THE MOVEMENT AND QUALITY OF COASTAL WATERS: A REVIEW OF MODELS RELEVANT TO LONG ISLAND, NEW YORK

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Leonard Ortolano
Philip S. Brown, Jr.

Prepared for the
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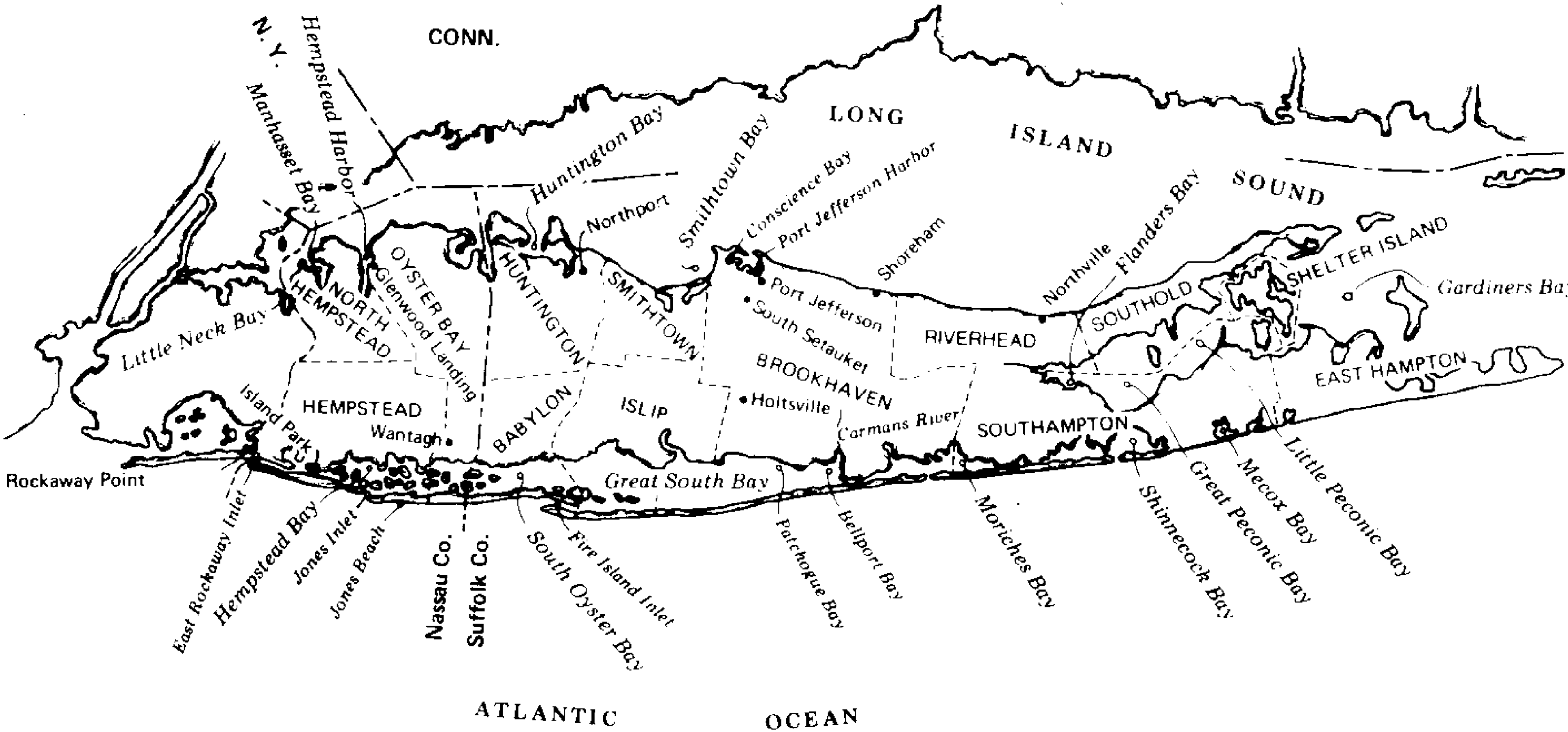
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N. Y.
LONG ISLAND SOUND
Hempstead Harbor
Manhasset Bay
Huntington Bay
Smithtown Bay
Conscience Bay
Port Jefferson Harbor
Flanders Bay
Northport
Shoreham
Northville
SHELTER ISLAND
Gardiners Bay
NORTH HEMPSTEAD
OYSTER BAY
Glenwood Landing
HUNTINGTON
SMITHTOWN
Port Jefferson
South Setauket
BROOKHAVEN
RIVERHEAD
SOUTHOLD
EAST HAMPTON
Little Neck Bay
Island Park
HEMPSTEAD
Wantagh
BABYLON
ISLIP
Holtsville
Carmans River
SOUTHAMPTON
Rockaway Point
Great South Bay
East Rockaway Inlet
Hempstead Bay
Jones Inlet
Jones Beach
Nassau Co.
Suffolk Co.
South Oyster Bay
Fire Island Inlet
Patchogue Bay
Bellport Bay
Moriches Bay
Shinnecock Bay
Great Peconic Bay
Mecox Bay
Little Peconic Bay
ATLANTIC OCEAN

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ABSTRACT

The literature on models for predicting flow patterns (including velocity and water height) and the distribution of materials in coastal waters is reviewed. The report, prepared for the Marine Resources Council of the Nassau-Suffolk Regional Planning Board, focuses on models that are potentially applicable to the Long Island coastal environment.

The report describes the purposes of modeling and what it means to verify a model. The potential utility of hydraulic models, small-scale three dimensional replicas of rivers and harbors, is discussed along with a number of real world applications. Mathematical models are introduced in two contexts: (1) hydrodynamic models used to predict flow patterns, and (2) water quality models used to predict the concentration of substances contained in wastes discharged to water courses. The emphasis is on describing the state-of-the-art and on indicating the extent to which the various models are used in practice.

The models described are put in perspective as one possible set of tools potentially useful to the Marine Resources Council in addressing Long Island's coastal problems. The material is arranged so that Section 1 and Section 5 (a non-technical summary) may be read sequentially with no loss in continuity; these two sections should provide an adequate review for many readers.

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ABSTRACT

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1.0 INTRODUCTION *

This is a review and cursory evaluation of what is known about modeling the movement and quality of coastal waters, with emphasis on potential applications to Long Island. It is part of a continuing study of the alternative uses of the coastal resources of Long Island, prepared for the Marine Resources Council of the Nassau-Suffolk Regional Planning Board. Other reports in this study have described the nature of resource allocation problems in terms of cause and effect sequences, geographical locations, changes over time, and the public and private groups that affect and are affected by conflicts in resource uses.

1.1 Scope

This study consisted of a review of the literature on models and theories that are potentially useful for understanding and predicting the impacts of alternative courses of action on the quality and movement of the coastal waters of Long Island. To ensure that the materials covered were pertinent to Long Island, the review was structured on the basis of the recent report entitled Fourteen Selected Marine Resource Problems of Long Island, New York: Descriptive Evaluations [2].

The models discussed below can help deal with Long Island's coastal problems by providing estimates of the consequences of alternative actions. To illustrate this, consider the problem of locating the discharge from a proposed wastewater treatment plant on the south shore. Models could be developed to estimate the changes in the levels of water quality indicators (say, dissolved oxygen and coliform bacteria) if the discharge were made directly to a south shore bay.

* We gratefully acknowledge the comments and suggestions made by Professor Robert V. Thomann of Manhattan College in reviewing a preliminary draft of this report.

Different models could be used to estimate the changes in water quality that would result if the discharge were made to the Atlantic Ocean, instead of a bay. In more general terms, models of the type described herein could be used to determine the effects of different levels of waste treatment and points of discharge on selected water quality indicators.

While such models would give useful results they would not, by themselves, yield all the information that is relevant to deciding on what level of treatment to employ, and where to locate the waste discharge. Important considerations that are not addressed by such models include the following:

- The effects of waste discharges on important water quality characteristics whose transport is poorly understood.
- The social and economic impacts of alternative levels of water quality.
- The costs of providing different levels of waste treatment and piping wastes to different discharge points.

Information of this sort, together with modeling results, would provide a useful basis for making decisions concerning waste treatment levels and discharge locations.

Since the literature on modeling natural water systems is indeed enormous, it would have been infeasible to discuss all of the potentially relevant approaches to modeling physical, chemical and biological interactions in the coastal zone. We chose to place emphasis on those models currently being used to help make decisions concerning coastal resource management. We also emphasized models that were quantitative, in the sense of yielding predictions in numerical terms.

For the most part, this review considers models for predicting patterns of flow (including velocity and water height) and the distribution of selected materials in coastal waters. While there is some discussion of chemical and biological interactions, these topics are not dealt with in a systematic fashion. Methods for evaluating the social and economic consequences of alternative actions are not dealt with at all. Furthermore, this report does not contain a ranking of models according to utility, nor does it suggest which, if any, models should be considered for implementation by the Marine Resources Council.*

1.2 Background Issues and Definitions

The word model is used here to mean an approximate or simplified representation of the operation of a real system, such as a tidal stream or bay which is too large, complex or diffuse to be studied conveniently in its entirety. The purpose of modeling such a system is to develop a tool (model) of manageable scale that adequately approximates the larger system and that can be altered and munipulated to infer the results of actions taken in the larger system.

Models must be developed and verified before they can be used for prediction. A physical model (i.e., a three-dimensional, small-scale replica) is developed by reproducing, in miniature, the significant details of the real system: topography, currents, fresh water inflows, etc. A mathematical simulation model is developed by formulating the theoretical bases for the actions of the real system, and then solving the appropriate equations, usually with the aid of a high speed computer. In both cases, the resulting model can be manipulated to infer what changes will occur in the real system if various alternate actions are taken upon it.

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* Note, however, that the discussion of Section 5.5 is especially relevant to these questions.

Model development usually involves a considerable amount of preliminary adjustment or "tuning". For physical models, this might take the form of increasing surface roughness or adding more electric fans to accurately simulate wind effects. For mathematical models it usually means modifying the numerical values of coefficients until the models' output is consistent with an historically observed sequence in the real system.

These preliminary adjustments are distinct (conceptually at least) from the process of verification; i.e., testing the model's validity by making predictions and comparing them with an independently observed sequence of events in the real system. In practice, it is often difficult to distinguish between this verification process and the tuning referred to above. This difficulty accounts for a considerable portion of the debate among specialists regarding the utility of various models.

However, a model is, in all cases, only an approximation of the system being modeled. The fidelity with which it models a specific system and the generality with which it may model all or many similar systems both depend largely on the levels of detail and complexity of the models and, consequently, their expense.

Developing and verifying models is both time consuming and expensive. It is, therefore, relevant to inquire about the extent to which models can be made general; i.e., capable of application to a wide range of issues in a number of different water bodies.

The question of generality can be approached by recognizing that the theoretical bases for many models (i.e., the fundamental "laws of motion" and mass conservation) can be written in a form applicable to all coastal water bodies. In this sense, they provide a very general representation. However, before a model can be used for prediction purposes, many aspects of these fundamental laws must be tailored to a particular water body and a specific set of variables to be examined.

Suppose, for example, a model for predicting the velocity of flow at selected points in Great South Bay has been developed and verified. With a modest increase in resource expenditure, the model could be expanded to yield information on water heights. With a substantial increase in resource expenditure, the model could be expanded to predict the concentrations of certain water quality characteristics, like coliform bacteria and dissolved oxygen concentrations. The model could be expanded still further to yield information on shoaling patterns - but any such predictions would have a relatively low reliability, since the state of knowledge on sediment transport is not highly developed.

By increasing the quantity of resources devoted to modeling, the hypothetical Great South Bay model could be made more and more general in the sense that predictions about a larger number of variables could be made. The increase in resources would be required to obtain appropriate field data involving the added variables. The cost of operating the model could also be expected to increase somewhat as the number of variables is increased. Note also that by devoting more time and money to modeling it is generally possible to increase the degree of spatial and temporal detail of model predictions.

The hypothetical model of Great South Bay could be expanded to examine an increasing number of marine resource problems with a finer degree of resolution in both time and space. In the short term, the limit to which the model could be expanded and refined would be determined by some combination of the availability of funds for modeling (including the acquisition of necessary field data), and the existing state of knowledge of the Bay's behavior.

Now, given that a model for Great South Bay has been developed and verified, can it be used directly for Shinnecock Bay? The answer is no, for the following reasons:*

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* The reasons are obvious for a physical model; i.e., a small-scale replica of Great South Bay. The reasons given in the text are for mathematical models.

1. The geometric configuration of Shinnecock Bay as well as other peculiar local characteristics will require that some modification be made in the underlying mathematical representation.

2. Input coefficients for the model will have to be developed for conditions appropriate to Shinnecock Bay.

3. The process of verification, which requires the comparison of model predictions with real world observations, will have to be carried out for Shinnecock Bay.

Note that there is enough similarity in the bays on Long Island's south shore to suggest that a model for Great South Bay would provide a very useful starting point for modeling Shinnecock Bay as well as others.* It is intuitively clear that a model of Great South Bay would be less uesful as a starting point in developing a model for Long Island Sound.

1.3 Organization

There are four major Sections in this report. Section 2.0 treats models that are scaled-down physical replicas of coastal water bodies. These replicas, often referred to as hydraulic models, have been widely used by the U. S. Army Corps of Engineers and others to examine problems relating to shoaling, dredging, storm surge, and the distribution of salinity and a limited number of wastewater constituents.

Section 3.0 describes a more abstract approach to modeling physical interactions in the coastal zone. It is shown that two fundamental principles, the conservation of mass and Newton's second law of motion, provide a basis for constructing mathematical representations capable of predicting aspects of coastal water movement. These representations, referred to as hydrodynamic models, are useful in determining how the velocity and flow of coastal waters are influenced by changes in geometric configuration, freshwater inflow, tidal action and wind.

* For example, it might be possible to use (with perhaps minor modification) the computer programs prepared in connection with a Great South Bay modeling study. In this connection see the discussion of Fischer's hydrodynamic modeling program in Section 3.3 below.

These fundamental principles are also shown to be useful in predicting the distribution of salinity in coastal waters.

Section 4.0 focuses exclusively on the use of mathematical models to determine the distribution of substances contained in wastewater discharges; these are referred to as water quality models. Section 4.2 treats situations in which wastes are discharged directly to the ocean; Section 4.3 deals with situations in which wastes are discharged to estuaries.* The particular wastewater constituents discussed include dissolved oxygen, biochemical oxygen demand, coliform bacteria, and compounds of phosphorous and nitrogen; waste heat and pesticides are also considered briefly.

Section 5.0 is a non-technical summary of Sections 2, 3 and 4 and, with the introduction, should provide an adequate review of this study for many readers. Sections 5.1 - 5.3 contain a summary of the main issues. Section 5.4 contains an example of how the models described can be used for purposes of decision making; the example concerns a realistic situation involving a Long Island water body. Section 5.5 suggests the kinds of issues that should be considered by the Marine Resources Council before initiating a large scale model development program; it describes the problems underlying the establishment of modeling priorities.

1.4 Selected References

1. Pritchard, D. W., "Estuarine Hydrography" in Advances in Geophysics (New York, Academic Press, 1952).

2. Smith, F. A., et al., Fourteen Selected Marine Resource Problems of Long Island, New York: Descriptive Evaluations, TRC Report 7722-377, The Travelers Research Corporation, Hartford, Connecticut, January, 1970.

* Following Pritchard [1] we define an estuary as "a semi-enclosed coastal body of water having a free connection with the open sea and containing a measureable quantity of sea-salt".

2.0 HYDRAULIC MODELS

2.1 Introduction

Hydraulic models have been used extensively during the past four decades for planning development in rivers and harbors. These models are small scale three dimensional replicas of real rivers and harbors. A host of mechancial devices, including electric fans and specially designed "wave generators", are used to simulate the influence of real wind and tidal action on the water's motion. Although the scales of the models vary, they are typically in the order of 1:1000 in the horizontal and 1:100 in the vertical.

The dimensions of a hydraulic model are chosen such that the behavior of the model is similar to that of the real system with respect to the processes under study.* In some cases, dimensions can be established on the basis of well founded theoretical principles which guarantee similarity between the model and the real system (or "prototype") with respect to geometry, motion and forces. However, for phenomena in the coastal zone, simple "similarity criteria" are generally impossible to satisfy and a number of additional steps must be taken. For example, to develop accurate hydraulic models of such phenomena as tidal motion and longitudinal and vertical salinity distributions in estuaries, it is generally necessary to depart from purely theoretical considerations in the adjustment of surface roughness.

Hydraulic models constructed to examine a given phenomena, as, for example tidal motion, may be completely unacceptable for modeling related phenomena, as, for example, material transport. Scaling considerations that are important

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* The theoretical criteria used to determine the dimensions of hydraulic models are discussed in general terms by Vennard [13]; a more advanced discussion relating to models used for coastal areas is given by Keulegan [3].

for modeling material transport may be of negligible importance for modeling tidal motion.

As implied above, the development of hydraulic models involves substantially more than the application of straightforward rules for establishing model dimensions. To obtain useful predictions with hydraulic models it is generally necessary to have the services of individuals highly trained in the development of such models and interpretation of model data. As observed by a noted advocate, hydraulic "model studies must be classified as art rather than science...[5]."

Below, we describe a number of ways in which hydraulic models have been used in order to suggest their potential utility in the Long Island area. In particular, we note instances where such models have been employed to deal with shoaling, dredging and spoil disposal, storm surge, salinity intrusion, and wastewater dispersion. In each case we indicate the Long Island related problem corresponding to the phenomena under consideration. Finally, in Section 2.7 we summarize the main advantages and disadvantages of hydraulic models.

2.2 Shoaling

Shoaling, the gradual reduction in channel depths, is an important factor in the maintenance of coastal waters for navigation. Long Island problems relating to shoaling were discussed in the report by Smith *et al.*, in the section on Coastal Stabilization and Protection [8]. Although hydraulic models have been used to examine shoaling and sediment transport, knowledge of the underlying physical process is so limited that only qualitative predictions can be made with confidence [11, p. 27].

