information developed from these models may prove useful in building estuarine ecosystems models. Schaaf (1975) suggests that traditional fishery biology will benefit from a broader ecosystem viewpoint and that extensive data and population modeling of fishery biology can play an important role in refining ecological models.

PART VI: MARINE WETLAND ECOSYSTEM MODELS

63. Marsh ecosystems are biologically, chemically, and physically complex systems. Figure 5 shows one view of the relationships that exist between these parameters in terms of the carbon flux through the system. Three zones of ecological interaction are depicted in this diagram: (1) terrestrial interactions in the abovewater part of the marsh; (2) aquatic interactions within the water in the tidal creeks and on the marsh during high tide; and (3) interactions within the largely anaerobic sediments (Wiegert and Wetzel 1979). The earliest marsh models tended to concentrate on interactions within just one of these zones; more recent modeling efforts have incorporated interactions in all three of the zones, although at various levels of complexity.

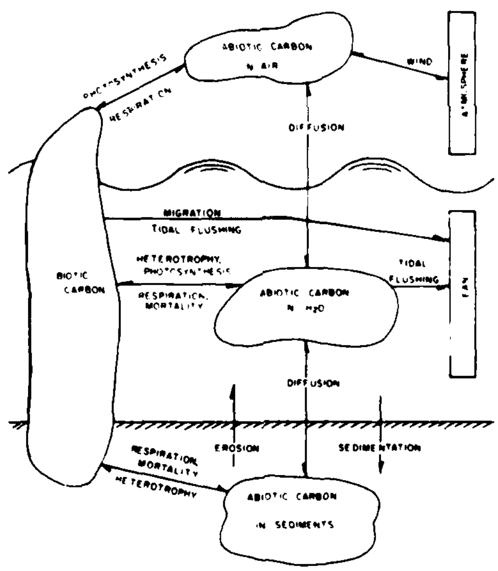

Figure 5. Diagram of carbon flow in a salt marsh. Carbon is viewed as either living or non-living and the marsh is divided into the air, water, and sediment zones (courtesy of Weigert and Wetzel 1979)

Marsh Zonal Models

64. Teal (1962) was among the first to use a conceptual model to demonstrate carbon flow through a system. This model concentrated on the biological components in the emergent portion of the marsh. The model was not developed beyond the conceptual stage.

65. Studies by Nixon and Oviatt (1973) emphasized energy flow in the marsh creeks and embayments that are linked with the tall grass stands and that serve as tidal pathways between the emergent marsh and the estuaries and offshore waters. Conceptual models were constructed for these habitats for both the summer and winter. A simulation model was developed which provided some quantitative detail in the conceptual model of diurnal dissolved oxygen in the tidal creeks and embayments.

66. Although the oxygen model included both biological and physical inputs, the amount of data available to construct the model and the need for simplification placed limits on the model (Nixon and Oviatt 1973). The model was used to simulate the effects of sewage input and temperature increases on oxygen concentrations in the embayments. Tidal inputs were found to have marked effects on the oxygen levels in the tidal creeks and embayments. The model in itself is useful in various respects, but, because of the limits inherent in the model, could best be utilized when coupled to a total ecosystem model. Predictions affecting biotic responses in a system could then be based on model results rather than extrapolating to the biota from data on oxygen concentrations in the system.

Integrated Marsh Models

67. More recent models have become more complex in their treatment of marsh ecosystems. Wiegert and Wetzel (1979) have developed a model of a Georgia Spartina marsh that includes seven biotic and seven abiotic compartments (Figure 6). This model represents a total ecosystem approach in that it incorporates biological, chemical, and physical interactions in the three ecological zones discussed earlier.

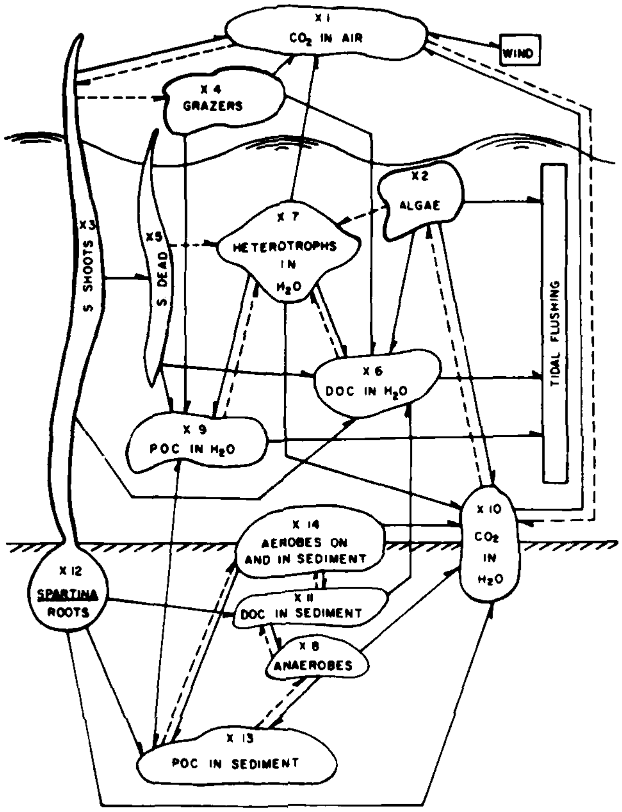

Figure 6. Pathways of carbon flux between the components of a 14-compartment salt marsh model continuing the structural and functional view outlined in Figure 5. Solid lines designate donor-controlled pathways. Dotted lines designate fluxes that respond to changes in either or both donor and recipient (courtesy of Weigert and Wetzel 1979)

Besides the 14 compartments, the model has 91 parameters and 44 fluxes.

68. The model is presently in its third, and final, version. Earlier versions of the model identified 21 parameters sensitive enough to change the final system steady-state organic accumulation by 0.5 percent (Wiegert et al. 1975). These sensitive parameters included the components: Spartina shoots and roots, algae, particulate organic sediments, sediment saprophages (both aerobic and anaerobic), and open-water heterotrophs. These earlier models also suggested that the scarcity of

space (as opposed to scarcity of material resources) is the major limiting factor for most components.

