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EVALUATION OF MARSH/ESTUARINE WATER QUALITY AND ECOLOGICAL MODELS: AN INTERIM GUIDE

by

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Preface

This report represents a summarization of Corps of Engineers (CE) field office problems in estuaries and intertidal wetlands, a review of marsh/estuarine water quality and ecological models, and an evaluation of the applicability of mathematical modeling methodologies to environmental assessments in estuaries and intertidal wetlands.

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Hamilton, P. 1980. "Marine Wetland and Estuarine Processes and Water Quality Modeling; Workshop Report and Recommendations," Miscellaneous Paper EL-80-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Hamilton, P., and Fucik, K. W. 1980. "Literature Review of Marine Wetland and Estuarine Water Quality and Ecosystem Models," Technical Report EL-80-5, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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EVALUATION OF MARSH/ESTUARINE WATER QUALITY AND
ECOLOGICAL MODELS: AN INTERIM GUIDE

Purpose and Scope

1. This report introduces marsh/estuarine water quality and ecological models and assists in evaluating the applicability of mathematical modeling methodologies to environmental assessments in estuaries and intertidal wetlands. This report provides preliminary guidance to District planners, engineers, and resource managers.

2. A brief summary of water quality and ecological modeling in the marsh/estuarine environment is provided as the basis for the modeling recommendations.

Water Quality and Ecological Problems

3. A survey of Corps of Engineers (CE) field offices with coastal responsibilities identified existing and anticipated water quality and ecological problems associated with CE activities in coastal marshes and estuaries. Existing and potential problems were classified and tabulated as to marine wetlands, coastal zone, and environmental monitoring (Table 1). The feasibility of numerical modeling techniques for addressing each identified problem is noted. A more detailed description of applicable modeling approaches is outlined in Table 2.

Marine wetlands

4. Mathematical modeling methodologies are not sufficiently developed to address the marine wetlands problems. Existing research is quantifying material cycling and primary and secondary production within the marsh and between the marsh and adjacent coastal waters. Existing mathematical models addressing these phenomena are research tools and are not suitable for planning and management.

5. Conceptual models should be used to guide studies that provide increased understanding and quantification. The potential applicability

of marsh and estuarine ecosystem models to these problems suggests that studies be designed to understand important processes and to provide data for future model verification.

Coastal zone

6. Mathematical modeling techniques are not suitable for coastal zone problems 12 and 13 (Table 1). However, mathematical models can be applied to problems 14-16 when used in conjunction with complementary study procedures.

7. Present mathematical modeling studies address the fate of dredged material. Mathematical modeling to assess the environmental effects of turbidity resulting from dredging and disposal is not recommended at this time (problem 14).

8. Problems 15 and 16 are directly addressable through mathematical modeling. However, a more detailed understanding of the hydrodynamics of very shallow waters--including sheet flow in marshes; flow in very shallow channels; sediment transport; periodic inundation; and the relationships of residence time to winds, tides, and freshwater inflow and rainfall--is needed. Present understanding of biological and chemical processes would limit simulations to assessing excessive algal growth and dissolved oxygen relationships. Additional knowledge would be required to simulate the cycling of toxic constituents.

Environmental monitoring

9. Mathematical modeling methodologies are not appropriate to address environmental monitoring problems.

Marsh/Estuarine Water Quality and Ecological Models

10. District planners, engineers, and resource managers require an understanding of the behavior of marsh/estuarine ecosystems and how the system would respond as a result of future CE activities.

11. One way to assess the effects of proposed activities is to make the actual changes in the system and directly observe the effects; however, such direct experimentation is usually impractical. An alternative is to model the physical system in such a way that essential

cause-and-effect relationships are maintained. The model may be a scaled physical representation or a mathematical description based on physical laws and empirical formulae.

12. In a mathematical model, the cause-and-effect relationships between system elements are represented by a set of mathematical equations. Mathematical models may vary from a few equations that can be solved by hand computation to hundreds of equations requiring the use of a digital computer. The complexity of the mathematical model selected depends largely on the questions to be asked about the behavior of the actual system.

13. Marshes and estuaries are complex interactive ecosystems. Salient features that contribute to their complexity are diverse topography, environmental gradients, and the large number of biological components.

14. No single model exists that can simulate all aspects of water quality and ecological processes in marsh/estuarine ecosystems. If such a model were developed, the resulting complexity, extensive data requirements, and cost of computation would make its use impractical. An alternative strategy is a wide variety of more specialized models developed to more effectively address particular aspects of water quality or ecosystem processes. This section of the report will review the types and uses of mathematical models.