Where the shoaling material is sand, and its movement and deposition are affected by wave action as well as tidal and density forces, a so-called "moveable-bed" hydraulic model may be employed to determine the long term changes in bed and bank configurations, as well as the shoaling patterns in navigation channels [5]. The Absecon Inlet model [6] constructed by the U. S. Army Corps of Engineers is an example of a moveable bed model. It was used to investigate the effects of alternative approaches to maintaining the depth of an inlet located near Atlantic City, New Jersey. The model was verified by reproducing the prototype bed configurations and the inlet shoaling rate (the latter was done to within about 8 percent); the verification effort involved 39 hours of model time, which corresponded to 3 years of real time. All dredging and spoiling operations accomplished in the prototype during the verification period were simulated in the model. A number of experiments were carried out with the model to determine methods for reducing shoaling of the entrance channel at the Inlet; consideration was also given to the maintenance of the quality of recreation beaches at nearby Atlantic City.

The Corps of Engineers has constructed hydraulic models for Fire Island Inlet and Moriches Inlet on the south shore of Long Island.* These models, which are located in the U. S. Army Waterways Experiment Station in Vicksburg, Mississippi, have been used to simulate the effects of various structural changes on channel depth and location; at the time of this writing the results from these simulation studies were unpublished.

2.3 Dredging and Spoil Disposal

The problem of determining locations for the ultimate disposal of dredge spoil is a common one in the coastal waters of Long Island. (See, for example, the section on Dredging and Dredging Spoil Disposal in the report by Smith *et al.*

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* W. Fine, U. S. Army Corps of Engineers, New York, New York, personal communication, October, 1969.

[8].) As mentioned in Section 2.2 above, hydraulic models have been employed to examine the impacts of dredging on the geometry of bay bottoms. Below, we mention a case where a hydraulic model was used to decide on dredge spoil disposal locations.

The Corps of Engineers constructed a hydraulic model to help locate a navigation channel in Matagorda Bay, Texas [5]. The Corps had to decide on where to dispose of the dredge spoil accumulated during channel excavation. They were concerned about the possible redistribution of dredge spoil in the newly created channel, the creation of cross-current velocities which would interfere with navigation, and the possible adverse effects on marine life. The Corps was able to employ the same model used to locate the channel to give some insight into the possible impacts of alternative spoil disposal strategies.

2.4 Storm Surge

Severe wind-wave action and storm surge off the shores of Nassau and Suffolk Counties have resulted in extensive damage [8]. Hydraulic models can be used to aid in the design and location of breakwaters and other wave impeding devices to reduce the damage resulting from such severe storms.

The Corps of Engineers constructed a model of Crescent City Harbor, California [10] to investigate proposed harbor improvements and to determine any modifications necessary to protect the harbor area from damaging short-period wind waves and tsunami (a wave generated by seismic activity). A similar hydraulic model has recently been constructed for Narragansett Bay [7] to study plans for protection of the Bay area against hurricane surges. Using a specially-designed surge generator, tests were carried out by placing barriers at various locations in the simulated bay. On the basis of these tests it was recommended that a system of strategically-placed barriers be constructed to prevent storm surges from reaching those portions of the coast of major concern. The Narragansett Bay model was also employed to provide information regarding the effect of the proposed barriers on the circulation, salinity, and pollution recovery characteristics of the Bay.

2.5 Salinity Distribution

Salt water intrusion is currently not a major problem on Long Island in terms of its impact on the quality of ground waters used for domestic purposes. However, it will require increasing attention as more public sewers are installed, because the latter result in the reduction of ground water recharge now accomplished from septic tanks and cess pools. In addition to its relation to ground water supplies, fluctuations in salinity levels have a direct influence on the life cycle of marine organisms, including shellfish. For these reasons, models for predicting salinity distribution are relevant to the Long Island area.

In most of the early studies carried out using hydraulic models little emphasis was given to problems of salinity. Nevertheless, as early as 1956, a hydraulic model was developed to investigate salinity intrusion in Vermilion Bay, Louisiana [7]. The main conclusion resulting form the modeling effort was that closure of the Southwest Pass, through which a main portion of salt water enters the bay with the incoming tide, would alleviate the problem of salt water intrusion during periods of low freshwater inflow. Although closing of the inlet would benefit particular interests (in this case the rice growers who pump water from the Vermilion River for irrigation purposes), such action could have a deleterious effect on the pollution recovery characteristics of the Bay.

2.6 Wastewater Dispersion

The ability to predict the fate of substances contained in wastewaters discharged to coastal water is an important consideration in deciding on the location and extent of treatment of such discharges. Problems relating to wastewater disposal in the coastal waters of Nassau and Suffolk Counties have been documented in a previous TRC Report [8]. Hydraulic models can play a very limited role in predicting the fate of contaminants in wastewater discharged to coastal waters.

The first hydraulic model to be used for the study of dispersion and flushing of wastes was the Delaware River model [1, 7]. The initial experiments, which involved the simulation of material transport using instantaneous dye injections, yielded information on the seaward progress of the centers of mass and peak concentration of the dye.* Another sequence of experiments was carried out to determine the dispersion and buildup of dye resulting from a continuous discharge under various stream flow conditions. Results from these experiments were used to obtain preliminary estimates of parameters that served as inputs to a mathematical model for predicting the transport of organic wastes.

Conceptual difficulties associated with the development of hydraulic models for predicting material transport stem from the impracticabity of simultaneously satisfying similarity criteria relating to gravitational forces (so called Froude similarity) and mass transfer processes. Harleman _et_ _al_. [2] have commented on this issue and suggested one possible mechanism for dealing with it. Apart from this difficulty, hydraulic models have not advanced to the state where they can be used to simulate the transport of materials that decay over time. This is quite a significant limitation since nearly all the water quality indicators of interest decay over time (e.g., coliform bacteria, and organic matter as represented by biochemical oxygen demand). As an extension of this point,

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* Dyes are typically used to simulate the transport of "conservative" materials; i.e., materials that do not decay over time.

observe that hydraulic models are incapable of coping with water quality variables that do not act independently of each other (e.g., dissolved oxygen and biochemical oxygen demand represent such a linked pair of water quality variables).

Other limitations of hydraulic models in pollution studies have been described in a report on the Galveston Bay Study. The study (which is still in progress) will involve both mathematical models and hydraulic models. Participants in the study offered the following reasons for rejecting the exclusive use of hydraulic models:

> The reliability [of hydraulic models] with respect to transport and water quality modeling is not definitely known... Furthermore, these [hydraulic] models do not interface efficiently with the numerical water quality models envisioned for this study. Because of the high cost of operating the [hydraulic] models, as well as the time, cost, and difficulty required to make alterations and to reverify, these models do not readily lend themselves to an economical evaluation of alternatives for water quality management [9, p. 26].

2.7 Concluding Remarks

A convenient way to summarize the possible uses of hydraulic models is to highlight the history of the Delaware Estuary and Bay model [6]. It was originally constructed by the Corps of Engineers in 1935, and was modified and substantially expanded in 1950. Model predictions of tidal ranges and elevations, time of high water and low water, current velocities over a tidal cycle, and surface and bottom salinity concentrations have been verified. The model has been used to determine changes in circulation patterns (current velocity and direction), tidal height and timing, and salinity distribution brought about by structural changes, and changes in mean sea level, tidal range and fresh water inflow. The model has also been used to give qualitative insights into problems relating to shoaling and wastewater dispersion. The possibility of using a single hydraulic model for a number of different purposes is clearly demonstrated by the history of the Delaware model. One testimony to its utility is the Corps of Engineers belief that it "will be used for another 20 years or more" [6].

The paragraph above implicity highlights the utility of hydraulic models in helping to understand and explain complex phenomena. To give a balanced view, we now reiterate some of the shortcomings. A practical limitation is that the construction, verification, and modification of hydraulic models is expensive and time consuming. Furthermore, large amounts of space are often required to house such models. The order of magnitude of costs of large scale hydraulic models is indicated by the following <u>total</u> costs (as of 1969) for models used over a number of years to study a variety of different issues: Galveston Harbor Entrance, $0.46 million; Columbia River, $1.095; and Delaware River, $1.5 million [12, pp. 38-43].

A theoretical limitation of hydraulic models is that they are very often not based on any fundamental model laws. Leendertse [4], quoting Birkhoff, summarized the issue as follows:

> In practice, theoretical considerations are seldom invoked in hydraulic model studies of rivers and harbors. Reliance is placed on reproducing various aspects of the observed behavior under actual conditions. It is hoped that variations in behavior due to altered conditions will then also be reproduced to scale - even though there is no rational agrument to support this hope.

Despite these limitations it often happens that hydraulic modeling is the optimal study approach, especially when the underlying physical processes are too poorly understood to be susceptible to mathematical representation.

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2. Harleman, D. R. F. et al., "Interpretation of Water Pollution Data from Tidal Estuary Models" in Proc. Advances in Water Pollution Research, Proc. of 3rd Int'l. Conf., Munich, Germany, Vol. 3 (Washington, D. C., Water Pollution Control Federation, 1967) pp. 49-63.

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3.0 HYDRODYNAMIC MODELS

3.1 Introduction

In Section 2.0 above, we observed that it is possible to construct models consisting of small scale replicas of coastal water bodies. However, alternative approaches to modeling are possible if the system's behavior can be described in mathematical terms. In this chapter, we consider the potential utility of such alternative approaches when the variables to be predicted include velocities and water heights (i.e., circulation patterns). The use of mathematical models for predicting material transport is taken up in Section 4.0.

Mathematical (i.e., "hydrodynamic") models for examining circulation patterns are based on the fundamental principles reflected in the equations of motion and continuity for a fluid particle.* In addition to these equations, appropriate boundary conditions are prescribed to represent the particular system to be modeled. For all but the simplest systems, these equations must be solved using numerical integration methods which generally require the use of high speed computing facilities; hence, the increase in the utility of hydrodynamic models is closely tied to advances in computer technology.

The models discussed below suggest the extent to which it is possible to predict changes in velocity and water heights resulting from natural or man induced changes in the coastal environment. The illustrative examples mentioned are relevant to the Long Island region in terms of the nature of the water body and/or the issues the model was developed to help resolve.

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* These equations are described below. Note that models for predicting ocean circulation patterns are considered beyond the scope of this report; but these models may be critical for examining off-shore waste disposal practices. An introductory discussion of this topic is given by Neumann and Pierson [18].

Section 3.2 describes the equations of motion and continuity, and Section 3.3 show how these equations are commonly used for coastal waters. Subsequent sections survey recent applications of hydrodynamic models to the following areas: storm surge, shoaling, tidal flow in inlets, and salinity distribution.

3.2 Fundamental Equations

The so-called equation of motion consists of Newton's second law, which states that the product of the mass and acceleration of a particle is equal to the sum of the external forces acting on it; i.e., mass x acceleration = Σ forces. By dividing both sides by the mass, the relationship states that acceleration is equal to the sum of the forces per unit mass (called "specific forces"). The principal specific forces acting on coastal waters are the pressure gradient force, $\vec{p}$, the gravitational force, $\vec{g}$, the frictional force, $\vec{m}$, and the Coriolis force, $\vec{a}$.* The form of Newton's second law typically used in hydrodynamic models is presented below, along with a sketch of the reasoning used to deduce it.**

Let x, y, and z represent the spatial coordinates in the longitudinal, lateral, and vertical directions, respectively.*** Also, let u, v, and w represent the x, y and z components of velocity, where each velocity component is a function of time (t) and space (x, y, z). The acceleration, which is by definition the derivative of velocity with respect to time, may be written as

$$\frac{D\vec{e}}{Dt} = \vec{p} + \vec{g} + \vec{m} + \vec{a} \qquad (3\text{-}1)$$

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* The symbol "> " is used to designate vector quantities.

** This brief sketch is based on the presentations of von Arx [26] and Kinsman [16]; these references can be consulted for thorough treatments of the subject.

*** For tidal streams the longitudinal coordinate is parallel to the direction of flow, and the lateral coordinate is horizontal in the direction perpendicular to it.

where $\vec{e}$, the velocity vector, is composed of u, v, and w, and the right-hand side is the summation of the specific forces.

Since the elements of $\vec{e}$ are functions of x, y, z and t, the "total derivative" of $\vec{e}$ may be written (using standard procedures from the calculus) as

$$\frac{D\vec{e}}{Dt} = \frac{\partial\vec{e}}{\partial t} + u\frac{\partial\vec{e}}{\partial x} + v\frac{\partial\vec{e}}{\partial y} + w\frac{\partial\vec{e}}{\partial z} . \qquad (3\text{-}2)$$

Equation (3-2) resolves the acceleration of a fluid particle into the sum of the local rate of change ($\partial/\partial t$) of the velocity as observed at a fixed point plus the "advective" rate of change which accounts for the fact that the particle may be swept into regions of different flow velocity. It is the three nonlinear advective terms involving products of a velocity component with a spatial derivative of velocity that present formidable obstacles to the solution of systems of hydrodynamic equations set down in general form.

Combining equations (3-1) and (3-2) yields a typical form for the vector representation of the equations of motion for coastal waters; i.e.,

$$\frac{\partial\vec{e}}{\partial t} + u\frac{\partial\vec{e}}{\partial x} + v\frac{\partial\vec{e}}{\partial y} + w\frac{\partial\vec{e}}{\partial z} = \vec{p} + \vec{g} + \vec{m} + \vec{a} . \qquad (3\text{-}3)$$

A second basic principle employed in hydrodynamic models of coastal waters is the "law of conservation of mass." This principle, when stated in mathematical terms for a fluid, is often referred to as the "continuity" equation. Essentially, it is based on a material balance of fluid entering and leaving a differential volume element fixed in space. After some simplification, such a material balance can be written as

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0, \qquad (3\text{-}4)$$

where ρ denotes the fluid density.* If it is assumed that the fluid is incompressible, and that the density of a fluid particle remains constant at all times, then (3-4) reduces to the simpler form

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \qquad (3\text{-}5)$$

Detailed descriptions of the equations of motion and continuity can be found in standard textbooks on hydrodynamics.

A hydrodynamic model of a coastal water system consists of the equations of motion and continuity together with appropriate boundary and/or initial conditions. Solutions for these equations yield the velocity and water height fields for the body of water in question. Solutions are generally impossible to obtain in "closed form," except for simple cases (e.g., see Ippen [14]) and, as a consequence, most models of practical significance must be solved using numerical integration methods on high speed electronic computing facilities.

For the numerical solution of the equations of motion and continuity, a set of grid points are first superimposed on the coastal water body in question; it is only at these points that the space-dependent physical quantities are evaluated. Appropriate finite-difference relations representing the equations are derived by replacing the various differential forms by approximate algebraic expressions. For the finite-difference scheme to be "consistent" the approximating forms must approach their differential counterparts as the spatial and temporal grid spacing is made smaller (i.e., the truncation error must approach zero). However, refinement of both time and

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* For analyses in which it is unreasonable to ignore density differences caused by variations in salinity, it is necessary to introduce an "equation of state;" for estuaries, a suitable form for this equation is

$$\rho = \rho_o + Kc,$$

where ρ_o in the density of fresh water, c is salinity, and K is a constant.

space grids is subject to the following restrictions: 1) computer storage capacity places an upper limit on the number of spatial grid points that can be included; 2) cost of computer time prohibits the use of an excessive number of time steps; and 3) prevention of numerical instability imposes a restriction of the relationship between the temporal and spatial grid spacing.

3.3 Tidal Flow Computations

A typical application of the use of the equations of motion and continuity in coastal planning involves determining changes in flow patterns and water heights that result from alteration in system geometry (e.g., the impact of installing new structures). Such information can also be used as an input to analyses of the dispersion and flushing of wastewater discharges.

To illustrate the ideas involved in tidal flow computations we describe the form of the equations typically used in one dimensional models.* For this reason, consider a rectangular channel in which waves are induced by tidal action and the flow is longitudinal. The equation of motion may be written as [5]

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = - g \frac{\partial H}{\partial x} - g \frac{u|u|}{C^2 R} \tag{3-6}$$

where,

- x = distance in the direction of flow,
- t = time,
- u = mean cross section velocity,
- g = acceleration due to gravity,
- H = elevation of water above a horizontal datum,
- C = roughness coefficient, and
- R = hydraulic radius.

The terms on the right-hand side of equation (3-6) represent the pressure force and friction force, respectively; forces due to wind and Coriolis acceleration are assumed to be negligible.

* Later in this section we discuss two dimensional models; we were unable to find any real world applications involving three-dimensional hydrodynamic models for coastal water bodies.

The equation of continuity takes the form [5]

$$\frac{\partial}{\partial x} (A\ u) + b \frac{\partial H}{\partial t} = 0 \qquad (3\text{-}7)$$

where A and b are the cross sectional area and the width of the channel, respectively.

Equations (3-6) and (3-7) are very general in that they describe the motion of flow in all channels meeting the assumed conditions. However, before we have a model for predicting water heights and velocity in a particular channel we must specify the following:

- Boundary conditions to describe the impact of fresh water flow at the ends of the channel.
- Initial conditions to describe the water height and velocity at a single point in time.
- Values of the "input" parameters or functions; i.e., C, R, A, and b.

Once this information is specified for a particular channel, then equations (3-6) and (3-7) can be solved to give velocity and water height in terms of location (x) and time (t). Dronkers [5] has summarized the alternative solution techniques that can be employed.

A demonstration of the usefulness of one-dimensional models in determining the flow patterns and velocities for a real system with complex geometry is provided by the work of Shubinski et al. [23] on the Sacramento - San Joaquin Delta in California.* The Sacramento River, flowing in a southerly direction,

* The results from this study were used as an input to a more comprehensive study to determine the impact of alternative water transfer schemes on the quality of water in the Delta.

and the San Joaquin River flowing in a northerly direction, join to form a complex network of tidal estuaries which drain ultimately to San Francisco Bay and the Pacific Ocean (see Figure 3-1). Shubinski et al. represented the Delta by a number of interconnected one-dimensional channels and nodes, and wrote equations of motion for the channels and equations of continuity for the nodes.