69. The most recent version of the model produced an acceptable simulation of the salt marsh system. The value of this model is that it has attempted to incorporate into the model all of the known physical and chemical processes which influence carbon fluxes. However, in order to simplify the model, compartments had to be generalized (e.g., grazers). This removed some of the usefulness of the model in predicting impacts to specific biotic components (e.g. birds). However, the model has been successful in satisfying its initial objective of describing and explaining the pathways and dynamics of carbon flow in the marsh.

70. Hopkinson and Day (1977) developed individual conceptual models for carbon and nitrogen flows in a Louisiana salt marsh. These two conceptual models were then combined to produce a single simulation model for the marsh system. This simulation model incorporated seven compartments from the carbon flow model and three nitrogen compartments. These latter compartments act in many places to control carbon flows. As in the Wiegert and Wetzel model, it was necessary to aggregate components of the ecosystem into single compartments. Hopkinson and Day (1977) recognized that this aggregation affected the realism of the model, which was evident in the model results. Probably the primary value of this modeling exercise is that it suggested new areas for further research and demonstrated the usefulness of models as a research tool besides being an end in itself.

71. Reimold (1974) and Zieman and Odum (1978) have developed models that simulated specific components of the system rather than taking the ecosystem approaches described above. Reimold's model was sensitive to discrete changes in _Spartina_ _alterniflora_. The model consisted of five compartments including water, sediments, _Spartina_ detritus and microflora, and detritus feeders. The model's usefulness lies in the capability of the model to predict the effects of perturbations on the _Spartina_ system.

72. Zieman and Odum's model simulated plant growth and succession on an estuarine salt marsh, based on an analysis of field studies of

Spartina alterniflora, S. patens, and Distichlis spicata and their response to tidal inundations. The model showed that plant growth and succession across a transect were controlled primarily by tidal inundation, with influences felt from radiation and temperature, but little influence due to salinity. The authors state that the model is limited in application due to incomplete parameterization of some of the processes, but has potential for wide applicability once these processes are better understood.

73. Extensive mangrove swamps are found in tropical and subtropical systems. Their greatest development in this country has occurred in Florida. These mangrove systems serve a similar function and importance as the salt marsh systems found in other parts of the country. Lugo, Sell, and Snedaker (1973) first constructed a conceptual model of these Florida mangrove systems to be used as a tool in designing research in the mangrove system. Inputs from this research were later used to provide a simulation of the system.

74. The simulation model was much less complex than the conceptual model and dealt only with mangrove production. As such, only three compartments were included in the simulation; these were mangrove biomass, detritus, and nutrients. Rate coefficients used in the simulation were based on average and/or maximum measured values. In addition, inputs to the nutrient pool from other than recycling were lumped to produce a single number. The model, then, is sufficient for simulating the system over the short term (months, weeks, or days) without redefining the constants. Therefore, the usefulness of the model would be a function of the long- or short-term nature of the questions the model needed to answer.

75. Several things are common in all of the models discussed above and should be mentioned. First is the multidisciplinary nature of the models: all incorporate various degrees of physical, chemical, and biological parameterization. Although in many cases it may be possible to model physical and chemical processes without significant biological inputs, it is not possible to model biological systems without these other processes. Therefore, any ecosystem modeling efforts should

involve the efforts of experts in the physical, chemical, and biological sciences.

76. Second, initial model building for most of the models included the construction of a conceptual model. Third, based upon this conceptual model, a research program was designed to satisfy the data needs identified in the conceptual model. Lastly, based on the data collected, the conceptual model was generally simplified and developed into a mathematical simulation model. The need to optimize research is always important and, because of the complexity of marshes, it is generally not feasible to model or measure all components of these ecosystems. This is the reason for the generalization and aggregation of ecosystem components seen in previous modeling efforts. Any modeling efforts in the future should, therefore, have well-defined objectives so that the model can provide answers for those questions for which it is designed.

Relationship between the Marsh and the Estuary

77. Perhaps the most important question facing the estuarine ecologist is the relation that exists between the marsh and the estuary. Gunnison (1978) has attempted to show the relationships that exist in his conceptual models of the marsh-estuarine system. Certainly, it can be said that the marsh-estuarine complex is intimately linked to produce a biologically productive system. It is generally accepted that the major importance of the estuary with respect to the marsh includes tidal inundation and nutrient input (both dissolved and particulate); the marsh is a major contributor of detritus and, to a lesser extent, dissolved minerals to the estuary (Gunnison 1978). Recently, however, this concept of a net import of materials on or off the marsh has begun to be questioned. In the studies of Nixon et al. (1976) on a Rhode Island salt marsh, the inorganic nutrients appeared to cycle within the sediment-detritus system of the embayment bottom suggesting little export of nutrients from the marsh during tidal exchanges with the estuary.

78. The investigation of the advective flux of material in shallow tidal creeks has proved to be very difficult. The usual method is

to use current meters and tide staffs and sample for the material concentration. Boon (1978) has given an illuminating analysis of the errors involved in calculating the flux of material in a Virginia tidal creek using a dense array of current meters that record current speed every minute. He showed that substantial errors in calculating a net flux are likely if only a few current meters are used with sample times of 30 min. Boon only sampled over a number of single tidal periods. Recently, Baylis-Smith et al. (1979) in a study of tidal creek flows in an English salt marsh showed that the net flux per tidal period can vary considerably over the spring-neap cycle; therefore, much longer sampling periods may be necessary in the future. Finally, Imberger (1979) has taken a new approach to the investigation of tidal creek flows by following water masses rather than measuring currents. He shows that the water masses maintain their integrity over many tidal cycles, implying that the exchange of detritus between the marsh and the tidal creek and the tidal creek and the estuary is probably small. There is the possibility, yet to be investigated, that storm events, such as thunderstorms and storm surges, effect a large flux of detritus from the marsh to the estuary at infrequent intervals.

79. The above discussion serves to point out the difficulty alluded to in earlier discussions on modeling of estuarine and marsh ecosystems, i.e., a lack of a basic understanding of processes within these systems. Gardner and Kitchens (1978) have reviewed the literature dealing with the exchange of sediments and chemicals between salt marshes and coastal waters. Their review showed that no clear patterns of marsh behavior are evident with the existing data.