Hydrodynamic models

15. The basis for water quality models and ecosystem models that use the principle of conservation of mass is a model of the circulation of the estuary. The circulation in a partially mixed estuary is mainly driven by the tide, river inflow, salinity gradient, and wind. It is now considered that, in many estuaries, all four forcing mechanisms are equally important in influencing the circulation and the transport of water quality constituents. Estuarine circulations are some of the most complex geophysical flows in existence.

16. Physical oceanography of estuaries is discussed in the texts by Dyer (1973), Officer (1976), and McDowell and O'Connor (1977); symposia edited by Kjerfve (1978) and Hamilton and Macdonald (1980); and

reviews by Liu and Leendertse (1978) and Hamilton and Fucik (1980).

17. One-dimensional models. One use of one-dimensional models that included an advection-dispersion equation was the study of salinity intrusion in an estuary (Stigter and Siemons 1967; Thatcher and Harleman 1972; Williams and West 1973). Neglect of the variation with depth of current and salinity meant that the upstream flux of salt due to density currents and mixing due to vertical phase differences in the tidal variations of current and salinity were lumped together in a one-dimensional longitudinal dispersion coefficient. Because the dispersion coefficient varied among estuaries and was highly dependent upon river-flow and distance from the estuary mouth (Williams and West 1973), one-dimensional models were difficult to use in a predictive mode in partially mixed estuaries. However, these models serve as the hydrodynamic basis for the majority of estuarine water quality models.

18. Two-dimensional models. Consideration of the depth dimension permits the inclusion of the majority of the fundamental physical processes that affect the advection and dispersion of water quality constituents. The first study demonstrating the importance of depth variation on currents and salinities was the steady-state analytical solution of Rattray and Hansen (1962). These equations were expanded to explicitly include the longitudinal salt balance (Hansen and Rattray 1965; Rattray 1967; Winter 1973; Festa and Hansen 1976).

19. Time-dependent equations for a partially mixed estuary were numerically solved by Hamilton (1975) and Blumberg (1975). The solution techniques were explicit with time steps of about 1 min. More recent semi-implicit methods permit time steps of about 30 min (Hamilton 1976; Wang and Kravitz 1980), thereby permitting wind-driven transients to be investigated (Wang 1980).

20. The vertically averaged equations of motion have been extensively used for storm surge modeling. Hinwood and Wallis (1975a, 1975b) provide a review of these models. Vertically averaged hydrodynamic models are now quite sophisticated employing variable grids and embedded subgrid features to handle complex geometry such as channels and barriers (Butler 1980; Reid et al. 1977; Reid, Vastano, and Reid 1977).

21. A few investigators have included vertically integrated advection-dispersion equations for salinity and other water quality constituents. Leendertse and Gritton (1971) hindcasted water quality constituents in Jamaica Bay, N. Y., and Hess and White (1977) modeled the dispersal of a marked fluid released in Narragansett Bay, R. I.

22. Three-dimensional models. Three-dimensional models are very complex and only a few have been developed. The model by Leendertse and Liu (1975, 1977) uses explicit finite difference methods and thus is extremely costly in computer time for any lengthy simulation. Caponi (1976) developed a time-dependent model that used the complete three-dimensional Navier-Stokes equations instead of the Boissinesq approximation. However, in an application to Chesapeake Bay, the use of a relatively coarse grid may have resulted in some anomalous circulations. Wang (1980) proposed the use of semi-implicit methods and mode splitting for increasing the computational efficiency of three-dimensional models.

23. Summary. Table 3 provides examples of the hydrodynamic models discussed. The list is not exhaustive, but is intended to show the variety of approaches to the numerical modeling of estuarine hydrodynamics.

24. Many one- and two-dimensional models include salinity advection and dispersion. Some models use tidally averaged velocity as input to salinity transport models. Investigations by Harleman (1971) indicate differences between the results of tidally averaged and time-dependent one-dimensional simulations of salinity transport. Furthermore, he concluded that the importance of the highly empirical longitudinal dispersion coefficient decreases as the accuracy of description of the advective motion increases.

25. The alternatives to using tidally averaged or net tidal velocities are to output the hydrodynamic computational results for subsequent input to salinity transport model or to embed the salinity transport equations within the hydrodynamic computations. Embedding permits coupling of the salinity gradient to the momentum equations. However, highly discretized hydrodynamic models have inherent stability problems requiring time steps on the order of seconds to minutes with maximum

simulation periods of days, while water quality phenomena of interest such as salinity distribution and phytoplankton growth may require simulation periods on the order of weeks or months, and possibly longer.