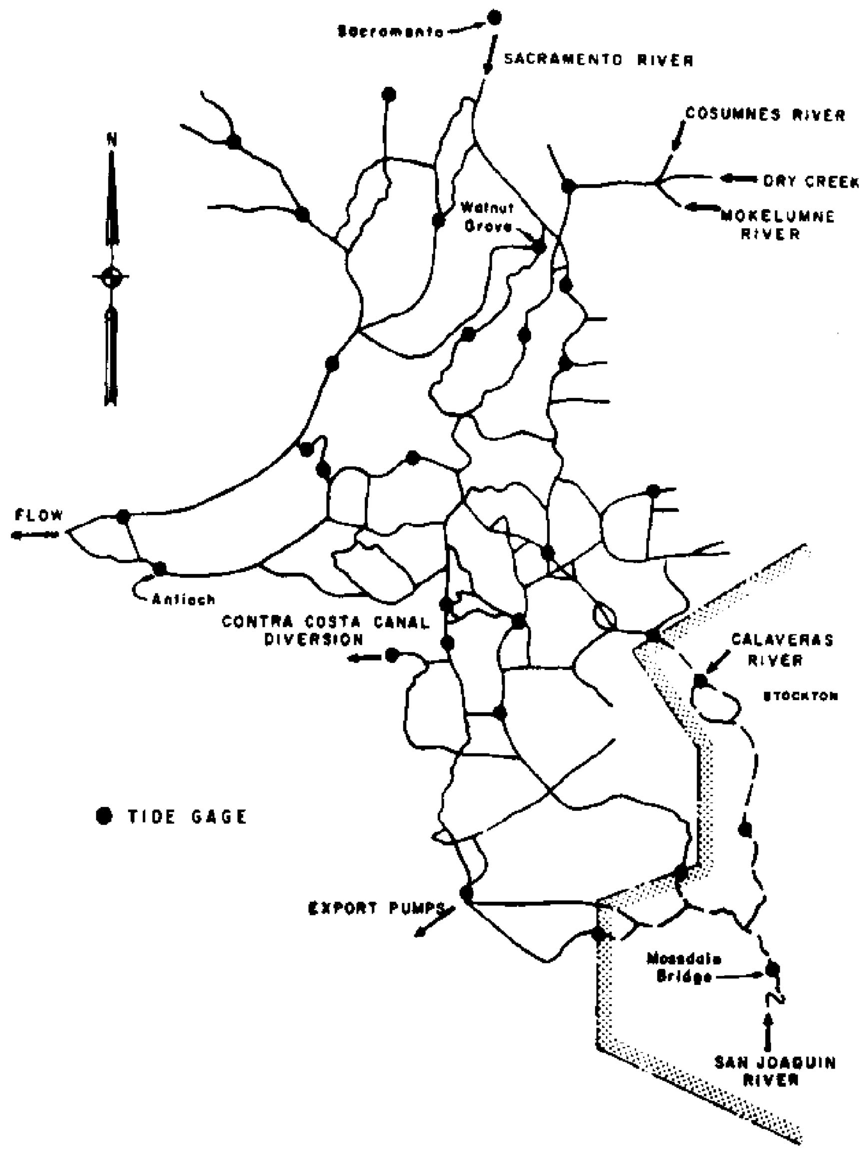

Fig. 3-1. Idealized Sacramento—San Joaquin Delta System (From Shubinski et al. [23]).

Figure 3-2 shows some of the results of the verification stage for the Delta model. The figure contains four graphs of predicted and observed values of tidal elevation versus time for widely separated gaging stations in the Delta region. Values predicted using the model are in reasonable agreement with observed values, especially after the lapse of ten hours. Shubinski et al., emphasized that these results were not obtained by varying model parameters to force agreement between observed and computed values. The predicted values were obtained using information that was essentially independent of the observed tidal elevations.

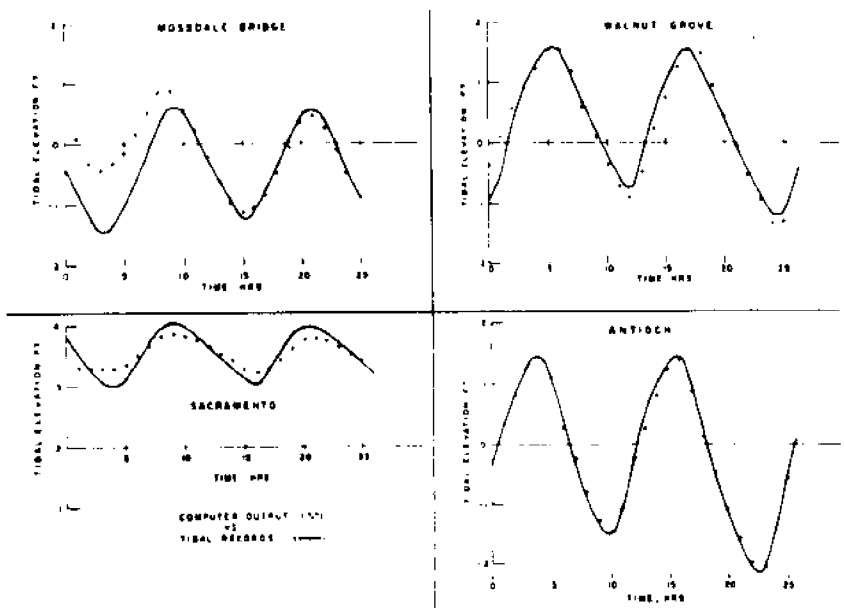

Fig. 3-2. Typical comparison stations (from Shubinski et al. [23]).

Several investigators have presented two dimensional models that could form the basis of a hydrodynamic analysis of those Long Island bays where vertical density stratification can be assumed negligible (e.g., Fischer [7]. Shankar and Masch [22], and Leendertse [16]). In fact Leendertse is actively working towards obtaining a verified model of Jamaica Bay, which is on the south shore west of the Nassau County line [16, p. 38].

We will describe Fischer's model because it is quite representative, and also because Fischer has provided a listing of the computer program he developed together with complete instructions for its use. Since his program is farily general it could prove valuable in future hydrodynamic model studies for Long Island.*

Fischer's model is specifically designed for a geometry in which a single river flows into a bay, which in turn is connected to the ocean. The river is treated using a one dimensional model, and the river flow is an input to the two dimensional model of the bay. Fischer's model consists of the two dimensional equation of continuity and the equations of motion when written as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} - g\frac{u\sqrt{u^2+v^2}}{C^2H} + fv + \frac{T^x}{\rho H}, \text{ and}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial y} - g\frac{v\sqrt{u^2+v^2}}{C^2H} - fu + \frac{T^y}{\rho H},$$

where t, u, v, x, y, g, and H are as defined above, and

T^x = shear stress due to wind in x direction,

T^y = shear stress due to wind in y direction,

f = Coriolis parameter, (a function of latitude), and

ρ = density of water (assumed constant).

* The discussion of Fischer's computer program is limited to the hydrodynamic modeling portions; in the full form the program can be used to predict the distribution of selected pollutants as well.

To accomplish the integration of these equations numerically it is first necessary to establish a grid network on the plan area of the bay. The model solution, which takes the form of values for u, v, and H, is given only at these grid points. The key input information needed in the development of the model for a specific application is as follows:

- Geometry - a delineation of the land - water interface, and also the depth of the bay bottom below a specified datum.
- Wind stress and Coriolis force - values of T^x, T^y and f.
- Bottom friction - values of C, the roughness coefficient, for all grid locations.
- Fresh water - water surface elevations at the river's mouth as a function of time.*
- Tidal action - tidal elevations at the mouth of the bay over a tidal cycle.

As of March, 1970 Fischer's two dimensional hydrodynamic model had not been verified for a real system, although a number of numerical experiments for a hypothetical system yielded plausible results. Fischer observed that models similar to the one he employed have been verified for water elevations, but the validity of predicted velocity distributions has not been established unambiguously [7, p. 13]. Future verification efforts, such as the one proposed by Leendertse for Jamaica Bay, should be helpful in this regard.

3.4 Storm Surge

Models based on the equations of motion and continuity have been used to predict the way in which structural changes can reduce the impacts of

* This is actually internal to Fischer's computer program since he combines the bay model with a one-dimensional river model.

storm induced waves in estuaries.* Below, we mention two practical illustrations of the use of these so-called "storm surge" models. Such illustrations are relevant to Nassau and Suffolk Counties, since the impacts of storm induced waves have caused substantial difficulties [24].

Reid and Bodine [21] developed a storm surge model to determine the wave action caused by a time varying wind over Galveston Bay, Texas. Their model was based on the equations of motion and continuity in two dimensions (i.e., lateral and longitudinal). They explicitly accounted for forces associated with pressure, bottom friction and wind stress; and they considered the Coriolis force and the advection of momentum negligible (see equation 3-2). The continuity equation was written to account for the time rate of change in water volume caused by the rainfall input during storms.

The Reid and Bodine model requires the prior specification of an appropriate surge height versus time for the sea adjoining the bay. This information, which enters their model as a boundary condition, accounts for the combined effects of winds and differential atmospheric pressure that give rise to the surge in the sea adjacent to the Bay. Their model also accounts for the overflow of low-lying barrier islands and for flooding from low-lying land areas.

The input parameters for the Reid and Bodine model were chosen such that the numerical solution would be in close agreement with observational data obtained for hurricane Carla (Sept. 9-12, 1961). The model was verified by computing surge heights for hurricane Cindy (Sept. 16-17, 1963). Close agreement between computed and observed results was reported for the period

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* A discussion of the voluminous literature relating to the prediction of wave heights and impacts on non-estuarine shorelines is beyond the scope of this report. Complete treatments of these subjects have been given by Wiegel [28] and Ippen [12].

of peak surge levels.*

A recent storm surge model of special relevance to Nassau and Suffolk Counties is a result of the Balloffet and Kupferman study [3] of Jamaica Bay, Long Island, carried out for the U. S. Army Corps of Engineers. Because of extensive past damage caused by storm surges, the Corps of Engineers has made plans for the construction of barriers at various locations in the bay in order to protect populous areas. Because the introduction of such barriers can have far-reaching effects upon the ecology of the estuary as well as upon navigation, the Corps has been charged with determining the influence of the barriers on water heights resulting from storm surges, and on the exchange of water throughout the Bay in response to normal tidal conditions. Since Jamaica Bay is divided into a network of channels winding around a number of islands and marshy regions, it was considered acceptable to describe the flow by representing the entire bay by a system of one-dimensional equations, each of which describes the flow in one of the connecting channels. The equation of motion was used to describe the flow in each channel; and the one-dimensional time dependent equation of continuity takes into account the discharge from the channel. Numerical integration methods were used to compute maximum surge levels as well as tidal currents through gaps in proposed barriers to determine effects on navigation. However, the effect of the proposed barriers on pollution of the Bay was not determined.

3.5 Shoaling

The transport of sediments and the consequent variations in the configuration of the bottoms of coastal waters can have significant effects on navigation and the state of organisms and marine vegetation important to

* Although the hydrodynamic equations used by Reid and Bodine were originally formulated to determine storm surge effects, they were found to provide a suitable preliminary hydrodynamic model for subsequent use in a study of the water quality problems of Galveston Bay [6].

fin and shellfish. The importance of these activities in the Long Island area has been described in sections on Sport and Commercial Finfish, Shellfish, and Coast Stabilization and Protection, in the report by Smith *et al.* [24].

Basic understanding of the processes associated with sediment transport is quite limited. Consequently, there are very few quantitative models to predict the influence of various activities (e.g., dredging and changes in freshwater inflow) on shoaling in coastal waters [27].

Quantitative studies of shoaling exploit the fact that shoaling in coastal waters is significantly related to the magnitude and direction of flow immediately above the bottom.* Correlations have been observed between the extent of shoaling and "bottom flow predominance;" i.e., a measure of the percent of flow (near the bottom at a given location) that is in the landward direction over a tidal cycle. The maximum shoaling zones in some estuaries have been shown to occur at the longitudinal location for which the bottom flow predominance is near fifty percent [11].

Harleman and Ippen [11] extended the flow predominance concept in developing a procedure for predicting the influence of changes in freshwater inflow and mean depth on the location of zones of heavy shoaling. They defined a "null point" as the longitudinal position at which the bottom flow predominance is fifty percent. This point is characterized by an average velocity (over a tidal cycle) of zero at a small distance above the bed. Harleman and Ippen have shown how to compute the change in location of the null point that results when there is an alteration in the freshwater velocity or mean

* This discussion highlights the relationship between shoaling and bottom velocity; sediment floculation and consolidation and the importance of grain size distribution in the shoaling process have not, to our knowledge, been dealt with except in a semi-quantitative fashion. (See Wicker [27].)

channel depth.*

An alternative approach to estimating shoaling locations involves the direct computation of the mean velocity of the fluid layer just above the bottom. Abbot [1] developed a model to determine this velocity using the two-dimensional form of the equations of motion and continuity.** He assumed that the surface velocity is longitudinal and varies as a sinusoidal function of time, with amplitude and phase lag dependent on the longitudinal space coordinate. The surface velocity is an input to Abbot's model and can be obtained by direct observation, or by means of a one-dimensional analysis (see Section 3.3 above).

Abbot's version of the equation of motion in the longitudinal direction accounts for the forces of pressure and friction. The gravity force (see equation [3-3] above) was omitted since it has no horizontal component, and the Coriolis force was considered negligible because the body of water under consideration was small.

Abbot used his model to develop a criterion for locating points at which an accumulation of loose bed material is likely. The criterion was used successfully in predicting the location of regions of heavy silting in the Thames Estuary in England.

In a later study, Abbot [2] investigated the effect of a longitudinal salinity gradient upon the mean velocity just above the bed. He derived a criterion for determining the direction of this velocity in estuaries where the extra pressure gradient due to a longitudinal salinity gradient is a

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* Their approach depends on the fact that the ratio of average bottom velocity to average freshwater velocity is correlated with a dimensionless parameter involving freshwater velocity, local density, and channel depth.

** Abbot's model assumes that there is no lateral variation across an estuary; i.e., the two-dimensional components are vertical and longitudinal.

predominating factor. Abbot applied his criterion to account for salinity effects in the Mersey Estuary and found that the mean velocity reverses direction in the vicinity of Eastham. This result was consistent with results obtained with a hydraulic model of the Mersey Estuary.

3.6 Tidal Flow in Inlets*

The tidal inlets along the south shore of Long Island exert a considerable influence on the extent to which flow is exchanged between the Atlantic Ocean and the south shore bays. Consequently, the status of these inlets is of importance in determining salinity patterns and the ability of south shore bays to assimilate wastewater discharges [24]. In addition, the size and shape of tidal inlets have direct implications for navigation.

Van de Kreeke [25] utilized a hydrodynamic model to determine the influence of freshwater inflows and tidal fluctuations on the ocean side of an inlet on the velocity and water height in the inlet. He employed the equation of continuity with a separate term to reflect the time rate of input of freshwater flow on the bay side of the inlet. The equation of motion was written in one-dimensional form with the inlet treated as a channel of constant cross section. The tidal fluctuations on the ocean side of the inlet were incorporated as boundary conditions.

Van de Kreeke presented illustrative computations using data from the Inlet of Macquarie Harbor, Tasmania. He determined how the flow rates and wave heights of water in the inlet responded to alternative freshwater inflow patterns. His computational procedures could also be used to investigate the impact of differences in inlet cross section and tidal action.

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* A tidal inlet is a short waterway connecting the tidal ocean or sea with an interior bay or lagoon. In stable tidal inlets, there is a balance between the scouring action of the tidal currents, tending to keep the channels open, and the longshore transport of beach sand, tending to close them. For introductory discussions see Caldwell [4] and Lockwood and Carothers [17].

3.7 Salinity Distribution

Information on the distribution of salinity concentrations in the coastal waters of Long Island is important because of the implications of varying salinity regimens on marine organisms. Such information is also important in determining the impact of varying salinity levels on the quality of the ground water supplies in Nassau and Suffolk Counties. In this section we note how the models discussed earlier in this chapter have been extended to yield models for predicting the distribution of salinity concentrations.

During the past two decades a number of researchers have developed mathematical models for predicting salinity concentrations in coastal water bodies. (See, for example, Ippen [13].) A commonly employed model uses the equations of motion and continuity for the fluid and one additional equation representing the conservation of salt; i.e., a material balance for salt entering and leaving a differential volume element fixed in space. As derived by Pritchard [19], the salt conservation equation takes the following form:

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} - v\frac{\partial c}{\partial y} - w\frac{\partial c}{\partial z} + \frac{\partial}{\partial x}\left[\varepsilon_x \frac{\partial c}{\partial x}\right] + \frac{\partial}{\partial y}\left[\varepsilon_y \frac{\partial c}{\partial y}\right] + \frac{\partial}{\partial z}\left[\varepsilon_z \frac{\partial c}{\partial z}\right], \tag{3-8}$$

where c, a function of space and time, represents the salinity concentration, and ε_x,ε_y and ε_z are coefficients of "eddy diffusivity" in the x, y and z directions, respectively. The first three terms on the right-hand side of equation (3-8) represent the so-called "advective transport", i.e., the salt carried by the physical displacement of a given volume of liquid. The last three terms represent the salt transport due to turbulent diffusion and non-uniformities in velocity distributions. A physical interpretation of these terms, including observations on the nature of the terms ε_x, ε_y and ε_z, has been given by Harleman [9, 10]; however, physical interpretations of the diffusivity coefficients differ depending on the nature of the time and space averaging involved in computing the velocities. In fact, the difficulties in interpretation have led some researchers to think of these coefficients simply as devices for accounting for all the transport that is not reflected in the advective terms [7, p. 4].

Shankar and Masch [22] used a two dimensional hydrodynamic model (similar to Fischer's model discussed in Section 3.3 above) together with an equation of continuity for salt to predict salinity distributions in a number of bays on the Texas Gulf Coast. Their study involved the development and application of models to predict the effect of the following actions on the salinity regimes of these bays:

- Alterations in the rate of freshwater inflow.
- The creation of new inlets and the enlargement of existing inlets.
- The alteration of bay bottom topography resulting from the removal of reefs and dredging activities.

Shankar and Masch postulated that water density was essentially a constant for the bays of interest to them; and consequently they ignored density stratification and eliminated the vertical (or z) direction from their analysis. This allowed them to determine the horizontal components of velocity independently of salinity patterns. That is, they first used a two dimensional hydrodynamic model to compute u and v; these values were then used as inputs to a two dimensional salt continuity equation which was solved to yield c(x, y, t), salinity as a function of location and time.

Figure 3-3 shows the grid network used for numerical integration by Shankar and Masch in analyzing Matagorda Bay, Texas. The grid points are actually represented by centers of the boxes shown in the figure. Stations at which velocity, water height and salinity data were available for model verification are also shown.