80. Attempts to understand the marsh-estuarine complex are complicated by the variation that exists within and between even similar marsh systems (Gardner and Kitchens 1978). In a comparative evaluation of ten intertidal salt marshes in Rhode Island, Oviatt, Nixon, and Garber (1977) found an apparent lack of intercorrelation among the parameters which they studied (e.g. marshes with large crab populations may have few fish, those with many fish may not have many shrimp, etc.).

Similarly, *Spartina* production was not always directly related to animal numbers.

81. As the earlier discussions have shown, attempts to model the marsh-estuarine ecosystem have generally emphasized a particular component of this system (i.e., either the marshes or the estuary). The present lack of understanding of the processes working within this system (i.e., detrital export and import), and the relationships that exist there (e.g., macrophyte production and animal productivity), presently limit the ability to model the total system. Gardner and Kitchens (1978) suggest long-term, continuous collection of transport data in conjunction with intensive studies of the intertidal processes and external conditions that control exchanges between the marsh and the estuary to alleviate this lack of knowledge.

REFERENCES

Alabaster, J. S. 1973. "Oxygen in Estuaries: Requirements for Fisheries Water Pollution Research," Tech. Paper 13, Department of the Environment, HMSO, London, UK, pp 15-23.

Ariathurai, R., and Krone, R. B. 1976a. "Finite Element Model for Cohesive Sediment Transport," J. Hydraulics Div. ASCE, Vol 102, No. HY3, pp 323-338.

Ariathurai, R., and Krone, R. B. 1976b. "Mathematical Modeling of Sediment Transport in Estuaries," In Estuarine Processes, Vol 11, ed. Martin Wiley, Academic Press, New York.

Ariathurai, R., MacArthur, R. C., and Krone, R. B. 1977. "Mathematical Model of Estuarine Sediment Transport," Technical Report D-77-12, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

Bahr, L. 1974. "Aspects of the Structure and Function of the Intertidal Oyster Reef Community in Georgia," Ph.D. Dissertation, University of Georgia.

Barrett, M. J., and Mollowney, B. M. 1972. "Pollution in Relation to the Thames Barrier," Phil. Trans. Roy. Soc. A, Vol 272, pp 213-221.

Barrett, M. J., Mollowney, B. M., and Casapieri, P. 1978. "The Thames Model: An Assessment," Prog. Wat. Tech., Vol 10, pp 409-416.

Baylis-Smith, T. P., Healey, R., Lailey, R., Spencer, T., and Stoddart, D. R. 1979. "Tidal Flows in Salt Marsh Creeks," Estuarine and Coastal Marine Science, Vol 9, pp 235-255.

Beck, M. B. 1973. Ph.D. Thesis, University Engineering Department, Massachusetts Institute of Technology, Cambridge, MA.

Beck, M. B. 1978. "Modeling of Dissolved Oxygen in a Non-Tidal Stream," In Mathematical Models in Water Pollution Control, ed. A. James, Wiley-Interscience, New York, pp 137-166.

Beverton, R. J. H., and Holt, S. J. 1957. "On the Dynamics of Exploited Fish Populations," Fish. Invest. Lond. Ser. 2, Vol 19, p 533.

Bierman, V. J., Jr., Verhoff, F. H., Paulson, T. L., and Tenney, M. W. 1974. "Multi-Nutrient Dynamic Models of Algal and Species Competition in Eutrophic Lakes," In Modeling the Eutrophication Process, ed. E. J. Middlebrooks, D. H. Falkenborg, and T. E. Maloney, Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp 89-110.

Billen, G., and Smitz, J. 1977. "Mathematical Models of Water Quality in a Highly Polluted Estuary," In Hydrodynamics of Estuaries and Fjords, ed. J. C. J. Nihoul, Elsevier, Amsterdam, pp 55-62.

Biswas, A. K. 1976. Systems Approach to Water Management, McGraw-Hill, Inc., New York.

Blumberg, A. F. 1975. "A Numerical Investigation Into the Dynamics of Estuarine Circulation," Tech. Rep. 91, Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, MD.

Blumberg, A. F. 1977. "Numerical Tidal Model of Chesapeake Bay," J. Hydraulics Div. ASCE, Vol 103, No. HY1, pp 1-10.

Boicourt, W. B. 1979. "Three-Dimensional Circulation Processes in the Potomac River Estuary," Abstract in "Wetland and Estuarine Processes and Water Quality Modeling Workshop; Report and Recommendations," Technical Report, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, in preparation.

Boon, J. D. 1978. "Suspended Solids Transport in a Salt Marsh Creek - An Analysis of Errors," In Estuarine Transport Processes, ed. B. Kjerfve, University of South Carolina Press, Columbia, SC, pp 147-160.

Bowden, K. F. 1977. "Turbulent Processes in Estuaries," In Estuaries, Geophysics and the Environment, National Academy of Sciences, Washington, DC, pp 46-56.

Bowden, K. F., and Hamilton, P. 1975. "Some Experiments With a Numerical Model of Circulation and Mixing in a Tidal Estuary," Estuarine and Coastal Mar. Sci., Vol 3, pp 281-301.

Butler, H. L. 1979. "Evolution of a Numerical Model for Simulating Long-Period Wave Behavior in Ocean-Estuarine Systems," Estuarine and Wetland Processes, ed. P. Hamilton and K. B. Macdonald, Plenum Press, New York.

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems, Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Caponi, E. A. 1976. "The Simulation of Estuarine Circulations With a Fully Three-Dimensional Numerical Model," in Estuarine Processes, Vol 11, ed. Martin Wiley, Academic Press, New York, pp 332-346.

Chen, C. W. 1970. "Concepts and Utilities of Ecologic Model," Proc., J. Sanit. Eng. Div. ASCE, Vol 96, No. SA5, pp 1085-1097.

Chen, C. W., and Orlob, G. T. 1972. "Ecologic Simulation for Aquatic Environments, Rept. PB-218-828, Office of Water Resources Research, EPA, Washington, DC.

Chen, C. W., and Orlob, G. T. 1975. "Ecologic Simulation for Aquatic Environments," In Systems Analysis and Simulation in Ecology, Vol III, ed. B. C. Patten, Academic Press, New York, pp 476-588.

Cushing, D. H. 1975. Marine Ecology and Fisheries, Cambridge University Press, Cambridge, UK.