Water quality and ecological models

26. Water quality models. Historically, the analysis of water quality has concentrated on the DO and BOD due to waste loads. The majority of DO-BOD models evolved from the study by Streeter and Phelps (1925), who assumed that the balance between DO and BOD concentrations was the result of two processes: the reaeration of the water column and the consumption of DO in the oxidation of BOD.

27. Later modeling emphasis has been on extending and refining the Streeter-Phelps formulation by using a more generalized mass balance approach and by the inclusion of additional processes such as benthic oxygen demand, benthic scour and deposition, photosynthesis and respiration of aquatic plants, and nitrification (Dobbins 1964; O'Connor 1967; Dresnack and Dobbins 1968; O'Connor and DiToro 1970; Grantham, Schaake, and Pyatt 1971; Whitehead and Young 1975).

28. The more comprehensive estuarine water quality models have been developed to include the nitrogen and phosphorus cycle and the lower trophic levels of phytoplankton and zooplankton (Chen and Orlob 1972; DiToro et al. 1977; Dahl-Madsen 1978).

29. Water quality modeling is discussed in the texts 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).

30. A few water quality modeling investigations of estuaries have addressed water quality constituents other than DO-BOD, nitrogen, phosphorus, and the lower trophic levels of the biological community. A number of investigators have modeled the algal nutrient silica (Festa and Hansen 1976; Peterson, Festa, and Conomos 1978; Ratray and Officer 1979).

31. Nihoul et al. (1979) and Billen and Smits (1977) modeled selected chemical constituents in an estuary by assuming thermodynamic equilibrium. The variable controlling partitioning between constituents

was redox potentials estimated by considering the oxygen budget. The authors admit that thermodynamic equilibrium is not necessarily fulfilled throughout the estuary.

32. There have been very few models simulating fate and effects of heavy metals. The fate of metals in estuaries is very complicated and unclear, involving adsorption-desorption reactions, flocculation, precipitation, sedimentation, and biological uptake. Jorgensen (1979) modeled heavy metals using the concept of trophic length level. The concept involved the consideration of a length scale introduced into the equations as an independent variable that represents the time a constituent remains in a particular trophic level.

33. Ecological models. In contrast to water quality models, ecological models are more descriptive, emphasizing exhaustiveness and resolution often to the limits of potential data availability. Ecological models include numerous biological species or species aggregates and emphasize food chain and species interactions.

34. Cushing (1975), in his book on marine ecology and fisheries, points out that, in marine ecological studies, the limiting nutrient concept has been abandoned with an increased emphasis placed on predator-prey relationships. Early marine ecosystem models concentrated on the nutrient-phytoplankton-zooplankton interactions with complex formulations describing the transfer of material between the components (Steele 1974). Early investigations did not include explicit spatial variations, but more recent studies allow both spatial and temporal variability in systems which have large physical gradients such as upwelling regions (Walsh 1971; O'Brien and Wroblewski 1972) and estuaries (Winter, Banse, and Anderson 1975; Kremer and Nixon 1978).

35. In contrast to the early marine models with few components but complex interactions is the approach advocated by Patten (1968). Patten's approach uses very complex model structures that involve many species, but the interactions between components are generally simple, linear, and empirical. These models tend to be very theoretical since little data are available for calibration.

36. Estuarine ecological models. Few estuarine ecosystem models

exist. Pomeroy et al. (1972) simulated phosphorus flux in several Georgia estuaries. Bahr (1974) simulated energy flux in Georgia oyster beds. Dame, Vernbert, and Bonnell (1977) used a similar model for South Carolina oyster beds emphasizing sensitivity analysis. Show (1979) developed a hydrological-biological model to investigate zooplankton distributions in a Texas coast embayment. Ferguson and Adams (1979) simulated epifauna and juvenile fish of an eelgrass community to investigate their response to temperature.

37. The two most comprehensive ecological models of estuaries are those by Winter, Banse, and Anderson (1975) and Kremer and Nixon (1978). Winter, Banse, and Anderson simulated primary production for the central basin of Puget Sound, which is a deep fjord with strong stratification. The model of Kremer and Nixon was applied to Narragansett Bay, which is a shallow, wide, and partially mixed estuary. Both models were based on extensive investigations by many researchers over many years.