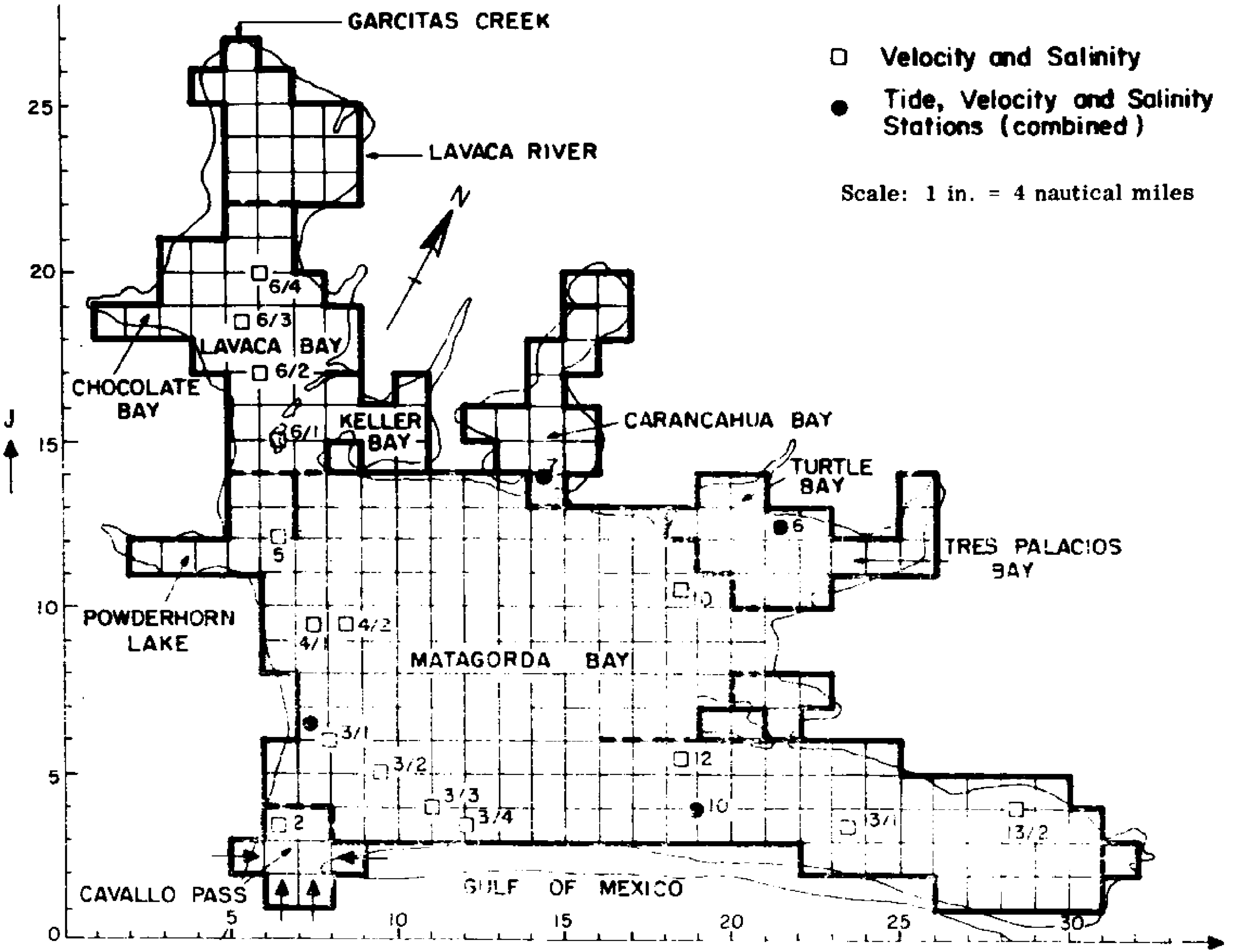

Fig. 3-3. Computational grid and location map—Matagorda Bay. (From Shanker and Masch [22]).

Results from a limited verification study for the Matagorda Bay model are shown in Figures 3-4 through 3-7. Good correlations between observed and predicted water heights are indicated by the results shown in Figure 3-4. However, the results for velocity are not nearly as good. Figures 3-5 and 3-6 show observed velocities at two stations, and velocities predicted using the hydrodynamic model; also shown are velocities predicted using a hydraulic model of the Bay. The discrepancies between model outputs (both mathematical and hydraulic) and real system observations are noteworthy.

Figure 3-7 contains the predicted and observed steady -state values of salinity at a number of stations. For most stations the values predicted by the model based on the salt continuity equation are reasonably close to observed values. Shankar and Masch attributed discrepancies to the use of constant values for the diffusivity coefficients [22, p. 70].

Although the total cost of developing and verifying their two dimensional models for Matagorda Bay was not reported, Shankar and Masch did mention the "running time" for various computations on a CDC 6600 computer. The velocities and water heights were obtained in one minute per tidal cycle. For salinities, a total of 200 tidal cycles were run to reach steady state (with constant inputs), and this took about six minutes [22, p. 67].

Shankar and Masch's model predicts salinity in the horizontal (or x, y) plane. Starting from the three dimensional form of the same fundamental equations, Hansen and Rattry [8, 20] developed a model for predicting salinity in the vertical plane (i.e., the x, z plane, which is parallel to the direction of flow in estuaries where a single dimension for flow is meaningful). Hansen and Rattry's model, which involved two dimensions and a simplified representation of system geometry, was used to predict longitudinal and vertical velocities and salt concentrations for the James River estuary. Their model differed essentially from that of Shankar

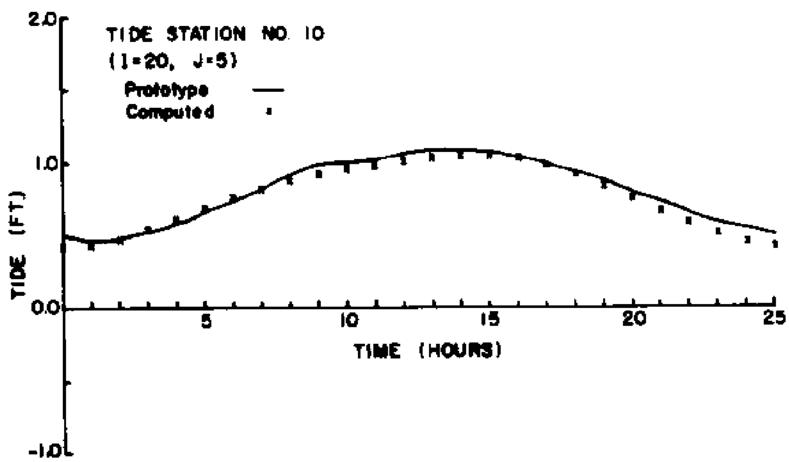

Fig. 3-4. Hydrodynamic verification of tide—Matagorda Bay. (from Shanker and Masch [22]).

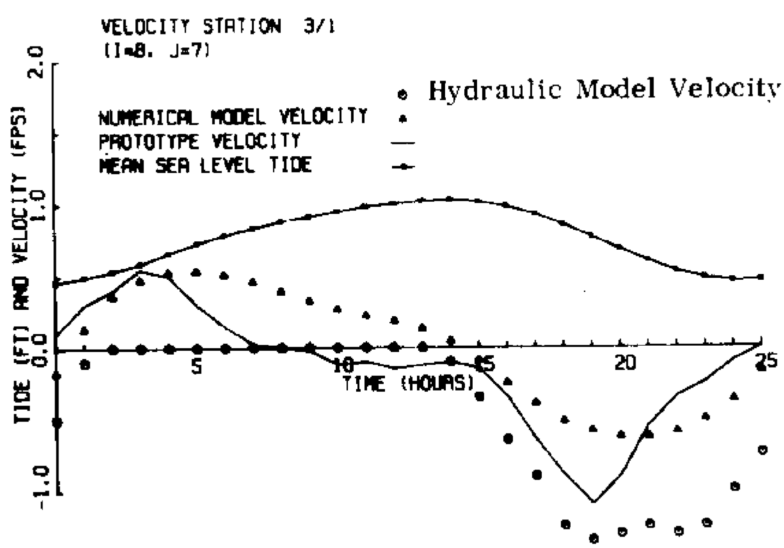

Fig. 3-5. Hydrodynamic verification of tidal velocities—Matagorda Bay. (from Shanker and Masch [22]).

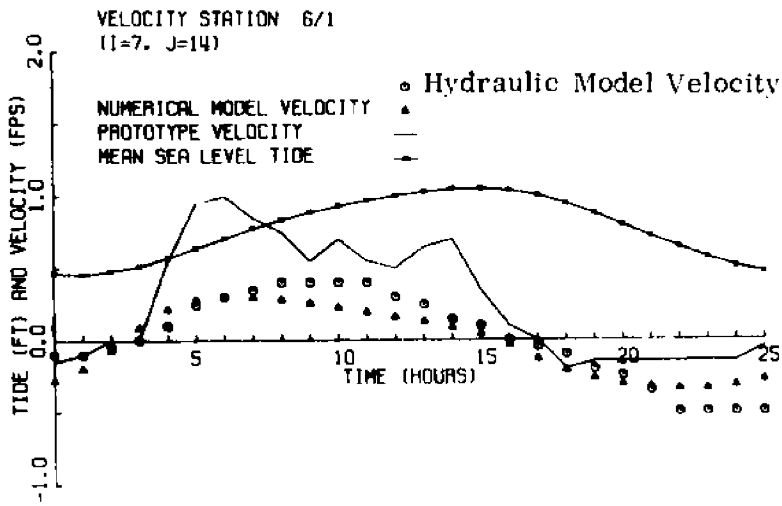

Fig. 3-6. Hydrodynamic verification of tidal velocities—Matagorda Bay. (from Shanker and Masch [22]).

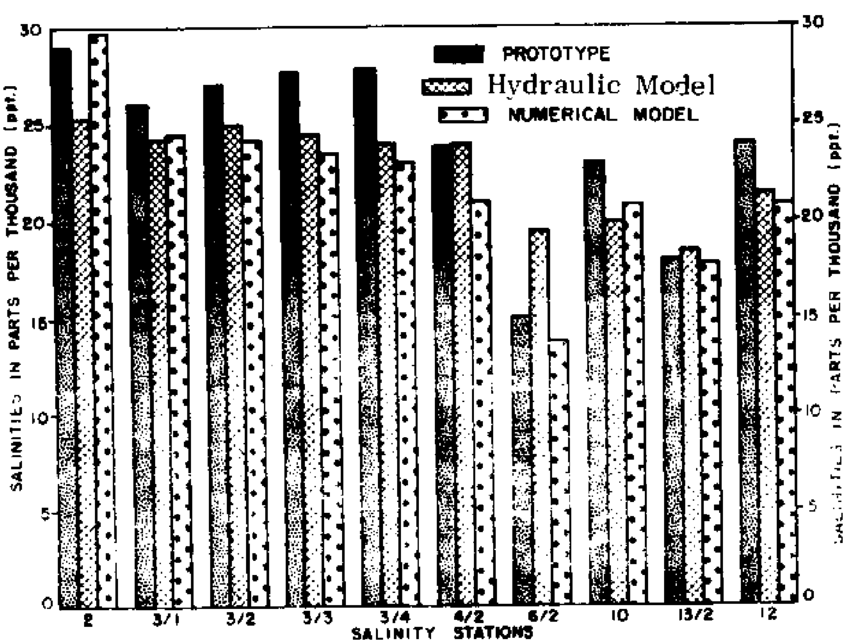

Fig. 3-7. Salinity model verification—Matagorda Bay. (from Shanker and Masch [22]).

and Masch in that it involved an equation of state to account for the influence of salinity on density. Since velocities were affected by the variable density regime, it was not possible to split the computation of salinity into two steps; i.e., first compute velocities, and then use the velocities as an input to the computation of salinity. Rather it was necessary to solve all equations simultaneously - a formidable task indeed. The solutions obtained by Hansen and Rattry were found to be in reasonable agreement with observational data for the James River estuary.

3.8 Concluding Remarks

In principle, the models of this chapter can be used to determine how velocity, water height and salinity are influenced by changes in geometric configuration (e.g., structural changes), tidal action, freshwater inflow, and wind stress. In practice, the extent to which such determinations can be made is limited by the size and speed of the current generation of electronic computers and the ability to devise numerical integration schemes that are both stable and convergent.

As compared to hydraulic models, the models of this chapter require no large building facilities, and they may, under some circumstances, provide greater flexibility in efforts to model a number of different processes simultaneously. There is, in the engineering community at least, no universal agreement on whether the "more physical" models of Section 2 or the more abstract models of this section should be used in any given circumstance. All models have their strengths and weaknesses, and decisions on which type to employ depend heavily on the particular circumstances involved.

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4.0 WATER QUALITY MODELS*

4.1 Introduction

Many of the marine resources problems of Long Island relate in one way or another to water quality. Although these problems have been discussed in detail in an earlier report [41], we note the following issues as being typical:

- Where should municipal and industrial wastewaters be discharged? What levels of treatment should be provided to protect alternative near shore activities?
- Should nutrient additions, such as those originating from duck farms or overland runoff, be controlled?
- Should the use of pesticides be restricted?
- How will waste heat from electric power plants be distributed in coastal waters?

In attempting to deal with these issues it is extremely useful to be able to predict how water quality is likely to be modified by following alternative courses of action. This section describes the extent to which such predictions can be made in quantitative terms. More carefully stated, this section describes mathematical models that yield information about the concentration fields for various substances, where the term "field" is used here to mean a relationship giving the concentration (c) of the substance in question in terms of location (x,y,z) and time (t). The models are based on the hydrodynamic equations described in Section 3.0 above, and the law of conservation of matter for particular substances.

* We use the term "water quality models" as a shorthand way of saying models for predicting the distribution of dissolved and suspended substances in waterways.

In Section 4.2 below we consider models for predicting concentration fields in situations where wastes are discharged directly to the ocean by means of so-called ocean (or submarine) outfalls. The use of ocean outfalls off Long Island is one of the more important possible solutions to the problem of disposing of liquid wastes. This can be inferred from the recent decision to locate the treated effluent from the new Nassau County Disposal District No. 3 outfall in the ocean, and not in a south shore bay.

Section 4.3 deals with approaches for predicting the concentration fields resulting from wastewater discharged to estuaries (including bays). The section contains a discussion of the historically significant tidal prism theory as well as models based on the advective-diffusion equation, a special form of the law of conservation of matter. This topic is relevant to Nassau and Suffolk Counties since bays have been widely used as receptors for liquid wastes.

In Section 4.4, we discuss, systematically, the extent to which the following wastewater constituents have been modeled in "real-world" situations: dissolved oxygen, biochemical oxygen demand, coliform bacteria, and compounds of phosphorous and nitrogen. Some remarks are also made about the transport of waste heat and pesticides, two kinds of potentially deleterious additions to the coastal environment of Nassau and Suffolk counties not generally associated with municipal wastewater.

4.2 Disposal of Wastewater in the Ocean

The use of the ocean as a direct sink for wastewater is quite common along both coasts of the United States. Submarine pipes are used to convey wastewater to a selected location (anywhere from several hundred to many thousands of feet from shore), where it is released in a single stream, or jetted through a diffuser. Models developed to assess the impacts of ocean disposal are relevant to Long Island, inasmuch as the use of ocean outfalls off the south shore has been the subject of a considerable number of engineering reports and special studies.* (See, for example, Udell [47] and Smith et al. [41].)

The disposition of wastewater discharged from an ocean outfall is conveniently examined in two parts: (1) mixing in the immediate vicinity of the discharge point, and (2) the lateral mixing and further spreading of the wastewater-seawater mixture. These items are discussed sequentially below.

4.2.1 Mixing at the Point of Discharge

The mixing process in the vicinity of the discharge point is often studied for the special case where the receiving water is stagnant and free of temperature gradients; and, except where noted, we will consider these circumstances. The extent of "turbulent mixing" that occurs near the point of discharge depends on the bouyancy and the initial momentum of the wastewater jet. The bouyant force, which decreases as the jet rises, is proportional to the difference in density between the seawater and the rising jet. The initial momentum, which results from the velocity of the discharging wastewater, also decreases as the jet rises since energy is dissipated in turbulent mixing.

Several investigators have focused on the problem of predicting the concentration field (or plume) of a dye emitted continuously in a fresh water solution which flows into a more dense receiving water. For conditions where the discharge is turbulent, it has been found that the important parameters determining the concentration field include the angle of discharge, the ratio of vertical distance below the water surface to outfall diameter, and the Froude number. The latter is a dimensionless parameter (F) defined as

* The models to be discussed are not adequate in themselves to accomplish the design of ocean outfalls. "Engineering judgment derived from theoretical analyses, oceanographic data, experience and other factors. . .is at present the major factor in successful marine outfall design" [26, p. 261].

$$F = \frac{V_o^2}{\frac{dg\ (\rho_s - \rho_o)}{\rho_s}}$$

where,

V_o = initial velocity of the discharged fluid,

d = discharge pipe diameter,

ρ_s = density of receiving water,

ρ_o = density of fluid before discharge, and

g = acceleration due to gravity.

Abraham [2] developed a model to determine the concentration field for a continuous discharge of dye through a horizontal pipe. The model consists of equations for the conservation of the discharged fluid and dye, the conservation of momentum, and geometric considerations; also, an assumption is made about the form of the profile of mean velocity and dye concentration in sections perpendicular to the axis of the jet.