Dahl-Madsen, K. I. 1978. "Mathematical Modeling of Eutrophied Coastal Areas," Prog. Wat. Tech., Vol 10, pp 217-235.

Dame, R. F., Vernbert, F. J., and Bonnell, R. J. 1977. "Analysis of the North Inlet Marsh-Estuarine Ecosystem," Helgolander Wiss. Meresunters, Vol 30, pp 343-356.

Defant, A. 1961. Physical Oceanography, Vol II, Chapt XIII, Pergamon Press, Oxford, UK, pp 457-474.

DiToro, D. M. 1976. "Combining Chemical Equilibrium and Phytoplankton Models-A General Methodology," In Modeling Biochemical Processes in Aquatic Ecosystems, ed. R. P. Canale, Ann Arbor Science, Ann Arbor, MI, pp 233-256.

DiToro, D. M., Thomann, R. V., O'Connor, D. J., and Mancini, J. L. 1977. "Estuarine Phytoplankton Biomass Models--Verification Analysis and Preliminary Applications," In The Sea, Vol 6, ed. E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, Wiley-Interscience, New York, pp 969-1020.

Dobbins, W. E. 1964. "BOD and Oxygen Relationships in Streams," Proc., J. Sanit. Eng. Div. ASCE, Vol 90, No. SA3, pp 53-78.

Dresnack, R., and Dobbins, W. E. 1968. "Numerical Analysis of BOD and DO Profiles," Proc., J. Sanit. Eng. Div. ASCE, Vol 94, No. SA5, pp 789-807.

Dronkers, J. J. 1964. Tidal Computations in Rivers and Coastal Waters, John Wiley and Sons, New York.

Dyer, K. R. 1973. Estuaries: A Physical Introduction, John Wiley and Sons, London.

Dyer, K. R. 1977. "Lateral Circulation Effects in Estuaries," In Estuaries, Geophysics and the Environment, National Academy of Sciences, Washington, DC, pp 22-29.

Elliott, A. J. 1975. "A Steady State Two-Layered Non-Coupled Dynamic and Kinematic Estuarine Model With Application to the Potomac Estuary," Special Rep. 44, Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, MD.

Elliott, A. J. 1976. "A Numerical Model of the Internal Circulation in a Branching Estuary," Special Rep. 54, Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, MD.

Ferguson, R. L., and Adams, S. M. 1979. "A Mathematical Model of Trophic Dynamics in Estuarine Seagrass Communities," In Marsh-Estuarine Systems Simulation, ed. R. F. Dame, University of South Carolina Press, Columbia, SC, pp 41-70.

Festa, J. F., and Hansen, D. V. 1976. "A Two Dimensional Model of Estuarine Circulation: The Effects of Altering Depth and River Discharge," Estuarine and Coastal Marine Sci., Vol 4, pp 309-323.

Festa, J. F., and Hansen, D. V. 1978. "Turbidity Maxima in Partially Mixed Estuaries: A Two-Dimensional Numerical Model," Estuarine and Coastal Marine Sci., Vol 7, pp 347-359.

Fleming, R. H. 1939. "The Control of Diatom Populations by Grazing," J. Cons. Explor. Mer., Vol 14, pp 210-227.

Ford, D. E., and Thornton, K. W. 1979. "Time and Length Scales for the One-Dimensional Assumption and Its Relation to Ecological Models," Wat. Res. Res., Vol 15, pp 113-120.

Gardner, G. B., Nowell, A. M., and Smith, J. D. 1979. "Turbulent Processes in Estuaries," Estuarine and Wetland Processes, ed. P. Hamilton and K. B. Macdonald, Plenum Press, New York.

Gardner, L. R., and Kitchens, W. 1978. "Sediment and Chemical Exchanges Between Salt Marshes and Coastal Waters," In Estuarine Transport Processes, ed. B. Kjerfve, University of South Carolina Press, Columbia, SC.

Gordon, R., and Spaulding, M. 1974. "A Bibliography of Numerical Models for Tidal Rivers, Estuaries, and Coastal Rivers," Marine Tech. Rep. 32, Dept. Ocean Engineering, University of Rhode Island, Kingston, RI.

Grantham, G. R., Schaake, J. C., and Pyatt, E. E. 1971. "Water Quality Simulation Model," Proc., J. Sanit. Eng. Div. ASCE, Vol 97, No. SA5, pp 569-585.

Gray, W. G., Pinder, G. F., and Brebbia, C. A. 1977. Finite Elements in Water Resources, Peutech Press, London, UK.

Green, K. A. 1975. "Simulation of the Pelagic Ecosystem of the Ross Sea. Antarctica: A Time Varying Compartment Model," Ph.D. Dissertation, Texas A&M University, College Station, TX.

Gunnison, D. 1978. "Mineral Cycling in Salt Marsh - Estuarine Ecosystems. Technical Report D-78-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

Hahn, H. H., and Schreiner, H. 1978. "Water Quality Modeling," Prog. Wat. Tech., Vol 10, pp 185-201.

Hamilton, P. 1975. "A Numerical Model of the Vertical Circulation of Tidal Estuaries and Its Application to the Rotterdam Waterway. Geophysical J. Roy. Astr. Soc., Vol 40, pp 1-21.

Hamilton, P. 1976. "On the Numerical Formulation of a Time-Dependent Multi-Level Model of an Estuary, With Particular Reference to Boundary Conditions," In Estuarine Processes, Vol 2, ed. M. Wiley, Academic Press, New York, pp 347-363.

Hamilton, P. 1979a. "Survey of Wetland and Estuarine Water Quality and Ecosystem Problems," Technical Report, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, in preparation.

Hamilton, P. 1979b. "Wetland and Estuarine Processes and Water Quality Modeling: Workshop Report and Recommendations," Technical Report, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, in preparation.

Hamilton, P., and Macdonald, K. B. 1980. Estuarine and Wetland Processes, Plenum Press, New York.

Hansen, D. V., and Rattray, M., Jr. 1965. "Gravitational Circulation in Straits and Estuaries," J. Marine Res., Vol 23, pp 104-122.

Harlemann, D. R. F. 1977. "Real-Time Models for Salinity and Water-Quality Analysis in Estuaries," In Estuaries, Geophysics and the Environment, National Academy of Sciences, Washington, DC, pp 84-93.