38. Marsh ecological models. Very few marsh ecological models exist. Wiegert and Wetzel (1979) developed a model of a Georgia Spartina marsh. The objective of model development was to describe the pathways and dynamics of carbon flow in the marsh. Hopkinson and Day (1977) simulated carbon and nitrogen flows in a Louisiana salt marsh.

39. Models have been developed to address specific components of the marsh. Nixon and Oviatt (1973) simulated diurnal DO in tidal creeks and embayments to investigate the effects of sewage input and temperature increases on the DO concentrations in the embayments. Reimold (1974) specifically addressed the effect on the Spartina system of perturbations to the marsh. Zieman and Odum (1978) simulated plant growth and succession on an estuarine salt marsh. Lugo, Sell, and Snedaker (1976) simulated mangrove production.

40. Summary. Table 4 provides a summary of the different approaches to water quality modeling. The list is not exhaustive but provides examples ranging from one-dimensional, tidally averaged DO-BOD models through two-dimensional, time-dependent models that include DO-BOD, plant nutrients, and the lower trophic levels.

41. Table 5 summarizes water quality models modified or developed

through grants by State and Federal water resource agencies and are thus readily available with user documentation.

42. The SEM and ES001 models provide the one-dimensional, tidally averaged analytical solution initially discussed by O'Connor (1960). The DEM model, and the derived models RECEIV and RIVSCI, are based on the WRE Link-Node hydrodynamic model. The model is basically a one-dimensional solution adapted to two-dimensional estuaries. The model has been characterized as a good descriptive tool but lacks a predictive capability. The ESTECO model was developed for the Texas Water Development Board and uses a two-dimensional, vertically averaged hydrodynamic model called HYDTID to generate a velocity field for the water quality module. The water quality module is based upon the concepts originally included in the DEM series of models.

43. In summarizing the review of marsh/estuarine water quality and ecological models, the following conclusions can be drawn:

- a. Additional studies are needed to investigate the appropriate procedures to couple hydrodynamic and water quality models since the time scales of interest may differ.
- b. The DO-BOD estuarine models are appropriate for investigating the assimilative capacity of estuaries to heavy organic enrichment. However, for mildly perturbed estuaries in which photosynthesis, algal respiration, decomposition, and mixing processes play dominant roles, the understanding and characterization of significant processes are less well known.
- c. Models developed to address eutrophication due to nutrient enrichment have not been verified in most cases. These models are not capable of predicting absolute values under varying environmental conditions. These models may be useful in evaluating minor perturbations, such as increased nutrient loadings or turbidity. However, these perturbations cannot be catastrophic. Events that significantly alter the species composition presently cannot be evaluated through simulations.
- d. Detailed mathematical ecological models presently are not sufficiently developed to be applicable to environmental impact analysis. The extensive data requirements exceed the capabilities of most specific project studies.

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Table 1
Existing and Potential Water Quality and Ecological Problems
Identified by a Survey of CE Field Offices with
Coastal Responsibility

<u>Problem</u>	<u>Description</u>	<u>Modeling Feasibility*</u>
<u>Marine Wetlands</u>		
1	Existing wetlands need to be surveyed.	--
2	Problems are encountered when applying the different kinds of available classification schemes.	--
3	Information is needed on the role of buffer zones around wetlands.	--
4	Wetland values need to be assessed by productivity measurements.	--
5	More information is needed on the management of diked impoundments.	--
6	More information is needed on the assimilation of effluent and dredged material by the wetland.	--
7	Delta growth as a means of marsh creation needs to be investigated.	--
8	Additional understanding of marsh creation through dredged material disposal is needed.	--
9	Importance of created marsh on the total bay-marsh ecosystem requires additional study.	--
10	Effects of changes in freshwater flow on wetland areas need to be investigated.	--
11	Procedures to evaluate the effects of stresses on the wetlands such as platforms and highway bridges need to be developed.	--

(Continued)

* Entries in this column are defined as follows: -- mathematical modeling methodologies are not sufficiently developed to address the problem; ✓ modeling is feasible.