The outputs (or solutions) from Abraham's model, as well as those of Fan and Brooks [11] who employed slightly different assumptions, are shown in Figure 4-1. The curves in the figure correspond to different values of S_m, the ratio of the concentration of dye in the discharge to the concentration on the centerline of the rising jet. The horizontal axis in the figure is the square root of the Froude number, and the vertical axis is the ratio of vertical distance, y, to discharge pipe diameter, d. The results in Figure 4-1 provide a means for computing the concentration of dye along the centerline of the rising jet given the Froude number, the pipe diameter, and the concentration of dye in the discharge. The results also suggest the extent of agreement by different investigators examining the same problem, but using different assumptions.*

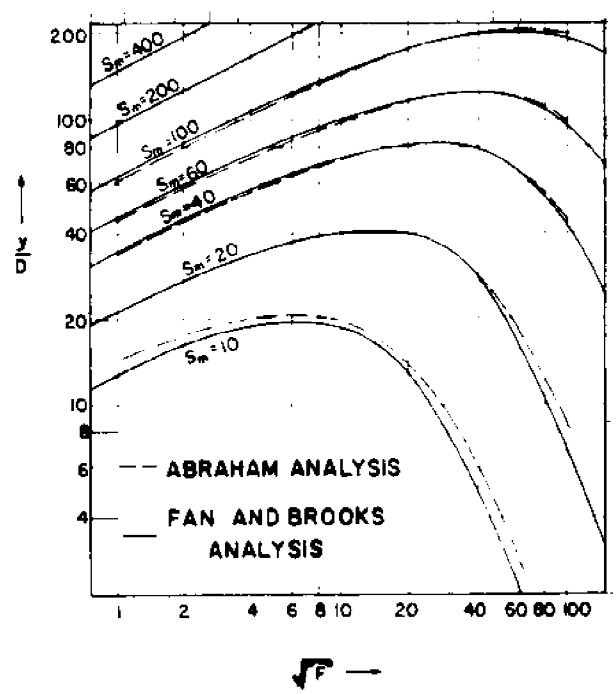

Fig. 4-1. Comparison of analyses for center line dilution, S_m, as function of y/D and $\sqrt{F}$ (from Fan and Brooks [11]).

* Empirical investigations of mixing in the vicinity of the point of discharge have been conducted by Frankel and Cumming [14], and Rawn et al. [38]. The former study, which involved variations in the angle of discharge, concluded that horizontal discharges are most efficient for ocean outfalls. It has been observed, however, that if it were "not for the problem of bottom scouring, downward jets would be even better" [10, p. 296].

The above results are for receiving waters that do not exhibit significant variations in density in the vertical direction. Under these circumstances the wastewater - seawater mixture rises to the surface and then begins spreading. In practice, however, the situation might be complicated by the existence of a thermocline (i.e., a marked change in temperature with depth caused by solar heating of the upper layers of the sea) which leads to density gradients in the vertical direction. Under these circumstances, depending on the relative densities, the wastewater - seawater mixture may begin spreading in the region below the surface, or it may reach the surface due to its momentum, and then plunge beneath the surface and continue spreading. Empirical and theoretical formulas for describing aspects of the concentration field in the presence of vertical density gradients have been developed by Hart [18] and Abraham [1].

4.2.2 Further Spreading of the Wastewater - Seawater Mixture

The above discussion focused on models for predicting the dilution of wastewater discharges in a stagnant receiving water. Below we consider a second aspect of the dilution problem, namely the additional mixing and spreading of the wastewater - seawater mixture that is accomplished by the natural turbulence generated within a moving current; in the sanitary engineering literature this topic is often referred to as the "sewage field problem". Brooks' [4] formulation and theoretical solution of the problem are instructive and are summarized with minor modification below.

Consider a multiple outlet diffuser discharging a wastewater containing a "conservative" (i.e., non-decaying) dye into seawater. Represent the diffuser by a continuous steady line source of length b perpendicular to the current, where the latter is considered uniform and steady with velocity U. Assume that the initial turbulent mixing (discussed in Subsection 4.2.1 above) has resulted in dilution of the original dye concentration to the extent that the wastewater - seawater mixture has a uniform concentration of c_o at the ocean surface (see Figure 4-2).*

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* The effect of the wastewater discharge on the ocean flow pattern and temperature structure is considered to be negligible. Also, no account is taken of the submerged spreading that might take place in the presence of substantial density stratification.

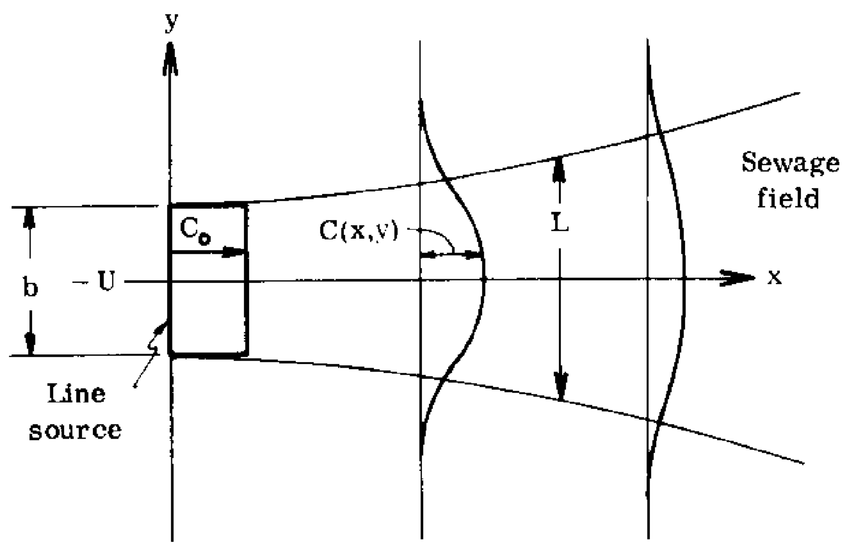

Fig. 4-2. Sewage field diffusing laterally in an ocean current (from Brooks [4]).

The "sewage field" formed by the line source is assumed to move downstream (the x direction in Figure 4-2) at the same rate as the prevailing current. As x increases, mixing takes place along the edges of the field, and the initial uniform distribution of concentration is gradually spread out. Brooks' analysis determines c(x, y), the concentration of dye at all points of the ocean surface downstream from the source.

Brooks' model consists of a mass conservation equation for the dye; one component of the equation accounts for the diffusion of dye caused by turbulent exchange. In describing the turbulent exchange process Brooks assumes that an analogy exists between molecular and turbulent exchange processes, and uses the analog to Ficks Law of Molecular Diffusion to describe the time rate of change of dye concentration in the y direction: i.e.,

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y} (\varepsilon \frac{\partial c}{\partial y}), \qquad (4\text{-}1)$$

where t is time, and ε is the coefficient of eddy diffusion in the y (or lateral) direction.*

To obtain an expression for the eddy diffusion coefficient in the lateral direction, Brooks relies on the substantial body of theoretical and empirical evidence [32] which indicates that ε is proportioned to the 4/3 power of the scale of the diffusion phenomena. In this case the scale refers to the length L (defined in Figure 4-2), which is assumed to be a function of the concentration distribution at a given station x. Since L is independent of y, the diffusion coefficient can be placed before the differential operator in equation (4-1).

In addition to turbulent exchange, dilution of the dye is accomplished by advective transport (i.e., the physical displacement of a given volume of liquid) in the x direction. Assuming steady state conditions (i.e., $\frac{\partial c}{\partial t} = 0$), the equation for mass concentration is

$$0 = + \varepsilon \frac{\partial^2 c}{\partial y^2} - U \frac{\partial c}{\partial x} , \qquad (4\text{-}2)$$

where the first and second terms account for material transport by turbulent exchange and advection, respectively.

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* Brooks assumes that turbulent exchange in the vertical direction is negligible because of the stability resulting from density stratification; and also that turbulent exchange in the direction of the current is negligible because the concentration gradients in this direction ($\partial c/\partial x$) are small compared to the gradients in the y direction.

For the center of the field (i.e., $y = 0$) the solution to this equation subject to suitable boundary conditions is presented in Figure 4-3.*

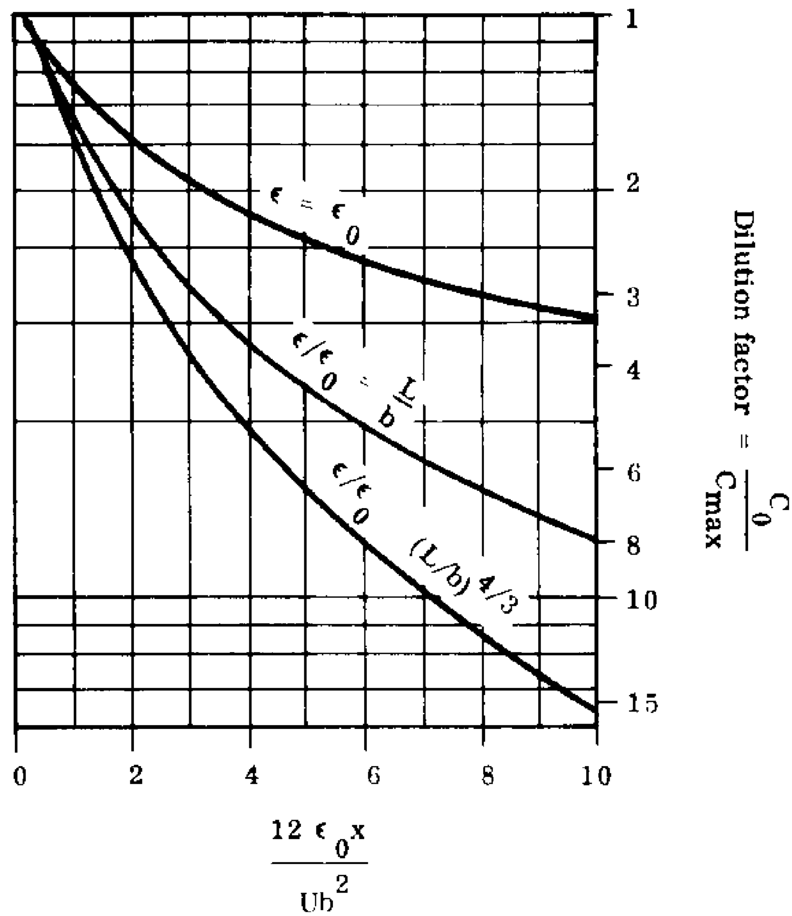

Fig. 4-3. Solutions to Eq. (4-2) (adapted from Brooks [4]).

* In Brooks' analysis the maximum concentration of dye occurs at the center of the field.

The horizontal axis in this figure represents a dimensionless factor that incorporates the effect of velocity, initial diffusivity, distance, and diffuser length; this factor is given by

$$\frac{12\varepsilon_o x}{Ub^2} ,$$

where ε_o = coefficient of eddy diffusion at x = 0, and the remaining terms are as defined above. The vertical axis represents a dilution factor, defined as the ratio of initial concentration to the maximum concentration at station x. The three curves shown in the figure are solutions to equation (4-2) corresponding to different assumed forms for the coefficient of eddy diffusion.

Brooks' model has been used to locate ocean outfalls in situations where a key design criterion was the preservation of levels of coliform bacteria to permit swimming in the shore zone. For such analyses c in equation (4-2) is interpreted as the concentration of coliform bacteria. The term k c is subtracted from the right-hand-side of equation (4-2) to reflect the disappearance of coliform due to mortality and sedimentation (k is an empirically deduced constant). In other words, the rate of disappearance of coliform bacteria is assumed to be proportional to the concentration.

Figure 4-4 is from an ocean outfall location analysis that was performed using Brooks' model. The figure shows the distances from a proposed outfall diffuser at which the indicated coliform concentrations (10 or 100 per milliliter) will occur at the frequency indicated (5 or 20 percent of the time). For example, at any sampling station outside the curve marked "100/ml - 5%", it may be expected that coliform concentrations will exceed 100 per milliliter in fewer than 5 percent of the samples. Other curves in figure represent different coliform concentrations, percentage levels, and current conditions. Analyses of this type can be of considerable value in locating outfalls to meet specified bacteriological standards.

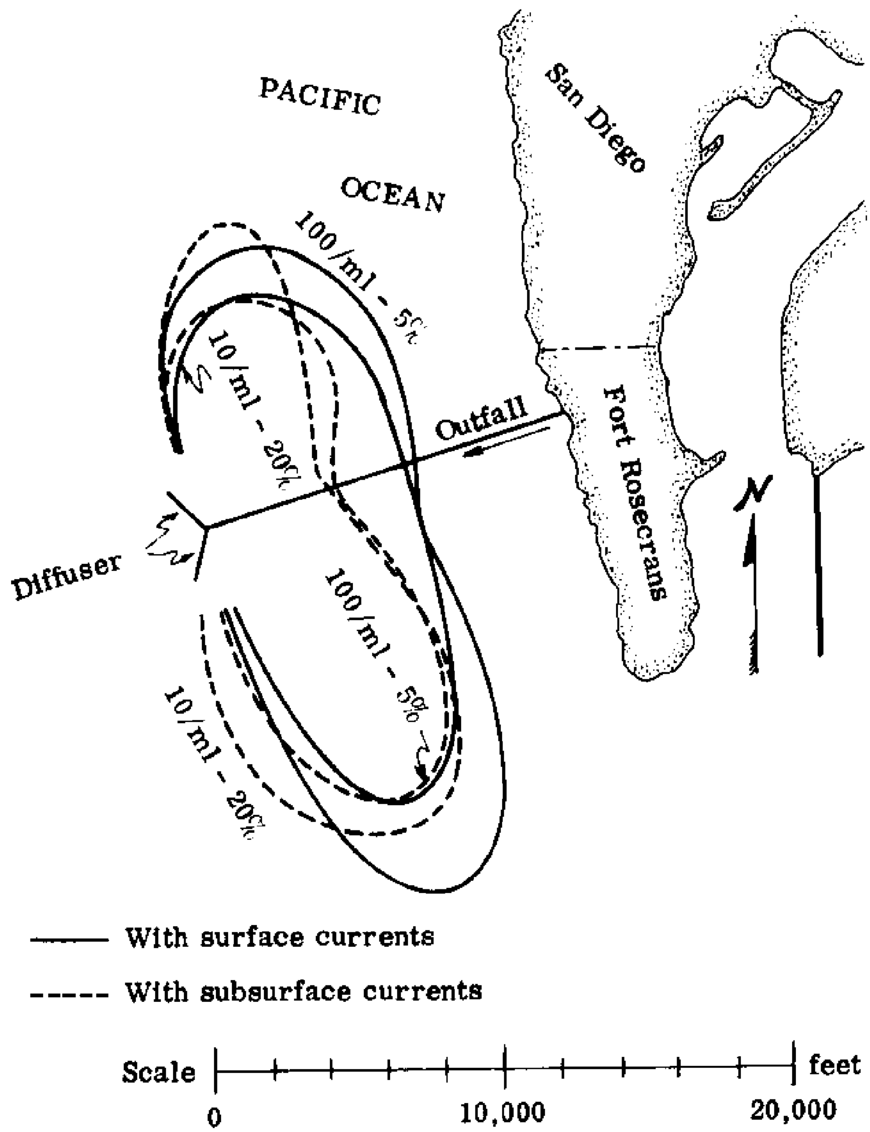

Fig. 4-4. Ocean outfall analysis. (Adapted from Brooks [4]).

An alternative approach to the one taken by Brooks consists in postulating that the concentration field downstream from a point wastewater discharge has a Gaussian distribution in the lateral and vertical coordinate directions. Using this approach Foxworthy and Kneeling [12] demonstrated that the maximum concentration of dye along the longitudinal axis of the plume could be described using

$$c_m = \frac{Q}{\pi U \sigma_y \sigma_z} , \tag{4-3}$$

where
- c_m = mean maximum dye concentration,
- Q = volume flowrate of the wastewater source,
- U = mean current speed, and
- $\sigma_y (\sigma_z)$ = standard deviation of dye concentration as a function of distance along a large scale plume.*

Figure 4-5 contains results from field experiments conducted by Foxworthy and Kneeling off the coast of California. The two curves represent the results of applying equation (4-3), and a variant in which vertical diffusion was assumed negligible (i.e., the result of a one-dimensional analysis). The results shown in the figure led Foxworthy and Kneeling to postulate that for this particular experiment vertical diffusion was indeed significant; mean wind speed was considered the principal factor influencing vertical diffusion near the ocean surface.

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* These coefficients can be related to the coefficients of eddy diffusion introduced above [12, p. 67].

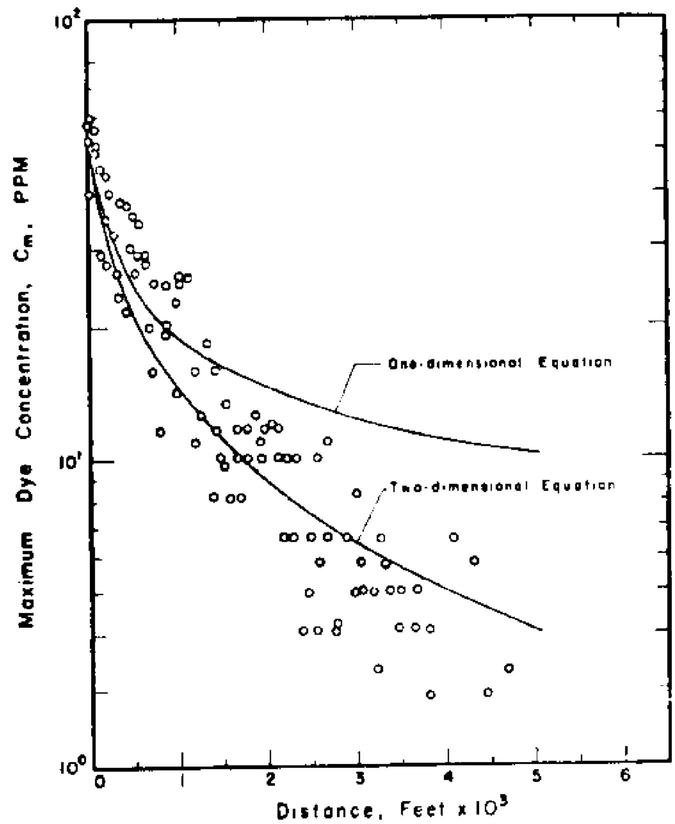

Fig. 4-5. Maximum dye concentration vs. distance along longitudinal axis of plume (from Foxworthy and Kneeling [12]).

The studies relating to wastewater dispersion from ocean outfalls described above characterize a small, but nevertheless important portion of the literature dealing with this subject. Additional information is contained in the works of Csanady [8], Johnson [21], Masch [25], Pearson [32], and Wiegal [40]; these references also contain extensive bibliographies.

4.3 Disposal of Wastewater in Estuaries

Material transport resulting from a steady ocean current is significantly different from transport accompanying oscillating tidal motion. When waste is discharged into a steady ocean current, the wastewater - seawater mixture spreads down current, much like a smoke plume from a smoke stack's emmission to the atmosphere. However, when wastewater is discharged into a receiving water subject to the oscillatory motion induced by tides, the plume folds back and forth upon itself; and as a consequence the features of the plume are greatly masked [36, p. 513]. The models discussed below relate to the determination of the concentration fields of various wastewater constituents when effluent is discharged to a system subject both to oscillatory tidal motion and to fresh water inflow from upland basins.