Hatzinger, O., Vanlelgveld, I. H., and Zoeteman, B. C. J. 1978. Aquatic Pollutants: Transformation and Biological Effects, Pergamon, Oxford, UK.

Head, P. C. 1976. "Organic Processes in Estuaries," In Estuarine Chemistry, ed. J. D. Burton and P. S. Liss, Academic Press, New York, pp 53-91.

Heaps, N. S. 1974. "Development of a Three-Dimensional Numerical Model of the Irish Sea," Rapp. P.-V. Reun. Cons. Int. Explor. Mer., Vol 167, pp 147-162.

Hess, K. W., and White, F. M. 1974. "A Numerical Tidal Model of Narragansett Bay," Marine Tech. Rept. 20, Dept. of Ocean Engineering, University of Rhode Island, Kingston, RI.

Hess, K. W., and White, F. M. 1977. "Modeling the Disposal of a Marked Fluid in Narragansett Bay," Marine Tech. Rep. 38, Dept. of Ocean Engineering, University of Rhode Island, Kingston, RI.

Hinwood, J. B., and Wallis, I. G. 1975a. "Classification of Models of Tidal Waters," J. Hydraulics Div. ASCE, Vol 101, No. HY10, pp 1315-1331.

Hinwood, J. B., and Wallis, I. G. 1975b. "Review of Models of Tidal Waters," J. Hydraulics Div. ASCE, Vol 101, No. HY11, pp 1405-1421.

Hodgins, D. O. 1979. "A Time-Dependent Two-layer Model of Fjord Circulation and Its Application to Alberni Inlet, British Columbia," Estuarine and Coastal Mar. Sci., Vol 8, pp 361-378.

Hopkinson, C. S., and Day, J. W. 1977. "A Model of the Barataria Bay Salt Marsh Ecosystem," In Ecosystem Modeling in Theory and Practice, ed. C. A. S. Hall and J. W. Day, John Wiley and Sons, New York, pp 235-266.

Imberger, J. 1980. In press, Limnology and Oceanography.

Jamart, B. M., Winter, D. F., Banse, K., Anderson, G. C., and Lam, R. K. 1977. "A Theoretical Study of Phytoplankton Growth and Nutrient Distribution in the Pacific Ocean Off the Northwestern U. S. Coast," Deep-Sea Res., Vol 24, pp 753-773.

James, A. 1978. Mathematical Models in Water Pollution Control, Wiley-Interscience, New York.

Johns, B. 1978. "The Modeling of Tidal Flow in a Channel Using a Turbulence Energy Closure Scheme," J. Phys. Oceanogr., Vol 8, pp 1042-1049.

Jorgensen, S. E. 1979. "Modeling the Distribution and Effects of Heavy Metals in an Aquatic Ecosystem," Ecol. Modeling, Vol 6, pp 199-222.

Kelly, R. A. 1975. "The Delaware Estuary Model," In Ecological Modeling in a Resource Management Framework, ed. C. S. Russell, Resources for the Future, Inc., Washington, DC.

Kelly, R. A., and Spafford, W. O. 1977. "Application of an Ecosystem Model to Water Quality Management. The Delaware Estuary," In Ecosystem Modeling in Theory and Practice: An Introduction With Case Histories, ed. C. S. Russell, Resources for the Future, Inc., Washington, DC.

Kemp, W. M., and Mitsch, W. J. 1979. "Turbulence and Phytoplankton Diversity: A General Model of the Paradox of Plankton," Ecol. Modeling, Vol 7, pp 201-222.

Kjerfve, B. 1978. Estuarine Transport Processes, University of South Carolina Press, Columbia, SC.

Kremer, J. N., and Nixon, S. W. 1978. A Coastal Marine Ecosystem: Simulation and Analysis, Springer-Verlag, New York.

Kuo, A., Nichols, M., and Lewis, J. 1978. "Modeling Sediment Movement in the Turbidity Maximum of an Estuary," Bulletin 111, Virginia Water Resources Research Center, Virginia Institute of Marine Science, Gloucester Point, VA.

Leendertse, J. J., and Gritton, E. C. 1971. "A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol III - Jamaica Bay Simulations," Rept. R-709-NYC, Rand Corp., Santa Monica, CA.

Leendertse, J. J., and Liu, S-K. 1975. "A Three Dimensional Model for Estuaries and Coastal Seas: Vol II - Aspects of Computation," Rept. 5-1764-OWRT, Rand Corp, Santa Monica, CA.

Leendertse, J. J., and Liu, S-K. 1977. "A Three Dimensional Model for Estuaries and Coastal Seas: Vol IV - Turbulent Energy Computation," Rept. R-2187-OWRT, Rand Corp., Santa Monica, CA.

Liu, S-K., and Leendertse, J. J. 1978. "Multidimensional Numerical Modeling of Estuaries and Coastal Seas," In Advances in Hydroscience, Vol 13, pp 95-164.

Lugo, A. E., Sell, M., and Snedaker, S. C. 1976. "Mangrove Ecosystem Analysis," In Systems Analysis and Simulation in Ecology, Vol IV, ed. B. C. Patten, Academic Press, New York, pp 113-145.

McDowell, D. M., and O'Connor, B. A. 1977. Hydraulic Behavior of Estuaries, John Wiley and Sons, New York.

Monod, J. 1942. Recherches Sur la Croissance des Cultures Bacteriennes, Hermann et Cie, Paris.

Nihoul, J. C. J., Ronday, F. C., Smitz, J., and Billen, G. 1979. "Hydrodynamic and Water Quality Model of the Scheldt Estuary," In Marsh-Estuarine System Simulation, ed. R. F. Dame, University of South Carolina Press, Columbia, SC, pp 71-82.

Nixon, S. W., and Oviatt, C. A. 1973. "Ecology of a New England Salt Marsh," Ecol. Monographs., Vol 43, pp 463-498.

Nixon, S., Candace, W., Oviatt, A., Gerber, J., and Lee, V. 1976. "Diel Metabolism and Nutrient Dynamics in a Salt Marsh Embayment," Ecology, Vol 57, pp 740-750.

O'Brien, J. J., and Wroblewski, J. S. 1972. "Analysis of a Nutrient-Limited Phytoplankton Model," Florida State University, Unpublished MS.