Table 1 (Concluded)

<u>Problem</u>	<u>Description</u>	<u>Modeling Feasibility</u>
<u>Coastal Zone</u>		
12	Offshore disposal sites are needed due to a lack of upland sites.	--
13	Problems are encountered with bioassays.	--
14	Concerns exist over the effects of turbidity produced by dredging and disposal operations.	✓
15	Water quality problems such as eutrophication or pollution exist in estuaries or rivers.	✓
16	Procedures for evaluating the impacts of cumulative development of dead-end canals, small boat harbors, and marinas are needed.	✓
17	Field offices need hydrodynamic and advection-dispersion models.	✓
<u>Environmental Monitoring</u>		
18	Methods of storing and handling data and literature for environmental assessments need to be modernized.	--
19	Longer lead times are needed for comprehensive studies for environmental impact assessment.	--
20	More long-term monitoring is needed to permit impact evaluations.	--
21	Long-term studies are needed to provide additional understanding of problems unique to the field office.	--
22	Exchange of technical information between field offices needs to be improved.	--

Table 2
Existing and Potential Water Quality and Ecological
Problems and Applicable Modeling Approaches

Problem	Applicable Modeling Approaches			
	Water Quality		Ecosystem	
	<u>DO-BOD</u>	<u>Phytoplankton</u>	<u>Marsh</u>	<u>Estuary</u>
Marine wetlands				
1				
2				
3				
4				
5	*	*	**	
6			**	
7			**	**
8			**	**
9			**	**
10			**	
11			**	
Coastal zone				
12				
13				
14		*		
15	*	*		
16	*	*		
17	*	**	**	**
Environmental monitoring				
18				
19				
20				
21				
22				

Note: DO = dissolved oxygen; BOD = biochemical oxygen demand.

* State of the art ready for application with only minor adaptations.

** State of the art not ready for application but development for selected purposes is feasible.

Table 3
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 (1980)	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 & 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, Vastano, and Reid (1977)	x, y, t	Explicit Finite differences (subgrid scale) (channels & barriers)	$\zeta(x, y, t)$ $u(x, y, t)$ $v(x, y, t)$	Continuity u-momentum 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)	$\zeta(x, y, \omega)$ $u(x, y, \omega)$ $v(x, y, \omega)$	Continuity u-momentum v-momentum	Tide	Hood Canal Wash. (Jamart personal 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
Butler (1978)	x, y, t	Semi-implicit (variable grid, sub-grid scale features)	$\zeta(x, y, t)$ $u(x, y, t)$ $v(x, y, t)$	Continuity u-momentum v-momentum	Tide Wind Riverflow Tsunami	Masonboro Inlet & estuary (tide) Corson Inlet & estuary (tide) Great Egg Harbor Inlet & estuary (tide) Coos Bay & South Slough, Oregon (tide) Bolsa Chica Bay (tide) Los Angeles & Long Beach Harbor (tide) Galveston Bay (tide & surge) Crescent City, California (tsunami) Hauula-Punaluu region, Oahu, Hawaii (tsunami)

Variable	Definition
x	Longitudinal horizontal axis
y	Across-channel horizontal axis
z	Depth axis
t	Time
ω	Harmonic decomposition of time (i.e. $\zeta(x, t) = \sum A_n(x) \exp(i\omega_n t)$)
u, v, w	Velocities in the x-, y-, and z-directions, respectively
u, 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

* From Hamilton and Fucik (1980).

Table 4
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 Anaerobic kinetics included when DO < 5% saturation	Tidal amplitude, riverflow, wind, carbonaceous 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)	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-node 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 Sørfjorden Trondheims fjorden (Norway)

* From Hamilton and Fucik (1980).

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

† Numbers in parentheses indicate the number of simulations available.

Table 5

Representative Estuarine Water Quality Models Available With User Documentation

Model	References	Hydrodynamic Circulation Submodel	Water Quality State Variables
SEM	Hydroscience, Inc. (1971, 1972)	1-D tidally averaged	DO-BOD
ES001	Chapra and Gordimer (1973a, 1973b)	1-D tidally averaged	DO-BOD
DEM	Feigner and Harris (1970) Callaway, Byram, and Ditsworth (1969) Callaway and Byram (1970) Water Resources Engineers (1974)	1-D time-dependent link-node transport-dispersion model	DO-BOD, temperature, algae, nitrogen, phos- phorous, coliforms, TDS,* heavy metals (2), pesticides (2)
RECEIV	Metcalf and Eddy, Inc., University of Florida, and Water Resources Engineers, Inc. (1971)		DO-BOD, four conserva- tive or nonconserva- tive (first-order decay) constituents
RIVSCI	Systems Control, Inc., and Snohomish County Planning Department (1974)		DO-BOD, temperature, total and fecal coli- forms, nitrogen, phos- phorus, copper, lead, two conservative constituents
ESTECO	Texas Water Development Board (1977)	2-D (horizontal) time- dependent transport- dispersion model	DO-BOD, temperature, algae (2), nitrogen, phosphorus, coliforms, detritus, alkalinity, TDS, zooplankton, benthos, pH, carbon, fish (3)