This section begins with a brief mention of tidal prism theory, a relatively simple but historically significant approach to examining the disposition of wastewater in receiving waters subject to tidal action. Following this we consider more commonly used models based on the advective-diffusion equation, a special form of the law of conservation of matter.

4.3.1 Tidal Prism Theory*

Early mathematical models used to describe the "flushing" process in estuaries were based on the so-called "tidal prism" theory, a tidal prism being defined as the difference between the volumes of water in an estuary at high tide and at low tide. The basic assumptions of the theory are that water entering an estuary on the flood tide is completely mixed with the water contained in the estuary at the previous low tide, that steady state conditions prevail, and that water leaving on the ebb tide does not return. Since complete mixing is postulated, a fraction of the pollutant is flushed from the estuary during each tidal cycle, this fraction being given by the ratio of the tidal prism to the volume of water in the estuary at high tide.

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* This discussion is based on the presentation given by Pritchard [35].

Since observed salinity distributions showed clearly that complete mixing of estuarine waters does not occur, the tidal prism concept was known to present a gross oversimplification. Ketchum [22] extended the theory by assuming that an estuary may be partitioned into a series of volume segments whose horizontal boundaries are limited by the average excursion lengths of water particles during the flooding tide. In each segment total mixing is assumed to occur at high tide so that the tidal prism theory may be applied to each volume segment in succession. For segment n, an exchange ratio, r_n, is defined as

$$r_n = \frac{P_n}{P_n + V_n} ,$$

where P_n is the local intertidal volume and V_n is the low-tide volume.

To see how Ketchum's theory applies to the computation of the distribution of wastewater constituents, consider a given tidal cycle during which an amount R_1 of conservative material enters the n^{th} volume segment. At the end of this cycle an amount $R_1 (1 - r_n)$ will remain in the segment and $R_1 r_n$ will leave on the ebb tide. But what of the material (in amount R_2) which entered the n^{th} segment during the previous tidal cycle? At the beginning of the current cycle, $R_2(1 - r_n)$ will be in segment n; at the end of the current cycle this amount will have been reduced to $R_2(1 - r_n)^2$. This same reasoning can be used to compute the amounts of material currently remaining in segment n from additions made during all previous tidal cycles. To deduce the total amount of material currently in the n^{th} segment it is necessary to add up these quantities; i.e., add $R_1(1 - r_n)$ to $R_2(1 - r_n)^2$, etc. If it is assumed that the amount of material entering the n^{th} segment is constant over time at level R, and if the additions of material over an infinite number of previous cycles are accounted for, then it can be shown [22] that the amount of the substance in the n^{th} segment at high tide will be constant at R/r_n.*

Ketchum applied tidal prism theory to three estuaries having quite different physical characteristics: the Raritan River and Bay, New Jersey; Albernie Inlet, Vancouver Island, B. C.; and Great Pond, Falmouth, Massachusetts. The results computed from the theory proved to be in close agreement with observed distributions although corrections were required for the latter two estuaries to account for incomplete vertical mixing. Tidal prism theory was also considered by Phelps and Velz [34] in their pollution study of New York Harbor. In a recent water quality study of Galveston Bay, Texas, tidal prism theory proved quite useful for preliminary analyses [46].

4.3.2 The Advective-Diffusion Equation

The advective-diffusion equation is a statement of the law of conservation of mass. In dealing with a given estuary the appropriate form of this equation depends ultimately on the degree of mixing.

The simplest case to deal with is a well mixed (or "sectionally homogeneous") estuary; i.e., an estuary that is characterized by the absence of concentration gradients in cross sections perpendicular to the direction of net flow. For such cases a one-dimensional form of the mass conservation equation for a particular substance (referred to as the advective-diffusion equation) can be used to examine the transport of the substance.** It may be

* This result also indicates that to determine the movement of a wastewater constituent when the steady state concentration distribution is known, it is only necessary to multiply the exchange rate (r_n) by the average concentrations in the volume segments.

** This form of the equation would be inappropriate for bays where there is no logical axis on which to construct a one dimensional model.

written as

$$\frac{\partial c}{\partial t}(x, t) = \frac{\partial}{\partial x}\left[E(x, t)\frac{\partial c}{\partial x}(x, t)\right] - U(x, t)\frac{\partial c(x, t)}{\partial x} + R(x, t), \qquad (4\text{-}4)$$

where,

t = time,

x = distance in the longitudinal direction (i.e., the direction parallel to flow),

$c(x, t)$ = concentration,

$E(x, t)$ = longitudinal dispersion coefficient,

$U(x, t)$ = velocity, and

$R(x, t)$ = flux of material resulting from the net effect of sources and sinks.

This equation results from an accounting of the material input to, output from, and decaying within an infinitesimal volume element fixed in space.*

The first term on the right-hand side of equation (4-4) describes the material transport due to mixing. The physical processes incorporated in this term include turbulent diffusion and the dispersion caused by non-uniformities in velocity resulting from the combined effects of boundary friction and density currents, and tidal action. The function $E(x, t)$ is determined empirically, generally by using concentration profile data relating to salinity or dye tracers.**

The second term on the right-hand side of equation (4-4) represents the material transport due to advection; i.e., the physical displacement of

* Derivations of equation (4-4) have been presented by Harleman [15, 16]. Observe that equation (4-4) is, aside from the $R(x, t)$ term, the one dimensional form of equation (3-8) above.

** The similarity between the mixing term in equation (4-4) and the turbulent diffusion expression given by equation (4-1) results because a Fick's law analog is postulated in both cases.

a given volume of liquid. The expression $U(x, t)$, which represents the sum of tidal flow and fresh water flow as a function of time and distance can be determined using hydrodynamic models (see Section 3.0 above).

The third term on the right-hand side of equation (4-4) represents the net rate of production of the substance in question. In the case of dissolved oxygen, for example, $R(x, t)$ represents the difference between oxygen sources (including re-aeration from the atmosphere and the photosynthetic activities of aquatic plants) and sinks (including the biochemical oxidation of organic matter, respiration of aquatic plants, and the metabolic activities of organisms present in bottom deposits).

The model characterized by equation (4-4) is made complete with the specification of boundary conditions and functions for $E(x, t)$, $U(x, t)$ and $R(x, t)$. In practice, a simplified form of the model which abstracts from variations in concentration within a tidal cycle is often employed. Such an analysis can be structured by assuming steady state conditions and considering only a single point within a tidal cycle, such as the time when the tidal flow is zero (i.e., high or low water "slack"). Under these circumstances the concentration of material at given locations at the specified time within a tidal cycle is independent of the number of cycles that has elapsed. Such analysis is said to be for quasi-steady state conditions, where the term "quasi" is used to emphasize that the oscillations of the tide do not permit the concentration of material at a point to be constant within a tidal cycle. In other words, if all other things are constant, tidal fluctuations will cause a repetitive periodic cycle in the value of concentration at a given location.*

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* We emphasize this quasi-steady state case because it is widely employed and relatively simple. However, one dimensional models (with variables averaged over a tidal cycle) have been used to account for variations in fresh water inflow, water temperature, and wastewater discharges over periods of time as long as a year (see, e.g., Pence et al. [33]). Furthermore, models to account for the influence of tidal flow in causing variations in concentration within a tidal cycle have also been developed and are mentioned below.

A common use of equation (4-4) in water quality studies involves the determination of quasi-steady state dissolved oxygen (DO) concentration fields resulting from the combined effects of natural reaeration from the atmosphere and oxygen consumption to oxidize organic matter.* In the most highly simplified case such an analysis involves constant values for E (x, t) and U (x, t); and the water quality variable examined is D, the dissolved oxygen deficit (i.e., the difference between the exisitng value of dissolved oxygen and the maximum possible value). In this case, and with the time derivative set equal to zero because of the postulated quasi-steady state condition, equation (4-4) takes the following form.

$$E \frac{d^2D}{dx^2} - U \frac{dD}{dx} + K_1L - K_2D = 0, \qquad (4\text{-}5)$$

where K_1 and K_2 are empirical constants, and $(K_1L - K_2D)$ represents the difference between the oxygen input due to atmospheric reaeration $(-K_2D)$ and the oxygen consumed in stabilizing organic material (K_1L). The variable L represents the concentration of biochemical oxygen demand (BOD), an operationally defined measure of the biodegradeable organic matter present.

Equation (4-5) cannot be solved without specification of L. This can be deduced using a separate mass conservation analysis for BOD. Under the conditions postulated above equation (4-4) written for BOD takes the form

$$E \frac{d^2L}{dx^2} - U \frac{dL}{dx} - K_1L = 0, \qquad (4\text{-}6)$$

where K_1L represents the rate of change of BOD resulting from biochemical

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* Although more complex effects can be dealth with (e.g., respiration of aquatic plants), this simple situation is satisfactory for our purposes.

oxidation of organics. The inputs of organic waste in the form of effluent discharges are introduced in the analysis as boundary conditions.

Equations (4-5) and (4-6) represent a coupled set of differential equations that must be solved simultaneously to yield the dissolved oxygen deficit and BOD concentration fields. This is an especially simple coupled set since equation (4-6) can be solved for L independent of D.* The resulting solution then serves as input to equation (4-5) which in turn is solved for D.

The results from a study by O'Connor [29] can be used to illustrate the extent to which predictions from quasi-steady state analyses can reproduce observed data. O'Connor used one-dimensional advective-diffusion equations (similar to equations (4-5) and (4-6), above) as the basis for a model to predict dissolved oxygen and biochemical oxygen demand in the Upper East River, New York. Figure 4-6 shows a comparison between predicted and observed values for both water quality indicators. Although the modeling results do not yield details concerning variations in concentration within a tidal cycle, they are often considered satisfactory for purposes of devising basin wide water pollution control programs.**

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* More sophisticated models might involve several differential equations that must be solved simultaneously because of the interactions between the various water quality variables. This occurs, for example, in modeling the distribution of compounds of nitrogen in water. (See Thomann *et al.*, [45]).

** See Smith and Morris [40] for a detailed review of how a similar model for the Delaware Estuary was used to devise pollution control programs.

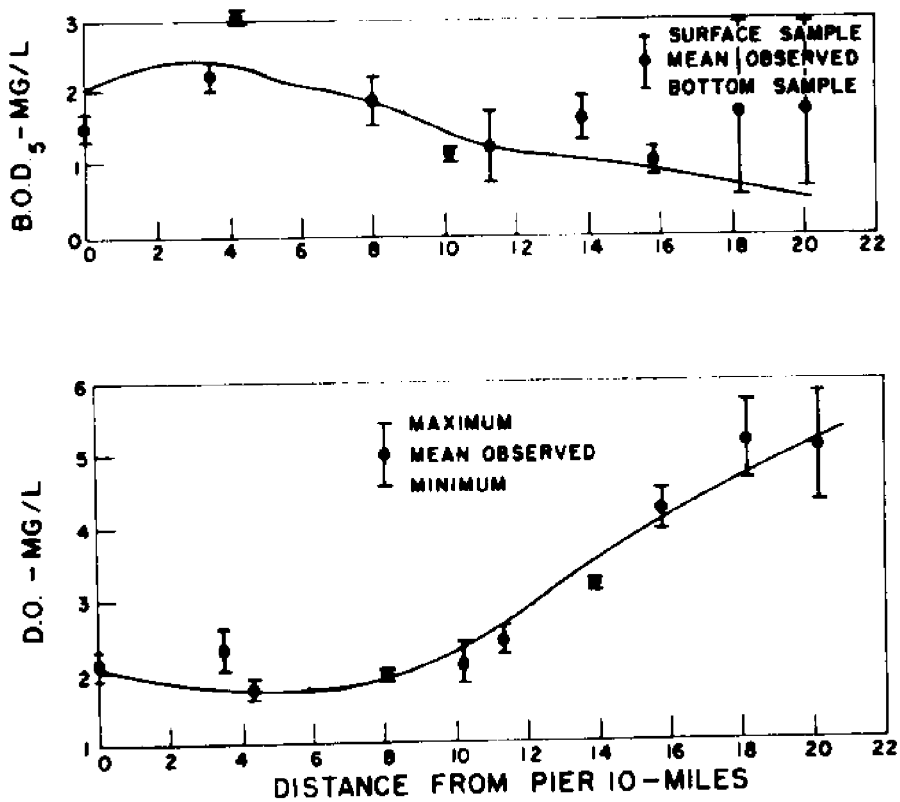

Fig. 4-6. BOD and DO distributions, East River, N. Y., July 1960 (from O'Connor [29]).

A number of one-dimensional models for deducing the spatial distribution of wastewater constituents (typically dissolved oxygen and BOD) under quasi-steady state conditions have been developed for estuaries in the New York metropolitan area. In a study for the Interstate Sanitation Commission, Quirk, Lawer and Matusky [36] prepared such models for two major systems: the Arthur Kill, including the bounding waters of Newark Bay, Raritan Bay and the Raritan River, and the lower Hudson River, including the bounding waters of the East River and Upper New York Bay. O'Connor's [29] models for the Upper East River were mentioned above.*

We have described, above, the use of the one dimensional advective-diffusion equation to determine longitudinal concentration profiles in a well mixed estuary. However, for many of the Long Island coastal waters a one-dimensional analysis may be difficult to structure in a meaningful way (e.g., bays having no logical single direction of net flow). In such cases a two-dimensional model (or in special cases, a model based on a network of one-dimensional channels) may be called for. While there is only limited experience with such models to date, it is anticipated that they will be used with increasing frequency in the near future.**

Early in 1970 Leendertse [24] and Fischer [13] reported on two-dimensional water quality models capable of predicting the distribution of materials that are either conservative, or can be assumed to decay according to first order reaction kinetics (e.g., coliform, BOD). Leendertse' model is based on on a two-dimensional form of the advective-diffusion equation (i.e., the x, y plane). Fischer's model uses a somewhat different approach; it traces the

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* Still other examples of the use of models based on the advective-diffusion equation are given in works by Pritchard [36], O'Connor [30], Hetling [20], and Thomann and Sobel [44], among others.

** We know of no three dimensional water quality models that have been used for real-world systems.

behavior of individual "markers particles" throughout a tidal cycle.* However, the models are similar in that they:

- Assume a uniform water density, and no vertical density stratification,
- Use a two-dimensional hydrodynamic analysis as a preliminary step to develop the horizontal components of velocity,**
- Have yielded plausible results for computations based on hypothetical systems, and
- Await verification with field data.

Leendertse is actively pursueing the verification of his model using data for Jamaica Bay [24, p. 38]. Fischer has been unable to obtain "data taken under sufficiently well controlled conditions to provide verification" [13, p. 133].

4.4 Specific Wastewater Constituents

In the two preceding sections we described a number of approaches for predicting aspects of the concentration fields associated with various wastewater constituents. However, we have not given any indication of the relative ease (or difficulty) with which specific components can be modeled in practice. This topic is considered below for wastewater characteristics of established significance in the coastal waters of Nassau and Suffolk Counties [41]; i.e., dissolved oxygen, biochemical oxygen demand, coliform bacteria and compounds of phosphorous and nitrogen. Brief remarks are also made about the transport of waste heat and pesticides, because of the potentially deleterious effects accompanying their additions to the coastal waters of Nassau and Suffolk Counties.

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* Fischer's approach is described in reference [13], which also contains a listing of the related computer program and instructions for its use.

** Temporal variations within a tidal cycle are accomodated.

The wastewater characteristics that have received the greatest amount of attention by water quality specialists are dissolved oxygen, biochemical oxygen demand, and coliform bacteria. The distribution of dissolved oxygen and biochemical oxygen demand in natural watercourses has been the subject of active research for more than five decades, and consequently there is a considerable body of relevant information available (See, e.g., O'Connor [31], and also Section 4.3 above). Models for dealing with these constitutents can formally account for the following factors: direct inputs of oxygen and organic wastes, scouring and sedimentation of organics, benthal deposit oxygen demand, and the respiration and photosynthesis of plant life.

As mentioned, the problem of determining the concentration field of coliform bacteria has also received considerable attention. (See, also, Section 4.2 above.) A committee of the American Society of Civil Engineers (ASCE) has observed that "the sanitary bacteriology of waste disposal in marine waters has received more attention from engineers than all other aspects" [3, p. 125]. Laboratory and controlled field experiments have indicated that bacterial survival in marine waters is influenced by sedimentation, sunlight, stravation, bactericidal substances, microbial antagonism, bacteriophage, and predation. Further details are given in the works of Camp [5] and the ASCE Committee on Sewerage and Sewage Treatment [3].

Important wastewater constituents whose distributions are difficult to model include the various compounds of phosphorous and nitrogen; these compounds play an important role in the production of "excessive" growths of aquatic plants. Difficulties in modeling result from the various interactions among the water quality variables (e.g., ammonia, nitrate, nitrite) and also with the life processes of aquatic organisms. Efforts to describe quantitatively the transport of nitrogen and phosphorous compounds in streams have been initiated only recently.

(See, for example, Stratton and McCarty [43], and Hetling [19].) For coastal waters, where salinity, flow, and the degree of mixing are highly variable, the situation is correspondingly more complex than it is in streams.* (See Thomann et al., [45]).

A somewhat different aspect of wastewater disposal in coastal waters concerns the disposition of waste heat which often originates as cooling water from electric power plants. Models which rest fundamentally on a heat balance equation have been developed to predict the temporal and spatial distribution of water temperature for a number of circumstances. For a sectionally homogeneous estuary such models are based on equations having a form analogous to equation (4-4), where the variable c(x, t) corresponds to temperature, and the R(x, t) term incorporates the various heat sources and sinks like short wave solar radiation, long wave atmospheric radiation, etc. Edinger and Geyer, in reviewing the literature on models for predicting temperature in natural waterways, observed that "use of the basic heat equation is an act which depends for success on the experience and imagination of the individual as well as on an abundance of observational data" [9, p.99].