O'Connor, D. J. 1967. "The Temporal and Spatial Distribution of Dissolved Oxygen in Streams," Water Resources Res., Vol 3, pp 65-79.

O'Connor, D. J., and DiToro, D. M. 1970. "Phytosynthesis and Oxygen Balance in Streams," Proc., J. Sanit. Eng. Div.' ASCE, Vol 96, No. SA2, pp 547-571.

O'Connor, D. J., DiToro, D. M., and Mancine, J. L. 1972. "Mathematical Model of Phytoplankton Dynamics in the Sacramento-San Joaquin Bay Delata," Hydroscience, Inc., Westwood, NJ.

O'Connor, D. J., DiToro, D. M., and Thomann, R. V. 1975. "Phytoplankton Models and Eutrophication Problems," in Ecological Modeling in a Resource Management Framework, ed. C. S. Russell, Resources for the Future, Inc., Washington, DC, pp 149-210.

O'Connor, D. J., Thomann, R. V., and DiToro, D. M. 1977. "Water Quality Analyses of Estuarine Systems," In Estuaries, Geophysics and the Environment, National Academy of Sciences, Washington, DC, pp 71-83.

Odd, N. V. M., and Owen, M. W. 1972. "A Two Layer Model of Mud Transport in the Thames Estuary," Proc. Inst. Civil Engineers, London, Vol 9, Paper 75175 Suppl., p 175.

Officer, C. B. 1976. Physical Oceanography of Estuaries (and Associated Coastal Waters), John Wiley and Sons, New York.

Officer, C. B. 1980. "Box Models Revisited," Estuarine and Wetland Processes, ed. P. Hamilton and K. B. Macdonald, Plenum Press, New York.

Orlob, G. T. 1975. "Present Problems and Future Prospects of Ecological Modeling," In Ecological Modeling in a Resource Management Framework, ed. C. S. Russell, Resources for the Future, Inc., Washington, DC.

Oviatt, C. A., Nixon, S. W., and Garber, J. 1977. "Variation and Evaluation of Coastal Salt Marshes," Environ. Manag., Vol 1, pp 201-211.

Patten B. C. 1968. "Mathematical Models of Plankton Production," Int. Rev. Ges. Hydrobiol., Vol 53, pp 357-408.

Patten, B. C. 1971. "A Primer for Ecological Modeling and Simulation With Analog and Digital Computers," In Systems Analysis and Simulation in Ecology, Vol. I, Academic Press, New York, pp 3-121.

Pearson, C. E., and Winter, D. F. 1977. "On the Calculation of Tidal Currents in Homogeneous Estuaries," J. Phys. Oceanogr., Vol 7, pp 520-531.

Peterson, D. H., Festa, J. F., and Conomos, T. J. 1978. "Numerical Simulation of Dissolved Silica in San Francisco Bay," Estuarine and Coastal Mar. Sci., Vol 7, pp 99-116.

Pitbaldo, R. M., and Prince, R. G. H. 1977. "The Application of a Two-Layer Time Dependent Model to Pollution Assessment and Control in a Short Stratified Estuary," Prog. Wat. Tech., Vol 9, pp 217-231.

Platt, R., Denman, K. L., and Jassby, A. D. 1977. "Modeling the Productivity of Phytoplankton," In The Sea, Vol 6, ed. E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, Wiley-Interscience, New York, pp 807-856.

Pomeroy, L. R., Shenton, L. R., Jones, R. D. H., and Permold, R. J. 1972. "Nutrient Flux in Estuaries," Limnology Oceanography Special Sym., Vol 1, pp 274-291.

Pritchard, D. W. 1969. "Dispersion and Flushing of Pollutants in Estuaries," J. Hydraulics Div. ASCE, Vol 95, No. HY1, pp 115-124.

Rattray, M., Jr. 1967. "Some Aspects of the Dynamics of Circulation in Fjords," In Estuaries, ed. G. H. Lauff, American Association for the Advancement of Science, pp 52-62.

Rattray, M., Jr., and Hansen, D. V. 1962. "A Similarity Solution for Circulation in an Estuary," J. Marine Res., Vol 20, pp 121-133.

Rattray, M., Jr., and Officer, C. B. 1979. "Distribution of a Non-Conservative Constituent in an Estuary With Application to the Numerical Simulation of Dissolved Silica in the San Francisco Bay," Estuarine and Coastal Mar. Sci., Vol 8, pp 489-494.

Reid, R. O., Vastano, A. C., and Reid, R. J. 1977a. "Development of Surge II Program With Application to the Sabine-Calcasieu Area for Hurricane Carla and Design Hurricanes," Tech. Paper. No. 77-13, U. S. Army Corps of Engineers, Coastal Engineering Research Center.

Reid, R. O., Vastano, A. C., Whitaker, R. E., and Wanstrath, J. J. 1977b. "Experiment in Storm Surge Simulation," In The Sea, ed. E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, John Wiley and Sons, New York, pp 393-406.

Reimold, R. J. 1974. "Mathematical Modeling - Spartina," In Ecology of Halophytes, ed. R. J. Reimold and W. H. Queen. Academic Press, New York, pp 393-406.

Riley, G. A. 1946. "Factors Controlling Phytoplankton Populations on Georges Bank," J. Mar. Res., Vol 6, pp 54-73.

Riley, G. A. 1947. "A Theoretical Analysis of the Zooplankton Population of Georges Bank," J. Mar. Res., Vol 6, pp 104-113.

Riley, G. A., Stommel, H., and Bumpus, D. F. 1949. "Quantitative Ecology of the Plankton of the Western North Atlantic," Bull. Bingham Oceanogr. Coll., Vol 12, pp 1-169.

Rutherford, J. C., and O'Sullivan, M. I. 1974. "Simulation of Water Quality in Tarawera River," Proc., J. Env. Eng. Div. ASCE, Vol 100, No. EE2, pp 315-331.

Schaaf, W. E. 1975. "Fish Population Models: Potential and Actual Links to Ecological Models," In Ecological Modeling in a Resource Management Framework, ed. C. S. Russell, Resources for the Future, Inc., Washington, DC.

Seip, K. L. 1979. "A Mathematical Model for the Uptake of Heavy Metals in Benthic Algae," Ecol. Modeling, Vol 6, pp 183-197.