The problem of predicting the transport of pesticides from their point of application to coastal waters is extremely complex because of the poorly understood intermediate physical, chemical and biological interactions. Research done on the fate of pesticides in soils and water has indicated that losses may occur "by processes of volatilization, chemical decomposition, photodecomposition, biological metabolism, and mechanical removal through crop absorption" [27, 28]. Compared to substances mentioned above,

* There is a substantial body of qualitative information describing the fate of phosphorous and nitrogen compounds in coastal waters. (See, for example, Ketchum [23] and Reid [39].) The vast literature on phytoplankton population models is also relevant to these issues. (See Di Toro et al., [7]).

the ability to predict pesticide transport is quite poor.*

4.5 Concluding Remarks

The various models that have been described in this chapter yield information about the concentration fields for particular wastewater constituents discharged to coastal waterways. The reliability of predictions vary greatly among the different substances of importance in the Long Island area. Using available theories it is possible to obtain fairly good predictions for dissolved oxygen, biochemical oxygen demand, coliform bacteria, and temperature. However, we know far less about the transport of compounds of phosphorous and nitrogen, and pesticides, and consequently we can expect the resulting predictions to be fairly poor.

The question of "linking" hydrodynamic models with the models described in this section requires a word of explanation. If water quality predictions under "quasi-steady state conditions" are all that is required, then it may be quite unnecessary to undertake a detailed hydrodynamic analysis of the type described in Section 3.0 because the net tidal flowrate integrated over a tidal cycle is zero. All that is required in the models based on the advective-diffusion equation is the net freshwater flowrate. On the other hand, if predictions of concentrations within a tidal cycle or under non-steady-state conditions are desired, then some form of hydrodynamic analysis is required to determine the tidal component of flowrate (or velocity) as a function of time.

* There have been a large number of empirical investigations of pesticide transport [76, 42] but, understandably, a relatively small effort has been devoted to the development of mathematical models for prediction (see, e.g., Hamaker [15]).

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5.0 SUMMARY

5.1 Hydraulic Models

Hydraulic models are small-scale replicas of water bodies and have been widely used by the U. S. Army Corps of Engineers and others to examine the movement (and to a lesser extent the quality) of coastal waters. The dimensions of hydraulic models are chosen such that the model and the real system behave similarly with respect to forces and motions for the processes under study.* In simple situations, it is often possible to use well-founded theoretical principles to obtain model dimensions. However, for phenomena in the coastal zone, simple similarity criteria are generally impossible to satisfy and it is necessary to depart from purely theoretical considerations. This usually involves physically modifying the model until accurate reproductions of real system behavior are obtained. The validity of such models for the prediction of changes in the real system under altered conditions is theoretically a moot question, but the models have yielded useful results in practice. In cases where phenomena are so complex that more rigorous methods of analysis are impractical, the use of a hydraulic model may be the only fruitful approach. Because of such necessary departures from theory, hydraulic modeling has been called "art rather than science."

On the basis of several hydraulic modeling studies of coastal processes in diverse water bodies, there appears to be no difficulty, in principle, in constructing and verifying hydraulic models for the coastal waters of Long Island. These models might be expected to explain aspects of tidal circulation,

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* While the ratio of lengths between a model and the corresponding real system varies, typical values are in the order of 1:1000 in the horizontal and 1:100 in the vertical. Consequently, extensive building facilities are sometimes required to house such models.

and salinity patterns as they are influenced bv shoaling, wind and storm action, dredging, freshwater flow, and tidal action. The role of hydraulic models in predicting the distribution of wastewater constituents is rather limited, because of the difficulty in simulating the behavior of materials that decay over time.

5.2 Hydrodynamic Models

Hydrodynamic modeling is a more abstract approach in which physical interactions in the coastal zone are represented in a mathematical simulation by appropriate equations. One such equation, a mathematical representation of Newton's second law of motion, states that the sum of the forces acting on a fluid particle is equal to the product of the particle's mass and acceleration. Forces acting in coastal water bodies include the Coriolis force,* and forces due to changes in pressure, and to gravity and friction. A second fundamental relationship, referred to as the "continuity equation," is a mathematical statement of the balance between fluid entering and leaving an arbitrarily small volume of fluid fixed in space.

A hydrodynamic model of a coastal water body consists of these basic equations of motion and continuity, together with suitable boundary and/or initial conditions.** Solutions for these equations yield the velocity field and the water height field for the water body in question. (Velocity field denotes velocity as a function of time and space.) Most hydrodynamic models of practical significance must be solved using numerical integration methods, which involve high-speed electronic computing facilities. When solving hydrodynamic models numerically, a set of grid points is superimposed on the coastal water body in question; it is only at grid points that measures of

* An apparent deflection force acting on a moving water body due to the rotation of the earth.

** These conditions prescribe values of selected model variables to reflect the geometric configuration and initial state of the real system.

the velocity and water height are evaluated. The extent to which the time and/or space coordinate grid can be refined is limited by the following conditions: 1) computer storage capacity; 2) cost of computer time; and 3) theoretical conditions to prevent numerical instability in the solution technique.

Individual hydrodynamic modeling studies have been carried out for numerous coastal water bodies in the United States. One study is cited in Section 3.3 to demonstrate the approach followed in a typical determination of flow velocities and water heights. The related discussion (in Section 3.3) serves to illustrate the following:

- One-dimensional forms of the basic equations are appropriate in some circumstances.

- Boundary and/or initial conditions, and particular model "input" parameters and coefficients serve to make the basic equations representative of the water body under study.

- Model predictions (in this case, computed values of velocity and water height) are obtained by solving the basic equations with location specific boundary conditions, etc.

- Model verification involves making predictions using the model and comparing these with corresponding observed data to determine the level of agreement between the two.

Other studies in Section 3.0 are used to describe how hydrodynamic modeling can be employed to examine storm surge, shoaling, flow through inlets, and salinity patterns. Modeling of salinity distribution requires the stipulation of a continuity equation for salt, in addition to the equations of motion and continuity mentioned above. The need for this additional equation explains, in part at least, why models for predicting salinity patterns in detail are not solved as easily as those involving only the determination of velocities and water heights.

Two models in Section 3.0 are especially noteworthy. One involves a two dimensional hydrodynamic model of Jamaica Bay that is currently (1970) being investigated. The second involves a similar model, also appropriate for bays, that has been presented in farily general form with a complete listing of the requisite computer program and instructions for its use.

In principle, hydrodynamic models can be used to determine how velocity, water height and salinity are influenced by changes in geometric configuration (e.g., widening bay inlets), tidal action, freshwater inflow, and wind. In practice, the feasibility of such determinations is limited by the size and speed of the present electronic computers, and the ability to devise numerical integration schemes that are both stable and convergent. Compared with hydraulic models, the hydrodynamic models require no large building facilities and they may, under some circumstances, provide greater flexibility for modeling a number of different processes simultaneously. Among modeling specialists, there is no general agreement on whether the "more physical" hydraulic models or the more abstract hydrodynamic models should be used in specific circumstances. All models have strengths and weaknesses; decisions on which type to employ depend heavily on the circumstances involved, including the purpose of the model.

5.3 Water Quality Models*

Water quality models are mathematical representations designed to assess the mixing, transport and reactions of substances contained in wastewater discharges They are useful for predicting the concentration of wastewater constituents in coastal waters as a function both of time and space. Wastewater constituents of interest in the Long Island area include dissolved oxygen, biochemical oxygen demand, coliform bacteria, and compounds of phosphorous and nitrogen as well as pesticides and waste heat.

Wastewater discharges may be made directly into the ocean via "submarine outfalls," or indirectly into the ocean via discharges into estuaries (including bays). The task of tracing the impact of direct discharges on the concentration of various substances can be described in two parts: (1) mixing in the immediate vicinity of the discharge point, and (2) the lateral mixing and further spreading of the wastewater-seawater mixture. The extent of laboratory and field level research that has been conducted, and the extent of agreement obtained by different investigators using alternative approaches to the same problems, are reviewed briefly in Section 4.2.

For situations where wastewaters are discharged to estuaries, tidal prism theory can be used to obtain preliminary estimates of waste transport.** (A tidal prism is the difference between the volume of water present in an estuary at high and low tide.) Predictions of waste transport can be based on a postulated mechanism by which the prism flushes wastes to sea on the ebb tide (see Section 4.3).

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* Models for predicting the movement and quality of ground water were considered beyond the scope of this report. However, many of the equations (e.g., equations of motion and material conservation) and modeling procedures described herein are involved. (See, e.g., Nelson [3].) Issues related to sludge disposal, while important to Long Island, were also outside the scope of this report.

** While this approach is no longer used widely, it is important because of its simplicity and historical significance.

Detailed estimates of waste transport in estuaries can be obtained using models based on the "advective-diffusion equation," a special form of the law of conservation of matter written for particular wastewater constituents. One-dimensional forms of this equation have been used recently to predict the distribution of municipal waste discharges in several water bodies in the New York Metropolitan area, including the lower Hudson River, the East River, and Arthur Kill. A two dimensional form of the advective-diffusion equation is being used in a current (1970) effort to model water quality in Jamaica Bay.*

There are significant differences in the relative ease (or difficulty) involved in modeling different wastewater constituents. Using currently available theories it should be possible to obtain fairly good predictions for dissolved oxygen, biochemical oxygen demand, coliform bacteria and temperature. However, much less is known about the transport of compounds of phorphorous and nitrogen, and pesticides, and consequently the resulting predictive schemes can be expected to yield results that are fairly poor.

5.4 Models and Decision Making - An Example

The models described herein have considerable utility in providing background information on the environmental impacts of alternative courses of actions. A recent modeling study for the Village of Freeport, Long Island serves to demonstrate the way such models can be used.

In 1969, Hydroscience, Inc., reported on the results of a study to determine the following [2]:

- The impact of existing discharges from the Village of Freeport sewage treatment plant on the quality of portions of Hempstead Bay influenced by the tidal prism of Jones Inlet.
- The changes in water quality likely to result from increasing the levels of reduction in biochemical oxygen demand at the existing plant.

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* Subsection 4.3.2 makes reference to an unverified two-dimensional model for selected water quality variables that has been presented with a listing of the requisite computer program and instructions for its use.

- The changes in water quality likely to result by locating the plants' discharge at different points in Hempstead Bay - with and without additional waste treatment to remove nutrients.

- The distribution of coliform organisms likely to accompany the discharge of the plant's waste at alternative ocean disposal locations.

The portions of Hempstead Bay comprising the study area are shown in Figure 5-1. The water quality models were structured by assuming a one-dimensional flow pattern in each of the several creeks and channels. Figure 5-2 shows the idealized network of one-dimensional channels.

Because only net flows over a tidal cycle were considered, no hydrodynamic modeling was required. (The water quality studies were for assumed steady-state conditions.) The water quality model of the Bay consisted of alternative forms of the advective-diffusion equation for the following variables: biochemical oxygen demand, dissolved oxygen, chlorides, total nitrogen and total phosphorous.*

The principal boundary conditions related to the input of waste load from various sources, and the technical consistency of the idealized network. Concerning the latter, it was required that the concentration of a substance entering and leaving a given channel inter-connection be equal. Similarly, it was required that materials be conserved at such inter-connections. In its final form the model had 37 equations which were solved simultaneously using a digital computer.

Once the model of Hempstead Bay was structured, it was necessary to examine records of existing data to estimate the various coefficients that served as inputs to the model. These included the following: cross sectional areas for all channels; freshwater flows from tributary streams and overland runoff; values for dispersion coefficients, rates of decay for nonconservative

* The model assumed that total nitrogen and total phosphorous are conservative, and neglected the role of aquatic plants in the nitrogen and phosphorous cycles.

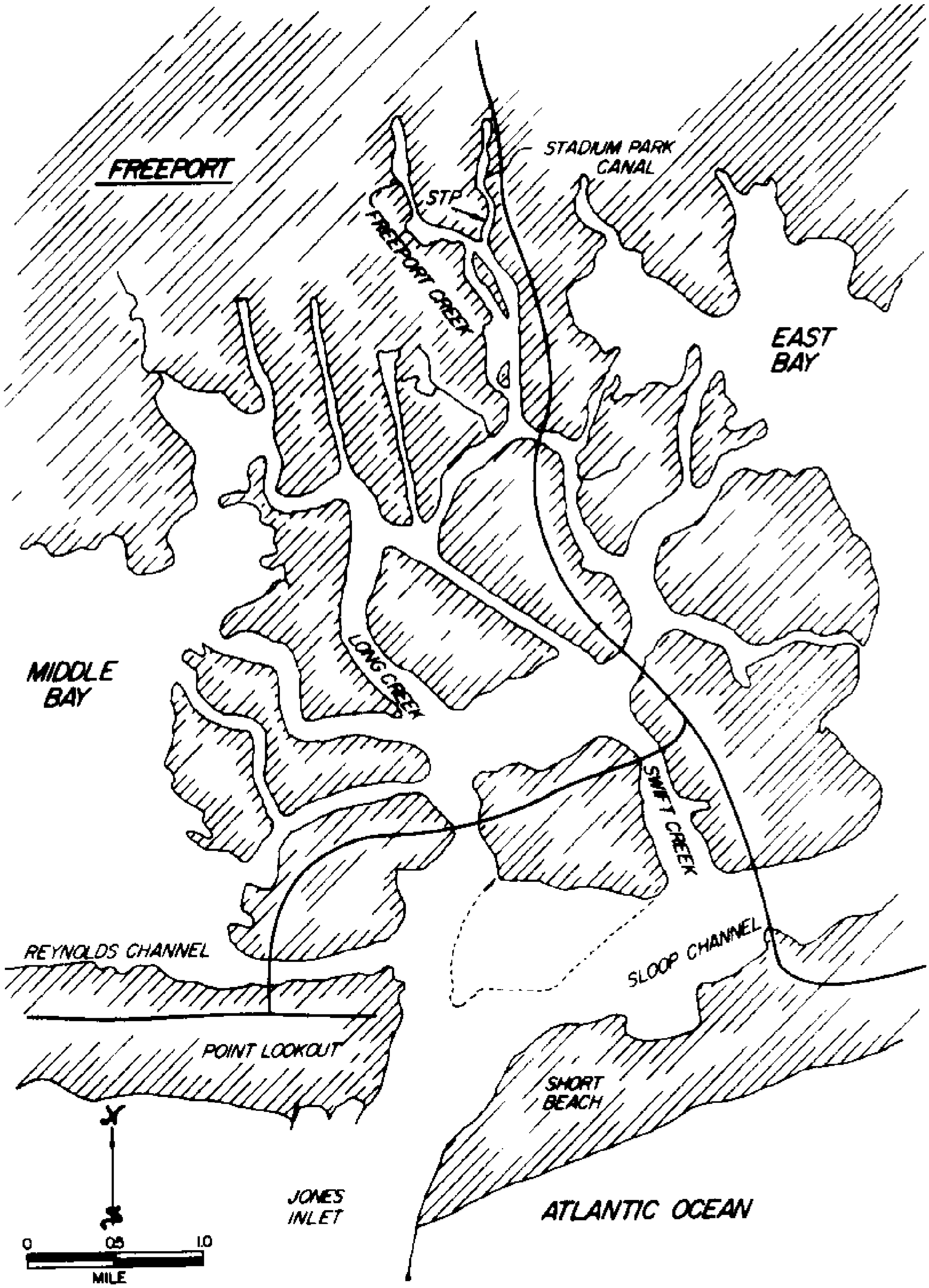

Fig. 5-1. Location map - Hempstead Bay (from Hydroscience, Inc. [2]).

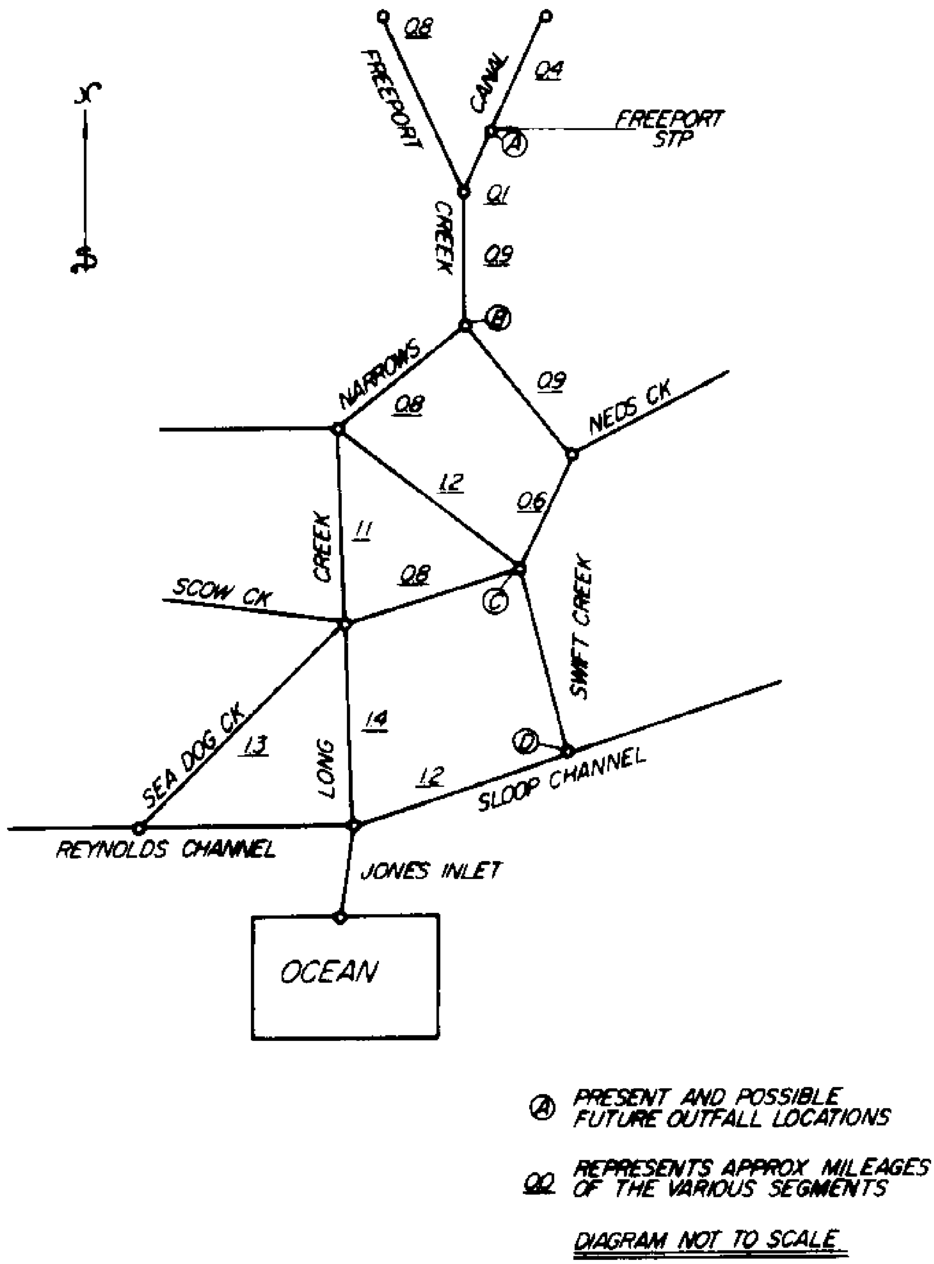

Fig. 5-2. Schematic diagram of study area. (from Hydroscience, Inc. [2]).

substances, and rates of reoxygenation from the atmosphere. It was also necessary to estimate the quality and quantity of the effluent from the Village of Freeport sewage treatment plant.

The requisite input information was determined and the model was "run" to see how well its predictions correlated with historical observation. Hydroscience, Inc., concluded that the agreement between observed and predicted water quality distributions was "reasonably satisfactory", and that the model was ready for use in estimating water quality for future loading conditions. It was acknowledged, however, that in the event a Bay discharge appears practicable, "further sampling work should be conducted to verify and refine the mathematical model" [2, p. 45].

The model was used to estimate the distribution of dissolved oxygen and nutrients (as represented by orthophosphate and total inorganic nitrogen) for a variety of postulated discharge locations; i.e., points labeled A, B, C and D in Figure 5-2.* A typical model output is given in Figure 5-3 which shows the dissolved oxygen reductions associated with future waste loads from the Freeport plant when discharged at points B, C and D. The horizontal axis in the figure represents distance along the path from the Freeport sewage treatment plant to Jones Inlet via Swift Creek and Sloop Channel. The figure also shows the expected increase in orthophosphate and total inorganic nitrogen concentrations associated with discharge locations B, C and D. Other model computations related to the distribution of coliform bacteria in the Bay, and the effect of providing additional waste treatment to remove nutrients.

The Hydroscience study also examined the implications of discharging the effluent from the Village of Freeport sewage treatment plant at various points

* In estimating future conditions it is necessary to account for possible changes in model inputs (especially decay coefficients) that would obtain under the postulated conditions; such changes are accounted for on the basis of experience and judgement.

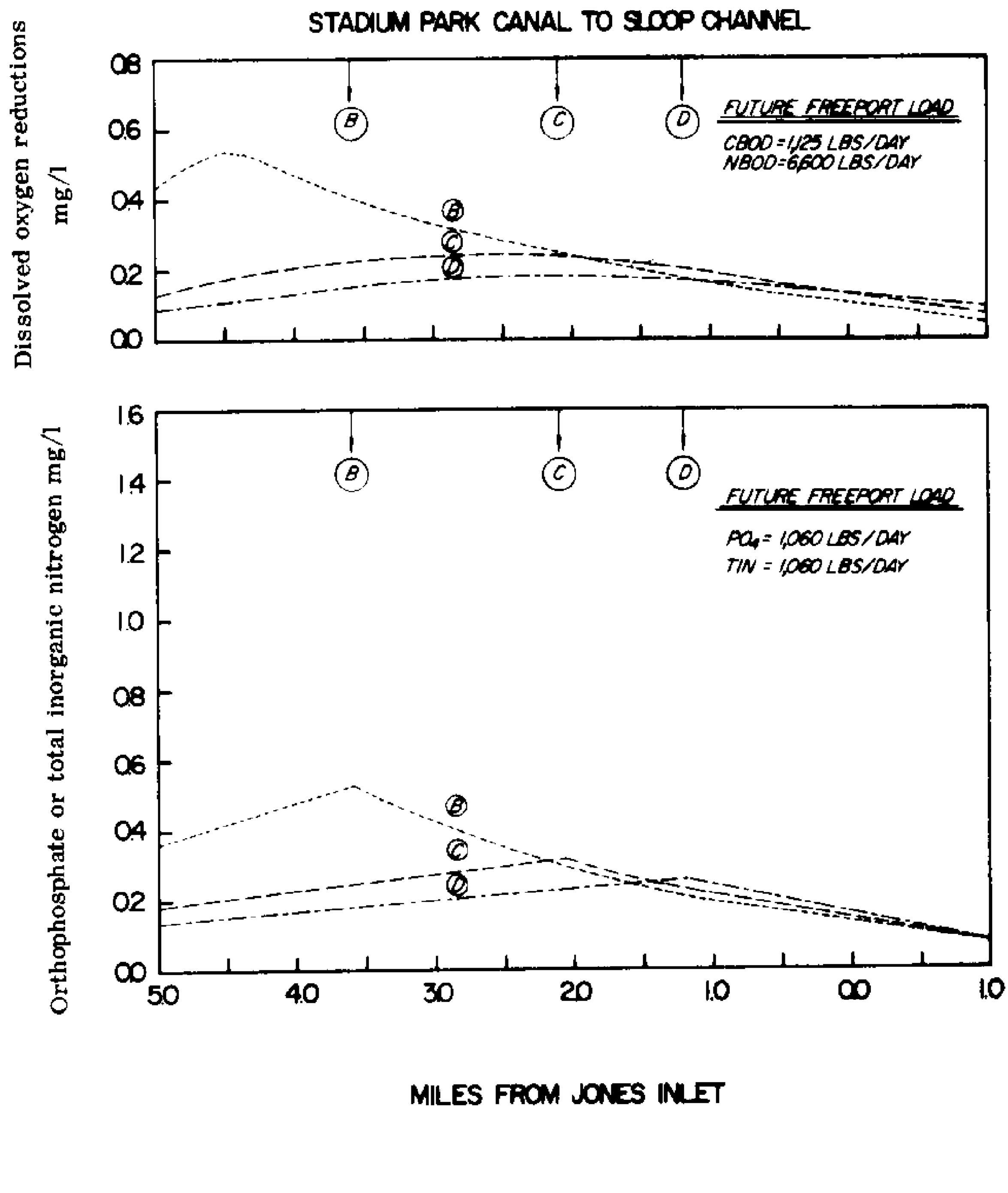

Fig. 5-3. Projected dissolved oxygen reductions and nutrient distributions for alternate outfall locations. (from Hydroscience, Inc. [2]).

in the ocean. They used results similar to those described in Sub section 4.2.1 above to compute the dilution resulting from turbulent mixing at the points of discharge. Brooks' model (see Sub section 4.2.2, above) was used to determine the coliform concentrations at various points between the proposed outfall locations and beaches on the south shore. Reducing coliform concentrations to acceptable levels and maintaining aesthetic quality were important criteria in deducing acceptable ocean outfall locations.

The information presented in the Hydroscience report is of direct relevance for deciding on a location and extent of treatment for the Village of Freeport's wastewaters. In addition to describing the concentration distributions associated with various proposals, the report considered existing water quality standards and the various water uses influenced by different quality levels. All of this information could be supplemented with estimates of the costs of alternative schemes; i.e., the costs of building and operating the different combinations of waste treatment and piping.* Taken together, the information on alternative schemes, (i.e., their costs and impacts on water quality and water use) can provide the basis for deciding on how much to treat and where to locate the point of effluent discharge.

5.5 Models in Perspective

We have alluded to Long Island's coastal problems and described a number of models that could be useful in managing these problems. Below, we put the role of the models described above in perspective; they are, after all, capable of yielding information about only some aspects of a selected number of problems.

Figure 5-4 indicates a number of issues that should be considered by the

* The Hydroscience report was not intended to be complete in this regard; in fact, it was conducted for Baldwin and Cornelius Company, a consultant to the Village of Freeport.

1. Identify: Problems	Wetlands Preservation	Thermal Pollution	Dredging & Spoil Disposal; Coastline Stabilization -- etc.
Water Bodies	Great South Bay	Huntington Bay	Long Island Sound -- etc.
Specific Issues	Should Moriches Inlet by widened? Should more public beaches be provided? Should spoil disposal in Great South Bay be prohibited?		
2. MRC Priority Issues	Should direct waste discharges to Great South Bay be permitted? ⋮		
3. Examine options for further study	None, decide now.	Study, but <u>not</u> with models of the type described herein.	Study with models of the type described herein.

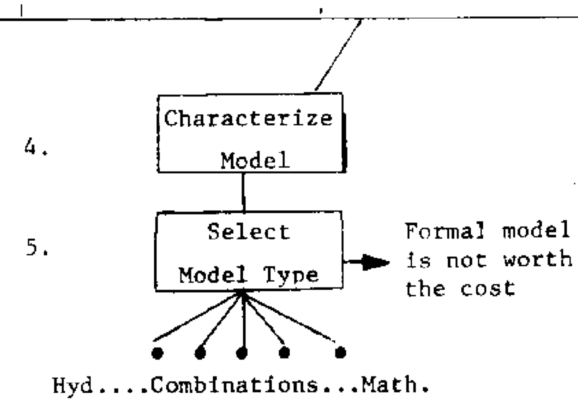

Figure 5-4: Initiating Model Development

Marine Resources Council before initiating any large-scale model development program. The first item in the figure needs no elaboration since it represents the materials presented in earlier TRC reports [1, 4]. This involves identifying marine resource problems for various locations on Long Island and raising questions for further consideration by the Council and others.

The Marine Resources Council could not possibly address in depth each potential problem or issue that is identifiable on Long Island; and, as was emphasized in Section 1.2 above, no single model could be developed to deal with all problems. Clearly, some form of screening will be necessary if models of the type described herein are to be exploited by the Marine Resources Council. The criteria to be used in selecting issues (Item 2) to be examined in depth are linked to the value system and perspectives of the Council. In other words, the screening will be tied intimately to the role that the Council feels it should play in dealing with Long Island's coastal problems.

There is no "value free" (or completely objective) manner in which problems can be selected for detail study involving the time and expense of model building. Because the selection of problems for detailed analysis is well beyond the scope of this report, we will assume, for purposes of this discussion, that the Council has identified issues of high priority that warrant detailed study. An illustrative example might relate to whether direct waste discharges to Great South Bay should be permitted.

Given that the Marine Resources Council has before it a specific issue, there are (again, for purposes of this discussion) three possibilities (Item 3). The Council might decide that it is too expensive to delay any decisions by waiting for the results of a study. On the other hand, it might decide that further studies are both possible and desirable, but that such studies should relate to ecological issues, or economic questions, or in fact, something other than the models discussed herein. The third possibility, and the one we pursue below, is the case where the models described above appear appropriate for further consideration by the Council, either alone or in addition to other studies.

At this stage (assuming the third possibility were followed), it would be appropriate to develop preliminary ideas about model characteristics and to initiate a dialogue with engineers and scientists expert at modeling. These preliminary characteristics (Item 4) would include the approximate physical boundaries of the study area, the most pertinent physical processes to be considered,* and the detail or resolution (in time and space) required of a model to be developed.

In general, the greater the degree of resolution required in model predictions, the more costly the model. A useful exercise to help identify preliminary characteristics of a model is to postulate a set of model predictions, and then determine how they would be used to influence a decision about the problem under study. This can serve to reveal the level of detail required in model outputs.

Assuming it has been decided to consider developing a model to examine a particular issue, or set of issues, a host of questions remain (Item 5): Should a hydraulic model, a mathematical model, or a combination of both model type be developed?** Given the substantial costs for development and verification, should a model study be initiated at all? Should the model predictions be

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* For example, an issue related to the impact on flow patterns of dredging in a particular bay might require a model for predicting velocities; material transport would be of less or no importance.

** The state-of-the-art in modeling physical processes in the coastal zone is such that one could not expect to obtain agreement among experts as to the kind of model that should be used to examine a particular issue. An expanded discussion of this point is contained in Masch's review of a recent Corps of Engineers study on modeling [5, Appendix II-B].

at a level of detail to reflect variations within a tidal cycle, or should they be average values over a tidal cycle? These questions relate directly to the reliability of the output predictions and the associated costs of the modeling effort.

The questions posed in the preceding paragraph are, in principle at least, amenable to the kind of formal cost-benefit comparison often used in making decisions involving the expenditure of public funds. In practice, because of the difficulties in estimating benefits (see, e.g., [5]), these questions are generally resolved on the basis of expert judgement and experience. In any case the expenditure of tens (and often hundreds) of thousands of dollars required for model development and verification dictates that the question of modeling costs and benefits be addressed at some level.

5.6 Selected References

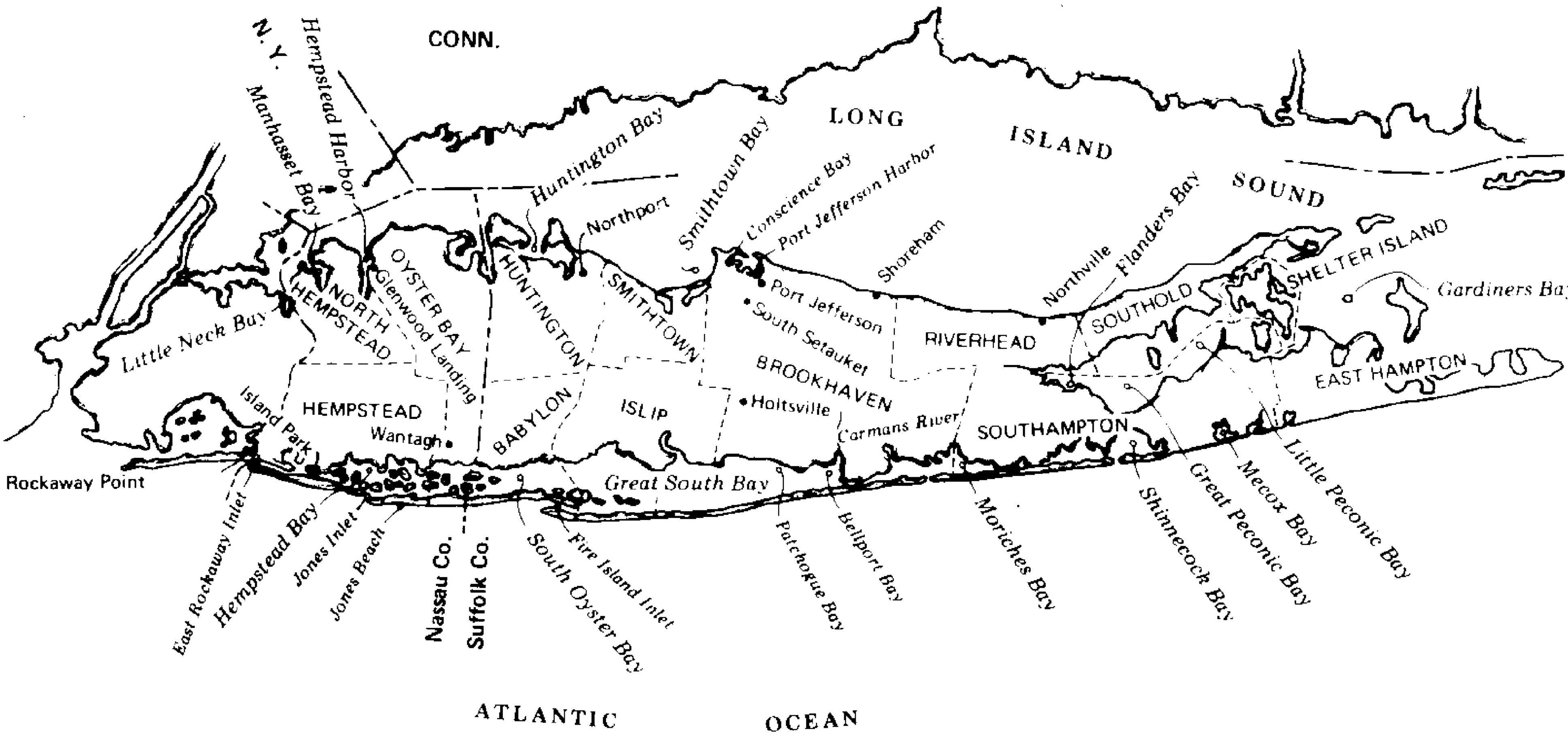
1. Ellis, R. H., et al., The Classification of Marine Resource Problems of Nassau and Suffolk Counties, TRC Report No. 7722-347b, The Travelers Research Corporation, Hartford, Conn., April 1969.

2. Hydroscience, Inc., The Influence of Freeport Wastes on Water Quality in Hempstead Bay and Requirements for Ocean Disposal, Leonia, New Jersey, July 1969.

3. Nelson, R. W., "A Sequence for Predicting Waste Transport by Ground Water," Water and Sewage Works, Reference Number - 1966, pp. R-85 through R-93.

4. Smith, F. A., et al., Fourteen Selected Marine Resource Problems of Long Island, New York: Descriptive Evaluation, TRC Report No. 7722-377, The Travelers Research Corporation, Hartford, Conn., January 1970.

5. U. S. Army Corps of Engineers, Guidelines for Evaluating Estuary Studies, Models and Comprehensive Planning Alternatives, Washington, D. C., August 1969.


CONN.
N.Y.
LONG ISLAND SOUND
Manhasset Bay
Hempstead Harbor
Huntington Bay
Northport
Smithtown Bay
Conscience Bay
Port Jefferson Harbor
Shoreham
Northville
Flanders Bay
SHELTER ISLAND
Gardiners Bay
Little Neck Bay
NORTH HEMPSTEAD
OYSTER BAY
Glenwood Landing
HUNTINGTON
SMITHTOWN
Port Jefferson
South Setauket
BROOKHAVEN
RIVERHEAD
SOUTHOLD
EAST HAMPTON
HEMPSTEAD
Island Park
Wantagh
BABYLON
ISLIP
Holtsville
Carmans River
SOUTHAMPTON
Rockaway Point
Great South Bay
East Rockaway Inlet
Hempstead Bay
Jones Inlet
Jones Beach
Nassau Co.
Suffolk Co.
South Oyster Bay
Fire Island Inlet
Patchogue Bay
Bellport Bay
Moriches Bay
Shinnecock Bay
Great Peconic Bay
Mecox Bay
Little Peconic Bay
ATLANTIC OCEAN