Seip, K. L., Lunde, G., Melsom, S., Mehlum, E., Melhuus, A., and Seip, H. M. 1979. "A Mathematical Model for the Distribution and Abundance of Benthic Algae in a Norwegian Fjord," Ecol. Modeling, Vol 6, pp 133-166.

Show, I. T. 1979. "An Application of Compartmental Models to Meso-Scale Marine Ecosystems," In Ecosystem Models, Statistical Ecology Series, Vol 10, ed. J. H. Matis, B. C. Patten, and G. C. White, International Cooperative Publ. House, Burtonsville, MD, pp 73-97.

Steel, J. H. 1974. The Structure of Marine Ecosystems, Harvard University Press, Cambridge, MA.

Steele, J. H., and Henderson, E. W. 1977. "Plankton Patches in the Northern North Sea," In Fisheries Mathematics, ed. J. H. Steele, Academic Press, London, pp 1-20.

Stigter, C., and Siemons, J. 1967. "Calculation of Longitudinal Salt Distribution as a Function of Time," Delft Hydraulics, Lab. Publ. No. 52.

Streeter, H. W., and Phelps, E. B. 1925. "A Study of the Pollution and Natural Purification of the Ohio River," Bulletin No. 146, U. S. Public Health Service.

Taft, J. L., Elliott, A. J., and Taylor, W. R. 1978. "Box Model Analysis of Chesapeake Bay Ammonium and Nitrate Fluxes," In Estuarine Interactions, Academic Press, New York, pp 115-130.

Teal, J. M. 1962. "Energy Flow in the Salt Marsh Ecosystem of Georgia," Ecology, Vol 43, pp 614-624.

Thatcher, M. L., and Harleman, D. R. F. 1972. "A Mathematical Model for the Prediction of Unsteady Salinity Intrusion in Estuaries," Tech. Rep. No. 144, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Eng., MIT, Cambridge, MA.

Thomann, R. V. 1972. "Systems Analysis and Water Quality Management," Report, Environmental Research and Applications, Inc., New York.

Thomann, R. V. 1979. A Trophic-Length Level Model of the Fate of Hazardous Substances in the Aquatic Food Chain, EPA Report (In Press).

Thomann, R. V., DiToro, D. M., and O'Connor, D. J. 1974. "Preliminary Model of Potomac Estuary Phytoplankton," Proc., J. Env. Eng. Div. ASCE, Vol 100, No. EE3, pp 699-715.

Turekian, K. K. 1977. "The Fate of Metals in Estuaries," In Estuaries, Geophysics and the Environment, National Academy of Sciences, Washington, DC, pp 121-127.

Vernberg, F. J. 1971. "Dissolved Oxygen: Animals," In Marine Ecology, ed. O. Kinne, Wiley-Interscience, New York.

Vreugdenhil, C. B. 1970. "Computation of Gravity Currents in Estuaries," Delft Hydraulics Laboratory, Publ. No. 86.

Walsh, J. J. 1971. "Relative Importance of Habitat Variables in Predicting the Distribution of Phytoplankton at the Ecotone of the Antarctic Upwelling System," Invest. Presq., Vol 35, pp 309-330.

Wang, D-P. 1980. "Observation and Modeling of the Circulation in the Chesapeake Bay," Estuarine and Wetland Processes, ed. P. Hamilton and K. B. Macdonald, Plenum Press, New York.

Wang, D-P., and Kravitz, D. W. 1980. "A Semi-Implicit Two-Dimensional Model of Estuarine Circulation," J. Phys. Oceanogr., Vol 10, pp 441-454.

Wang, J. D., and Connor, J. J. 1975. "Mathematical Modeling of Mean Coastal Circulation," Rept. No. 200, Ref. R75-19, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, MIT, Cambridge, MA.

Whitehead, P. G., and Young, P. C. 1975. "A Dynamic Stochastic Model for Water Quality in Part of the Bedford-Ouse River System," In Computer Simulation of Water Resources Systems, North-Holland Publishing Co., Amsterdam, pp 417-438.

Wiegert, R. G., Christina, R. R., Gallagher, J. L., Hall, J. R., Jones, R. D. H., and Wetzel, R. C. 1975. "A Preliminary Ecosystem Model of a Coastal Georgia Spartina Marsh," In Estuarine Research, Vol I-Chemistry, Biology and the Estuarine System, ed. L. E. Cronin, Academic Press, New York, pp 583-601.

Wiegert, R. G., and Wetzel, R. C. 1979. "Simulation Experiment with a Fourteen-Compartment Model of a Spartina Salt Marsh," In Marsh-Estuarine Systems Simulation, ed. R. F. Dame, University of South Carolina Press, Columbia, SC, pp 7-39.

Williams, D. J. A., and West, J. R. 1973. "A One-Dimensional Representation of Mixing in the Tay Estuary," Water Pollution Research Tech. Paper 13, Department of the Environment, HMSO, London, pp 118-125.

Winter, D. F. 1973. "A Similarity Solution for Steady State Gravitational Circulation in Fjords," Estuarine and Coastal Mar. Sci., Vol 1, pp 387-400.

Winter, D. F., Banse, K., and Anderson, G. C. 1975. "The Dynamics of Phytoplankton Blooms in Puget Sound, a Fjord in the Northwestern United States," Mar. Biol., Vol 29, pp 139-176.

Wollast, R. 1977. "Modeling of Biological and Chemical Processes in the Scheldt Estuary," In Hydrodynamics of Estuaries and Fjords, ed. J. C. J. Nihoul, Elsevier, Amsterdam, pp 63-77.

Wyatt, T., and Quasim, S. Z. 1973. "Application of a Model to an Estuarine Ecosystem," Limnol. Oceanogr., Vol 18, pp 301-306.

Zieman, J. C., and Odum, W. E. 1978. "Modeling of Ecological Succession and Production in Estuarine Marshes," Technical Report D-77-35, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

Zitta, V. L., Shindala, A., and Corey, M. W. 1977. "A Two Dimensional Mathematical Model for Water Quality Planning in Estuaries," Water Resources Res., Vol 13, pp 55-61.

Table 1

Representative Types of Hydrodynamic Models of Estuaries

Reference	Dimensions	Solution Technique	Variables	Equations	Forcing	Application
Elliott (1975)	x (2 layer)	Noncoupled kinematic and dynamic box model	$s_{u,l}(x)$ $u_{u,l}(x)$ K_v, K_h	Continuity Salt balance u-momentum (approximated)	Riverflow	Potomac Estuary
Hamilton (1975) Blumberg (1975) Wang and Kravitz (1979)	x,z,t	Explicit Finite differences Semi-implicit	$\zeta(x,t)$ $u(x,z,t)$ $w(x,z,t)$ $s(x,z,t)$	Continuity u-momentum Salt conservation	Riverflow and tide + wind	Rotterdam Waterway Potomac Estuary
Hodgins (1979)	x,t (2 layer)	Finite differences Semi-implicit	$\zeta(x,t)$ $h(x,t)$ $u_{u,l}(x,t)$ $s_{u,l}(x,t)$	Continuity u-momentum Salt conservation	Wind Riverflow	Alberni Inlet, British Columbia
Johns (1978)	x,z,t	Finite differences Explicit x-coord Semi-implicit z-coord	$\zeta(x,t)$ $u(x,z,t)$ $w(x,z,t)$ $E(x,z,t)$	Continuity u-momentum Turbulent energy	Tide	Rectangular uniform channel
Reid et al. (1977a)	x,y,t	Explicit Finite differences (subgrid scale) (channels & barriers)	$\zeta(x,y,t)$ $\bar{u}(x,y,t)$ $\bar{v}(x,y,t)$	Continuity $\bar{u}$-momentum $\bar{v}$-momentum	Tide & wind	Sabine-Calcasieu area of gulf coast
Pearson and Winter (1977)	x,y,t	Finite elements (time decomposed into tidal harmonics ω)	$\zeta(x,y,\omega)$ $\bar{u}(x,y,\omega)$ $\bar{v}(x,y,\omega)$	Continuity $\bar{u}$-momentum $\bar{v}$-momentum	Tide	Hood Canal Wash. (Jamart personel communication)
Liu and Leendertse (1978)	x,y,z,t	Finite differences Semi-implicit	$\zeta(x,y,t)$ $u(x,y,z,t)$ $v(x,y,z,t)$ $w(x,y,z,t)$ $s(x,y,z,t)$ $E(x,y,z,t)$	Continuity u-momentum v-momentum Salt conservation Turbulent energy	Tide Wind Riverflow	Long Island Sound San Francisco Bay Chesapeake Bay

Variable	Definition
x	Longitudinal horizontal axis
y	Across-channel horizontal axis
z	Depth axis
t	Time
ω	Harmonic decomposition of time (i.e., $\zeta(x,t) = \Sigma A_n(x)\exp(i\omega_n t)$)
u,v,w	Velocities in the x-, y-, and z-directions, respectively
$\bar{u},\bar{v}$	Depth-averaged velocities in the x- and y-directions, respectively
s	Salinity
E	Turbulent kinetic energy
ζ	Free surface elevation
h	Interface depth of two-layer models
K_v, K_h	Vertical and horizontal turbulent diffusion coefficients, respectively
Superscripts u,l	Upper and lower layers, respectively

Table 2

Representative Types of Water Quality Models of Estuaries

Reference	Hydrodynamic Circulation Submodel*	Water Quality State Variables	Kinetics and Comments	Forcing	Application
Barrett and Mollowney (1972)	1-D tidally averaged box model	Organic carbon, organic nitrogen, ammonia, nitrate, DO	Linear Anerobic kinetics included when DO < 5% saturation	Tidal amplitude riverflow, wind, carbonacous and nitrogenous loads, temperature	Thames Estuary (U.K.)
Nihoul et al. (1979)	1-D time-dependent dynamic transport dispersion model	DO, nitrate, ammonia, iron, manganese	Thermodynamic equilibrium assumed. Redox potentials control reaction rates assumed to be due to bacterial activity Highly polluted - no nutrient limitation	Tide, riverflow	Scheldt (The Netherlands)
Leendertse and Gritton (1971) Leendertse and Liu (1975)	2-D (horizontal) time-dependent dynamic transport-dispersion model	Coliforms, salinity (chlorides), DO-BOD	Linear	Tide, fresh and storm drain flow, BOD load, wind	Jamaica Bay (N.Y.)
Chen and Orlob (1972)	1-D time-dependent link-mode dynamic transport-dispersion model	Temperature, salinity ammonia nitrogen, nitrate nitrogen, phosphorus, DO-BOD, algae (2), zooplankton, fish (2)	Linear and Monod	Tide, riverflow, waste and nutrient loads, wind, light	San Francisco Bay Delta System
DiToro et al. (1977)	1-D tidally averaged transport-dispersion model	DO-BOD, phosphorus (organic and inorganic), silica, nitrogen (nitrate, ammonia, organic), phytoplankton, zooplankton	Linear and Monod	Tide, riverflow, wind, temperature, light, carbonaceous and nitrogenous waste loads	San Francisco Bay-Delta System Potomac Estuary
Dahl-Madsen (1978)	Box models or 1-D time-dependent transport-dispersion model	Phytoplankton (carbon, nitrogen, phosphorus), zooplankton (carbon), detritus (carbon, nitrogen, phosphorus), inorganic nitrogen, inorganic phosphorus, DO - BOD, sediment carbon	Linear and Monod	Riverflow, tide, temperature, light, nutrient and organic loads	Various Danish fjords and estuaries Principally Limfjorden
Seip (1979) and Seip et al. (1979)	None (observed hydrographic regime used as forcing for four-layer, four- horizontal section model)	Benthic algae (8 age classes), biomass, zinc, iron	Model of population dynamics with toxicity-related mortality	Light, salinity, temperature, nitrogen (limiting nutrient)	Hardanger fjord Sorfjorden Trondheims fjorden (Norway)

* 1-D = one dimensional; 2-D = two dimensional.

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References: p. 40-51.

1. Ecosystems. 2. Estuarine ecology. 3. Estuary models. 4. Hydrodynamics. 5. Marine environment. 6. Models. 7. Sediment transport models. 8. Water quality models. 9. Wetlands. I. Fucik, Kenneth W., joint author. II. Science Applications, Inc. III. United States. Army. Corps of Engineers. IV. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; EL-80-5.
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